NEPR

Received:

Oct 23, 2019

2:32 PM

COMMONWEALTH OF PUERTO RICO
PUBLIC SERVICE REGULATORY BOARD
PUERTO RICO ENERGY BUREAU

IN RE: INTEGRATED RESOURCE PLAN FOR THE PUERTO RICO ELECTRIC POWER AUTHORITY	**CASE NO.**: CEPR-AP-2018-0001 **SUBJECT**: PETITION OF PROGRESSION ENERGY TO INTERVENE

PROGRESSION ENERGY'S MOTION SUBMITTING WRITTEN TESTIMONY

TO THE HONORABLE PUERTO RICO ENERGY BUREAU:

COMES NOW Progression Energy ("PE"), through the undersigned counsels, and respectfully states, alleges and claims as follows:

1. Pursuant to the Puerto Rico Energy Bureau Procedural Calendar, PE hereby submits Kevin Banister Direct Testimony.

2. Mr. Banister's testimony is duly attested. However, he is currently outside the jurisdiction of the United States. Therefore, such document will be notarized before a Notary Public at the earliest convenience.

RESPECTFULLY SUBMITTED,

IN SAN JUAN, PUERTO RICO, THIS 23 DAY OF OCTOBER 2019.

CERTIFICATION OF FILING AND SERVICE

I hereby CERTIFY that on **October 23 2019**, I have sent the above Motion submitting Written Testimony to the Puerto Rico Energy Bureau through its electronic filling tool at https://radicacion.energia.pr.gov; and to secretaria@energia.pr.gov and wcordero@energia.pr.gov; the Bureau's Office of Legal Affairs to legal@energia.pr.gov and sugarte@energia.pr.gov and to the Puerto Rico Electric Power Authority to the following: Nitza D. Vázquez Rodríguez nvazquez@aeepr.com; Astrid I. Rodríguez Cruz astrid.rodriguez@prepa.com; Katiuska Bolaños kbolanos@diazvaz.law and to Jorge R. Ruíz Pabón Jorge.ruiz@prepa.com. And to: acarbo@edf.org; javier.ruajovet@sunrun.com; pedrosaade5@gmail.com; rmurthy@earthjustice.org; carlos.reyes@ecoelectrica.com; ccf@tcmrslaw.com; victorluisgonzalez@yahoo.com; mgrpcorp@gmail.com; hrivera@oipc.pr.gov; jrivera@cnslpr.com; manuelgabrielfernandez@gmail.com; acasellas@amgprlaw.com; corey.brady@weil.com; paul.demoudt@shell.com; agraitfe@agraitlawpr.com; castrodieppalaw@gmail.com; voxpopulix@gmail.com; cfl@mcvpr.com; sierra@arctas.com; tonytorres2366@gmail.com; info@liga.coop; amaneser2020@gmail.com; escott@ferraiuoli.com; sproctor@huntonak.com; mpietrantoni@mpmlawpr.com; apagan@mpmlawpr.com

LEDESMA & VARGAS, LLC.
P.O. Box 194089
San Juan, Puerto Rico 00919
Tel. (787) 296-9500

f/*Mariana Ortiz Colón*
MARIANA ORTIZ COLÓN
RUA Número 15394
E-mail: maortiz@lvprlaw.com

DÍAZ & NEGRON, LLC
P.O. Box 363004
San Juan, Puerto Rico 00936-3004
Tel. (787) 396-3413

f/*Raúl Negrón-Casasnovas*
RAÚL NEGRÓN-CASASNOVAS
RUA Número 11085
E-mail: rnegron@dnlawpr.com

COMMONWEALTH OF PUERTO RICO
PUBLIC SERVICE REGULATORY BOARD
PUERTO RICO ENERGY BUREAU

IN RE: INTEGRATED RESOURCE PLAN FOR THE PUERTO RICO ELECTRIC POWER AUTHORITY	**CASE NO.**: CEPR-AP-2018-0001 **SUBJECT**: PETITION OF PROGRESSION ENERGY TO INTERVENE

Direct Testimony of

KEVIN BANISTER

On Behalf of

PROGRESSION ENERGY

OCTOBER 23, 2019

Q: Please state your name, title, employer, and business address

A: My name is Kevin Banister. I am a Vice President and Head of Development of Principle Power, Inc (PPI). PPI was incorporated in the State of Nevada, USA and has its office located at 5901 Christie Ave #303, Emeryville, CA 94608.

Q: On whose behalf are you testifying?

A: I am testifying on behalf of Progression Energy as Principle Power, Inc. is a partner in multiple offshore wind projects.

Q: Have you previously testified or made presentations before the Energy Bureau?

A: No

Q: Are there any exhibits attached to your testimony (bio here:)

A: Yes.

Q: What is your professional experience in offshore wind?

A: As mentioned above, I am a Vice President and the Head of Development for Principle Power, the owner/designer of the proprietary WindFloat technology, a floating foundation for offshore wind turbines. The WindFloat enables access to the world class wind resource in deeper waters further from shore, and also presents a paradigm shift in the way offshore wind is deployed, reducing cost and risk across the spectrum. I lead Principle Power's business development activities around the world, which include interactions with utilities, developers, government officials, stakeholders and policy makers in Europe, Asia and the United States. Based on the West Coast of the US, I have almost 20 years in renewable energy with experience in energy policy, energy project development and contract negotiation and planning. I have worked on the establishment of Renewable Portfolio Standards and other policy mechanisms and developed projects ranging from electric vehicle charging stations, to solar power, wave energy and offshore wind projects.

I have also served on the board for the Ocean Renewable Energy Coalition (OREC), am the Board Chair for the Pacific Ocean Energy Trust (POET) and am a founding member of Offshore Wind California.

I am a graduate of the University of California at Santa Barbara and hold a Master of Science ("MSc") degree in Economic Development from the London School of Economics.

Q. What are the purposes and subjects of your Direct Testimony?

A. My Direct Testimony addresses the following purposes and subjects:

1. Provide information showing that offshore wind is a viable and cost-effective renewable energy resource that must be included into PREPAs Integrated Resource Plan ("IRP") to ensure that the Puerto Rican rate payers have access to low cost, indigenous, resilient renewable power that is not depended on imported commodities.
2. I identify specific reports that shows PREPA characterizing that there is a "lack

of reliable data" on offshore wind is inaccurate.

3. Provide preliminary data showing that offshore wind is a complementary resource to solar PV and on shore wind.
4. Provide Levelized cost data for offshore wind projects showing that costs are consistent with PREPAs own 2015 study that estimated the cost of offshore wind energy to reach a cost of $0.10/kWh by the year 2020.
5. Show that PREPA will find it difficult to meet the renewable energy mandate if offshore wind is excluded from the IRP.

Q: Has the IRP evaluate all available resources?

A: No, the IRP did not evaluate all resources. It limited its evaluation to gas fired thermal units and PV systems and some energy storage.

Q: Was offshore wind energy evaluated as a resource?

A: No, the IRP failed to do a thorough analysis of offshore wind energy. Specially, it completely ignored the capabilities associated with offshore wind energy. PREPA stated on section 6.8 the following:

"Offshore Wind was considered but it not included since it is expected to have cost higher than the equivalent Solar PV project.

With respect of Onshore Wind, we can indicate the following:

- *A search for information on offshore wind found lack of reliable data to suggest that the offshore wind in Puerto Rico would be comparable to locations in the northwest United*

States or Europe, that are rich on this resource. The search considered location, permitting feasibility, project costs, resulting energy prices, etc.

- *Preliminary studies for Puerto Rico do identify potential offshore wind locations but the projected costs are significantly higher than those associated with solar PV or wind installations on the island. This study indicated that "including the additional costs to produce offshore wind energy, the expected end cost of energy due to offshore wind energy production in Puerto Rico could reach similar to the current cost of energy in the Island. Therefore, it is unlikely that offshore wind energy is a viable near term option to the solution of the energy crisis in Puerto Rico". Further, the study concluded that if cost reductions are made in offshore wind technology, then this technology may become viable in the future.*
- *Furtheranalysistostudyoffshorewindcouldbeinitiatedbutthiswouldrequirean expensive and time-consuming study. The time requirements alone place this technology out of reach to meet the current time requirements for this IRP.*
- *This IRP does include substantial amounts of solar PV installations. If offshore wind were to become practical and cost-competitive with solar PV installations, then we would expect some of the solar PV installations to be replaced by offshore wind. As previously noted, the cost and availability of the solar PV versus wind must show that wind is a lower cost alternative to justify its inclusion over solar PV. Our study analysis shows only a fraction of conditions where wind is included in the results."*[1]

Q. Do you concur with the statement above that there is a "lack of reliable data" on offshore wind? Explain your opinion?

[1] IRP2019 Main Report Rev 2 06182019 wERRATA, pages 6-42.

A. I do not concur with the statement. There is plenty of publicly available data that easily questions the validity of this statement. The US Department of Energy through its Office of Energy Efficiency and Renewable Energy released its 2018 report “2018 Offshore Wind Technologies and Market Report,” available to the public, that provides extensive information on offshore wind technologies and costs. A key finding of the report shows PPA prices as low as $65/MWh.[2]

Figure 1 shows the projections and LCOE estimates of various research organizations regarding fixed bottom technologies.[3] **Figure 2** shows the projections and the levelized cost of energy (“LCOE”) estimates of various research organizations regarding floating technologies.

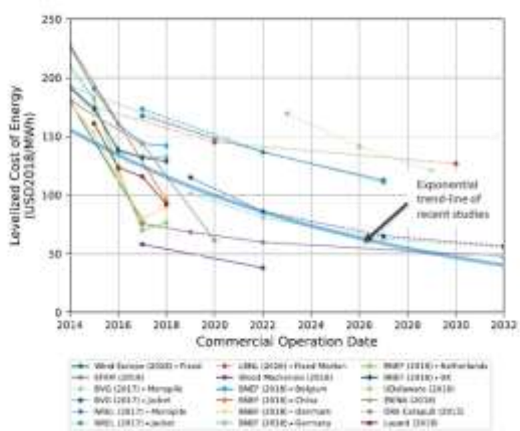


Figure 1. Fixed Bottom Offshore Wind Cost Trends[4]

---

[2] US Department of Energy 2018 Offshore Wind Technologies and Market Report.
[3] US Department of Energy 2018 Offshore Wind Technologies and Market Report, page 57.
[4] US Department of Energy 2018 Offshore Wind Technologies and Market Report, page 57.

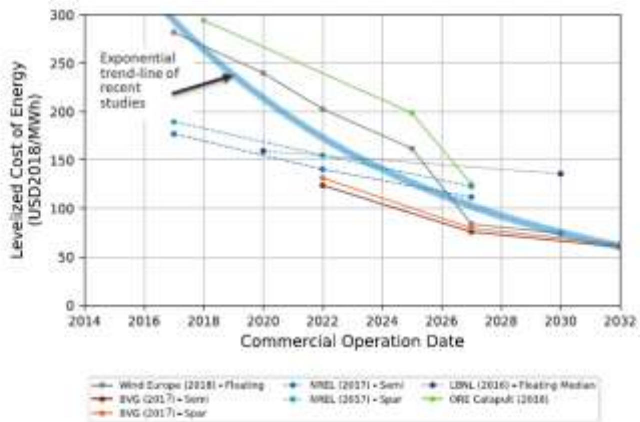


Figure 2. Floating Offshore Wind Cost Trends[5]

Both figures represent a continuous downward trend as the technology matures.

Q. The figures above show a higher LCOE for floating compared to fixed bottom technologies. Do you have any recent pricing data in the US that shows declining levelized costs for offshore wind?

A. Yes. The National Renewable Energy Laboratory ("NREL") released a study in October 2019 called "Oregon Offshore Wind Site Feasibility and Cost Study," showing that the levelized cost of offshore wind in Oregon is expected to be around $63/MWh. See the study's conclusion below:

In this study, we estimated the cost-scaling relationship between the 24-MW WindFloat Pacific project proposed by Principle Power in 2014 and a 600-MW project located at the same site (Site 4 off Coos Bay, Oregon). The LCOE was approximately three times higher for the 24-MW pilot-scale project. This cost difference mostly reflects the capital and operation cost economies of scale that

[5] US Department of Energy 2018 Offshore Wind Technologies and Market Report, page 64.

allow fixed cost items to be spread over the entire project cost. As the comparison is made in model year 2032, the estimated costs shown in Table A-2 also represent technology improvements assumed to be realized since the WindFloat Pacific was originally proposed, such as larger turbines that are assumed to be available in a decade. The LCOE for the pilot-scale project was calculated to be $183/megawatt-hour, whereas the commercial-scale project LCOE was found to be $63/megawatt-hour.[6]

Q. Are there additional studies that are specific to Puerto Rico?

A. Yes, in addition to the study PREPA cites, the University of Puerto Rico carried out studies evaluating offshore wind. Most of the studies are focused on fixed bottom technologies and the technologies available at the time.

The University of Puerto Rico carried out a study titled “Achievable Renewable Energy Targets for Puerto Rico’s Renewable Portfolio Standards during October 2018 – November 2009 (ARET). The ARET study developed a chapter to different renewable resources. The study’s chapter 2 is dedicated to wind energy, both inland and offshore wind.

The study mainly focused on fixed bottom technologies at waters 30 meters deep.

---

[6] Oregon Offshore Wind Site Feasibility and Cost Study, Walter Musial,1 Philipp Beiter, Jake Nunemaker, Donna Heimiller, Josh Ahmann, and Jason Busch, National Renewable Energy Laboratory, Parametrix, Pacific Ocean Energy Trust.

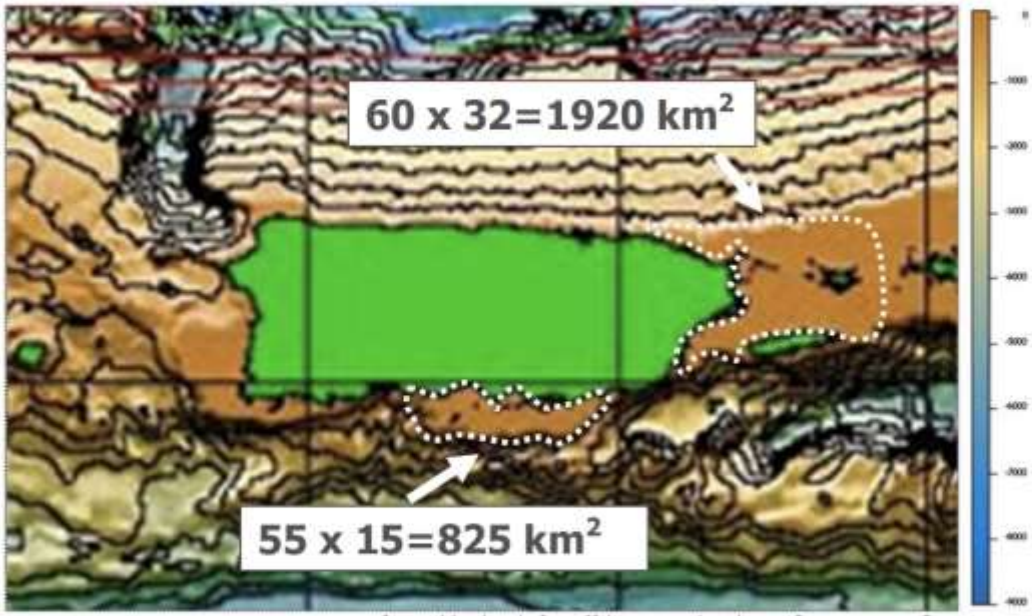


Figure 3. Areas identified on ARET that are 30 m deep[7]

After identifying the areas for the available fixed bottom technologies at the time, the ARET study concluded that 1,372 MW of offshore wind could be installed at that time. The biggest turbine analyzed on that study was a Vestas V90 with a 3 MW capacity. It is worth mentioning that the turbines available today are of a much larger capacity, 8 MW and above.

Q: Are there additional challenges to the penetration of offshore wind energy resources?

A: Yes, PREPA commissioned Siemens to perform a Renewable Generation Integration Study on early 2014. On the study, Siemens evaluated existing PV and onshore wind projects. On that study, Siemens concluded inland wind resource to follow the PV production curve (see **Figure 4**). This assessment by Siemens validates the conclusion arrived by ARET for diurnal wind speed (see **Figure 5**).

[7] Achievable Renewable Energy Targets, Chapter 2, p 51

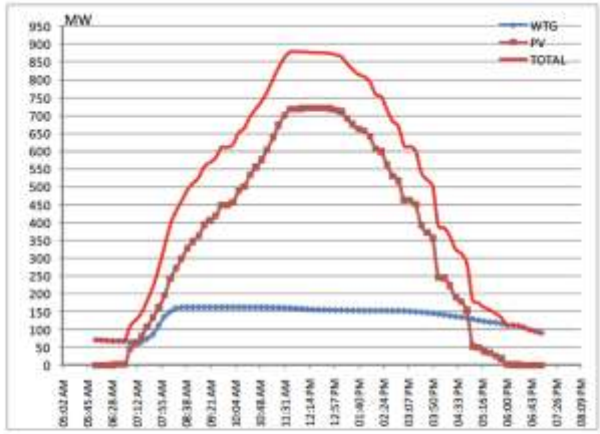


Figure 4. Siemens profile of renewable generation inland.[8]

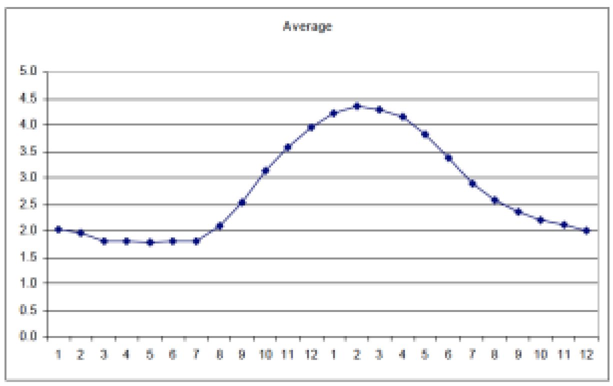


Figure 5. ARET Puerto Rico Average Diurnal Wind Speed Effect[9]

PREPA has determined that it only needs to evaluate PV as inland wind follows a similar production curve as PV. The result is that PREPA tends to model only PV and assume wind can participate on future RFPs. PREPA and Siemens have applied the same production curve to offshore wind and disregarded its evaluation as a separate resource.

Q. Why is the production curve an important factor?

A. PREPA has stated the daily load profile for Puerto Rico to be as stipulated on **Figure 6**.

---

[8] PREPA Renewable Integration Study, p6-30 figure 6-31.
[9] Achievable Renewable Energy targets, Chapter 2, p34, figure 2-7.

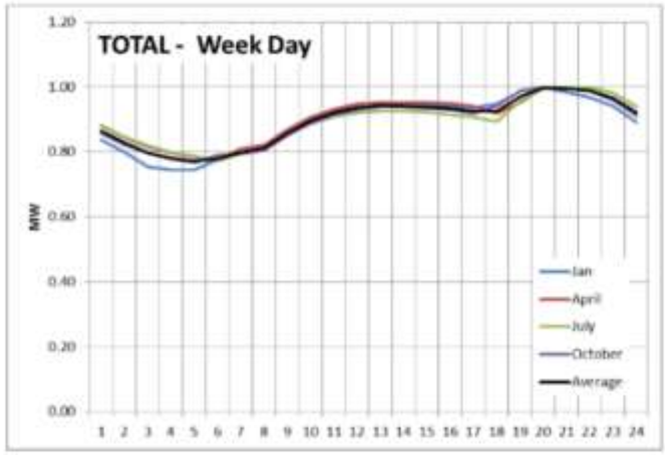


Figure 6. Daily load profile on Puerto Rico (excerpt from exhibit 3-22 filed IRP)[10]

As can be seen on **Figure 6**, Puerto Rico has a daily peak occurring between 11 AM – 2 PM and a higher nightly peak occurring between 8-10 PM.

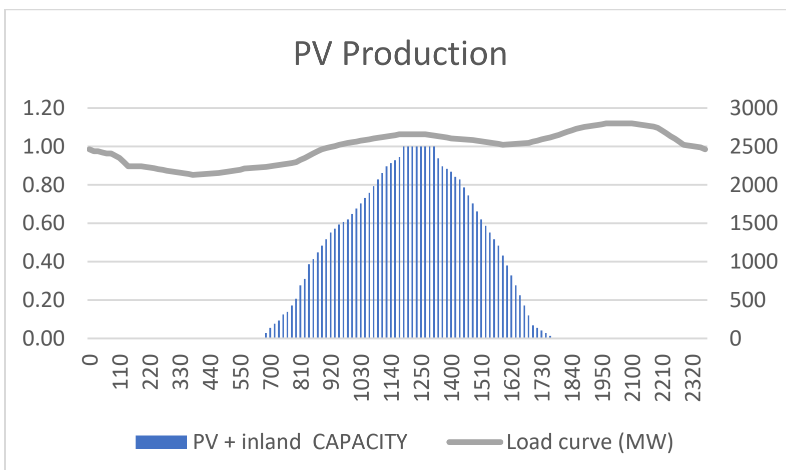


Figure 7. Estimated PV daily production vs load curve

Figure 7 shows a typical PV daily production superimposed over the daily load curve. The values for this graph were approximate values taken from figures 4 and 6 to compare peak PV production with peak load demand.

[10] PREPA IRP Load Forecast p3-19, Exhibit 3-22.

PREPA and Siemens have expressed the challenge of supplying the night peak via renewable energy resources with the existing outdated thermal infrastructure. As such, PREPA has favored a portfolio with a substantial amount of natural gas infrastructure, committing ratepayers' dollars to assets that have a great potential of becoming stranded assets by 2050.[11]

Q. Was PREPA and Siemens incorrect to assume offshore wind resource availability to the the same as in-land (onshore)?

A. Yes, the assumption is incorrect and a fatal flaw on the resource analysis. In my experience abroad, I have seen offshore wind to be complimentary to solar PV production. The tendency abroad is for the wind resource to peak late during the day/early evening. It is an additional renewable energy production resource before having to add energy storage.

Q. Is there a way to determine the behavior of offshore wind in PR?

A. Yes, on the National Oceanic and Atmospheric Administration there is a National Data Buoy Center.[12] The website has historical data collected from Buoys around the Commonwealth and the World. In addition, the Caribbean Coastal Ocean Observing System ("CarICCOS") maintains a website with forecast information.[13]

Q. Do you have data to support the claim that offshore wind is a complimentary

[11] Act 17-2019 requires all retail sales of energy to be provided fully, a 100% of it, by renewable energy sources.
[12] https://www.ndbc.noaa.gov
[13] https://www.caricoos.org

resource to solar PV and onshore wind?

A. Yes. Data collected by a Buoy owned by National Oceanic and Atmospheric Administration ("NOAA") and maintained by Caribbean Integrated Coastal Ocean Observing System ("CarICOOS") moored at: 18.474 N 66.099 W (18°28'28" N 66°5'56" W) has been collecting data for years. The chart on **Figure 9** below shows averages for 2018.

Figure 8. San Juan Buoy Information[14]

Station Number: 41053 San Juan, Site elevation: sea level, Air temp height: 3 m above site elevation, Anemometer height: 4 m above site elevation, Barometer elevation: 3 m above mean sea level, Sea temp depth: 1 m below water line, Water depth: 32 m, Watch circle radius: 60 yards.

[14] https://www.caricoos.org/station/san-juan/us

The wind profile shown on Figure 9 is the profile measured by the buoy 41053 located north of San Juan. The data is measured at 4 meters from site elevation. The figure shows how the 4 meter wind resource peaks around 7 m/s from 4-8 PM and also maintains a high wind resource level of 6.5 m/s until 10 PM. The figure shows how the north wind resource tends to peak simultaneously with the peak load demand.

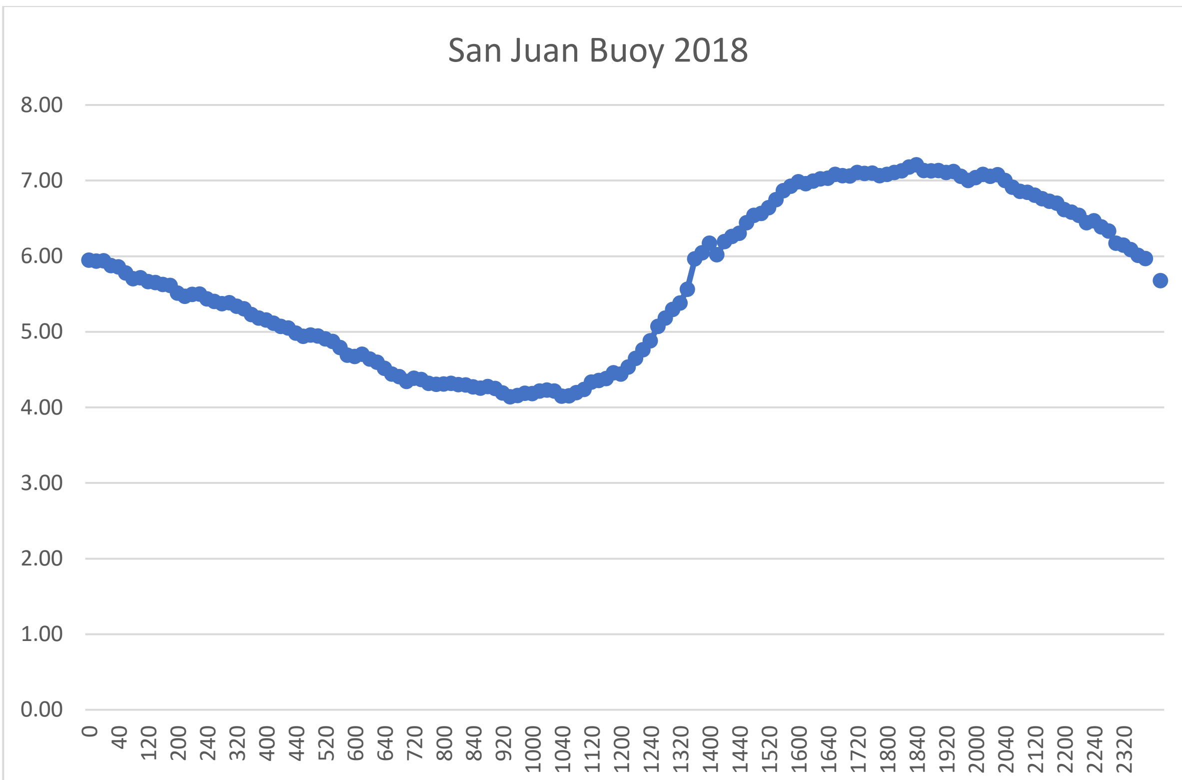


Figure 9. San Juan Buoy 2018 Average Wind Daily Wind Profile

Q. How would you estimate wind speed at 100 m from the data on figure 9?

A. The ARET study properly explains the use of the one seventh power law.[15] Using this

[15] ARET, page 25.

formula we can adjust the 4 m measured values to 80 m (see figure 10).[16] At these wind speeds we could expect a 50% capacity factor.

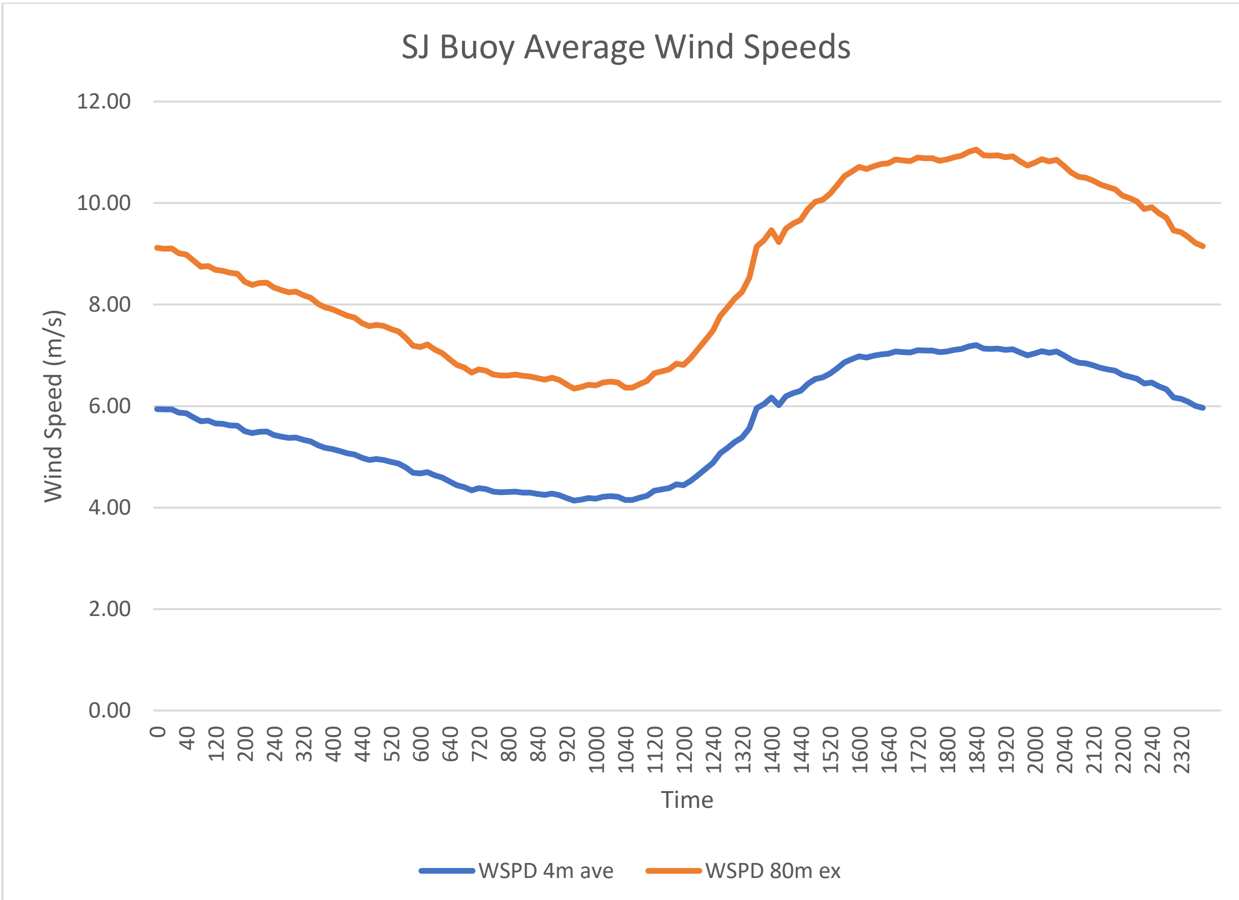


Figure 10. San Juan Buoy 2018 Average Wind at 4 & 80 m

Q. What would be the wind power production at this wind speeds on the north?

A. The power production can be calculated with the power curve of the wind turbine. Using the turbine and formula provided by Siemens on the Generic Wind Modelling on page 6-39 of the IRP we can calculate the production there (see **Figure 11**).

---

[16] The turbines we would install would be bigger and would take advantage of 100 m winds. However, Siemens performed the wind analysis with the Siemens SWT-3-101 Turbine with speeds at 80m.

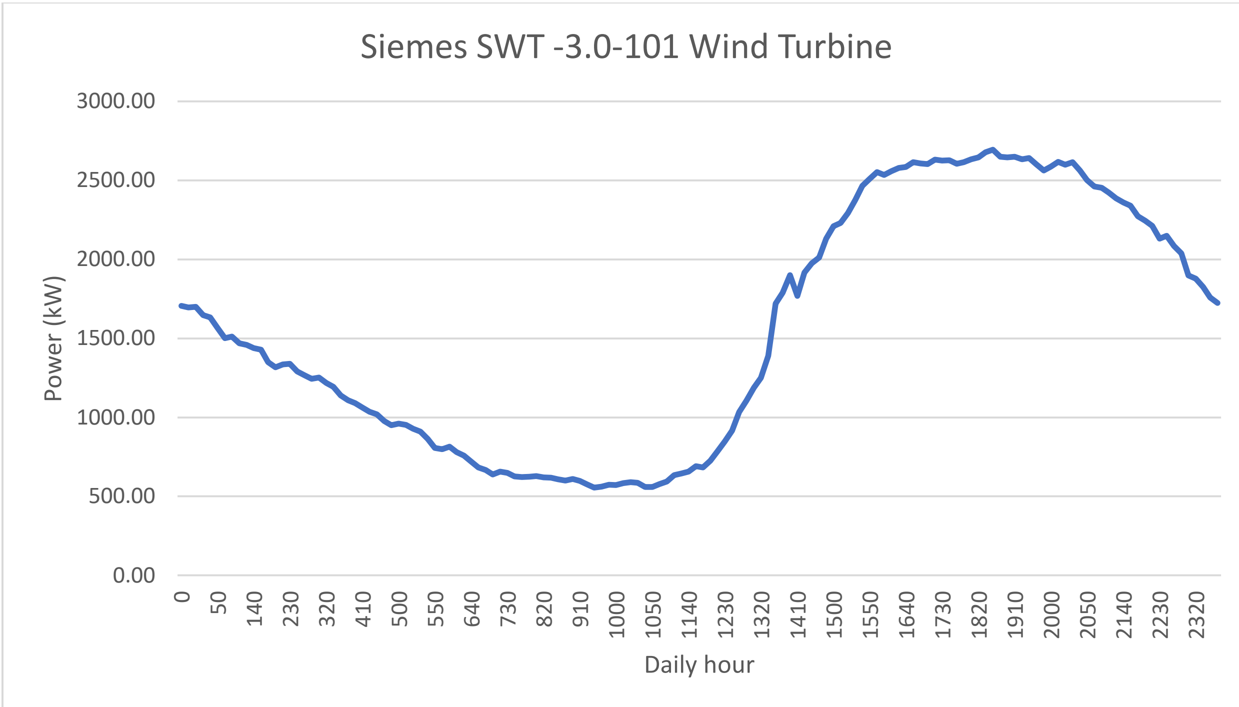


Figure 11. Siemens Wind Turbine Power per IRP formula

Q. How does the CapEx cost of offshore wind compare to other renewable generating resources?

A: Capex cost is not a good measure when evaluating offshore wind since they are so high compared to onshore wind and solar. The costs are mainly due to larger turbines that are located further away from shore and the infrastructure needed to bring the power back onshore. However, those higher costs lead to higher energy yields which shows up in the levelized cost of energy. Some of the most economical offshore wind energy projects have levelized costs between $50 and $60 per megawatt hour.

Q. What would be an estimate of the production of the renewable energy resources on the island?

A: We can combine the estimate power production of PVs and offshore wind on the north shown on **Figures 7** and **11** (see **Figure 12**). I have graphed the production based on a per unit basis to show the daily production of an individual unit. The production is plotted against the load demand backdrop. This figure shows the potential of combining the renewable resources to supply the island's energy supply.

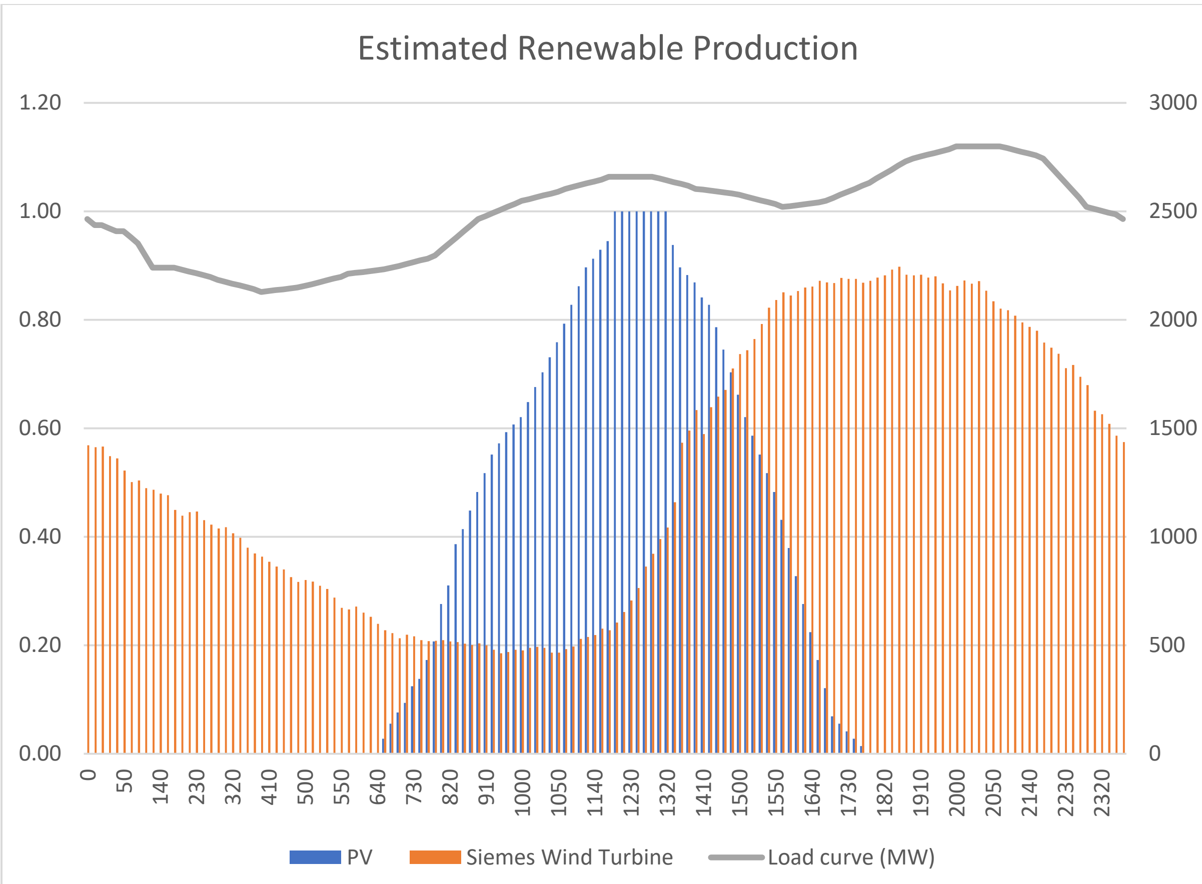


Figure 12. Estimated PV and Offshore wind daily production profile

R. What are your conclusions and recommendations?

A. PREPA and Siemens neglected to review and the multiple public sources of information available on offshore wind. PREPA (through Siemens) unduly discriminated against offshore wind. The result is a portfolio of resources that haven't been thoroughly analyzed and vetted against all possible renewable energy sources. My conclusions and recommendations are the following:

1. Offshore wind is a viable and is ready to deploy is Puerto Rico and a price that is competitive with all other generating resources.
2. Offshore wind's production profile is complementary to existing and future onshore renewable resources.
3. Further analysis should be carried out. Wind profiles for each cardinal point should be evaluated. The 4-m wind profile should be extrapolated to 100-m and wind power production estimated. Wind variability should be evaluated.
4. The Bureau should not approve an IRP that does not properly evaluate all generating resources. PREPA has selected a preferred portfolio that has multiple natural gas resource plants. PREPA didn't evaluate offshore wind as a resource alternative to the gas plants even though public reports as ARET identified areas on the east and south coast for offshore sitting.
5. Offshore wind with floating technology, like our WindFloat technology, is appropriate to be used on deep water areas. This technology is a proper fit for the north shore of PR.[17]
6. PREPA should include up to 500 MW of offshore wind into the current IRP.

Q. Does this complete your testimony?

A. Yes. I might supplement my testimony as my company performs further analysis on the energy market of Puerto Rico.

[17] The Puerto Rico Trench is located on the north of Puerto Rico.

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

2018 **Offshore Wind Technologies Market Report**

NOTICE

This report is being disseminated by the U.S. Department of Energy (DOE). As such, this document was prepared in compliance with Section 515 of the Treasury and General Government Appropriations Act for fiscal year 2001 (public law 106-554) and information quality guidelines issued by DOE. Though this report does not constitute "influential" information, as that term is defined in DOE's information quality guidelines or the Office of Management and Budget's Information Quality Bulletin for Peer Review, the study was reviewed both internally and externally prior to publication. For purposes of external review, the study benefited from the advice and comments of nine energy industry stakeholders, U.S. Government employees, and national laboratory staff.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at SciTech Connect http:/www.osti.gov/scitech

Available for a processing fee to U.S. Department of Energy and its
contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
OSTI http://www.osti.gov Phone:
865.576.8401
Fax: 865.576.5728
Email: reports@osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce National
Technical Information Service 5301
Shawnee Road
Alexandria, VA 22312 NTIS
http://www.ntis.gov
Phone: 800.553.6847 or 703.605.6000
Fax: 703.605.6900
Email: orders@ntis.gov

2018 Offshore Wind Technologies Market Report

Primary Authors

Walter Musial, National Renewable Energy Laboratory

Philipp Beiter, National Renewable Energy Laboratory

Paul Spitsen, U.S. Department of Energy

Jake Nunemaker, National Renewable Energy Laboratory

Vahan Gevorgian, National Renewable Energy Laboratory

List of Figures

List of Tables

Acknowledgments

This work was supported by the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory (NREL). Funding for the work was provided by the DOE Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The report was reviewed by a diverse group of offshore wind industry stakeholders including four developers, three wind turbine manufacturers, two state government representatives, one nongovernmental organization, seven internal Office of Energy Efficiency and Renewable Energy staff, three NREL management staff, four consultants, and three regulators. The authors would like to extend thanks to Patrick Gilman and Gary Norton (contractor) from the DOE Wind Energy Technologies Office for supporting this research. Thanks also to Valerie Reed, Liz Hartman, Rich Tusing, Dan Beals, and Alana Duerr of the DOE Wind Energy Technologies Office for their support and strategic guidance.

The authors would like to thank the following reviewers and contributors from NREL including Brian Smith, Paul Veers, and Eric Lantz (NREL).

This report covers a wide range of industry projects, policies, and past reports that the authors have documented with extensive support from a diverse group of peer reviewers. These experts and stakeholders include Tom Harries (Bloomberg New Energy Finance), Darryl Francois and Stephen Boutwell (Bureau of Ocean Energy Management), James Glennie (Danish Trade Council/Embassy), Stephanie McClellan (Delaware Special Initiative on Offshore Wind and Renewable Consulting Group and Renewables Consulting Group), Knut Aanstad (Equinor), Albert Fisas (GE), Nils Bolgen (Massachusetts Clean Energy Center), Jason Folsom (MHI/Vestas), Nathanael Greene (National Resources Defense Council), Anne Marie McShea (New Jersey Board of Public Utilities), Gavin Smart (ORE Catapult), Kris Ohleth (Ørsted), Aaron Smith and Loris Canizares (Principle Power Inc.), and Fergus Costello and Soeren Daugaard (Siemens Gamesa).

Editing was provided by Sheri Anstedt (NREL) and graphics and cover design were created by John Frenzl (NREL). Additional communications and coordination were provided by Alex Lemke (NREL), Kiki Carpenter (NREL), Tiffany Byrne (NREL), and Carol Laurie (NREL).

Nomenclature or List of Acronyms

AC	alternating current
BESS	battery energy storage system
BNEF	Bloomberg New Energy Finance
BOEM	Bureau of Ocean Energy Management
BPU	Board of Public Utilities
CapEx	capital expenditures
CIP	Copenhagen Infrastructure Partners
COD	commercial operation date
DOE	U.S. Department of Energy
EDF	Électricité de France Renouvelables
EDPR	Energias de Portugal Renováeis
EnBW	Energie Baden-Württemberg AG
GW	gigawatt
HVDC	high-voltage direct current
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency
ITC	investment tax credit
kV	kilovolt
km	kilometer
LEEDCo	Lake Erie Energy Development Corporation
Berkeley Lab	Lawrence Berkeley National Laboratory
LCOE	levelized cost of energy
m	meter
MW	megawatt
MWh	megawatt-hour
nm	nautical mile
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research and Development Authority
O&M	operation and maintenance
OEM	original equipment manufacturer
OpEx	operational expenditures
OREC	offshore renewable energy certificate
OWDB	offshore wind database
PPI	Principle Power Inc.
PPA	power purchase agreement
REC	renewable energy certificate
RPS	renewables portfolio standard
s	second
SIOW	Special Initiative on Offshore Wind
TBD	to be determined
WEA	wind energy area

Executive Summary

Offshore wind energy is a rapidly growing global industry that creates electricity from wind turbines installed in coastal waters on either rigid or floating substructures anchored to the seabed or lake bottom. The *2018 Offshore Wind Technologies Market Report* was developed by the National Renewable Energy Laboratory (NREL) with support from the U.S. Department of Energy (DOE) and is intended to provide offshore wind policymakers, regulators, developers, researchers, engineers, financiers, supply chain participants, and other stakeholders with up-to-date quantitative information about the offshore wind market, technology, and cost trends in the United States and worldwide. This report provides detailed information on the domestic offshore wind industry to contextualize the U.S. market and help policymakers, researchers, and the general public understand technical and market barriers and opportunities. Globally, the scope of the report covers the status of the 176 operating offshore wind projects through December 31, 2018, and provides the status of, and analysis on, a broader global pipeline of 838 projects in various stages of development.[1] To provide the most up-to-date discussion of this dynamically evolving industry, this report also tracks the most significant domestic developments and events from January 1, 2018, through March 31, 2019. The following is a summary of the key offshore wind market findings.

U.S. Offshore Wind Energy Market–Key Findings

The U.S. offshore wind energy project development and operational pipeline[2] grew to a potential generating capacity of 25,824 megawatts (MW), with 21,225 MW under exclusive site control.[3] The overall size of the U.S. offshore wind pipeline grew from 25,464 MW to 25,824 MW in 2018—about 1.4% growth. The 25,824 MW that make up the U.S. offshore wind project development and operating pipeline comprise one operating project (Block Island Wind Farm), eight projects that have reached the permitting phase with either a construction and operations plan or a viable offtake mechanism for sale of electricity, 15 commercial lease areas in federal waters with exclusive site control, two unleased wind energy areas, and five projects (all Pacific-based) that have submitted unsolicited applications to the Bureau of Ocean Energy Management (BOEM),[4] the government agency that regulates energy development in federal waters. The pipeline has three projects located in state waters, including the operating Block Island Wind Farm, the Aqua Ventus I floating-wind project in Maine, and the Lake Erie Energy Development Corporation Icebreaker Wind project on Lake Erie. In addition, there is one BOEM research lease in Virginia federal waters.

Offshore wind project development and regulatory activities span multiple U.S. regions. Historic development and regulatory activities were concentrated in the North Atlantic region from Virginia northward. New offshore wind activities have been initiated in the Pacific, Great Lakes, and South Atlantic regions as well. In the past, there have been project proposals and leasing activity in the Gulf of Mexico that have been limited to Texas state waters, but in 2018 offshore wind development and regulatory activity in this region was inactive. Figure ES-1 shows a map of offshore wind pipeline activity as of March 31, 2019, as well as BOEM Call Areas, for the entire United States.

[1] Note that the *2016 Offshore Wind Technologies Market Report* covered operating projects through June 30, 2017, with a focus on developments in 2016 and the first half of 2017 (Musial et al. 2017).

[2] The project development and operational pipeline, commonly referred to as "the pipeline," is represented by the database that the National Renewable Energy Laboratory uses to monitor the progress of the commercial offshore wind industry. It includes sites under development as well as operating projects. In the United States, the pipeline does not include Call Areas because their boundaries are not fixed. Unleased wind energy areas in the United States are included because they have a defined area.

[3] Federal law requires the Bureau of Ocean Energy Management to conduct a fair public auction for offshore wind sites in which there is interest from more than one developer (i.e., "competitive interest"). A developer cannot proceed until they have been awarded exclusive rights to the site through the competitive auction process.

[4] A lease area is a parcel of ocean area that is auctioned to prospective developers. Wind energy areas can comprise one or more lease areas. A Call Area is a precursor to a wind energy area.

State-level policy commitments accelerated, driving increased market interest. At the end of 2017, U.S. offshore state wind procurement policies totaled over 5,300 MW targeted for deployment by 2030. By early 2019, the sum of official state offshore wind capacity commitments increased to 19,968 MW by 2035. In 2018, new commitments were added in Massachusetts (additional 1,600 MW authorized by 2035), New York (6,600 MW added by 2035), and New Jersey (2,400 MW added by 2030), while Connecticut and Rhode Island both agreed to purchase power from Ørsted's 600-MW Revolution project. In 2019, new policy commitments were enacted in Connecticut (2,000 MW) and Maryland (1,200 MW). In some states without offshore-wind-specific targets, like California and Hawaii, 100% renewables portfolio standards and carbon reduction policies are driving these markets, which are progressing toward the creation of new offshore wind lease areas.

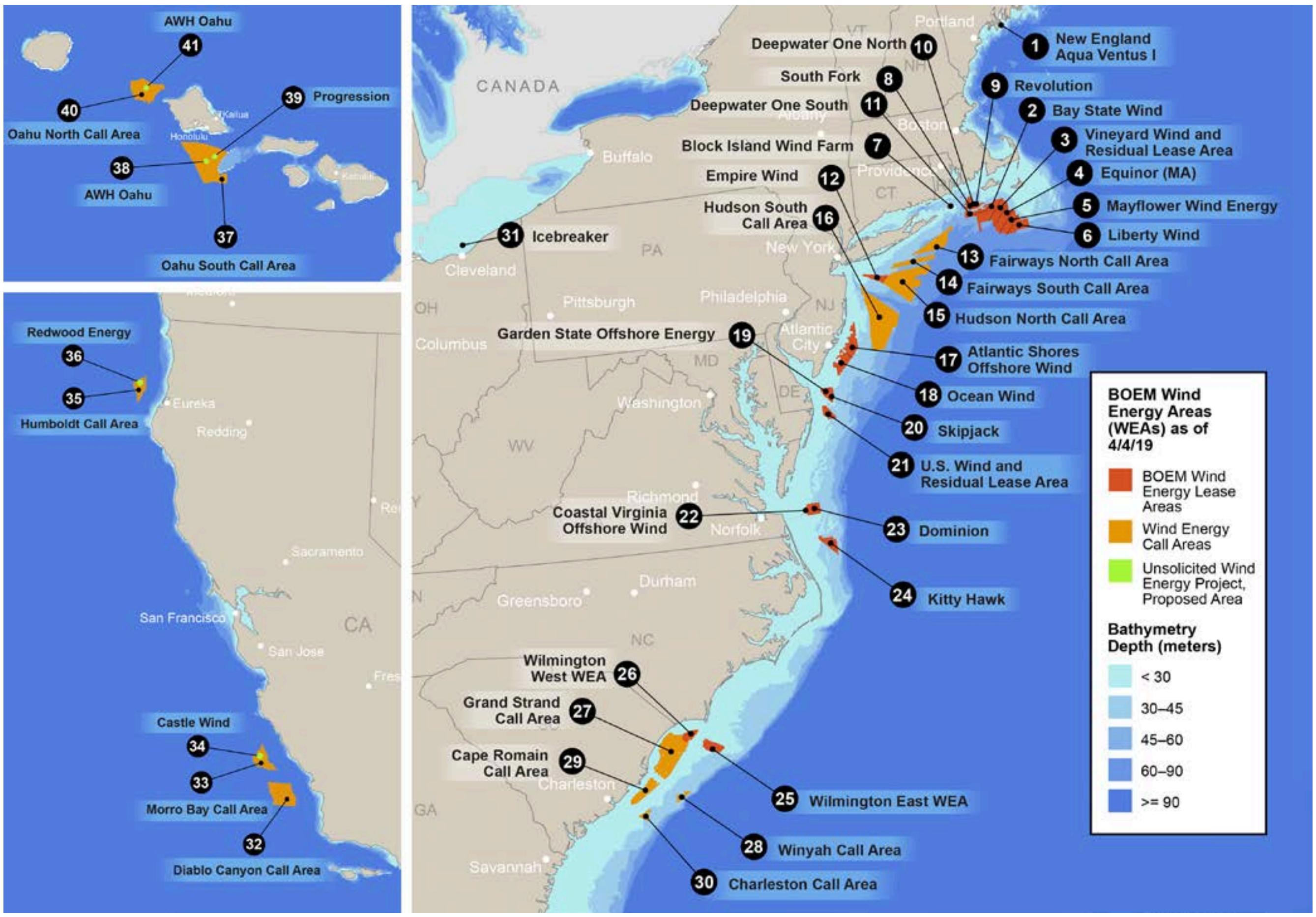


Figure ES-1. Locations of U.S. offshore wind pipeline activity and Call Areas as of March 2019. *Map provided by NREL*

Increased U.S. market interest spurred strong competition at offshore wind lease auctions. BOEM auctioned a total of 1,573 square kilometers (km^2), an area about half the size of Rhode Island, in three adjacent offshore wind lease areas off Massachusetts in December 2018. Each winner (Equinor, Mayflower Wind, and Vineyard Wind) submitted a bid of $135 million, more than tripling the previous lease area sale price record for a single lease area of $42 million in 2016 for the New York lease area submitted by Equinor. Higher offshore wind lease sale prices indicate 1) increased confidence in future market growth driven by state policies, 2) confidence in the regulatory and financial institutions to support offshore wind project development in the nascent U.S. market, 3) continued cost reductions, and 4) heightened demand for offshore wind in the northeastern United States.

Several U.S. projects advanced in the development process. U.S. offshore wind market progress was more evident from the advancement of major projects in the pipeline in 2018 than the capacity growth of the pipeline. Most notably, the commercial-scale Vineyard Wind project and Ørsted's Revolution project negotiated electricity sale offtake agreements with major electric distribution companies and utilities and took major steps in permitting at both the state and federal level. Overall, in the United States, four projects have submitted construction and operations plans, nine projects have had site assessment plans approved, and six have signed power offtake agreements. Vineyard Wind and South Fork are the most advanced commercial-scale U.S. projects, having both obtained a power purchase agreement (PPA) and completed state permits and site surveys, with a construction and operations plan under review by BOEM. Vineyard Wind reports a commercial operation date of 2022 for their Phase 1 facility, consisting of the first 400 MW.

Industry forecasts suggest U.S. offshore wind capacity could grow from 11 to 16 gigawatts (GW) by 2030. Figure ES-2 shows three industry forecasts for offshore wind deployment in the United States for the period extending to the year 2030. These estimates were developed by Bloomberg New Energy Finance (BNEF 2018a), 4C Offshore (2018), and University of Delaware's Special Initiative on Offshore Wind (SIOW 2019),[5] respectively. Together, they illustrate the degree of possible market growth as well as the potential variability associated with future deployment.

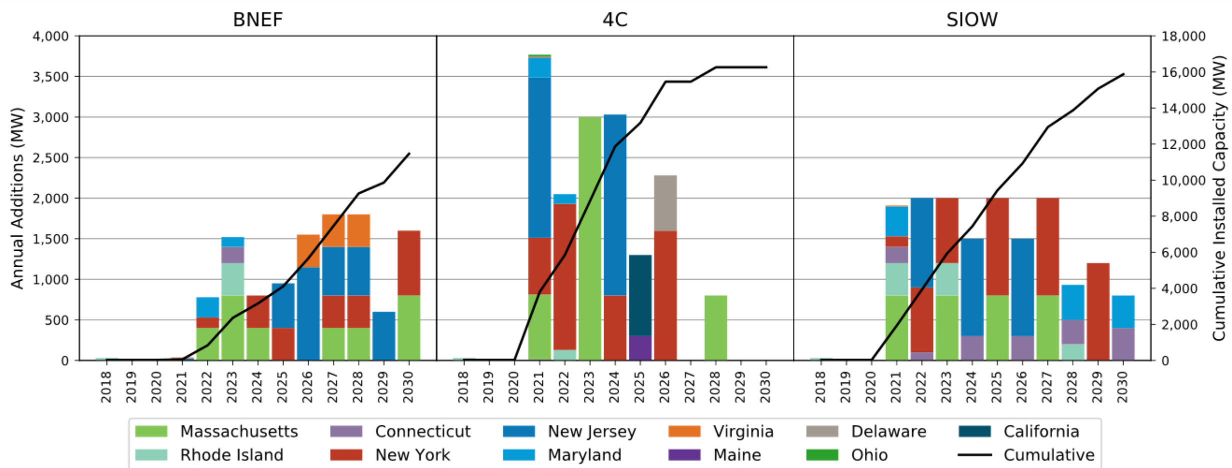


Figure ES-2. U.S offshore wind market forecasts for annual additions (left axis) and cumulative capacity (right axis) through 2030

Offtake prices for the first commercial-scale offshore wind project in Massachusetts were lower than expected. On July 31, 2018, Massachusetts electric distribution companies and Vineyard Wind LLC negotiated a PPA for delivery of offshore-wind-generated electricity at a first-year price of $74/megawatt-hour (MWh) (2022$) for Phase 1 (400 MW) and $65/MWh (2023$) for Phase 2 (400 MW). An NREL study showed that these PPA prices may not accurately reflect the true cost of the project at face value because other revenue sources, such as the investment tax credit, are not accounted for (Beiter et al. [2019]; see Section 5). Nevertheless, this price was lower than expected given the presumed risks associated with building the first U.S. commercial project with an immature U.S. supply chain. Vineyard Wind's apparent ability to access relatively low-cost financing and take advantage of the waning federal investment tax credit helped them set a competitive benchmark for the U.S. offshore wind industry. The Vineyard Wind PPA price provides a reference point for commercial-scale offshore wind generation in the United States that falls within the price

[5] Please note University of Delaware's SIOW forecast is based on the expected date a state selects to procure offshore wind capacity. A 3-year time lag is assumed from the time the procurement occurs until the project becomes fully operational.

range of European offshore wind projects scheduled to begin commercial operations in the early- to mid-2020s. Additional commercial price points are anticipated in New York and New Jersey in 2019.

Attention to offshore wind in California increased in 2018. California passed Senate Bill 100, The 100 Percent Clean Energy Act of 2018, making it the largest state to establish a 100% electric renewable energy goal, and setting a carbon-free target year of 2045. Amid continued negotiations with the U.S. Department of Defense, on October 18, 2018, BOEM published a Call for Information and Nominations and received 14 nominations from companies interested in commercial wind energy leases within three proposed Call Areas off central and northern California. All together, these three Call Areas total approximately 2,784 km^2 (687,823 acres), which could support an offshore-wind-generating capacity for nascent floating wind technology of up to 8.4 GW.

New national technical research consortium was launched to spur innovation. DOE has committed $20.5 million to the New York State Energy Research and Development Authority to form a National Offshore Wind R&D Consortium. The New York State Energy Research and Development Authority agreed to match the DOE contribution and launched a funding organization to make research and development awards on prioritized topics that will support developers in achieving their near-term deployment and cost targets. The first solicitation was released on March 29, 2019, and the first awards are expected in 2019.

Global Offshore Wind Energy Market–Key Findings

Globally, industry installed a record 5,652 MW of offshore wind capacity in 2018. Annual capacity additions increased by more than 50% relative to 2017. The increase in global generating capacity can be attributed to increased deployment in China, with 2,652 MW of new capacity, followed by 2,120 MW commissioned in the United Kingdom, 835 MW in Germany, 28 MW in Denmark, and about 17 MW divided among the rest of the world. By the end of 2018, cumulative global offshore wind installed capacity grew to 22,592 MW from 176 operating projects. Projections indicate 2019 global capacity additions will be even higher based on projects currently under construction. As of December 31, 2018, the global pipeline for offshore wind development capacity was about 272,000 MW.

The pace of European auctions slowed in the second half of 2018, but forecasts show sustained industry growth. European auction strike prices[6] in 2018 validated earlier cost reduction trends (see Section 5) but the number of auctions decreased, with only three occurring in the first two quarters of 2018. Adjusted strike prices[7] for these auctions ranged from $74/MWh to $79/MWh for commercial-scale projects. The slowdown can be partially attributed to the depletion of viable grid connections in the German markets (Foxwell 2018a). However, long-term forecasts indicate that this trend may be temporary as global offshore wind capacity is projected to reach between 154 and 193 GW by 2030, with more than 50% coming from Europe (and another major fraction coming from China).

Offshore Wind Energy Technology Trends–Key Findings

Industry is seeking accelerated cost reductions through larger turbines with rated capacities of 10 MW and beyond. Through technology innovation, turbine original equipment manufacturers have been able to limit the rise in turbine cost ($/kilowatt) and manage the increase in mass (kilogram/kilowatt) to allow turbine growth to continue upward to at least 12 MW, if not 15 MW, in the next decade. There are no indications that

[6] The strike price for an offshore wind project from an auction is usually the lowest bid price at which the offering can be sold. It usually covers a specific contract term for which that strike price will be paid for the energy produced. The offeror of that strike price is awarded the rights to develop a particular parcel under predetermined conditions set in the tender offer that may vary by country or market. It should not be confused with levelized cost of energy, which may be calculated using different financing and cost assumptions.
[7] The strike prices were adjusted to enable comparisons among projects in different countries to consider a range of possible subsidies and benefits that are available to some projects, such as the cost of the electrical grid connections.

turbine growth is slowing or has reached a limit for offshore wind. Although the market has experienced a steady upgrade of turbine drivetrain nameplate generating capacity, turbine rotor diameters have grown more slowly. The Vestas V174-9.5 is currently the largest machine in the commercial market (Richard 2019). However, the next generation of turbines promises larger rotors and lower specific power ratings[8] suited for U.S. offshore markets in the next few years. Specific examples of next-generation turbines include Siemens Gamesa SG 10.0–193DD turbine announced in January 2019, which is planned by Siemens Gamesa to be market ready by 2022, and the GE Haliade-X 12-MW turbine, which should arrive on the market by 2021 (Siemens 2019; GE 2018b).

Adoption of 66-kV(kilovolt) array cables is increasing to lower electrical infrastructure costs. As the rated power capacity of offshore wind turbines continues to grow, project developers and operators are increasing their use of 66-kV array cable technology instead of the conventional 33-kV systems to connect individual turbines within an array. In 2018, three projects incorporated 66-kV array cables versus only one in 2017. Operation at a higher voltage offers important life cycle cost-efficiency benefits, such as the possibility of reducing the number of offshore substations, decreasing the overall length of installed cables, and minimizing electric losses. During 2018, the 66-kV technology was demonstrated by Nexans in three pilot wind power plant projects: the Blyth Offshore Demonstrator (United Kingdom), Nissum Bredning Vind (Denmark), and Aberdeen Bay (United Kingdom).

The floating wind energy project pipeline is growing, with multiple floating pilot projects advancing. The global pipeline for floating offshore wind energy reached 4,888 MW in 2018. The pipeline comprises 38 announced projects, including 46 MW of operating projects. The floating offshore wind energy industry is well into a second-generation, multiturbine, precommercial pilot phase. There are 14 projects representing approximately 200 MW that are currently under construction, having achieved either financial close or regulatory approval. These projects are distributed over nine countries. Figure ES-3 shows a turbine in Equinor's 30-MW floating array off the coast of Peterhead, Scotland—the world's first commercial floating wind energy project—which is now operating into its second year.

[8] Specific power is the ratio of the nameplate rating of the turbine divided by the rotor's swept area and is given in Watts per meter squared.

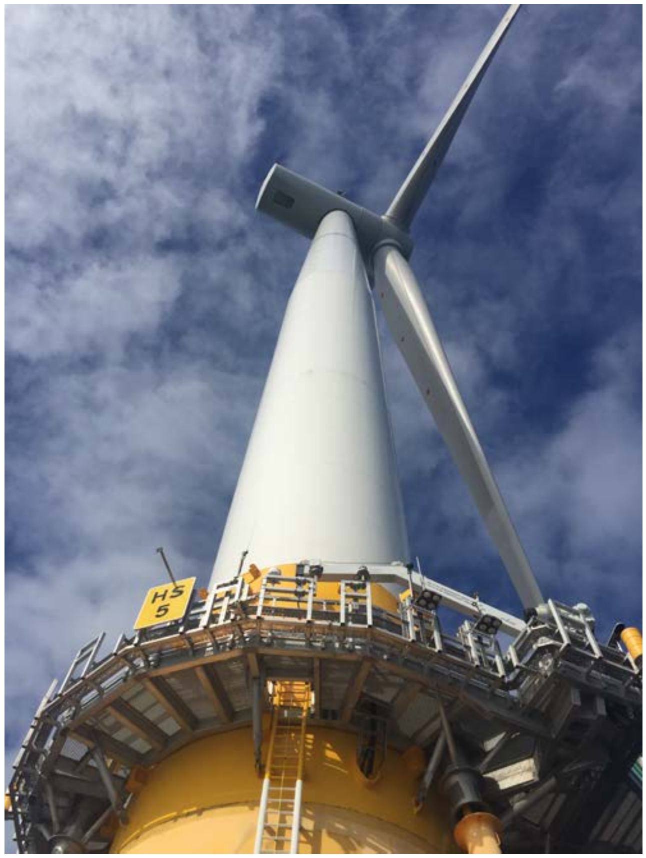


Figure ES-3. A 6-MW floating wind turbine in Equinor's 30-MW array near Peterhead, Scotland.
Photo from Walt Musial, NREL

Semisubmersible substructures dominate the market for floating support structures, but new hybrid platform technologies are being introduced that could compete in future projects. Semisubmersibles, which use buoyancy and the water plane area to achieve stability, make up 94% of floating projects on a capacity-weighted average because they are inherently a stable buoyant floating substructure with low draft that allows for in-port or nearshore assembly. Several new hybrid technologies (platforms that combine the characteristics of spars, tension-leg platforms and semisubmersibles) are being introduced this year that may rival these substructures. Stiesdal Offshore Technologies's TetraSpar and the SBM tension leg platform are highlighted in Section 4 and may be deployed as early as 2019.

Offshore Wind Energy Cost and Price Trends–Key Findings

Offshore wind auction strike prices in 2018 validate current cost reduction trends. Prices from European offshore wind auctions and PPAs in 2018 help validate the previously documented trends indicating prices dropping from approximately $200/MWh for projects beginning operation between 2017 and 2019 to approximately $75/MWh for projects beginning operation between 2024 and 2025. In the United States, Vineyard Wind LLC signed two PPAs with Massachusetts electric distribution companies in July 2018 for a combined 800 MW of offshore wind capacity expected to become operational in 2022 and 2023, respectively. After adjusting for contract type, transmission, policy, and access to external revenue, the Vineyard Wind project has an all-in price of $98/MWh. The Vineyard Wind price point indicates that U.S. projects may not be subject to a large price premium because of nascent U.S. market structures or a limited domestic supply chain. Figure ES-4 indicates the adjusted Vineyard Wind PPA prices are competitive with European offshore wind prices.

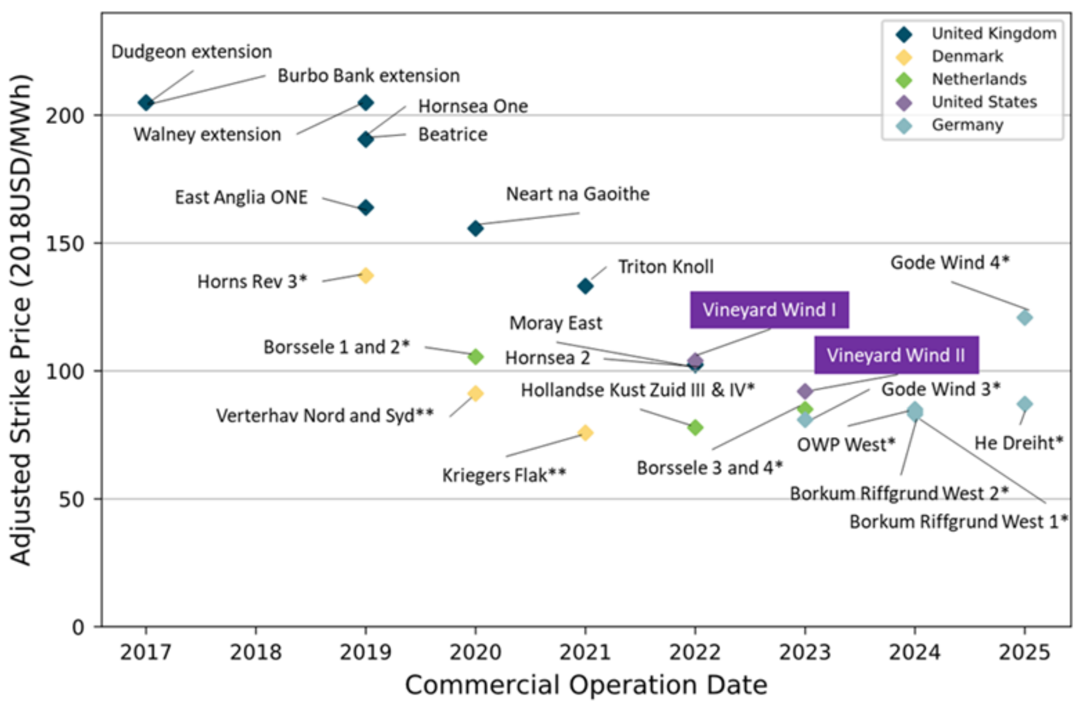


Figure ES-4. Adjusted strike prices from European offshore wind auctions

Sources: 4C Offshore (2018, 2019) and Beiter et al. 2019

Notes: *Grid and development costs added; **Grid costs added and contract length adjusted

Future Outlook

Offshore wind market projections show accelerated growth in the next decade, with cumulative capacity ranging from 154 to 193 GW by 2030, and long-range predictions of over 500 GW by 2050 (BNEF 2018a; 4C Offshore 2018; International Renewable Energy Agency 2018). In this context, offshore wind is still at an early stage with respect to the maturity of the technology, supply chain, and infrastructure. The pace of progress and development of the global supply chain is likely to be strongly influenced in the near term by the growth in turbine generating capacity, rising toward 15 MW. Although larger turbines improve project costs in the long run, they may also delay industry maturity. It may take several years for the corresponding industrial facilities and infrastructure needed for fabrication, installation, and maintenance to stabilize at ever-increasing turbine scales. This upscaling issue is likely to persist not only in the United States but globally as well.

In the United States, individual states may continue to push for greater commitments for offshore wind, but further declines in offshore wind offtake prices are far from certain in the near term. Offshore wind projects, such as Vineyard Wind, will be able to take advantage of the expiring investment tax credit (see Section 5.1.1.), which will enable low prices (on par with Europe) for the first commercial solicitation in Massachusetts. However, as the investment tax credit expires in 2020, projects will have to make up the difference by raising prices or lowering costs. This may increase the urgency to implement near-term solutions to manage costs, such as developing U.S.-flagged Jones-Act-compliant vessels or accelerating the growth and maturity of the domestic manufacturing supply chain (see Section 4).

If demand for offshore wind energy continues to increase in states along the U.S. Atlantic and Pacific coasts, as it did in 2018, state policy commitments that are now almost 20 GW could exceed the capacity of the available sites. Presently, there is just over 21 GW of capacity in BOEM lease areas where developers have been granted exclusive site control. Additional state policy commitments may create possible site shortages in some regions, which could trigger the development of more lease areas.

1 Introduction

Offshore wind energy is a rapidly growing global industry that creates electricity from large wind turbines installed in coastal waters on either rigid or floating substructures anchored to the seabed or lake bottom. The *2018 Offshore Wind Technologies Market Report* was developed by the National Renewable Energy Laboratory (NREL) for the U.S. Department of Energy (DOE) to provide offshore wind policymakers, regulators, developers, researchers, engineers, financiers, and supply chain participants with up-to-date quantitative information about the offshore wind market, technology, and cost trends in the United States and worldwide. This report includes detailed information on the domestic offshore wind industry to provide context to help navigate technical and market barriers and opportunities. It also covers the status of the 176 operating offshore wind projects in the global fleet through December 31, 2018, and provides the status and analysis on a broader global pipeline of 838 projects at varying stages of development. In addition, this report provides a deeper assessment of domestic developments and events through March 31, 2019, for this dynamically evolving industry.

This report includes data, obtained from a wide variety of sources about offshore wind projects that are both operating and under development, to offer current and forward-looking perspectives. It is a companion to the *2018 Wind Technologies Market Report* and *2018 Distributed Wind Market Report* funded by DOE and written by the Lawrence Berkeley National Laboratory (Berkeley Lab) (Wiser et al. 2019) and Pacific Northwest National Laboratory (Orrell et al. 2019), respectively. The reports cover the status of utility-scale and distributed, land-based wind energy located primarily in the United States, and provide quantitative, independent data for use by the wind industry and its various stakeholders.

Global offshore wind deployment in 2018 set a new record for a single year (5,652 megawatts [MW]), and optimism for the future is high, with long-term industry projections of over 150 gigawatts (GW) by 2030 and over 500 GW by 2050 (Bloomberg New Energy Finance [BNEF] 2018b; 4C Offshore 2018; International Renewable Energy Agency [IRENA] 2018). However, 2018 was somewhat unusual by historical standards as the Chinese market saw its largest deployment ever, with over 2,600 MW of new installations. Offshore wind in Europe installed 2,994 MW, representing about 50% of the new installed capacity.

The offshore wind market in the United States evolved rapidly in 2018 because of a series of positive global and domestic market growth indicators. After bids for a few offshore wind projects in Europe reinforced developers' confidence of zero-subsidy projects in some markets, the United States also saw low-price signals from its first commercial project. In 2018, the U.S. market logged the first competitive bid for an 800-MW commercial wind power plant—Vineyard Wind—in Massachusetts, which seemed to indicate that European market prices can be achieved in the northeastern United States for projects commissioned as early as 2022. The possibility of achieving European offshore wind price levels in U.S. waters coincided with a new wave of state policy support for offshore wind, which originally began in 2016, but increased in late 2018 through the present day. Several new states made offshore wind commitments in 2018, whereas several of the already-committed states aggressively increased their commitments (McClellan 2019). In addition, market optimism likely helped drive lease area auction prices to record highs, as observed in the Massachusetts wind energy area (WEA) lease sales in December 2018 ($135 million per lease area), which were each three times higher than the previous winning lease area bid in New York just 2 years earlier. These record-high prices may indicate a heightened demand for new WEAs as well as an increase in the financial caliber of the bidders, as new members of well-capitalized oil companies and utilities try to establish themselves as offshore wind developers in the emerging U.S. market. All told, the U.S. market developments in 2018 appear to be laying the groundwork for the formation of a new multibillion-dollar offshore wind industry that is likely to bear fruit in the next 5 to 10 years (BNEF 2018a; 4C Offshore 2018; McClellan 2019).

The data and information in this report provide insight into the domestic and global market status, technology trends, and costs, and are key inputs to the annual *Cost of Wind Energy Review* report, which provides an updated summary of the cost of land-based and offshore wind energy in the United States to support DOE's programmatic reporting on the cost of wind energy (Stehly et al. 2017, 2018).

1.1 Approach and Method

1.1.1 NREL Offshore Wind Database

The *2018 Offshore Wind Technologies Market Report* uses NREL's internal offshore wind database (OWDB), which contains information on more than 1,700 offshore wind projects located in 49 countries and totaling approximately 623,329 MW of announced project capacity (both active and dormant). The database includes both fully operational projects dating back to 1990 and anticipated future projects that may or may not have announced their commercial operation date (COD). The OWDB contains information on project characteristics (e.g., water depth, wind speed, distance to shore), economic attributes (e.g., project- and component-level costs and performance), and technical specifications (e.g., component sizes and masses). The database also contains information on installation and transport vessels, as well as ports used to support the construction and maintenance of offshore wind projects.

The OWDB is built from internal research using a wide variety of data sources including peer-reviewed literature, press releases, industry news reports, manufacturer specification sheets, subscription-based industry databases, and global offshore wind project announcements. Unless stated otherwise, the data analysis in this report—both globally and domestically—is derived by NREL from the OWDB and reflects the best judgment of the authors and industry subject matter experts that were consulted. To ensure accuracy, NREL verified the OWDB against the following sources:

- The 4C Offshore Wind Database
- The Bureau of Ocean Energy Management (BOEM)
- The WindEurope Annual Market Update
- BNEF's Renewable Energy Project Database
- The University of Delaware's Special Initiative on Offshore Wind (SIOW).

Although the data were validated and harmonized with these other sources, minor differences in their definitions and methodology may cause the data in this report to vary from data reported in other published reports. For example, the method for counting annual capacity additions often varies among different sources, because of terms such as "installed" or "operational," and "first power" or "commercial operation date" are defined differently. NREL considers a project to be commercially operational when all turbines are fully operational and transmitting power to a land-based electricity grid (see Table 1). Data may also vary in quality and are subject to high levels of uncertainty, especially data for future projects that are subject to change based on developer and regulatory requirements. Despite annual variability and potential future project-level uncertainty, longer-term trends reported elsewhere are consistent with long-term market trends in NREL's OWDB.

Cost and pricing data in the OWDB span a lengthy time period and are reported in different currencies. To analyze these data, all information in this report were normalized into 2018 U.S. dollars (USD) by:

- Converting costs and prices to USD, using the exchange rate for the year in which the latest data were reported (United States Treasury Bureau of Fiscal Service 2019)
- Inflating the values, which are in nominal USD after the exchange rate conversion, to 2018 USD using the U.S. Consumer Price Index (United States Department of Labor Bureau of Statistics 2019).

1.1.2 Classification of Project Status

The "pipeline" is an offshore wind project development and operating project tracking process, which provides the ability to follow the status of a project from early-stage planning through decommissioning. The primary tracking method is aligned with the regulatory process. All offshore wind projects must navigate through the regulatory process that formally begins when a regulator initiates a leasing process to offer developers the opportunity to bid for site control through a competitive lease auction[9] or when an unsolicited project application is formally submitted. In parallel with the regulatory process is the developer's efforts to characterize the economic viability of the project and its capability for long-term energy production to obtain financing. The parallel regulatory and financing pathways have several dependencies, but information about the regulatory path is more easily accessed in the public domain and is therefore the primary method used to track projects in this report. Therefore, the "pipeline" is defined as the set of all offshore wind projects, beginning with those that have formally entered the regulatory leasing process to bid for site control and development rights through projects that have been decommissioned. If known, information on a project's offtake mechanisms and financial close is specifically reported as well.[10]

Offshore wind projects remain in the pipeline from early-stage planning through the operating and decommissioning phases. In the early stages of a project, the exact project footprints and capacities are not always known, but NREL assumes that all lease areas will eventually be fully developed with an array density of 3 MW/square kilometer (km^2). This is a common metric for computing the available wind resource over an area but is not meant to be restrictive (Musial et al. 2013, 2016). Some developers may want higher array densities for their lease areas, or conversely, could decide or be required to leave areas undeveloped for various reasons. The pipeline is adjusted when these decisions are publicly announced.

Table 1 describes the system used in this report for classifying and tracking the development of offshore wind projects and that has been used in past DOE-sponsored offshore wind market reports (Smith, Stehly, and Musial 2015; Musial et al. 2017; Beiter et al. 2018). Note that the criteria used in Table 1 also apply to the global project classification, but some differences may not allow for direct comparisons, especially during the earlier stages of planning. This disconnect is mainly because some countries have different methods of establishing "site control."

[9] Applies to U.S. projects on the Outer Continental Shelf but varies internationally and in state waters.

[10] The "pipeline" is often measured by the quantity of policy commitments made by states. These figures are tracked separately in Section 2.4.2 and offer a good metric for comparison.

Table 1. Offshore Wind Project Pipeline Classification Criteria

Step	Phase Name	Start Criteria	End Criteria
1	Planning	Starts when a developer or regulatory agency initiates the formal site control process	Ends when a developer obtains control of a site (e.g., through competitive auction or a determination of no competitive interest in an unsolicited lease area [United States only])
2	Site Control	Begins when a developer obtains site control (e.g., a lease or other contract)	Ends when the developer files major permit applications (e.g., a construction and operations plan for projects in the United States) or obtains an offtake agreement
3	Permitting = Site Control + Offtake Pathway	Starts when the developer files major permit applications (e.g., construction and operations plan or obtains an offtake agreement for electricity production)	Ends when regulatory entities authorize the project to proceed with construction and certify its offtake agreement
4	Approved	Starts when a project receives regulatory approval for construction activities and its offtake agreement	Ends when sponsor announces a "financial investment decision" and has signed contracts for construction work packages
5	Financial Close	Begins when sponsor announces a financial investment decision and has signed contracts for major construction work packages	Ends when project begins major construction work
6	Under Construction	Starts when offshore construction is initiated[11]	Ends when all turbines have been installed and the project is connected to and generating power for a land-based electrical grid
7	Operating	Commences when all turbines are installed and transmitting power to the grid; COD marks the official transition from construction to operation	Ends when the project has begun a formal process to decommission and stops feeding power to the grid
8	Decommissioned	Starts when the project has begun the formal process to decommission and stops transmitting power to the grid	Ends when the site has been fully restored and lease payments are no longer being made
9	On Hold/Cancelled	Starts if a sponsor stops development activities, discontinues lease payments, or abandons a prospective site	Ends when a sponsor restarts project development activity

1.2 Report Structure

The remainder of the report is divided into four sections:

- Section 2 summarizes the status of the offshore wind industry in the United States, providing in-depth coverage on the project development pipeline, regulatory activity, offtake mechanisms, infrastructure trends, and regional developments.
- Section 3 provides an overview of the global offshore wind market. Operational and proposed future projects are tracked by country, status, commercial operation date, and capacity. Developments on international floating offshore wind projects are also covered in detail.
- Section 4 describes offshore wind siting and technology trends focusing on turbine technologies, turbine manufacturers, project performance, fixed-bottom substructures, electrical power, export systems, and floating technologies.
- Section 5 provides insight into global and domestic offshore wind prices, capital and operational costs, and financing trends for both fixed-bottom and floating technologies. This section also compares historical and forecasted future prices between the European and U.S. offshore wind markets.

[11] Note that some developers may elect to start construction at an onshore landing area to secure certain subsidies or tax incentives.

2 U.S. Offshore Wind Market Assessment

2.1 U.S. Offshore Wind Industry Overview

In 2018, the U.S. offshore wind market continued to attract significant attention from the global community, primarily brought on by a large increase in state policy commitments. From the end of 2017 until June 10, 2019, the total offshore wind capacity that was committed by the states nearly quadrupled. At the end of 2017, U.S. state offshore wind procurement policies required over 5,300 MW of offshore wind by 2030. By June 2019, the sum of official state offshore wind targets increased to 11,468 MW by 2030 and 19,968 MW by 2035. Even in states without offshore wind procurement targets like California and Hawaii, 100% renewables portfolio standards (RPS), clean energy, or carbon reduction goals are driving new market activity and the potential development of new offshore wind lease areas.

The U.S. offshore wind project pipeline was 25,824 MW at the end of 2018, remaining relatively constant, with only a 1.4% increase in total pipeline capacity relative to 2017. Multiple projects made significant progress with electricity offtake agreements and environmental permitting at both the state and federal level. Currently, nine projects have an offtake agreement or are negotiating offtake terms. State-level procurement goals have increased the attractiveness of the U.S. offshore wind market and encouraged competition between developers at recent BOEM auctions. BOEM's auction of three offshore wind lease areas off Massachusetts in December 2018 established a new lease sale price record of $135 million each, more than tripling the previous record of $42 million, signaling increased market confidence, higher demand, and the existence of a committed pool of well-capitalized bidders (BOEM 2019a, 2019b). Interest in the Pacific offshore wind markets also continued to grow in 2018 (BOEM 2019c). BOEM issued Calls for Information and Nominations for offshore wind development in California prompted by multiple prospective floating wind developers. In addition, a 20-year power purchase agreement (PPA) signed with Vineyard Wind in 2018 revealed a first-year price of $74/megawatt-hour (MWh) (2022$) and $65/MWh (2023$), respectively (Beiter et al. 2019).

Despite an increasing number of offshore wind projects submitting their construction and operations plans and engaging local suppliers, supply chain investment in the United States was not commensurate with regulatory advancement. There has yet to be a U.S.-flagged installation vessel or any domestic manufacturing centers built. Also, states have not yet engaged significantly in land-based grid planning or transmission infrastructure upgrades necessary to integrate the expected levels of offshore wind power (Lefevre-Marton et al. 2019). Nevertheless, two U.S.-flagged crew transfer vessels are being built, multiple ports received significant investments to upgrade infrastructure, and states have developed portals to connect developers with local suppliers. Moreover, the near-term lag in the development of a robust domestic supply chain may not be a barrier to the first few commercial-scale projects because the European supply chains can serve the U.S. market in the near term. At the same time, delays in the development of the domestic supply chain could force U.S. project costs above European market costs for large-scale commercial deployment in the mid-2020s and beyond. New technical programs sponsored by DOE and others aim to spur innovation and increase industry supply chain activity (New York State Energy Research and Development Authority [NYSERDA] 2019).

2.2 U.S. Offshore Wind Market Potential and Project Pipeline Assessment

2.2.1 U.S. Offshore Wind Pipeline

As of December 31, 2018, NREL estimates the U.S. offshore wind pipeline to be 25,824 MW of capacity, which is based on the sum of current installed projects, existing lease areas, unleased WEAs, and unsolicited project applications. Table 2 shows the U.S. market broken into five segments by capacity. The U.S. pipeline capacity has one operational project (30 MW), 15 lease areas where developers have site control (estimated 19,151 MW), two unleased WEAs (estimated 2,250 MW), and five unsolicited project applications (2,350 MW). Only installed projects (30 MW) and projects with site control that have advanced through the initial permitting process and are negotiating offtake agreements (2,043 MW) use actual developer-specified capacity values. This is roughly 8% of the total capacity, or 2,073 MW. These projects have a clear project plan and a site boundary that has been specified including much of the design details.

The rest of the pipeline capacity in the other three categories—lease areas with site control, unleased WEAs, and unsolicited project applications—are all estimations based on the potential of the lease area using a capacity density function of 3 MW/km^2 (Musial et al. 2016). Therefore, these estimated values are likely to change over time as project parameters are defined more precisely and lease areas are converted from an unspecified or residual area to actual project capacity. Figure 1 shows each of those categories as a percent of the total U.S. pipeline.

Table 2. U.S. Offshore Wind Pipeline Capacity for Five Categories

	Status	Description	Capacity
1	**Installed**	The project is fully operational with all turbines generating power to the grid.	30 MW
2	**Projects Permitting with Site Control and Offtake Pathway**	The developer has site control and has initiated permitting processes to construct the project and sell its power.	2,043 MW
3	**Lease Areas with Site Control**	Developer has acquired the rights to a lease area. Capacity is estimated using a turbine density of 3 MW/km^2. Depending on market demand, developers may or may not incrementally build out projects to use a given lease area's entire size/potential.	19,151 MW (Estimated)
4	**Unleased Wind Energy Areas**	The rights to lease areas have yet to be auctioned to developers. Capacity is estimated using a 3 MW/km^2 turbine density function.	2,250 MW (Estimated)
5	**Unsolicited Project Applications**	Developer lacks site control but has submitted a project proposal to BOEM. Project application capacities estimated using a 3-MW/km^2 density and project footprint size identified in the proposal.	2,350 MW (Estimated)
		Total	**25,824 MW**

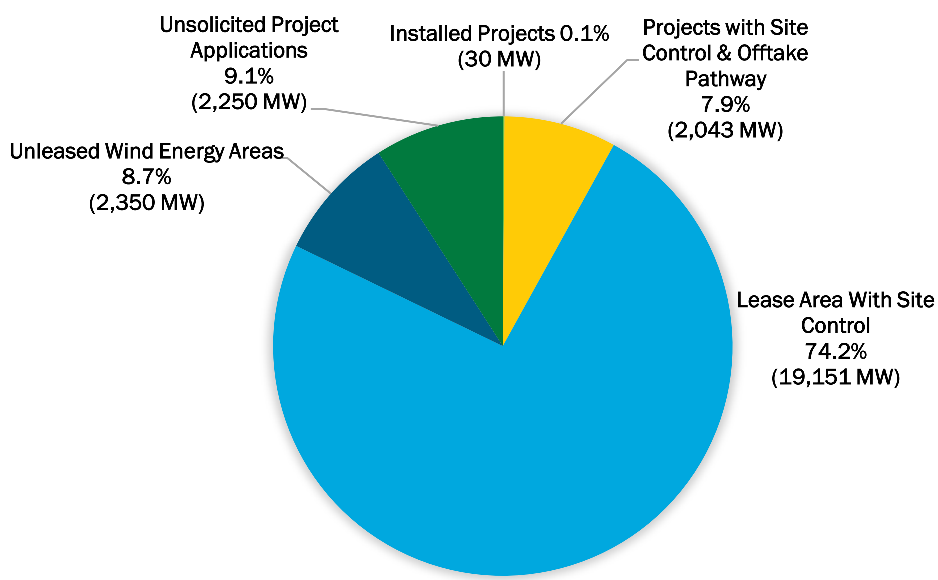


Figure 1. Percentages of U.S offshore wind pipeline (25,824 MW) by classification category

Figure 2 shows the U.S. pipeline activity as of June 10, 2019, for all categories shown in Table 1 by state.[12] Breaking down the 2018 U.S. pipeline by project status: one project (30 MW) has been installed; nine projects (2,043 MW) have site control, made major permitting progress, or secured a power offtake contract or have a viable pathway to obtaining one; developers have the rights to possibly develop projects in 15 lease areas with a technical potential of 19,151 MW; two unleased WEAs have the potential to support 2,250 MW; and six unsolicited project applications (2,350 MW) may be developed but must comply with BOEM's competitive leasing processes. Projects progressing through offtake and permitting approval processes continued to be primarily located in the northeast United States, where state-level procurement drives the market and project development. However, there is also an increased interest in developing floating projects along the Pacific Coast, as described in Section 2.3.2.

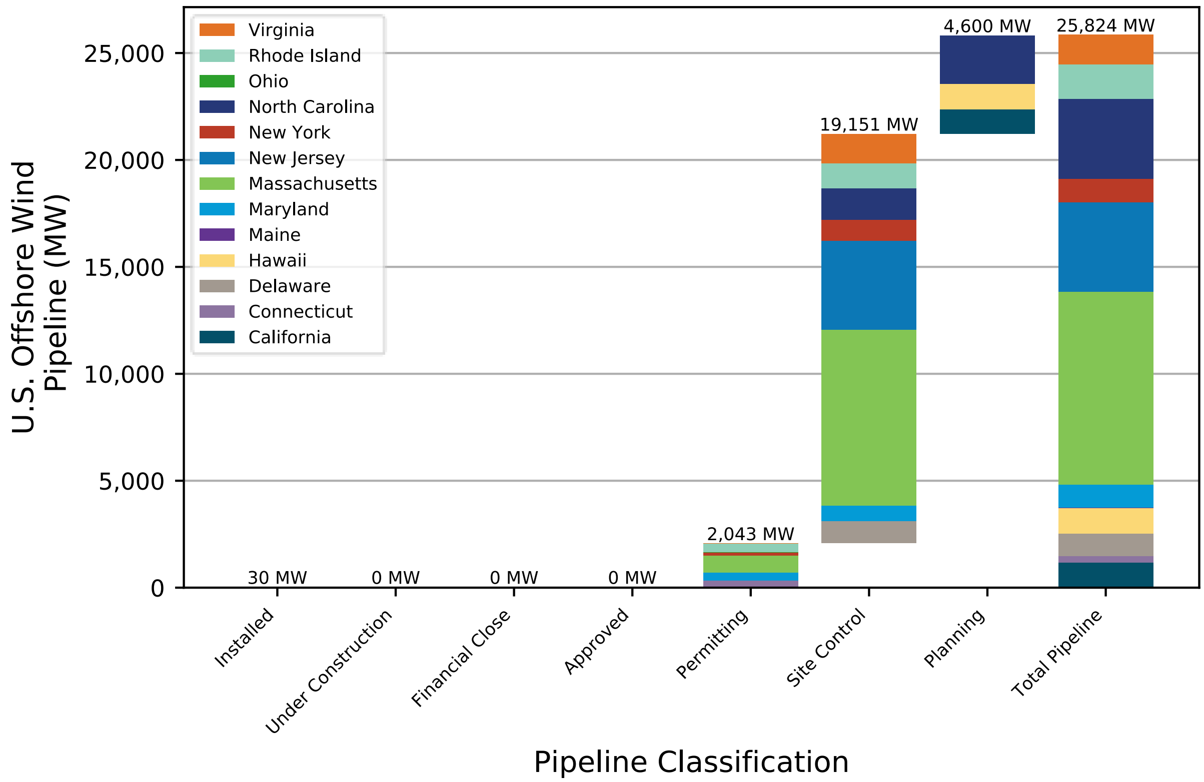


Figure 2. U.S. project pipeline classification by state[13]

There were only minor changes in NREL's estimation of the U.S. offshore wind pipeline from 2017 to 2018 (reporting 25,464 MW in 2017 [Beiter et al. 2018]). The cancellation of the Nautilus Offshore Wind Project in New Jersey accounted for a 24-MW reduction; the expansion of South Fork from 90 MW to 130 MW shifted 40 MW from the Deepwater One North lease area; the Redwood Coast Offshore Wind Project in California added 150 MW; and the proposed Castle Wind Project in California increased its capacity from 765 MW to 1,000 MW. All told, the pipeline only increased by a slight 1.4%.

[12] State in Figure 2 refers to the state the project intends to sell its power to. If a project has not signed an offtake agreement, the state refers to its physical location.

[13] The location of the project is defined by where the project's power is intended to be sold. If the project does not have an offtake agreement, the location is its physical location. This clarification is needed where projects are located in a certain location but sell their power to a neighboring state market.

Figure 3 provides a different breakdown of the U.S. pipeline by state. From the chart, Massachusetts, New Jersey, and North Carolina possess the most offshore wind potential[14] as of March 31, 2019. Note that the hashed bars on the chart indicate the pipeline capacity that was estimated on a 3 MW/km^2 area basis and the solid (green) colored bars are specific projects.

It is important to be cautious about interpreting these geographic lease areas that have been assigned to specific states, because their physical location does not indicate where the offshore wind power will ultimately be delivered. For example, power from Massachusetts can feasibly be delivered to New York and vice versa. In this sense, projects being developed in nearby WEAs may sell power and other grid services to adjacent states because of market demand, state-level offtake policies, or other factors. Current projects in the pipeline that plan to sell power to neighboring markets include:

- Revolution Wind in the Rhode Island/Massachusetts WEA is planning to deliver power to both Connecticut and Rhode Island
- South Fork in the Rhode Island/Massachusetts WEA is planning to deliver power to Long Island New York
- Skipjack in the Delaware WEA is planning to deliver power to the Delmarva grid in Maryland.

Accordingly, state policy may be a more important driver in determining what projects move forward and which markets they serve than the physical location of the leases.

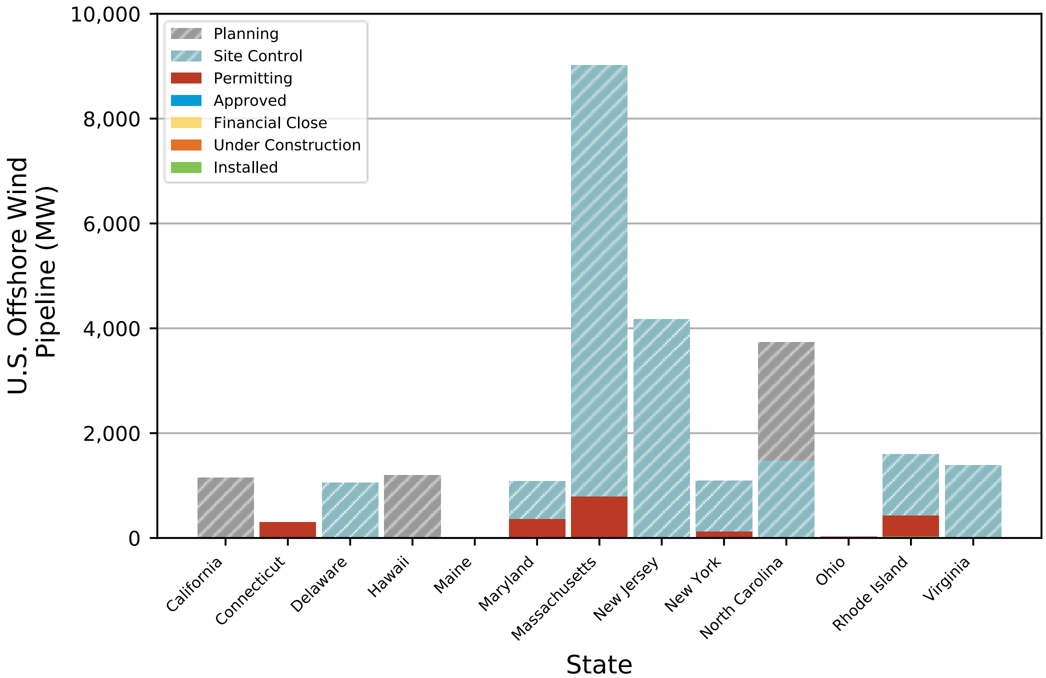


Figure 3. U.S. project pipeline by state[15]

---

[14] Offshore wind potential estimates are made with a significant amount of uncertainty. Uncertainty comes from future market demand, assumed density function, and regulatory proceedings.

[15] The location of the project is defined by where the project's power is sold to. If the project does not have an offtake agreement, the location is the project's physical location. This clarification is needed for projects located in a state's WEA that sells their power to a neighboring state market.

All of the 25,824 MW that make up the U.S. offshore wind pipeline in the United States are itemized as an individual project or project opportunity in Table 3, and in the maps shown in Figures 4, 5, and 6, corresponding to the eastern Atlantic Coast (and Great Lakes[16]), California Coast, and Hawaii, respectively.

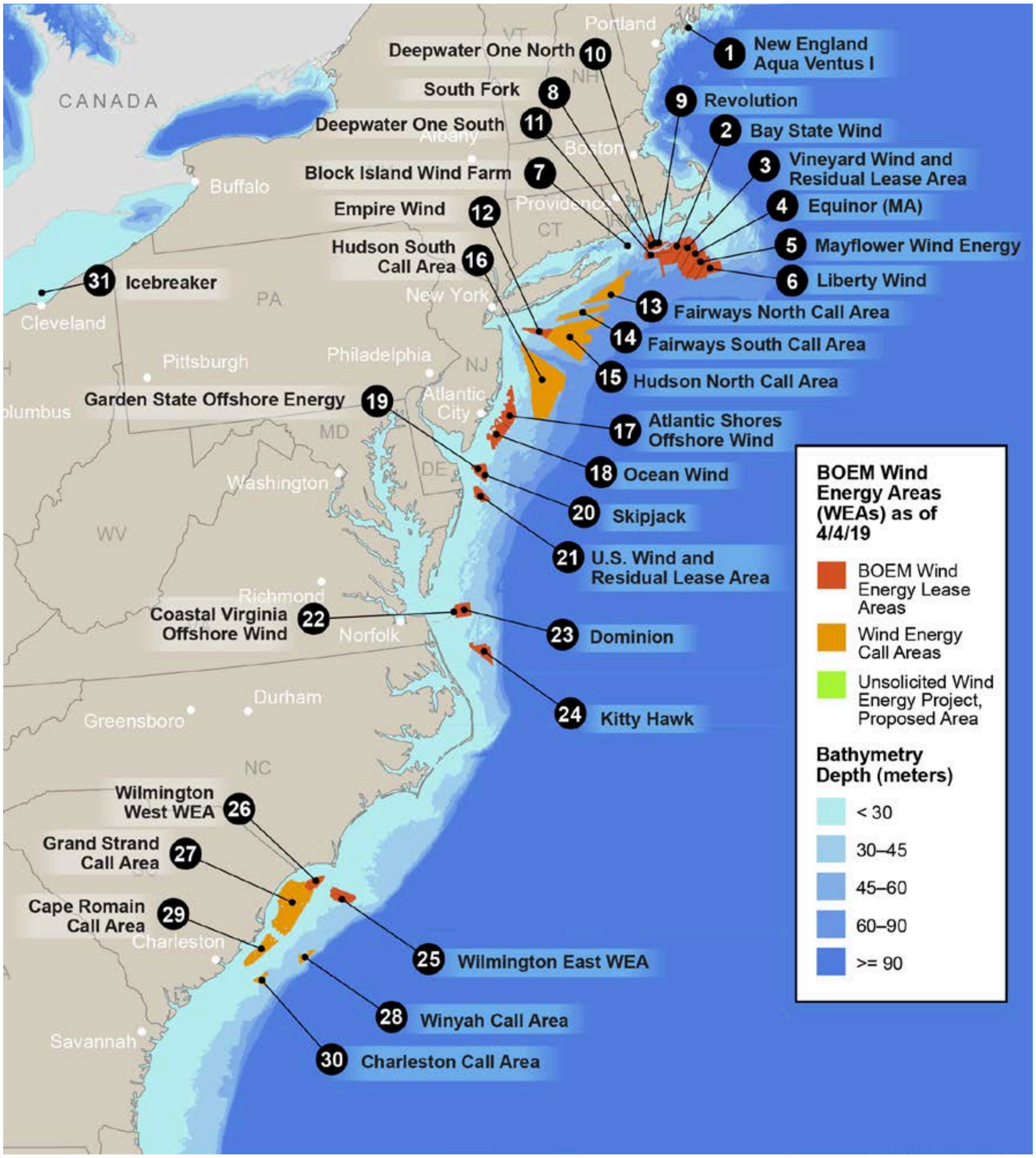


Figure 4. Locations of U.S. Atlantic Coast offshore wind pipeline activity and Call Areas as of March 2019.

Map provided by NREL

[16] Please note the Great Lakes are outside BOEM's jurisdiction.

Most activity is concentrated in the North Atlantic region (Figure 4), but the pipeline activities extend to the Pacific, Great Lakes, and South Atlantic regions. Although there is interest in offshore wind development in the Gulf of Mexico, proposed projects and leasing activities have remained inactive since 2014.

In addition, Table 3 includes 13 Call Areas[17] that are located in three regions, but the capacity of the Call Areas is not calculated or counted in the total pipeline capacity because Call Areas are too preliminary and likely to change in size and location. In total, there are 41 sites in the United States (as shown on the maps) where there is significant offshore wind development activity. The 25,824 MW of pipeline activity comprises

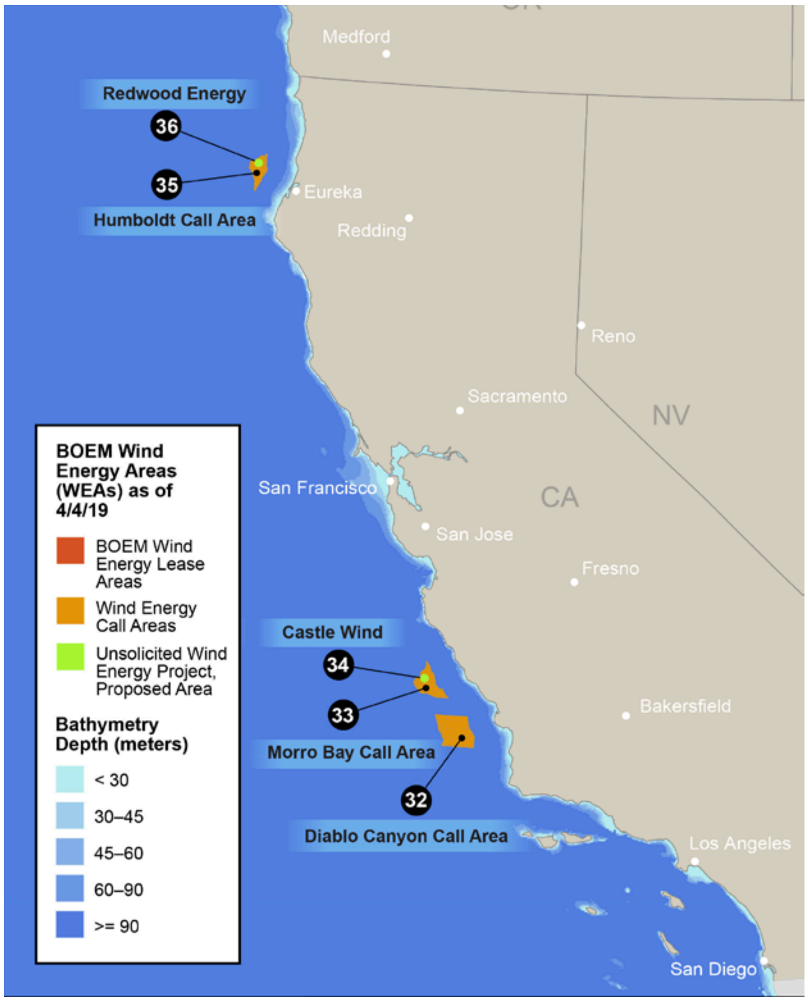


Figure 5. Locations of U.S. West Coast offshore wind pipeline activity and Call Areas as of March 2019.
Map provided by NREL

one operating project (Block Island Wind Farm), nine projects at the permitting phase with an offtake strategy, 15 lease areas with exclusive site control, two unleased WEAs, and five projects (all Pacific-based) that have submitted unsolicited applications to BOEM (BOEM 2019c, 2019d). The pipeline has three projects located in state waters, including the operating Block Island Wind Farm in Rhode Island, New England Aqua Ventus I in Maine, and the Lake Erie Energy Development Corporation (LEEDCo) Icebreaker project located in Lake

[17] BOEM periodically issues calls for information and nominations (Call Areas) to obtain public and developer feedback on what ocean areas may be suitable for future commercial offshore wind development.

Erie, just north of Cleveland. Both Aqua Ventus and Icebreaker were originally funded under the DOE Advanced Technology Demonstration Project program, which began in 2012 (DOE 2019). As a result, they have advanced further in the permitting process than many other projects, having acquired most site approvals from their respective states and establishing reasonable pathways to finalize their PPAs.

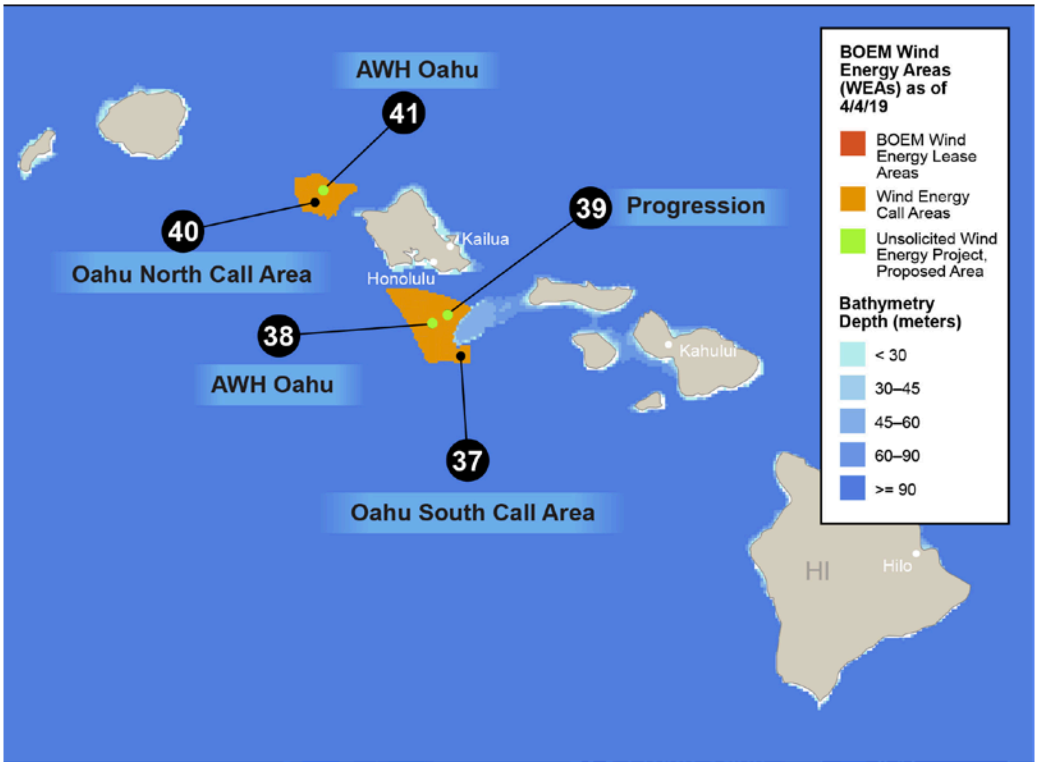


Figure 6. Locations of Hawaiian offshore wind pipeline activity and Call Areas as of March 2019.
Map provided by NREL

Table 3. 2018 U.S. Offshore Wind Pipeline

#	Location[1]	Project Name[2]	Status	COD[3]	Announced Capacity (MW)[4]	Lease Area Potential (MW)[5]	Pipeline Capacity (MW)[6]	Lease Area	Size (km^2)[7]	Offtake (MW)	Developer(s)
1	ME	New England Aqua Ventus I	Permitting	2022	12	0	12	State Lease	9	ME-12	Aqua Ventus
2	MA	Bay State Wind	Site Control	-	0	2,277	2,277	OCS-A 0500	759	TBD	Ørsted/Eversource
3	MA	Vineyard Wind + Residual[8]	Permitting	2023	800	1,225	2,025	OCS-A 0501	675	MA-800	Avangrid/CIP
4	MA	Equinor (MA)	Site Control	-	0	1,564	1,564	OCS-A 0520	521	TBD	Equinor
5	MA	Mayflower Wind Energy	Site Control	-	0	1,547	1,547	OCS-A 0521	516	TBD	EDPR/Shell
6	MA	Liberty Wind	Site Control	-	0	1,607	1,607	OCS-A 0522	536	TBD	Avangrid/CIP
7	RI	Block Island Wind Farm	Installed	2016	30	0	30	State Lease	10	RI-30	Ørsted/Eversource
8	RI	South Fork	Permitting	2022	130	0	130	OCS-A 0486		NY-130	Ørsted/Eversource
9	RI	Revolution	Permitting	2023	700	0	700	OCS-A 0486	395	CT-300 RI-400	Ørsted/Eversource
10	RI	Deepwater ONE North	Site Control	-	0	355	355	OCS-A 0486		TBD	Ørsted/Eversource
11	RI	Deepwater ONE South	Site Control	-	0	816	816	OCS-A 0487	272	TBD	Ørsted/Eversource
12	NY	Empire Wind	Site Control	-	0	963	963	OCS-A 0512	321	TBD	Equinor
13	NY	Fairways North	BOEM Call Area	-	-	-	-	N/A	-	-	-
14	NY	Fairways South	BOEM Call Area	-	-	-	-	N/A	-	-	-
15	NY	Hudson North	BOEM Call Area	-	-	-	-	N/A	-	-	-
16	NY	Hudson South	BOEM Call Area	-	-	-	-	N/A	-	-	-
17	NJ	Atlantic Shores Offshore Wind	Site Control	-	0	2,226	2,226	OCS-A 0499	742	TBD	EDF/Shell
18	NJ	Ocean Wind	Site Control	-	0	1,947	1,947	OCS-A 0498	649	TBD	Ørsted
19	DE	Garden State Offshore Energy	Site Control	-	0	1,050	1,050	OCS-A 0482	284	TBD	Ørsted
20	DE	Skipjack	Permitting	2023	120	0	120	OCS-A 0519	107	MD-120	Ørsted
21	MD	US Wind + Residual[8]	Permitting	2023	248	718	966	OCS-A 0490	322	MD-248	US Wind
22	VA	Coastal Virginia Offshore Wind	Permitting	2022	12	0	12	OCS-A 0497	9	VA-12	Ørsted/Dominion Energy
23	VA	Dominion	Site Control	-	0	1,371	1,371	OCS-A 0483	457	TBD	Dominion Energy
24	NC	Kitty Hawk	Site Control	-	0	1,485	1,485	OCS-A 0508	495	TBD	Avangrid
25	NC	Wilmington East WEA	Unleased[9]	-	0	1,623	1,623	N/A	209	-	-
26	NC	Wilmington West WEA	Unleased[9]	-	0	627	627	N/A	541	-	-
27	SC	Grand Strand	BOEM Call Area	-	-	-	-	N/A	-	--	-
28	SC	Winyah	BOEM Call Area	-	-	-	-	N/A	-	-	-
29	SC	Cape Romain	BOEM Call Area	-	-	-	-	N/A	-	-	-
30	SC	Charleston	BOEM Call Area	-	-	-	-	N/A	-	-	-
31	OH	Icebreaker	Permitting	2022	21	0	21	State Lease	10	OH-21	LEEDCo/Fred Olsen
32	CA	Diablo Canyon	BOEM Call Area	-	-	-	-	-	-	-	-
33	CA	Morro Bay	BOEM Call Area	-	-	-	-	-	-	-	-
34	CA	Castle Wind	Unsolicited Project Application	-	0	1,000	1,000	N/A	334	TBD	Trident Winds/EnBW
35	CA	Humboldt	BOEM Call Area	-	-	-	-	-	-	-	-
36	CA	Redwood Energy	Unsolicited Project Application	-	0	150	150	N/A	50	TBD	EDPR/PPI
37	HI	Oahu South	BOEM Call Area		-	-	-	-	-	-	-
38	HI	AWH Oahu South	Unsolicited Project Application	-	0	400	400	N/A	133	TBD	AW Wind
39	HI	Progression	Unsolicited Project Application	-	0	400	400	N/A	133	TBD	Progression Wind
40	HI	Oahu North	BOEM Call Area	-	-	-	-	-	-	-	-
41	HI	AWH Oahu North	Unsolicited Project Application	-	0	400	400	N/A	133	TBD	AW Wind
		Total			**2,073 MW**	**23,751 MW**	**25,824 MW**				

1. Location refers to physical location of the project. The offtake column identifies where the project sells its power and other attributes.
2. Some project names may change based on successful bids to state procurement solicitations
3. Future commence operation dates are subject successfully negotiating offtake agreement and may change
4. Announced capacity describes the size of a project as stipulated by a developer to regulators
5. Lease Area Potential describes the potential capacity that could be installed in a lease area using a 3MW/km^2 density
6. Pipeline capacity represents the lease area potential minus any developer announced capacity
7. Sizes for Unsolicited Project Applications are likely to change during stakeholder and regulatory review processes and may be eliminated in the future
8. Lease areas can often accommodate multiple projects or project phases built incrementally. The "+ Residual" refers to remaining space in the lease area that may be utilized in the future
9. The two Wind Energy Areas in North Carolina have currently not been leased by BOEM

2.2.2 U.S. Offshore Wind Market Forecasts to 2030

Figure 7 is a compilation of three independent industry forecasts for offshore wind deployment in the United States for the period extending to the year 2030. These estimates were developed by BNEF (2018b), 4C Offshore (2018), and University of Delaware's SIOW (2019),[18] respectively. Combined, they illustrate the degree of expected market growth and the possible variability associated with the year, size, and location of future projects.

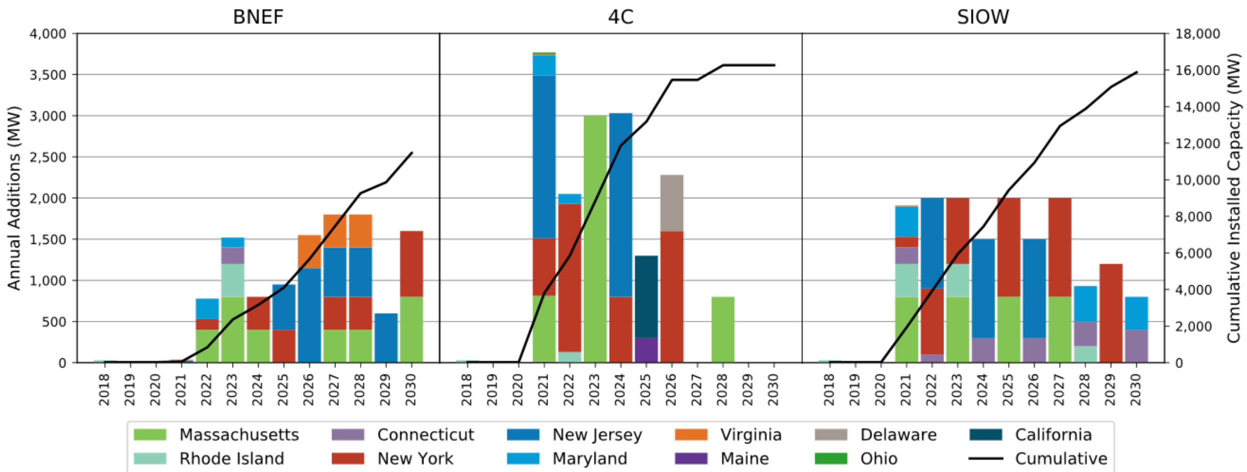


Figure 7. U.S offshore wind market forecasts (annual additions–left axis) (cumulative capacity through 2030–right axis)

The forecasts estimate that the U.S. offshore wind market will cumulatively deploy between 4 and 13 GW by 2025, and 11 and 16 GW by 2030. All three forecasts agree that the U.S. market has the potential to be greater than 10 GW by 2030, but the size and speed of build-out are likely to be impacted by regulatory uncertainty, availability of installation vessels and port infrastructure, land-based grid planning and upgrades, and evolving market demand. All forecasts predict the majority of future offshore wind deployment out to 2030 will occur on the East Coast in states with currently existing or planned offshore wind procurement goals. Only 4C Offshore's forecast includes commercial-scale floating projects by 2030: one on the West Coast off California, and one off the state of Maine.

The main factor causing variability in the forecasts is uncertainty regarding state policy as well as the size and regularity of future procurements beyond state-level solicitations that have already been announced. Other significant factors include potential problems acquiring project financing, vessel availability, cost reduction challenges, problems with environmental and geotechnical surveys, and unexpected issues with competing ocean uses. The forecasts likely assume the creation of new offshore wind lease areas to fully support state procurement targets, but this is not stated explicitly. For example, New York's 9-GW-by-2035 target may necessitate obtaining capacity from neighboring WEAs in states like Rhode Island, Massachusetts, and New Jersey, and establishing new lease areas. As such, there has been much speculation over the four Call Areas in the New York Bight but at this time it is not known if or when BOEM will propose new WEAs (BOEM 2019b).

[18] Please note University of Delaware's Special Initiative for Offshore Wind forecast is based on the expected date a state selects to procure offshore wind capacity. A 3-year time lag is assumed from the time the procurement occurs until the project becomes fully operational.

2.3 Regulatory Activity

2.3.1 Lease Activity

Acquiring exclusive rights to develop a lease area in federal waters (where most lease areas are located) is the first fundamental step toward building an offshore wind project in the United States. Market consolidation was a major trend in 2018, driven by international developers purchasing the assets of smaller U.S. companies. Although construction for commercial projects has not yet begun in earnest, approximately $1.39 billion was exchanged in the United States this year in gross revenue involving lease areas and corporate acquisitions:

- In April 2018, Ørsted asked BOEM to reassign 107 km^2 in the southern portion of lease area OCS-A 0482 (Garden State Ocean Energy) in Delaware to the Skipjack project. Skipjack now has its own lease area: OCS-A 0519.

- In December 2018, Atlantic Shores Offshore Wind, a partnership between Électricité de France Renouvelables (EDF) and Shell New Energies, bought lease area OCS-A 0499 from US Wind for $215 million pending regulatory approval (offshoreWIND.biz 2018a).

- In November 2018, Ørsted completed the acquisition of Deepwater Wind's offshore assets including their lease areas for a reported $510 million (Ørsted 2018).

- In February 2019, Ørsted sold a partial ownership stake for $225 million in some of their newly acquired Deepwater projects to Eversource Energy, a utility serving Connecticut, Rhode Island, and Massachusetts (Eversource Energy 2019).

Another major market trend in 2018 was an increase in offshore lease area prices, as demonstrated in BOEM's sale of three offshore wind lease areas in the Massachusetts WEA. Each lease area sold for at least $135 million. The lease areas had previously been up for auction in January 2015 but did not receive any bids. The results of this auction are shown in Table 4.

Table 4. BOEM's Massachusetts Offshore Wind Auction Results from December 2018

State	Lease Area	Auction Date	Provisional Winner	Winning Bid	Size (km^2)	Lease Area Potential
MA	OCS-A 0520	12/14/18	Equinor	$135,000,000	521	1,564 MW
MA	OCS-A 0521	12/14/18	Mayflower Wind Energy	$135,000,000	516	1,547 MW
MA	OCS-A 0522	12/14/18	Vineyard Wind	$135,100,000	536	1,607 MW

In aggregate, the three lease areas in Massachusetts have the potential to support at least 4.7 GW of new capacity. Figure 8 shows the overall trend of increasing lease sale prices in the United States since 2013, on the basis of $/km^2.

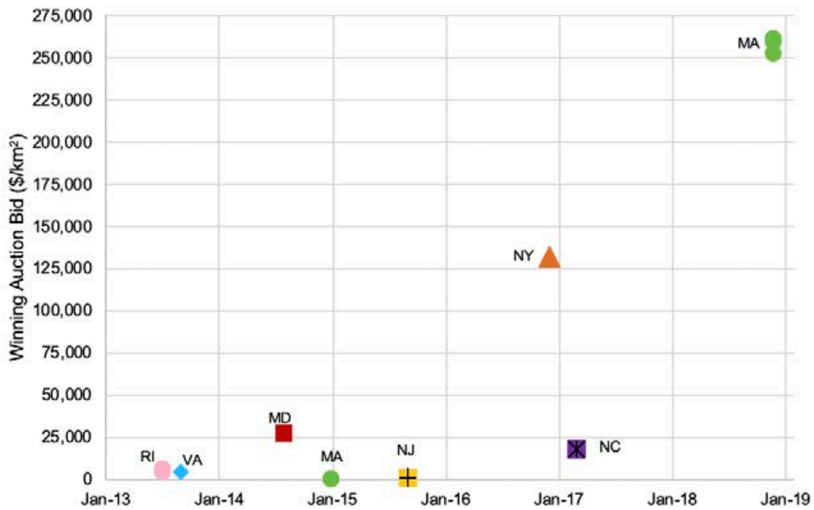


Figure 8. U.S. offshore wind lease sale prices to date by year

Notably, the winning auction bid price of $135 million surpassed the previous record-winning sale price of $42.4 million in Equinor's 2016 acquisition of the New York lease area. Not surprisingly, the highest-priced leases were in states with both proposed and implemented offshore wind offtake policies (e.g., Massachusetts, New York, Maryland, and Massachusetts) in 2018.

Although increased lease sale prices may be a signal that the offshore wind market is maturing and the bankability of future projects is increasing, it may also offset some expected (or required[19]) project price reductions and could increase the delivery price of a project's electricity. As an example, NREL calculated that recent Massachusetts lease sale prices could increase the levelized cost of energy (LCOE) for a hypothetical 800-MW project by about 5% relative to U.S. projects that acquired lease areas prior to 2016.

2.3.2 New Area Identification

BOEM periodically publishes Calls for Information and Nominations to assess commercial competitive interest for offshore wind development on specific parcels of ocean acreage in federal waters. The information gathered during these calls is used by BOEM in conjunction with other stakeholder input to identify future WEAs and subsequent lease area auctions. A Call Area is a precursor to a defined wind energy area, but not all Call Areas become wind energy areas, and they are typically modified (reduced in size) to address stakeholder input. In 2015, BOEM issued calls for four areas in federal waters off South Carolina and in 2016 issued calls for two areas off the Hawaiian island of Oahu (BOEM 2019d). There are currently 13 Call Areas for offshore wind today in the United States. Table 5 lists the seven newest Call Areas created by BOEM in 2018, including four in New York and three in California. These can also be found on the maps in Figures 4 and 5, and in Table 3 (BOEM 2019b, 2019c).

Table 5. 2018 BOEM Offshore Wind Call Areas

State	Name	Call Period
NY	Fairways North Call Area	4/11/2018–7/30/2018
NY	Fairways South Call Area	4/11/2018–7/30/2018
NY/NJ	Hudson North Call Area	4/11/2018–7/30/2018

[19] Some states, such as Massachusetts, have procurement policies that mandate that project prices in future solicitations must be lower than previous project prices to require a downward cost trend.

NY/NJ	Hudson South Call Area	4/11/2018–7/30/2018
CA	Humboldt Call Area	10/19/2018–1/28/2019
CA	Morro Bay Call Area	10/19/2018–1/28/2019
CA	Diablo Canyon Call Area	10/19/2018–1/28/2019

2.3.3 Stakeholder Engagement

The offshore wind industry in the United States continues to look for strategies to responsibly develop projects that minimize interference with the environment as well as the following preexisting ocean uses:

- **Fishing**. In cooperation with the Rhode Island Coastal Resources Management Council and local fishermen, Avangrid-Copenhagen Infrastructure Partners (CIP) established a $12.5-million trust fund to compensate fishermen who may be negatively impacted[20] by Vineyard Wind's construction (Rhode Island Coastal Resources Management Council 2019). The Responsible Offshore Science Alliance has partnered with fishermen, the National Oceanic and Atmospheric Administration (NOAA), Equinor, EDF, Shell, and Ørsted to disseminate salient and credible fisheries data (Froese 2019a). Ørsted partnered with the Responsible Offshore Development Alliance to improve communication between fishermen and their project planners (Saltzberg and Dowd 2019). Equinor and EDF also joined the alliance's Joint-Industry Task Force to ensure fishing and offshore wind development can coexist (Froese 2019b). The Responsible Offshore Development Alliance has also partnered with BOEM, NOAA, the U.S. Coast Guard, and other fishing industry liaisons to ensure that stakeholder concerns and best mitigation practices are incorporated into regulatory review processes. The group conducted multiple workshops in 2019 to minimize potential impacts of offshore wind development on fishermen.

- **Environmental**. Offshore wind construction and operations could potentially impact marine mammals,[21] fisheries, or avian species. Of specific interest in the northeast is the North Atlantic right whale, one of the world's most endangered marine mammals with historical migration routes that transit multiple offshore WEAs. In April 2018, Bay State Wind announced it would provide $2 million in research grants to help protect New England marine mammals (Bay State Wind 2018). In 2019, Equinor partnered with the Conservation Society and Woods Hole Oceanographic Institute to deploy acoustic buoys to better understand whale activities near proposed construction areas (Lillian 2019). Vineyard Wind signed an agreement with the National Wildlife Federation, Natural Resources Defense Council, and Conservation Law Fund to develop a construction strategy that minimizes pile driving and geophysical surveys during North Atlantic right whale migration periods, sets vessel speed limits to minimize marine mammal collision, and adopts new technologies like bubble screens to minimize installation noise (Skopljak 2019a). Vineyard Wind is also accepting proposals from universities and private companies for new passive acoustic monitoring systems to detect when whales are in the vicinity and appropriately pause construction activities to mitigate negative impacts (Skopljak 2019b). LEEDCo continues to work through federal and state regulations to minimize the impact of offshore wind energy on bird and bat species. As a resource for the public, DOE's Tethys database[22] provides users with access to scientific studies that can help developers, regulatory staff, stakeholders, and researchers effectively site renewable projects and employ installation and operations techniques that minimize impact to the environment (DOE 2018). Additional public resources relevant to offshore wind include BOEM's Environmental Science Database (BOEM 2019e), the Northeast Regional Ocean Council Data Portal (NOAA 2019a), and the Mid-Atlantic Ocean Data Portal (NOAA 2019b).

[20] Offshore wind construction may impact the availability of certain fish species or interfere with the ability of fishermen to fish in certain locations.
[21] Underwater noise associated with offshore wind construction (especially pile driving) may impact marine mammal communication and migration.
[22] Please visit DOE's Tethys database at https://tethys.pnnl.gov/.

- **Navigation**. To avoid collisions and entanglement of fishing gear, Vineyard Wind proposed maritime transit corridors through their lease area with the support of BOEM, local stakeholders, and the U.S. Coast Guard (Vineyard Wind 2018d).

- **Military**. As reported in the *2017 Offshore Wind Technologies Market Update*, offshore wind developers, state agencies, the U.S. Department of Defense, and BOEM have been working together to resolve potential offshore wind conflicts with military operations, training, and radar. Areas with military activities and potential offshore wind development include California, Hawaii, New York, Delaware, Maryland, North Carolina, and South Carolina. These discussions are continued in 2018 and are likely to remain active in the foreseeable future.

2.4 U.S. Offshore Wind Project Offtake and Policy Assessment

2.4.1 Project Offtake Agreements

In addition to obtaining site control and regulatory approval, negotiating an offtake agreement to sell the electricity and other possible clean power attributes (e.g., offshore renewable energy credits [ORECs]) is one of the three crucial steps to developing a bankable project. In the United States, each state has unique procurement targets and uses different mechanisms to negotiate the duration and terms of buying an individual project's electrical generation from a developer.[23] Eight offtake agreements have been signed for seven U.S. projects and two projects are in the process of negotiating terms with electric distribution companies, as shown in Table 6. (Note that Revolution is one project but is selling power to two different states.)

Table 6. U.S. Offshore Wind Offtake Agreements as of June 10, 2019

Project	Offtake State	Offtake Mechanism	Public Utility Commission Approved	Offtake Mechanism Price	Description
Block Island Wind Farm	RI	PPA	Yes	$244/MWh	In 2014, Deepwater Wind signed a 20-year PPA with National Grid for $244/MWh, with a 2.5% annual escalator.
South Fork	NY	PPA	Yes	Undisclosed	In 2017, Deepwater Wind signed a 20-year PPA with Long Island Power Authority for 90 MW at an undisclosed price. In 2019, Long Island Power Authority executed an amendment in the PPA to increase the offtake agreement to 130 MW.
US Wind	MD	MD ORECs	Yes	$131.92/MWh	In 2017, Maryland awarded US Wind ORECs[24] for 248 MW of capacity for 20 years. Each year, 913,945 ORECs will be sold. The levelized OREC price is $131.94/MWh.
Skipjack[25]	MD	MD ORECs	Yes	$131.92/MWh	In 2017, Maryland awarded Skipjack ORECs for 120 MW of capacity for 20 years. Each year, 455,482 ORECs will be sold. The levelized OREC price is $131.94/MWh.
Vineyard Wind	MA	PPA	Yes	$74/MWh $65/MWh	In 2018, Vineyard Wind signed two 400-MW PPAs with Massachusetts utilities for 20 years. The levelized first-year prices of the PPAs were $74/MWh (2022$) and $65/MWh (2023$), respectively.
Coastal Virginia Offshore Wind	VA	Utility Owned	Yes	$780/MWh[26]	In 2018, Virginia regulators approved Dominion/Ørsted to construct a 12-MW demo project. The estimated levelized cost of energy is $780/MWh.

[23] As shown in Table 6, some of the most common offtake agreement types are PPAs; legal contracts where a developer sells a project's power and other attributes to a buyer for a specified price and term; offshore renewable energy credits, in which each credit represents 1 MWh of energy and other attributes generated from an offshore wind energy project; and utility owned, wherein an offshore wind project is fully owned by a utility and sells power directly to utility customers.

[24] Each OREC represents 1 MWh of offshore wind generation and is a remuneration mechanism for the environmental attributes of offshore wind generation.

[25] Note that Skipjack is both a lease area and a project.

[26] Please note the levelized price for Coastal Virginia Offshore Wind is significantly higher than other projects because it is a demonstration project and is unable to leverage economies of scale.

Project	Offtake State	Offtake Mechanism	Public Utility Commission Approved	Offtake Mechanism Price	Description
Revolution Wind	CT	PPA	Yes	$94/MWh	In 2018, Ørsted signed a 20-year PPA with Eversource and United Illuminating for 200 MW, with a levelized PPA price of approximately $94/MWh. Ørsted has been approved to start negotiations on an additional 100 MW.
Revolution Wind	RI	PPA	Yes	$98.43/MWh	In 2019, Ørsted signed a 20-year PPA with National Grid for 400 MW. The proposal was approved by the Public Utility Commission, and the all-in price is $98.43/MWh.
Icebreaker	OH	PPA	Pending	TBD	LEEDCo is working to secure offtake with multiple partners for the project's electricity.
Aqua Ventus I	ME	PPA	Pending	TBD	Aqua Ventus I is negotiating a PPA with Central Maine Power.

2.4.2 State Policies

The U.S. offshore wind market continues to be driven by an increasing amount of state-level offshore wind procurement activities and statutory policies. In aggregate, these activities now call for the deployment of 19,968 MW of offshore wind capacity by 2035, almost four times the aggregate state-level targets identified at the end of 2017. These commitments are shown in Table 7.

Note that the states that have adopted offshore wind energy policies listed in Table 7 may not have their own offshore wind resources. For several projects (e.g., Revolution, Skipjack, South Fork), deployment is being planned in a WEA adjacent to the state[27] that will receive the power, generally at a location where the most favorable PPAs can be negotiated. The primary requirement is that the project is close enough to the onshore injection point to avoid prohibitive costs for the export cables.

Table 7. Current U.S. Offshore Wind State Policies and Activity as of June 10, 2019

State	2018 Capacity Commitment[28] (MW)	Offshore Wind Solicited (MW)	Contract Type	Target Year	Statutory Authority	Year Enacted	RPS Goal[29]	State RPS Year
MA	**1,600**	1600	PPA	2027	An Act to Promote Energy Diversity (H.4568)	2016	35%	2030
	1,600[30]	-	PPA	2035	An Act to Advance Clean Energy (H.4857)	2018		
RI[31]	**400**	400	PPA	-	-	-	31%	2030
NJ	**3,500**	1,100	OREC	2030	Executive Order 8 AB No. 3723	2018	50%	2030
MD	**368[32]**	368	OREC	2030	Maryland Offshore Wind Energy Act	2013	24%	2020
	400	-	OREC	2026		2019		

[27] For example, the Phase 1 New York offshore wind solicitation allows generators to interconnect with other markets (PJM Interconnection or ISO New England), as long as the power can be sold into the New York control area.
[28] State commitments in this table are listed incrementally and are additive (e.g., New York has a 9,000 MW goal by 2035).
[29] RPS goals are often staged over time; for this table, only the nearest-term RPS goal is included for simplification purposes.
[30] H.4857 authorized Massachusetts Department of Energy Resources to consider an additional 1,600 MW procurement by 2035. On May 31, 2019, the Department of Energy Resources said it would use the authorization and hold ~800-MW solicitations in 2022 and 2024, and in 2026, if needed.
[31] Rhode Island has a strategic goal to increase the state's clean energy to 1,000 MW by 2030. However, the state has no offshore-wind-specific statutory requirement or goal.
[32] The Maryland Offshore Wind Energy Act of 2013 limits an offshore wind RPS carve-out to 2.5% of total retail electric sales in state. This proportional goal corresponds to the OREC award on May 11, 2017, for 368 MW awarded to Skipjack Offshore Energy (120 MW) and US Wind (248 MW). (Total retail electric sales in Maryland were 59,303,885 MWh in 2017 [Energy Information Administration 2019]).

	400	-		2028	Senate Bill 516[33]			
	400	-		2030				
NY	**2,400**	930[34]	OREC	2030	Case 18-E-0071 Order Establishing Offshore Wind Standard and Framework for Phase 1 Procurement	2018	50%	2030
	6,600	-	TBD	2035	Climate Leadership and Community Protection Act	2019		
CT	**300[35]**	300	PPA	2020	House Bill 7036 (Public Act 17-144)	2017	44%	2030
	2,000	-	TBD	2030	House Bill 7156[36]	2019		
VA	-	12	Utility Owned	2028	Virginia Energy Plan	TBD	-	-
TOTAL	**19,968 MW**	**4,710 MW**						

In April 2018, New Jersey increased its RPS goal to 50% by 2030 and its offshore wind goal from 1,100 MW to 3,500 MW by 2030 (New Jersey State Legislature 2018). In August 2018, Massachusetts passed new legislation to increase its offshore wind procurement goal from 1,600 MW by 2027 to 3,200 MW[37] by 2035 (Commonwealth of Massachusetts 2018). In October 2018, Virginia published a state energy plan that proposed an offshore wind target of 2,000 MW by 2028 (BVG Associates 2018a).[38] In January 2019, New York's Governor Cuomo increased the state's offshore wind goal to 9,000 MW by 2035 (New York State 2019a), which was codified into law in the *Climate Leadership and Community Protection Act* in June 2019 (New York State 2019b). Maryland also passed legislation in April 2019 to mandate the deployment of an additional 1,200 MW of offshore wind by 2030 (Maryland General Assembly 2019). In June 2019, Connecticut passed new legislation to procure 2,000 MW of offshore wind capacity by 2030 (Connecticut General Assembly 2019).

To meet their committed procurement targets, multiple states issued solicitations for commercial projects in 2018, and executed significant planning around future solicitations including the following:

- In New York, NYSERDA issued a solicitation for approximately 800 MW of capacity worth of ORECs. Bids were due February 19, 2019, and NYSERDA announced that Atlantic Shores Offshore Wind (EDF/Shell), Empire Wind (Equinor), Liberty Wind (Avangrid/CIP), and Sunrise Wind (Ørsted and Eversource) all responded to the solicitation. Winners are expected to be announced in spring 2019.

- New Jersey issued a solicitation for 1,100 MW of ORECs that was open from September 20 to December 28, 2018. Three developers responded to the solicitation: Board Walk Wind (Equinor), Atlantic Shores Offshore Wind (EDF/Shell), and Ocean Wind (Ørsted). The Board of Public Utilities (BPU) is expected to announce a winner by summer 2019.

- NYSERDA plans to have another 800-MW solicitation in 2019 (NYSERDA 2019).

- The New Jersey BPU also announced plans for two additional solicitations for 1,200 MW in 2020 and 2022 (New Jersey BPU 2019).

[33] Maryland legislature passed SB516 May 25, 2019. It mandates the procurement of 400 MW by 2026, 800 MW by 2028, and 1,200 MW by 2030.
[34] Long Island Power Authority solicited 90 MW for the South Fork project in 2017. The project size was later increased to 130 MW. NYSERDA solicited 800 MW in 2018.
[35] Public Act 17-144 limits authority to procure offshore wind to 3% of Connecticut electric distribution companies' total electric, which corresponds to approximately 200 MW. The other 100 MW come from technology-neutral auctions.
[36] CT House Bill 7156 was signed into law June 10, 2019. It requires Connecticut to procure 2,000 MW by 2030 and DOE and Environmental Protection to issue a solicitation by June 24, 2019.
[37] Note the additional 1,600 MW is at the discretion of the Massachusetts Department of Energy Resources, so the ultimate procurement target could change.
[38] The state energy plan recommends 2,000 MW and is awaiting action from the governor.

- Maryland's new offshore wind procurement legislation requires the state to procure 400 MW by 2026, 800 MW by 2028, and 1,200 MW by 2030 (Maryland General Assembly 2019).
- Massachusetts Department of Public Utilities issued its second offshore wind solicitation on May 27, 2019, to meet the state's 1,600-MW-by-2027 goal. The request for proposals asks developers to submit plans for designs between 400 and 800 MW (Massachusetts Department of Energy Resources 2019a). Bids are due by August 9, 2019.
- The Massachusetts Department of Energy Resources conducted an offshore wind study to investigate the necessity, benefits, and costs of requiring Massachusetts's electric distribution companies[39] to conduct additional offshore wind generation solicitations of up to 1,600 MW. The agency found that the additional capacity was in the best interest of the state and announced it will hold additional solicitations for up to 800 MW of offshore wind in 2022 and 2024, and if necessary to meet the 1,600 MW target, in 2026 (Massachusetts Department of Energy Resources 2019b).

2.5 U.S. Infrastructure Trends

2.5.1 Vessels and Logistics

A lack of specialized, U.S.-flagged offshore wind installation vessels and limitations imposed by the Jones Act[40] continues to be a potential bottleneck for the nascent U.S. offshore wind industry. As reported in past market reports, multiple marine engineering companies (e.g., Gusto MSC, Zentech, AK Suda) have drafted designs and conducted cost studies for U.S.-flagged installation vessels, but no offshore installers publicly announced construction of a new vessel in 2018. The only known vessel development in 2018–2019 was Ørsted entering into partnership with WindServe Marine to construct two crew transfer vessels—one in North Carolina and the other in Rhode Island—for use at the Coastal Virginia Offshore Wind and Revolution Wind projects (Foxwell 2019). The lack of specialized U.S.-flagged installation and support vessels will likely prompt initial commercial-scale projects to use foreign-flagged installations vessels and U.S.-flagged feeder barges.

2.5.2 Ports and Harbors

Although no investments have been made for U.S.-flagged offshore wind installation vessels, developers and state bodies have started to make investments in port infrastructure to make sure there are sufficient cranes and laydown space required for large-scale commercial projects. There are a number of ports in the United States that are potentially suitable for offshore wind construction, staging, and assembly. The few ports that have made recent infrastructure investments to upgrade and prepare for the first wave of projects are listed in Table 8. Going forward, this list is expected to grow.

Table 8. Ports with Recent Investments for the U.S. Offshore Wind Industry

State	Location	Description	Offshore Wind Projects
MA	Port of New Bedford	Vineyard Wind is leasing the New Bedford Commerce Terminal for 18 months as the primary staging and deployment base for its 800-MW project (Mass Live 2018).	Vineyard Wind
MA	Brayton Point	Anabaric and Commercial Development Company signed an agreement to invest $650 million into Brayton Point's Commerce Center to create an offshore wind hub that has a 1.2-GW high-voltage direct-current converter, 400-MW battery storage, and additional wind turbine component laydown space.	Multiple in MA and RI

[39] Electric distribution companies are regulated entities that purchase wholesale energy and sell it to retail customers.

[40] The Jones Act prohibits the maritime shipment of merchandise and passengers between two points in the United States by any vessel that is not U.S.-flagged (domestically manufactured, owned, and operated). For offshore wind development, this means foreign-flagged turbine installation vessels are unable to carry turbine components from a U.S. port to a construction site in U.S. waters.

CT	New London	Ørsted, the Connecticut Port Authority, and Gateway will invest $93 million in the State Pier at New London to expand the laydown space, increase its heavy-lift capacity, and add other features necessary for large-scale offshore wind development activities. Ørsted will lease rights to use the pier for 10 years.	Revolution Wind
MD	Tradepoint Atlantic (Formerly Sparrow Point)	In 2017, US Wind and Deepwater Wind agreed to invest $115 million in new manufacturing and port infrastructure.	US Wind and Skipjack

The development and timing of port infrastructure could become a significant bottleneck for the industry. This may be especially true as wind turbines and project sizes continue to grow and put a strain on the capacity of existing infrastructure in terms of heavy lifting, ship access, clearances, channel draft, and physical laydown space. According to a recent McKinsey report, approximately five staging ports will be required to meet the needs for the first 10 GW of offshore wind deployment on the Atlantic Coast alone (Lefevre-Marton et al. 2019).

2.6 Other Regional Developments

Most activity is centered on the WEAs and states that have specific offshore wind procurement activities. The activities highlighted here by region are notable yet were not documented earlier in this report.

2.6.1 North Atlantic

Other offshore wind activities for the North Atlantic region included the following:

- In February 2019, Maine's Governor Janet Mills signed an Executive Order to end a 2018 moratorium on the issuance of offshore wind permits in the state (Mills 2019). The University of Maine is now in the process of renegotiating the Aqua Ventus I PPA for its 12-MW floating demonstration project. If built, this project would likely be the first wind project using floating turbines in the United States.

- In January 2019, New Hampshire's Governor Christopher Sununu requested that BOEM establish an intergovernmental offshore renewable energy task force to coordinate renewable energy activities on the New Hampshire Outer Continental Shelf, including potential commercial leases for offshore wind (Sununu 2019).

- The New Jersey BPU denied EDF's application for 20 years of ORECs for its 24-MW Nautilus demonstration project (formerly known as Fishermen's Energy) (New Jersey BPU 2018). This ends a long process, which began in 2008, to build this offshore wind demonstration project approximately 2.8 miles off the coast of Atlantic City, New Jersey. Ultimately, the project failed because it was unable to demonstrate net-economic benefits, as required under law by the Offshore Wind Economic Development Act.

2.6.2 South Atlantic

Offshore wind activities for the South Atlantic region included the following:

- In September 2018, BVG Associates and the Sierra Club published their *Offshore Wind in Virginia: A Vision* report. This study recommended that the state set a target to support 2 GW of offshore wind development by 2028 and claimed this policy could create thousands of local jobs and make the state an offshore wind hub (BVG Associates 2018a). In 2018, *The Virginia Advantage: The Roadmap for the Offshore Wind Supply Chain in Virginia* assessed the state's port infrastructure and found that five ports could support offshore wind construction and manufacturing activities without significant upgrades (BVG Associates 2018b).

- In March 2019, North Carolina Governor Roy Cooper approved an offshore wind study to assess the state's ability to develop successful ports and manufacturing facilities (Durakovic 2019).

2.6.3 Pacific

Offshore wind activities for the Pacific region included the following:

- In 2018, California passed SB 100 (*100 Percent Clean Energy Act*), committing the state to realizing 100% of its total retail electricity sales from eligible renewable energy and zero-carbon resources by 2045. To comply with this mandate, California will consider the large-scale development of offshore wind. The state's offshore wind technical resource has been determined by NREL to be over 100 GW, and offshore wind deployment scenarios studied suggest that a potential build-out of several gigawatts may be feasible using floating technology. Floating technology is expected to be commercially available by the mid-2020s (Musial et al. 2016, 2017).

- On October 18, 2018, BOEM published a Call for Information and Nominations to gauge interest from prospective floating wind developers in commercial wind energy leases within three proposed areas off central and northern California (BOEM 2019c). The Call Areas are shown in Figure 5 on the central and northern California coasts. All together, these three Call Areas total approximately 2,784 km^2 (687,823 acres), which could potentially deliver a generating capacity of up to 8.4 GW. In response to the call, BOEM received 14 nominations from developers identifying their interest in developing certain portions of the Call Areas. Interested developers include Algonquin Power Fund, Wpd Offshore Alpha, Avangrid Renewables, Castle Wind/Energie Baden-Württemberg AG (EnBW), Cierco Corporation, EDF Renewables, EDP Renewables North America, E.ON Development, Equinor Wind US, Mission Floating Wind, Northcoast Floating Wind, Northland Power America, Redwood Coast Energy Authority, and US Mainstream Renewable Power.

3 Overview of Global Offshore Wind Development

3.1 Global Offshore Wind Market

Following the 2017 deployment of more than 3,500 MW, a record capacity of 5,652 MW new offshore wind was commissioned globally in 2018, as shown in Figure 9. The increase in global capacity can be attributed to a strong increase in deployment from the Chinese market, with 2,652 MW of new Chinese offshore wind capacity coming on line, followed by 2,120 MW commissioned in the United Kingdom, 835 MW in Germany, 28 MW in Denmark, and about 17 MW divided between the rest of Europe and Vietnam. By the end of 2018, the global offshore wind installed capacity grew to 22,592 MW from 176 operating projects. Projections for 2019 indicate greater amounts of new global capacity based on projects currently under construction.

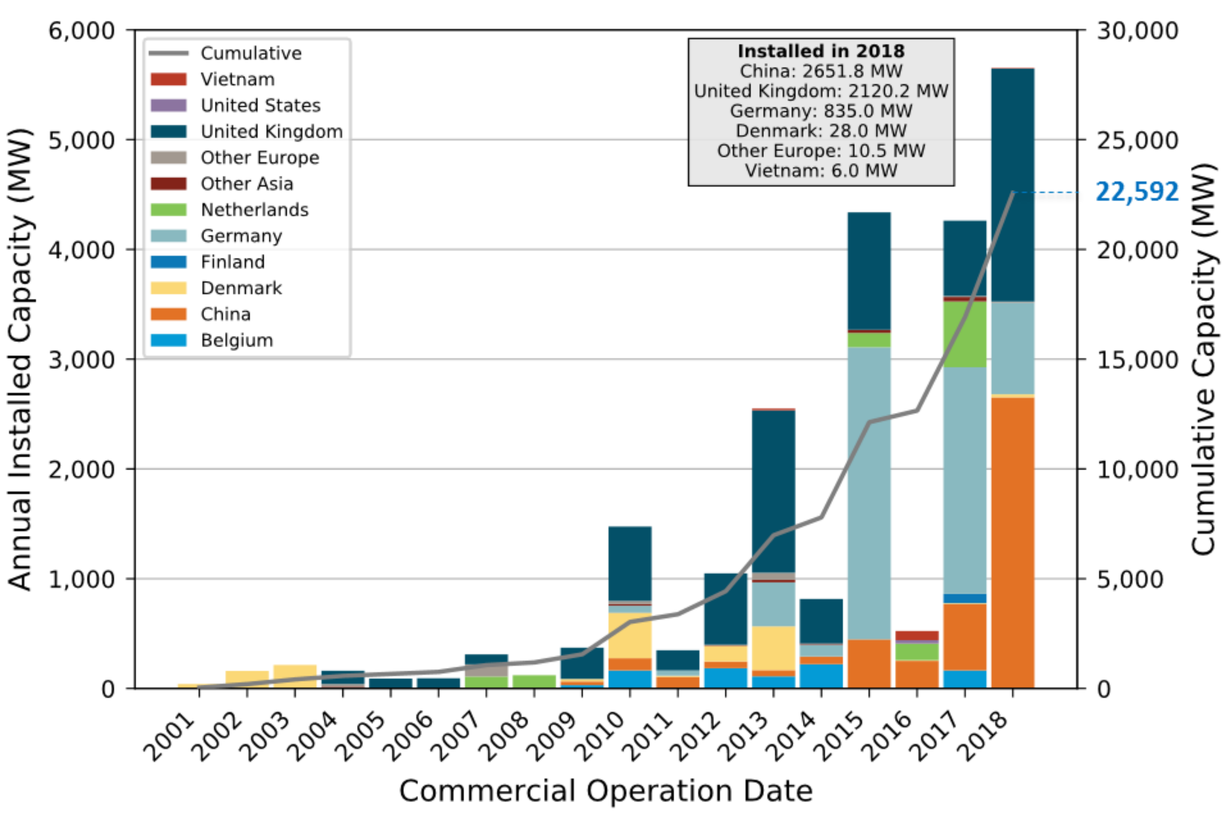


Figure 9. Global offshore wind in 2018 (annual installed capacity–left axis) (cumulative capacity–right axis)

The global offshore wind market is still centered in Europe, with approximately 17,979 MW of installed cumulative capacity. Asia is the second largest regional market, with 4,639 MW, and North America is the third largest market, with only 30 MW of capacity installed today. The OWDB indicates that future market growth will shift toward the Asian and U.S. markets.

Europe's large regional offshore wind market is sustained in part because it has the most transparent national offshore wind procurement schedules, regionally based original equipment manufacturers (OEMs) and installers, mature logistical and manufacturing supply chains, and strong research and development networks to support its development. In addition, Europe has had 28 years of offshore wind experience. However, the Asian offshore wind market may soon surpass the European market in terms of annual capacity additions, driven primarily by China's demand for renewable energy and the motivation to advance the country's domestic manufacturing capabilities. This shift is noticeable in the 2018 annual capacity additions. As shown in Figure 10, there were three main countries contributing to offshore wind capacity in 2018—China, the United Kingdom, and Germany.

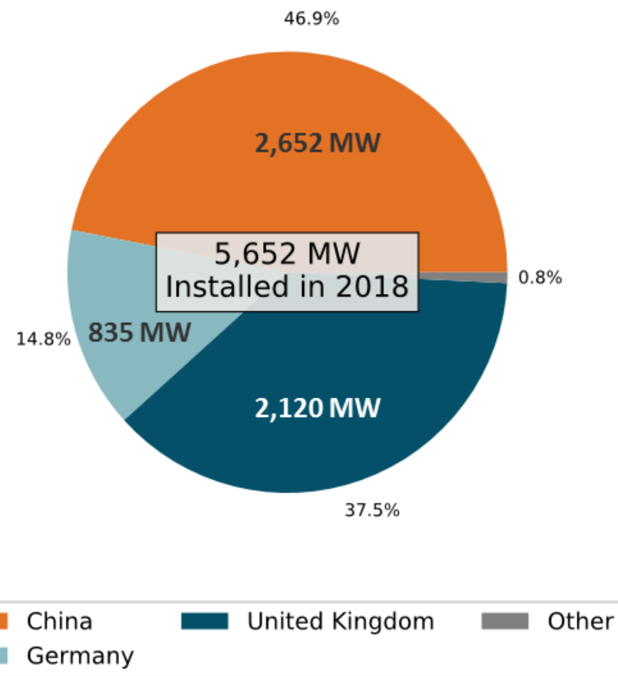


Figure 10. Installed offshore wind capacity by country in 2018

Of the 22,592 MW of cumulative offshore wind deployment recorded by the end of 2018, Figure 11 shows how that capacity is distributed among all countries. The United Kingdom continues to lead the world in terms of total deployment, with 35.2%, followed by Germany (27.4%), China (19.5%), Denmark (6.4%), the Netherlands (5%), and Belgium (3.9%).

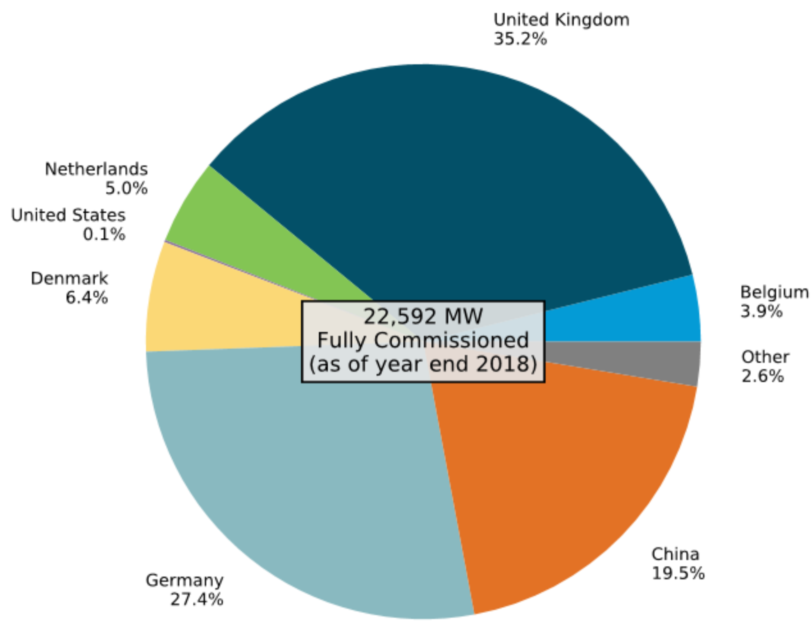


Figure 11. Cumulative offshore wind installed capacity by country

Figure 12 shows the same data plotted in Figure 9 but provides more insight into how the cumulative capacity changed by country.

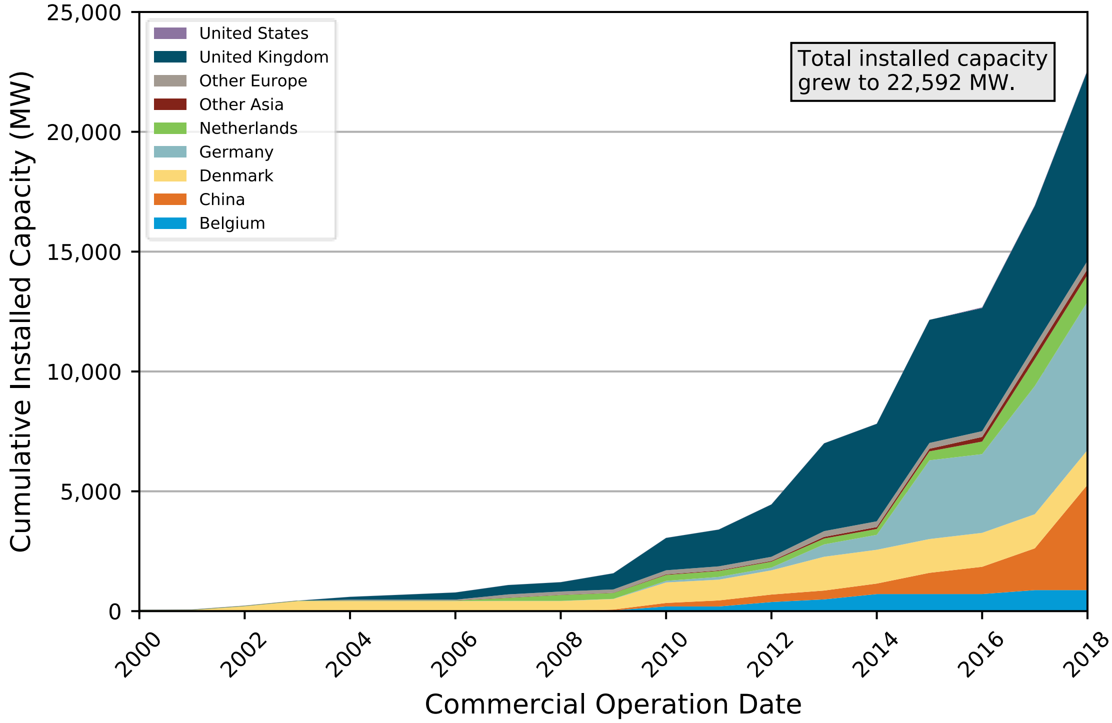


Figure 12. Cumulative installed offshore wind capacity by country over time

Historically, Denmark was clearly the first mover of the industry; however, being a small country, its long-term demand is smaller, and by 2010 the United Kingdom gained more total deployment. Germany began its transition to offshore wind around 2010 and has been increasing its deployment rapidly. Figure 12 also shows the sharp acceleration of the Chinese market, especially this past year—a trend that is likely to continue.

3.1.1 European Market Activities

As of December 31, 2018, 2,994 MW of additional offshore wind capacity was installed in Europe, bringing the total cumulative capacity to 17,979 MW. In 2018, Denmark installed 28 MW, France installed 2.2 MW, Germany installed 835 MW, Spain installed 5 MW, Sweden installed 3.3 MW, and the United Kingdom installed 2,120 MW. Table 9 provides a list of all the projects that reached commercial operation in 2018 by country. The table provides the project capacity values in megawatts and the name of the developer. Note that both of the French projects are subscale floating demonstration projects.

Table 9. European Projects Installed and Grid Connected in 2018

Country	Project Name	Capacity (MW)	Lead Developer
Denmark	Nissum Bredning Vind	28	Nissum Bredning Vindmallelaug
France	EOLINK 1/10 Scale Prototype	0.2	EOLINK
France	Floatgen	2	Ideol
Germany	Arkona	385	E.ON
Germany	Borkum Riffgrund 2	450	Ørsted
Spain	Elisa/Elican Demonstration	5	Elican and ESTEYCO
Sweden	Bockstigen	3.3	Momentum Gruppen A/S
United Kingdom	Aberdeen Offshore Wind Farm	93.2	Vattenfall
United Kingdom	Blyth Offshore Demonstration Array 2	41.5	EDF
United Kingdom	Galloper	353	Innogy
United Kingdom	Race Bank	573.3	Ørsted
United Kingdom	Rampion	400.2	E.ON
United Kingdom	Walney Extension	659	Ørsted

Looking beyond 2018, there has been a significant amount of additional offshore wind activity in Europe related to new policy, procurements, permits, and offtake agreements, indicating continued market growth. Some of the highlights of these activities by country include the following.

France. Although France initially implemented policies targeting 6 GW of offshore wind by 2020, disagreements over the feed-in tariff prices continually delayed commercial projects that had been approved in two tenders in 2012 and 2014. However, in June 2018, the French government finally approved the construction of six of the previously approved offshore wind projects after reducing the feed-in tariff.[41] Each project is expected to receive between 150 €/MWh and 200 €/MWh (Reuters 2018). The projects, all expected to come on line around 2022, are Saint-Nazaire (480 MW), Courseulles-sur-Mer (496 MW), Fécamp (498 MW), Dieppe-Le Tréport (496 MW), and Ile d'Yeu et Noirmoutier (496 MW) (Espérandieu 2018).

Germany. In April 2018, six projects with CODs from 2022 to 2024 were awarded grid connection in the second German offshore wind tender. The projects were Baltic Eagle (476 MW), Gode Wind 4 (132 MW), Kaskasi (325 MW), Arcadis Ost (248 MW), Wikinger Sud (350 MW), and Borkum Riffgrund West I (420 MW). The German Renewable Source Act drives the German offshore wind market and has targeted installing 6.5 GW by 2020 and 15 GW of offshore wind capacity by 2030. Because the German market is poised to achieve its offshore wind goals ahead of schedule, the German legislature initiated a grid reliability study to assess the feasibility of increasing the country's offshore wind goal to 20 GW by 2030 (Foxwell 2018b).

Poland. Poland held its first offshore wind tender in November 2018, awarding two projects the rights to connect to the grid. Additionally, the Polish Secretary of State announced the country was targeting 8 GW of offshore wind deployment by 2030 (offshoreWIND.biz 2018b).

Portugal. Portugal continues to support the development of the 25-MW floating WindFloat Atlantic project. The project is expected to reach financial close and initiate construction in late 2019 pending government

[41] A feed-in tariff guarantees the amount of compensation a developer receives for every megawatt-hour of electricity that their project supplies to the grid.

approval.

Spain. Spain deployed its first offshore wind project in the Canary Islands, the 5-MW Elisa/Elican, a novel gravity-base float-out system that can be fully assembled inshore, with a telescoping tower. According to 4C Offshore, the turbine became fully operational in March 2019. As such, this project will be counted toward the 2019 capacity additions (Skopljak 2019c).

United Kingdom. The United Kingdom continues to be the world leader in offshore wind, with over 7.9 GW of installed capacity. In November 2018, The Crown Estate announced the fourth round of offshore wind tenders would be held in May 2019 and subsequent tenders would occur every 2 years. Based on "market appetite," the tender was increased from 6 to 7 GW, and wind development regions that were limited to 50-m depths were extended to 60-m depths (The Crown Estate 2018).

3.1.2 Asian Market Activities

By the end of 2018, 2,658 MW of new offshore wind capacity was added in Asia, increasing the region's total cumulative installed capacity to 4,639 MW. In 2018, China added 2,652 MW and Vietnam added 6 MW. Table 10 provides a list of all of the Asian projects that reached commercial operation in 2018 by country.

Table 10. Asian Projects Installed and Grid Connected in 2018

Country	Project Name	Capacity (MW)	Developer
China	Fuqing Xinghua Bay - Phase 1	77.4	China Three Gorges New Energy Co.
China	Guodian Zhoushan Putuo District 6 Zone 2	252	GD Power Development Co.
China	Jiang Su Ru Dong Jiangjiasha H2	300	Shanghai Electric Power
China	Jiangsu Longyuan Chiang Sand H1	300	China Longyuan Power Group
China	Jiangsu Luneng Dongtai	200	Shandong Luneng
China	Laoting Bodhi Island Demonstration	300	Jointo Energy Investment
China	Longyuan Jiangsu Dafeng (H12)	200	China Longyuan Power Group
China	Longyuan Putian Nanri Island I	200	China Longyuan Power Group
China	SPIC Binhai North H2	400	State Power Investment Corporation
China	SPIC Jiangsu Dafeng H3	302.4	State Power Investment Corporation
China	Zhuhai Guishan Hai Demonstration - Phase 1	120	China Southern Power Grid
Vietnam	Ben Tre 10 – Phase 1	6	Mekong Wind Power

Looking beyond 2018, other significant offshore wind activities in Asia related to new policy, procurements, permits, and offtake agreements by country include the following.

China. China has a national offshore wind deployment goal of 5 GW by 2020; however, the rapid increase in the number of proposed projects has been driven by the individual province-level goals in Jiangsu (3.5 GW), Fujian (2 GW), and Guangdong (2 GW) (Deign 2019). In May 2018, China's National Energy Administration determined that offshore wind power prices in 2019 and beyond will be set by competitive auctions instead of feed-in tariffs in an effort to increase competition and spur cost reductions in the industry (Recharge News 2018). These cost-reduction and province-level procurement targets, in conjunction with a rapidly maturing supply chain, are expected to dramatically accelerate the future deployment of offshore wind in China, potentially making it a world leader by 2030 (see Section 3.2).

Japan. In November 2018, the Japanese government passed a bill that created a national framework for offshore wind development. Under the law, the Japanese government will designate at least five offshore wind lease areas, hold competitive auctions, and award leases for 30-year terms. In January 2019, Tokyo Electric Power Company, Japan's largest utility, signed a memorandum of understanding with Ørsted to develop the Chosi project near Tokyo (Ørsted 2019). Although Japan still lacks firm government targets for offshore wind, outside analysts such as Wood Mackenzie predict that by 2028 the country will have 4 GW of offshore wind (Hill 2019).

Taiwan. Taiwan has a national goal to develop 5.5 GW of offshore wind capacity by 2025 (Jacobsen 2018). In April and June 2018, the government awarded the first tranche of projects (~3.5 GW) the right to connect to the grid. In late 2018, the Taiwanese government proposed to reduce its feed-in-tariff before some of the awardees could finalize their power purchase agreements. This uncertainty led some developers to question the bankability of their projects and temporally suspend project development. Ultimately, the government settled on smaller feed-in-tariff reduction that enabled all projects to stay economically viable. In early 2019, Ørsted reached financial close on Changhua 1 (605 MW) and Changhua 2 (205 MW), Wpd reached financial close on Yunlin (640 MW), and Northland Power reached financial close on Hai Long 2A (300 MW) (4C Offshore 2019a).

South Korea. Although no projects were commissioned in South Korea in 2018, land-use constraints are shifting the focus for renewable energy to offshore wind power. In 2018, the government set a 12-GW offshore-wind-capacity-by-2030 target to help the country meet a 20% renewable energy target set earlier in 2017. In June 2018, the government adjusted the RPS to increase the renewable energy certificate (REC) value for offshore wind because of economic efficiency and ability to meet policy goals (Linklaters 2019). Offshore wind REC values are attractive because they increase with the distance from the interconnection facilities (Linklaters 2019).

3.2 Offshore Wind Market Projections

This report contains both near-term (2024) and medium-term (2030) projections for the global offshore wind market. Near-term trends are based on NREL's OWDB and medium-term trends are based on a collection of outside sources, but primarily BNEF and 4C Offshore. These projections can help illuminate broad market trends, identify different national and regional deployment trajectories, and approximate the level of uncertainty in future deployment estimates.

3.2.1 Project Pipeline Through 2024

The near-term project projection is based on data obtained for NREL's OWDB and represents our best understanding of the global offshore wind market. Note that market dynamics, policies, and future technological innovations are always subject to change, and could impact these projections.

Near-term projections are based on industry data reporting their status in the pipeline and the developers' expected commercial operation dates. Projects that have made it past financial close have a much higher probability of being completed and a much lower uncertainty about when they will be completed. Figure 13 shows that 9,511 MW of new offshore wind is underway globally, which is broken down by key countries.

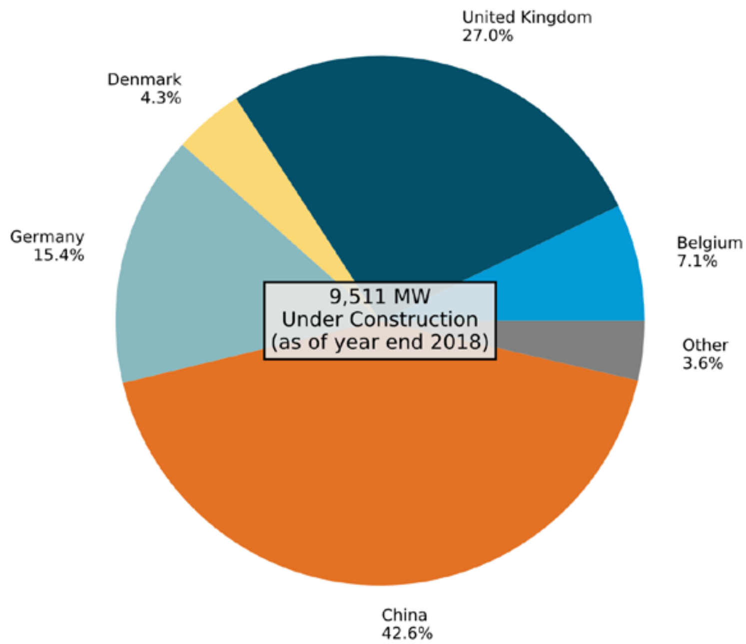


Figure 13. Offshore wind capacity under construction by country as of 2018

By the end of 2018, there were 12 European offshore wind projects under construction, representing 5,115 MW of new capacity to be commissioned.[42] The majority of ongoing construction in Europe is occurring in the United Kingdom (2,520 MW) and Germany (1,460 MW), with smaller amounts in Belgium (678.6 MW) and Denmark (406 MW). In Asia, 17 projects, with a combined capacity of 3,469 MW, are currently under construction. Of the projects under construction, 12 are located in China, three in Vietnam, one in Japan, and one in South Korea. The increased amount of construction in Asia, especially China, represents a new market segment that is expected to grow in future years.

In 2018, just over 10 GW of projects reached financial close. In Europe, 14 projects, representing 6,052 MW of capacity, reached financial close in 2018. In the Asian market, 17 projects, representing 4,178 MW of capacity, reached financial close. In total, there are about 19 GW of projects that have reached financial close or are under construction as of 2018.

Figure 14 provides a yearly estimate of new deployment based solely on the developer's estimation of when they expect their project to be commissioned. Although a project developer may not always be at liberty to disclose detailed updates or information related to their exact deployment schedule, the developer COD data is a rough proxy for near-term deployment. In 2019, annual capacity additions are expected to be dominated by the United Kingdom and China.

Although most deployments until 2024 are located in the United Kingdom and China, other European countries, such as Germany, the Netherlands, and Denmark, continue to approve new projects to meet their national renewable or offshore wind targets. Based on only the projects reporting COD dates in Figure 14, these new additions would result in approximately 44 GW of new capacity from 2019 through 2024.

[42] Generally, a project is assumed to be commissioned 2 years after construction begins.

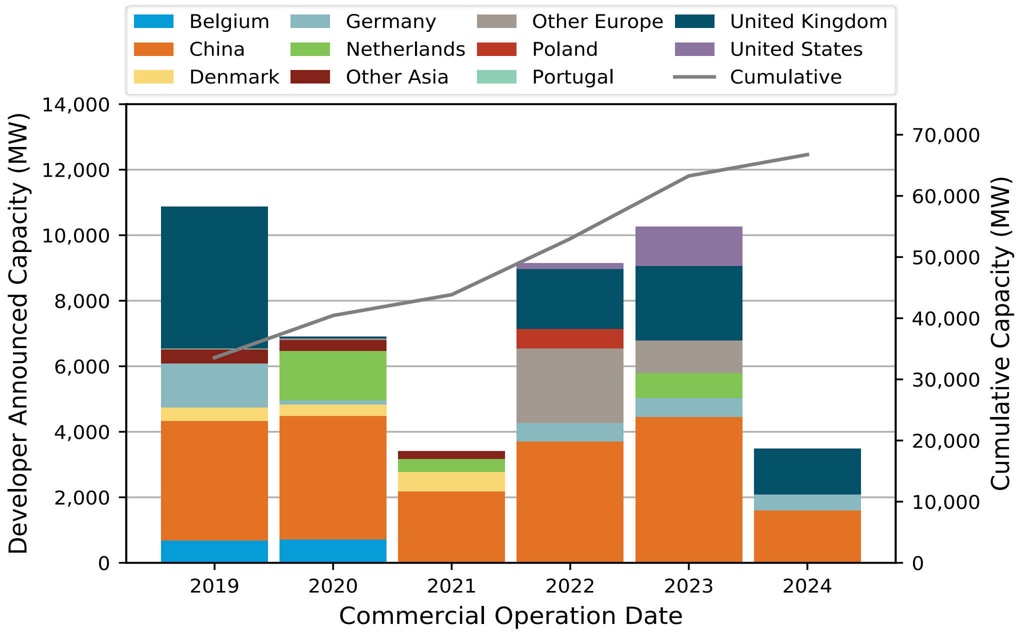


Figure 14. Developer-announced offshore wind capacity through 2024 for projects with financial close

Figure 15 extends Figure 12 beyond the present day using the data shown in Figure 14 as a proxy to estimate near-term offshore wind deployment through 2024.

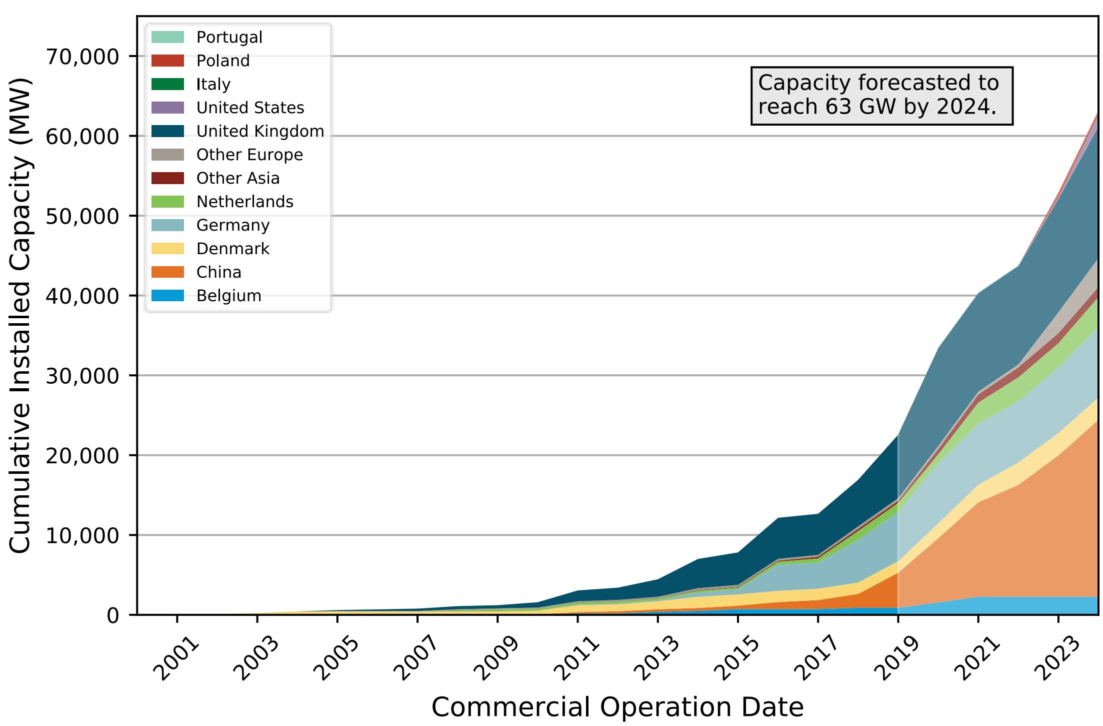


Figure 15. Estimated 2024 cumulative offshore wind capacity by country based on a developer-announced COD (shaded areas represent forecasted deployments)

The figure shows steady or accelerated growth for the next 5 years. Although new markets, such as Poland or Portugal, could help maintain the European share of total global offshore wind capacity, dramatic growth in Asian markets indicates that China may represent almost 50% of the cumulative global capacity in the next 5 years. In aggregate, cumulative global offshore wind deployment is expected to reach over 63 GW by 2024.

3.2.2 Total Global Pipeline

Figure 16 shows the global capacity of the operating and announced development pipeline for all offshore wind projects by region to be 272 GW, compared to approximately 230 GW in 2017. The uptick is primarily attributed to more Asian projects entering the planning phase. This figure does not provide information about the likely timing of developments within the long-term pipeline, but provides overall announced capacity for all active projects recorded in the NREL OWDB.[43] Generally, projects that are more advanced within the pipeline are more likely to reach COD and to be installed sooner than those at an earlier stage; however, international differences in regulatory structure can result in a wide range of development timelines. The global project pipeline illustrates that the majority of the world's installed projects and projects under advanced development are in Europe, but the majority of the world's potential future capacity is in Asia. Looking at project status, there are approximately 63 GW of approved projects in the global pipeline—roughly three times the amount of capacity currently installed today. If all of the approved capacity gets built, the dramatic expansion of the global market will require the further maturation of global supply chains, expansion of manufacturing capabilities, and new installation vessels.

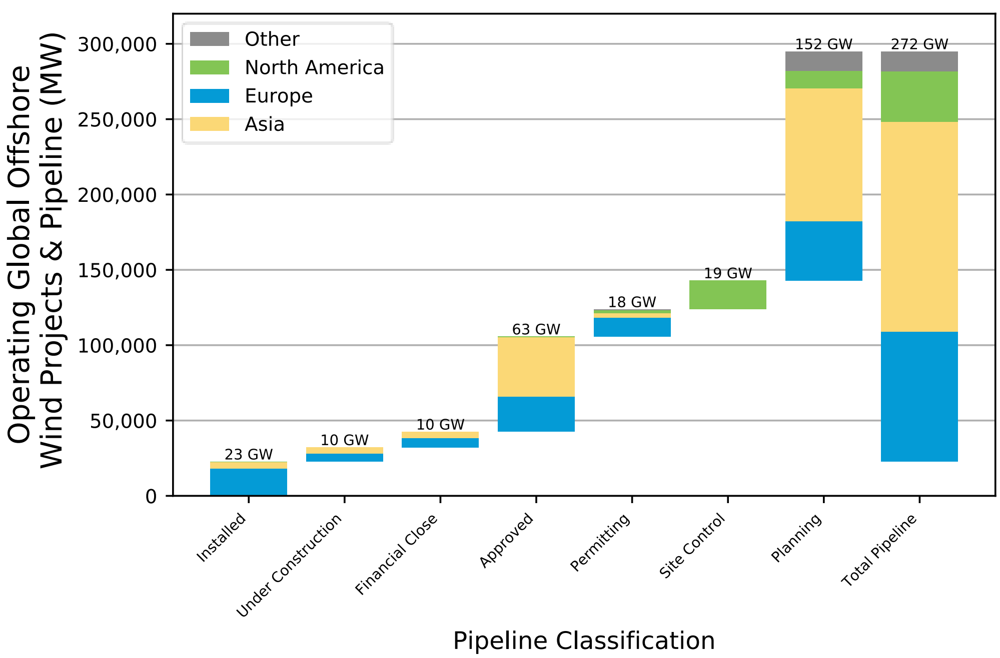


Figure 16. Total global pipeline by status

3.2.3 Medium-Term Projections

Figure 17 illustrates medium-term forecasts of global offshore deployment broken down by country from 2018 through 2030.

[43] The data in Figure 16 do not include projects that are dormant, cancelled, decommissioned, or development zones.

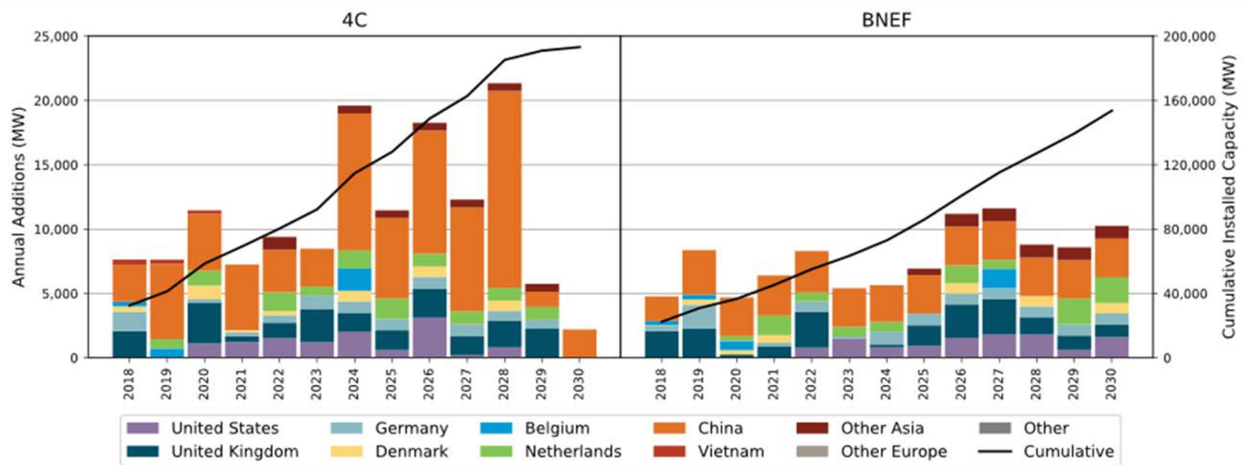


Figure 17. Medium-term wind capacity forecasts by country through 2030

In the figure, two independent forecasts are shown; one by BNEF (2018a) and one by 4C Offshore (2018), which estimate the future growth of the global offshore wind industry. BNEF forecasts offshore wind will reach 154 GW by 2030, whereas 4C Offshore estimates a projected deployment level of 193 GW by 2030. Both forecasts are provided to illustrate the variability and uncertainty associated with longer-range deployment estimates.

Like the near-term forecast to 2024, the most striking shift in offshore wind market dynamics in the 2030 forecast scenarios is the estimated growth of the Chinese market. Both forecasts expect China will cumulatively deploy between 41 GW and 84 GW by 2030. Forecasts also predict European developers will continue to incrementally build projects at a similar rate relative to today, with Europe holding roughly 47% of the total installed global offshore wind capacity by 2030. China itself is expected to represent 27% of the total 2030 installed capacity with the remaining other Asian countries (e.g., Korea, Japan, and Vietnam) accounting for 19%. Depending on the forecast scenario (4C Offshore or BNEF), the U.S. proportion of installed capacity could range from 6.5% to about 8.5% of the global total by 2030.

3.3 Floating Offshore Wind Market Trends

The floating offshore wind market is still driven by the prospect of accessing a much larger resource area with high-quality wind resources, but in water depths that are too deep (nominally greater than 60 m) for conventional fixed-bottom technologies. In the United States, more than 58% of the total technical offshore wind resource is located in water depths greater than 60 m, and in Europe that number is 80% (Musial et al. 2016; WindEurope 2018). Globally, the development of a floating offshore wind market is emerging quickly as experience and knowledge are gained from pilot projects in Europe, Asia, and North America. This pilot phase, which should be mostly operational by 2022, is expected to inform the development of cost-effective commercial-scale projects that may be possible by as early as 2025.

3.3.1 Existing Floating Projects

There are currently eight floating offshore wind projects installed around the world representing 46 MW of capacity. Five projects (37 MW) are installed in Europe and three (9 MW) are in Asia. There are an additional 14 projects representing approximately 200 MW that are currently under construction or have achieved either financial close or regulatory approval. Two projects (488 MW) have advanced to the permitting phase of development, and another 14 are in the early planning stages (4,162 MW). Overall, the 2018 global floating offshore wind pipeline represents approximately 4,888 MW of capacity, growing by 2,000 MW relative to the *2017 Offshore Wind Technologies Market Report Update*. Figure 18 illustrates the current offshore wind market pipeline in terms of market timeline, proposed project size, water depth, and host country. The figure illustrates how the floating offshore wind market evolved from small-scale, single-turbine prototypes (2009–2015) to multiturbine demonstration projects (2016–2022). Post-2022, the first large-scale floating projects are expected to become commercially viable.

Each of the 38 projects shown in Figure 18 are listed in Table 11, which also includes the project status, capacity developer, and substructure type.

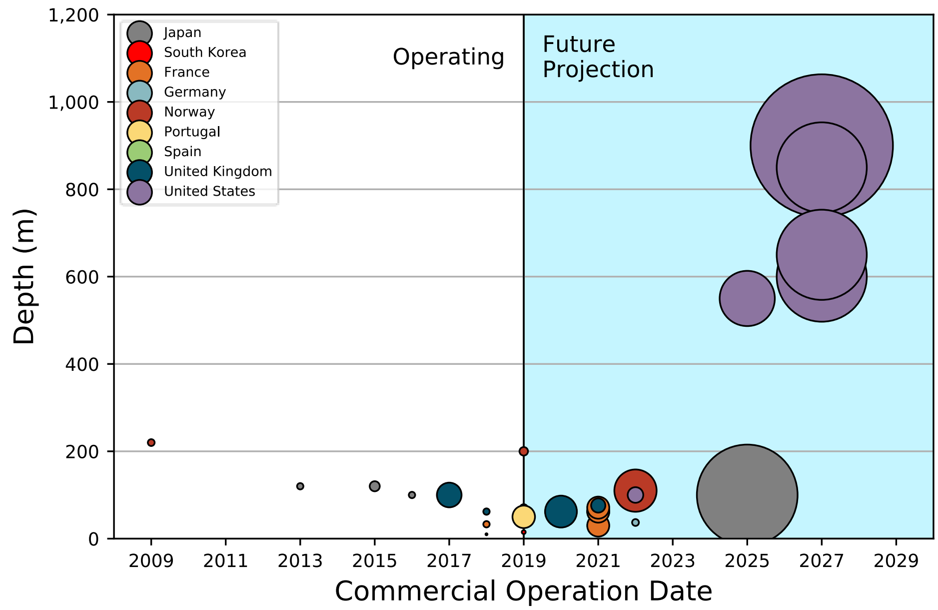


Figure 18. Global floating offshore wind pipeline

Table 11. Current Floating Offshore Wind Projects in Pipeline

Region	Project	Country	Pipeline Status	COD	Capacity (MW)	Water Depth (m)	Developer	Turbine Rating (MW)	Substructure
Asia	**Fukushima Floating Offshore Wind Farm Demo Phase 1**	Japan	Installed	2013	2	120	Marubeni Corporation	2	Semisubmersible
	Fukushima Floating Offshore Wind Farm Demo Phase 2	Japan	Installed	2015	5	120	Marubeni Corporation	5	Semisubmersible
	Sakiyama 2-MW Floating Wind Turbine	Japan	Installed	2016	2	100	TODA Corporation	2	Spar
	Kitakyushu – New Energy Development Organization (NEDO)	Japan	Under Construction	2019	3	70	NEDO/Ideol	3	Semisubmersible
	Hitachi Zosen	Japan	Permitting	2024	400	-	Equinor Hitachi	TBD	Semisubmersible
	Macquarie Japan	Japan	Planning	2025	500	100	Macquarie	TBD	TBD
	Ulsan 750-kilowatt Floating Demo	South Korea	Financial Close	2019	0.75	15	Consortium	0.75	Semisubmersible
	Donghae KNOC - Equinor	South Korea	Planning	2027	TBD	TBD	Equinor/KNOC	TBD	TBD
	Ulsan Shell, Coens, Hexicon	South Korea	Planning	2027	200	TBD	Shell/Coens/ Hexicon	TBD	Semisubmersible
	Ulsan Macquarie	South Korea	Planning	2027	200	TBD	Macquarie	TBD	TBD

Region	Project	Country	Pipeline Status	COD	Capacity (MW)	Water Depth (m)	Developer	Turbine Rating (MW)	Substructure
	Ulsan SK E&S - CIP	South Korea	Planning	2027	200	TBD	SK E&S/CIP	TBD	TBD
	Ulsan KFWind – Principle Power – Wind Power Korea	South Korea	Planning	2027	200	TBD	KFWind/PPI/WPK	TBD	Semisubmersible
	Floating W1N	Taiwan	Planning	2025	500		Eolfi/Cobra	TBD	TBD
Europe	**EOLINK 1/10-scale prototype**	France	Installed	2018	0.2	10	EOLINK S.A.S.	0.2	Semisubmersible
	Floatgen Project	France	Installed	2018	2	33	Ideol	2	Barge
	Groix Belle Ille	France	Approved	2021	24	62	EOLFI	6	Semisubmersible
	Provence Grand Large	France	Approved	2021	24	30	EDF	8	Tension Leg Platform
	Eolmed	France	Approved	2021	24	62	Ideol	6.2	Barge
	Les Eoliennes Flotant du Golfe du Lion	France	Approved	2021	24	71	Engie, EDPR, Caisse de Depots	6	Semisubmersible
	GICON Schwimmendes Offshore Fundament SOF Pilot	Germany	Financial Close	2022	2.3	37	GICON	2.3	Tension Leg Platform
	Hywind - Demo	Norway	Installed	2009	2.3	220	UNITECH Offshore	2.3	Spar
	TetraSpar Demonstrator	Norway	Financial Close	2019	3.6	200	Innogy, Shell, Stiesdal	3.6	Semisubmersible
	Hywind Tampen	Norway	Permitting	2022	88	110	Equinor	8	Spar
	NOAKA	Norway	Planning	2023	TBD	130	Equinor/Aker BP	TBD	TBD
	WindFloat Atlantic (WFA)	Portugal	Financial Close	2019	25	50	WindPlus S.A.	8	Semisubmersible
	DemoSATH - BIMEP	Spain	Approved	2020	2	68	Saitec Offshore Technologies	TBD	Semisubmersible
	X1 Wind prototype PLOCAN	Spain	Approved	2021	TBD	62	X1 Wind	TBD	Tension Leg Platform
	Floating Power Plant PLOCAN	Spain	Approved	2021	TBD	62	FPP	8 MW	Hybrid Wave Power Semisubmersible
	Hywind Scotland Pilot Park	United Kingdom	Installed	2017	30	100	Equinor	6	Spar
	Dounreay Tri	United Kingdom	Approved	2021	10	76	Hexicon	5	Semisubmersible
	Kinkardine Offshore Wind Farm Phase 1	United Kingdom	Installed	2018	2	62	Cobra	2 MW	Semisubmersible
	Kinkardine Offshore Wind Farm Phase 2	United Kingdom	Under Construction	2020	50	62	Cobra	9.5 MW	Semisubmersible
North America	**Castle Wind**	United States	Planning	2027	1,000	900	EnBW/Trident Winds	8+	Semisubmersible
	Redwood Coast Energy	United States	Planning	2025	150	550	EDPR/PPI	8+	Semisubmersible
	Aqua Ventus I	United States	Planning	2022	12	100	University of Maine	6+	Semisubmersible
	Oahu North	United States	Planning	2027	400	850	AW Wind	6+	Semisubmersible
	Oahu South	United States	Planning	2027	400	600	AW Wind	6+	Semisubmersible
	Progression Wind	United States	Planning	2027	400	650	Progression Wind	6+	Semisubmersible

3.3.2 Global Floating Market Assessment

The global offshore wind market continues to mature and show signs that it will accelerate its growth in the future. Major developments and trends in 2018 include the following.

- **Initial pilot and demonstration projects have validated functionality of floating technologies and encouraged further turbine upscaling**. Principle Power indicated that its 25-MW WindFloat Atlantic project in Portugal on its tri-hull asymmetrical semisubmersible substructures will be paired with three MHI Vestas V164-8.4 MW turbines, and the 50-MW Kincardine Floating Offshore Wind Park will use five MHI Vestas V164-9.5 MW turbines and one V80-2.0 MW turbine. Equinor also intends to deploy 8-MW (and above) turbines at its proposed 88-MW Tampen project aimed at powering two offshore oil and gas rigs in Norway. Similar to fixed-bottom technologies, floating systems seek larger turbines to help lower project costs (see Section 4).

- **Ideol installed a 2-MW demonstration project and France approved four demonstration projects**. Ideol's 2-MW Floatgen (dampening pool barge[44]) demonstration project was successfully installed 2 km off Le Crosic and connected to the grid in September 2018. The European Commission has offered financial support and the French government has approved four 24-MW demonstration projects: Groix Belle Ille in the Atlantic as well as Golfe du Lion, Eolmed, and Provence Grand Large on the Mediterranean (European Commission 2019).

- **Interest in offshore wind on the West Coast of the United States increased in 2018**. California's ambitious 100% renewable energy goals could necessitate the development of floating offshore wind projects in water depths up to 1,000 meters (m) (see Section 2). Two unsolicited offshore wind project applications have been filed with BOEM including Redwood Coast Energy (150 MW) and Castle Wind (1,000 MW). Because competitive commercial interest has been established, BOEM initiated three Call Areas (two are around these projects) and is accepting public comments on how to best shape potential future lease areas.

- **Nascent Asian markets showed strong interest in floating wind**. Japan has been interested in offshore wind since 2011 and installed some of the first prototypes using government funding appropriated after the Fukushima nuclear accident. New floating projects in Japan look increasingly promising now that the country has developed offshore wind deployment policies. In the near term, Japan's New Energy and Technology Development Organization announced that it is constructing a 3-MW demonstration project. Equinor has signed a memorandum of understanding with Korea National Oil Corporation to develop a floating project near the Donghae gas platform that is 58 km off the coast of Ulsan City, South Korea. Ulsan Metropolitan City and National Government also signed four memorandums of understanding with developers[45] to each develop 200-MW floating projects with a COD of 2023 (Quest Floating Wind Energy 2019).

---

[44] A dampening pool barge is a shallow-draft, buoyant foundation with a central opening that damps out platform motion caused by wave action.

[45] Developers include 1) Macquarie, 2) CIP and SK E&C, 3) PPI and Wind Power Korea, and 4) Shell, Coens, and Hexicon.

4 Offshore Wind Technology Trends

Technology advancements have played a key role in achieving the cost reductions experienced over the past few years that are enabling offshore wind energy to compete without subsidies in some energy markets. New technology and technical innovations are leading the industry to both lower costs and create new market regions. Continued cost reductions are allowing fixed-bottom offshore wind systems to compete in high-priced energy markets today, and floating wind technology, when matured, can open new regions that are currently inaccessible with existing technology (Gilman et al. 2016; WindEurope 2018). For many years, offshore wind technology advancements were measured by metrics, such as greater water depths and distances from shore (Beiter et al. 2016). More revolutionary technology advancements, such as floating wind turbines, promise larger payoffs in terms of dramatically greater siting options and wide-ranging increases in global electricity market penetration.

Using NREL's OWDB described in Section 1, this section relies substantially on empirical data for planned projects advancing through the pipeline to provide insight into global technology siting trends through 2024. The OWDB also provides insight regarding offshore wind turbine capacities, substructures, electric infrastructure, and logistical approaches for construction and maintenance activities. Much of the discussion is focused on fixed-bottom technologies, although floating technologies are also included.

4.1 Siting Trends for Global Offshore Wind Projects

Here we update trends observed in offshore wind fixed-bottom technology related to site characteristics of water depth and distance from shore. Figure 19 provides industry trends of four parameters—depth, distance, project status, and project size—and shows these trends for global offshore wind projects that have, at a minimum, advanced to the site-control phase. Global projects are color-coded by the project phase they have advanced to in the pipeline.

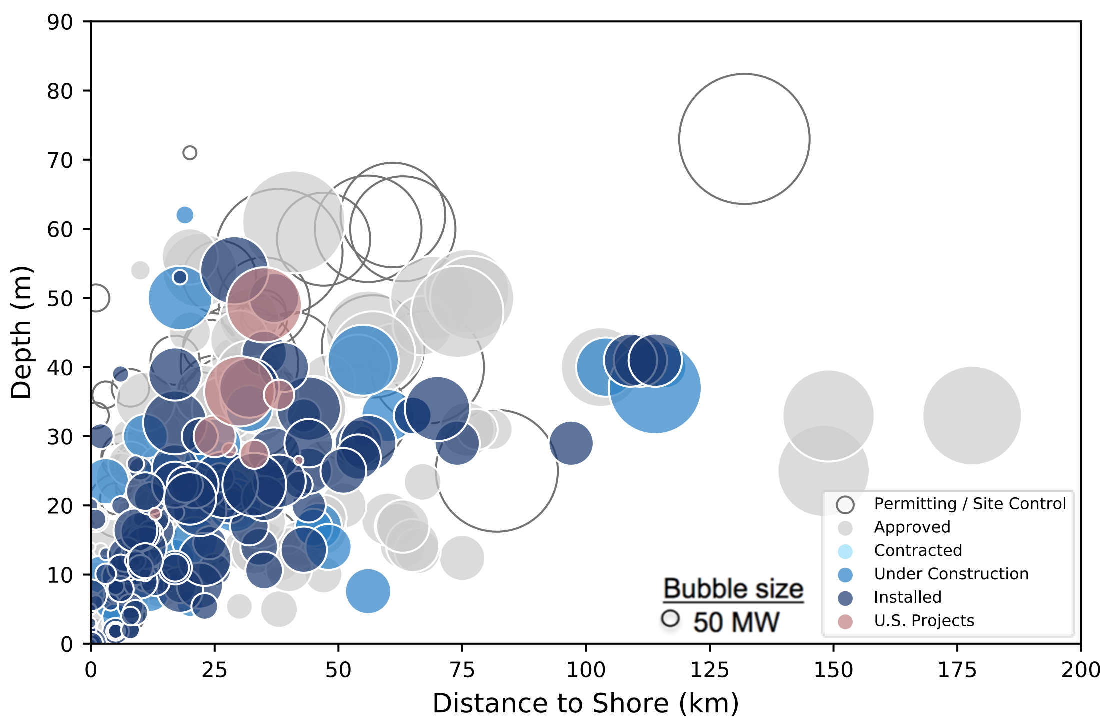


Figure 19. Fixed-bottom offshore wind project depths and distance to shore

In the figure, the project size is indicated by the diameter of the bubbles. The relative scale is shown with a representative 50-MW project in the key. This figure indicates a possible global trend toward larger projects (i.e., larger bubble sizes) sited farther from shore (i.e., the largest bubbles are at the 1,000-MW scale), particularly for those projects in the permitting and approval phase of development. Projects located further distances from shore (as far as 200 km) are enabled by the shallow bathymetry of the North Sea, where projects can be sited far from shore while still using fixed-bottom foundations.

Also included are the eight U.S. offshore wind fixed-bottom projects that have a viable pathway to an offtake agreement, have secured site control, and have significantly advanced in the permitting and regulatory process.[46] These projects have similar characteristics with respect to water depth and distance to shore; however, given the limited sample, it is difficult to judge longer-term trends. There are over 20 GW of capacity in the auctioned lease areas but distances from shore do not exceed 60 km in these areas and depths range from 20 to 65 m (Musial et al. 2013; BOEM 2019f).

Also, projects sited too close to shore can trigger public acceptance issues. Turbines sited beyond a certain distance from shore will generally be less visible and could raise fewer objections. This "acceptable" distance will vary depending on many factors including the land-based terrain and demographics, turbine scale, climate, and proximity to populations (Krueger et al. 2011). In the United States, public acceptance issues led to the demise of the first proposed commercial-scale U.S. project, Cape Wind, which may have contributed to BOEM's informal recommendation that new WEAs be at least 10 nautical miles (nm) from the shore (BOEM 2018). Therefore, with respect to distance from shore, near-term U.S. projects are likely to fall in a narrower vertical band (18–60 km depth) in Figure 19 than the global spread of distances. With respect to depth, some of the lease areas (e.g., Massachusetts WEA) have significant depths between 50 and 65 m, where projects will likely be built (Musial et al. 2013). Therefore, these depths up to 65 m in the existing WEAs will likely result in U.S. projects having slightly higher average depths than current European projects.

However, to judge a project's cost and complexity, it is more important to consider the distance to critical infrastructure than distance to shore. As more projects are permitted and built, developers may have more difficulty finding suitable grid connection points, thereby making export cable runs longer. Further, the cost of the electrical infrastructure for a wind project depends more on the length of the export cable than how far it is offshore. Similarly, the distance to construction and service ports will also be a strong cost factor, because turbine access, as well as construction and operation and maintenance (O&M) costs are directly related (Beiter et al. 2016).

As the industry matures, new technology and experience allows access to greater water depths, but projects with fixed-bottom foundations will pay a premium to access deeper water (Beiter et al. 2016). Floating foundations promise relief from water depth cost penalties, but it is still too early to fully understand these costs relative to fixed-bottom foundations on a commercial scale (Musial et al. 2016). However, if demand for offshore wind continues to increase, higher competing use constraints nearshore (e.g., fishing) may make it necessary to site some future Call Areas farther from shore, and therefore in deeper water where floating technology would be needed (Musial et al. 2016).

In Figure 19, the trends toward distance from shore or deeper water are not clear because new additions are difficult to track on a time-dependent basis. Figure 20 and Figure 21 show distance from shore and water depth as independent variables as a function of time (year of commissioning) for installed projects to help illuminate these trends better. These plots show the span of actual projects built for each year from 2000 to 2018, and projections that were made based on data from projects in the pipeline out to 2024. These data, provided for each year, indicate the capacity-weighted averages, and the range of all projects showing the highest and lowest values. For most years, the number of projects is too small to provide statistical significance, but the

[46] Note Aqua Ventus I is not shown because it is a floating project with different metrics for water depth.

overall trends out to 2024 can be inferred. Figure 20 indicates that the trend toward greater distances from shore may not be very strong. The data show there is a wider degree of variability from year to year, due, in part, to enabling technologies like high-voltage direct current (HVDC) transmission, which has been used in the North Sea to export power long distances to shore in several German projects.

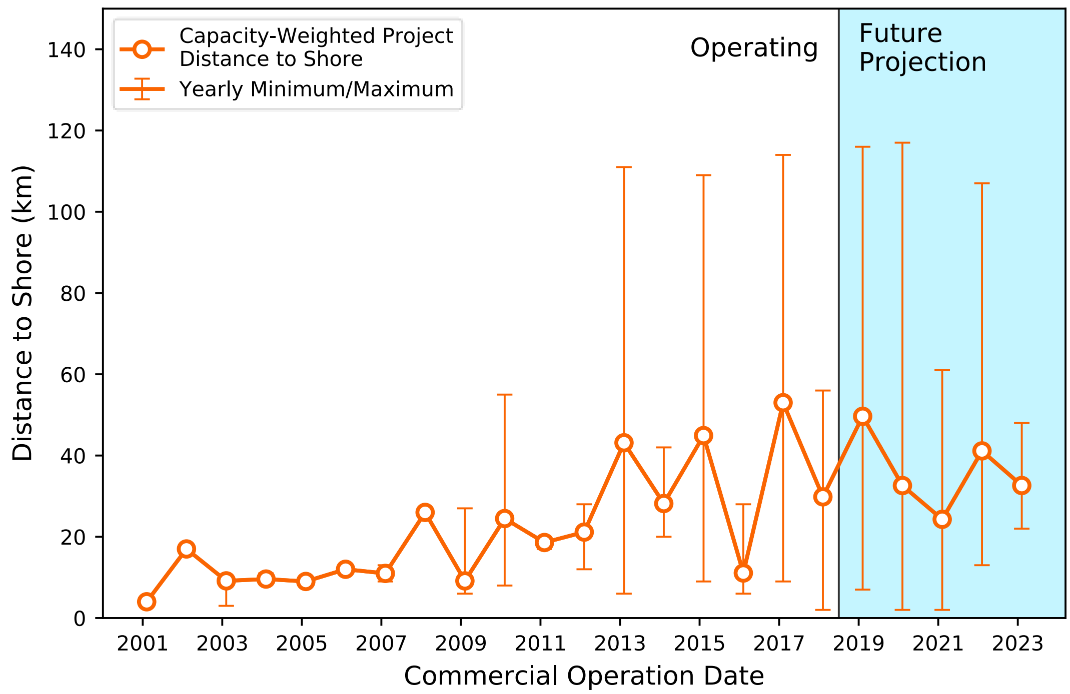


Figure 20. Project distance from shore trend to 2024

Similarly, Figure 21 shows the gradual trend in the global data toward greater water depths.

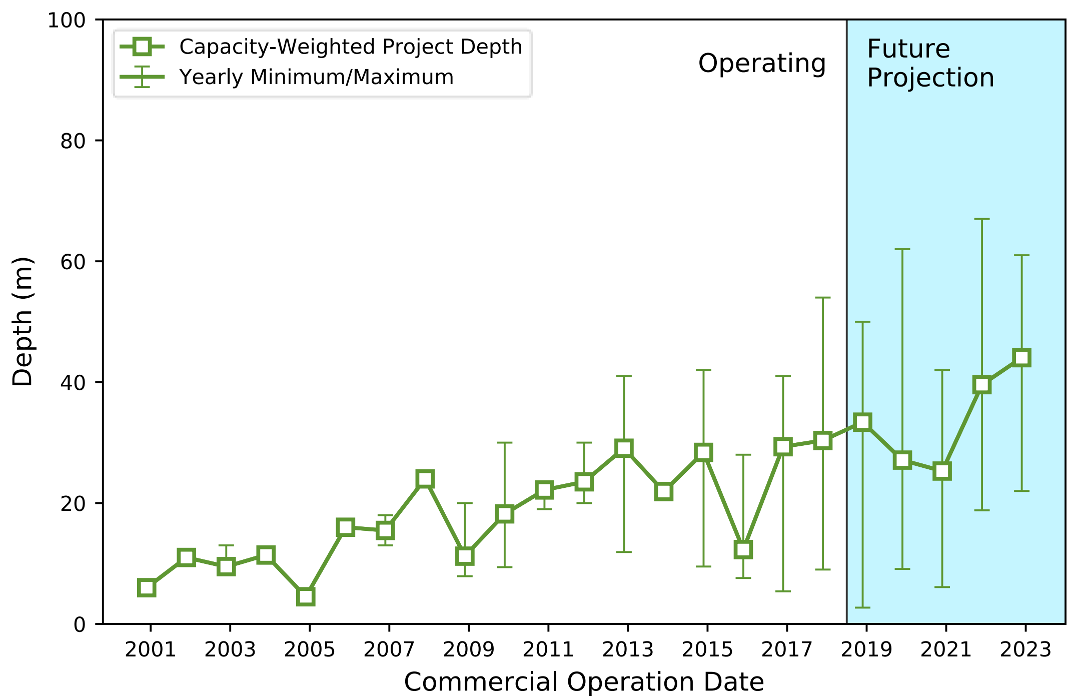


Figure 21. Project depth trend to 2024

The project trend toward deeper water is more defined than the trend toward greater distances to shore. Substructure designs have incrementally improved to overcome depth limits, thereby allowing access to more sites. Some deployments have already been successfully made at 50-m depths, and installations up to 60-m depths and beyond are planned before 2024 (The Crown Estate 2018). In the United States, some of the foundations at the Vineyard Wind site will be near a 50-m water depth (Vineyard Wind 2018a).

4.2 Offshore Wind Turbines

Here we address the trends in offshore wind turbine technology. In 2018, the industry's turbine manufacturers committed more confidently to increases in turbines size, indicating that a new 10-MW to 12-MW platform is under development for the next generation of turbines. This growth is being spurred by overall system cost reductions and energy production improvements associated with larger turbines. In addition, as the industry expands toward the Asian market (especially Taiwan, which committed to 5.4 GW earlier this year), turbine OEMs are beginning a serious effort to adapt turbines to extreme loads that may be generated by typhoons and seismic events.

4.2.1 Offshore Wind Turbine Technology

Offshore wind turbines are generally much larger than their land-based counterparts. Figure 22 shows global offshore wind turbine trends since 2000 along with the capacity-weighted[47] average turbine rating (blue bars; left axis), capacity-weighted average rotor diameter (green line; right axis), and capacity-weighted average hub height (orange line; right axis). Note that the future projection through 2023 for weighted average turbine capacity, rotor diameter, and hub height is based on only the subset of projects (21,037 MW) that have announced an agreement or partnership with a turbine OEM. These projections show that turbines are expected to continue to grow over time.

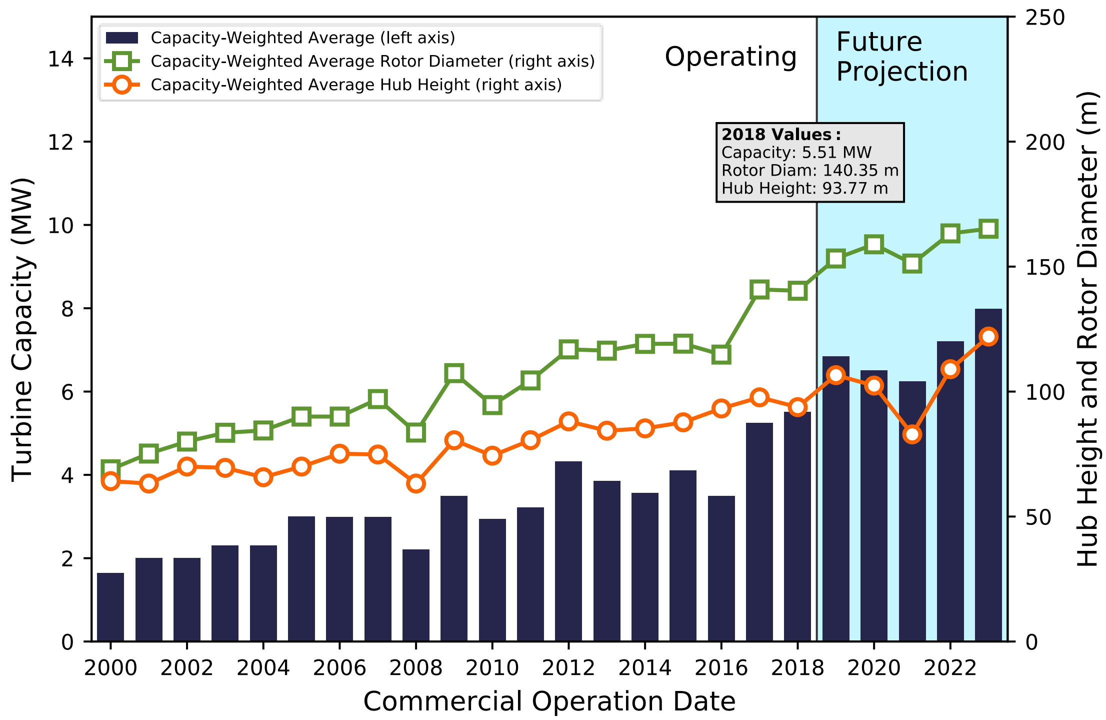


Figure 22. Offshore wind turbine rating, hub height, and rotor diameter

[47] A capacity-weighted average (weighted average) counts the contribution of a given characteristic (e.g., turbine rating) proportional to the amount of capacity (megawatts) the project delivers to the total capacity installed for a given year.

Although Figure 22 shows a steady turbine size growth trend, tracking the current and historical commercial deployments may not be the best way of predicting the absolute size of future wind turbines. To understand the cutting edge of new technology development, it is better to look directly at the turbine prototype development stage. This is especially important for offshore wind because the pace of turbine growth is much faster than land-based technology, and larger turbines are affecting all aspects of industry development including the economics, infrastructure, balance of plant, siting, and supply chain.

Increasing turbine size is one of the major factors that has been attributed to the sharp cost declines in offshore wind. Larger capacity turbines generally yield lower balance-of-plant costs, fewer and faster installations, and lower maintenance, as well as more energy per unit of area. Recent cost information also indicates that in addition to these project cost-scaling benefits, unit turbine costs may not be rising with turbine capacity as originally predicted by early models, such as the 2006 NREL Cost and Scaling Model (Fingersh 2006; for more recent assessments see Graré et al. 2018; Valpy et al. 2017; BNEF 2018e). In fact, a higher turbine rating may not result in an increase in per-unit turbine capital expenditures (CapEx) ($/kilowatt [kW]) at all. This new trend may potentially be a result of efforts by turbine manufacturers to manage increases in component mass using advanced engineering innovations and manufacturing methods, and through improved efficiencies in production and delivery. Therefore, a 6-MW wind turbine might have a similar cost per kilowatt as a 10-MW turbine. This trend may be incentivizing industry's push to further increase turbine capacity.

Because of these cost advantages, on a project level, developers will generally select the largest turbine available. At the end of 2018, the largest turbine installed was the MHI-Vestas V164–8.8 MW turbine at the Aberdeen Bay (European Offshore Wind Development Centre) project in Scotland, but the V174-9.5 is now available for commercial use and was ordered for the Baltic Eagle project in Germany. These Vestas turbines follow another industry trend to extend the nameplate power rating of the current turbine technology platforms for 6- and 7-MW turbines as high as possible by increasing drivetrain/generator capacities while maintaining rotor size. Most turbine manufacturers have conformed to this design approach over the past few years. In doing so, this has driven up the specific power rating[48] for these turbines, which could lower capacity factors in the interim while pushing the turbine technology platforms to their maximum energy extraction and load limits. These high specific power machines may still be well-suited for high wind sites in European waters but may not be the most efficient for lower wind speed sites in countries such as China, Japan, and Korea, and in the Great Lakes, mid-Atlantic, and South Atlantic regions of the United States.

In 2018, this trend in upscaling the existing turbine platforms was disrupted by the announcement of larger prototypes with increased rotor diameters—the next generation of offshore wind turbines on a new 10-MW to 12-MW technology platform. In March 2018, GE announced the 12-MW Haliade-X turbine, which has a prototype in production that is scheduled for installation in Rotterdam in 2019, and ready for market in 2021 (GE 2018b). The turbine is first in class, with a 12-MW direct-drive generator, 220-m rotor, and 140-m hub height. In January 2019, Siemens Gamesa announced the development of the SG10.0-193 DD turbine—a 10-MW direct-drive turbine with a 193-m rotor—which is planned to be ready for market in 2022 (Siemens 2019). This turbine would be a substantial departure from Siemens Gamesa's current SG 8.0-167 DD platform. Other manufacturers, such as Senvion (formally Repower), have been following suit with their own development plans for turbines in the 12- to 16-MW range (Foxwell 2018c). From recent industry trade press, it appears that the industry is likely to increase turbine size beyond 12 MW (Windpower Monthly 2018; Snieckus 2018).

To illustrate the pace at which turbines are growing in the offshore wind industry, Figure 23 shows the average turbine capacity growth from Figure 22 along with data contrasting the capacities of the largest prototypes available in the first year they were built since 2000. The turbine prototypes shown in Figure 23 were all later commercialized and have become part of the industry's commercial pipeline (e.g., blue bars).

[48] Specific power is the nameplate power rating of a turbine divided by its rotor's swept area in Watts/m^2.

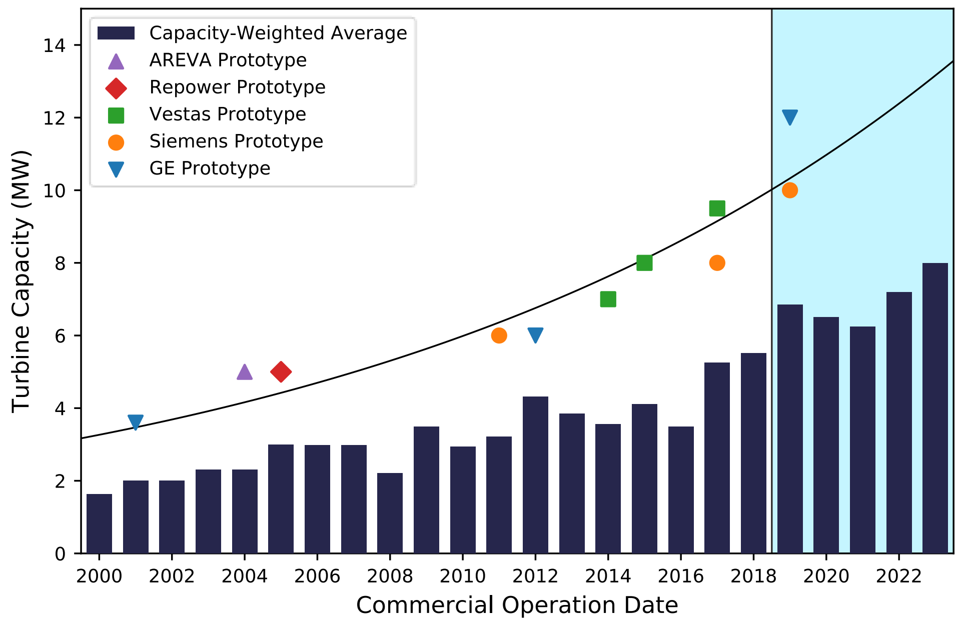


Figure 23. Average commercial offshore wind turbine rating compared to prototype deployment by year

Sources: Ragheb (2019), GE (2018), de Vries (2012), Composites World (2014), Adwen GmbH (2019),[49] Power Engineering (2005),[50] 4C Offshore (2017), Siemens (2013, 2019), Dvorak (2017)

From analysis of press releases, it takes at least 3 years for a turbine manufacturer to go from the first prototype to commercial production (GE 2018a; Siemens 2019). Historically, in many cases, this process is longer. Figure 23 shows that although offshore wind industry turbine size is indeed increasing, the maximum size of wind turbines that will be installed in later years is much larger than the weighted averages, and in 2018 there is no sign that offshore wind turbine growth is slowing down in spite of multiple logistical and infrastructure challenges. As shown, prototype capacity (shown in the colored symbols) has been consistently above the capacity of the weighted average turbine being installed.

4.2.2 Typhoons and Earthquakes

Offshore wind turbines are beginning to see more geographic diversity, especially as developers enter Asian markets wherein typhoons can bring extreme wave heights and wind speeds that exceed design specifications. Class 1A wind turbines are already designed to withstand wind gusts up to 70 meters per second (m/s) (156 miles per hour) but in these Asia-Pacific regions (and later in southern latitudes of the United States), the probability of major tropical cyclones (hurricanes) that produce loads exceeding the present design limits (set by International Electrotechnical Commission [IEC] standards) becomes more likely. Specialized hurricane-resilient designs are being developed to ensure that turbines, towers, blades, and substructures can withstand these extreme weather events.

Offshore wind turbines are currently designed using IEC 61400-01 and IEC 61400-03 standards, which define a 3-second maximum gust condition of 70 m/s (156 miles per hour) (IEC 2019a; 2019b). Oil and gas standards have been applied in the United States to manage the design of substructures. The recently released 2019 edition of IEC 61400-01 and 61400-03-1, the primary design standards for wind turbines, just added

[49] Note that AREVA is now a wholly owned subsidiary of Siemens Gamesa.
[50] Note that Repower now goes by the name Senvion.

provisions for a wind turbine typhoon class. Both Siemens Gamesa and Vestas have begun to ruggedize their turbine designs to adapt them to hurricane loading and comply with a more rigorous certification process to upgrade for the local conditions, particularly as they try and enter the Taiwan offshore wind market (Hill 2018). In some of these new offshore wind regions, there is also an increased threat of earthquakes; therefore, enhanced engineering activity to achieve seismic resilience has also been initiated.

4.2.3 Offshore Wind Turbine Manufacturers

Figure 24 shows the market share of each offshore turbine manufacturer for the cumulative installed capacity up to 2018, as well as the expected installations that have disclosed their intended turbine partner for near-term pipeline projects. After their merger, Siemens Gamesa continues to be the largest global supplier of offshore wind turbines, representing approximately 55% of installed capacity, or 12.3 GW, operating today. Siemens Gamesa is followed by MHI-Vestas, with just over 15% market share.

The right side of Figure 24 shows the OEM suppliers selected by developers for projects in the pipeline that have announced their turbine. The chart shows Siemens Gamesa's share of projected total global capacity is likely to grow to 60.3% for new projects, whereas Vestas is expected to hold on to about 14.5% total installed capacity. In addition, GE's share of total installed capacity is projected to grow to 8.9%. Other OEMs showing increased market share include Goldwind and Ming Yang, companies that are building strength in the emerging Chinese market.

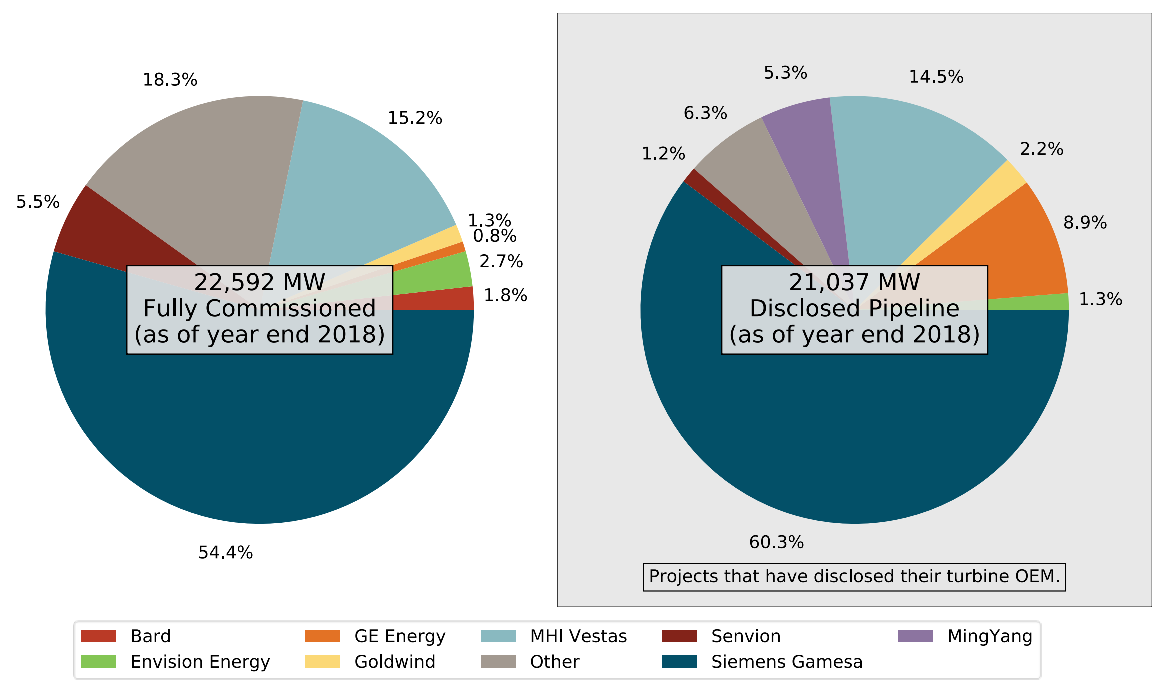


Figure 24. Offshore wind turbine manufacturers by market share for 2018 (left) and future (right)

4.3 Fixed-Bottom Substructures

Figure 25 shows the current mix of substructure types for fixed-bottom foundation projects operating at the end of 2018 along with the expected makeup of substructure types for the 37,203 MW of projects in the pipeline that have announced their intended substructure. In 2018, monopiles continued to dominate the operating fleet of global offshore wind turbines, representing 73.5% of the total market. Alternative substructure types, such as gravity-base, jacket, tripod, and floating foundations, each represent about 5% of the historical market share.

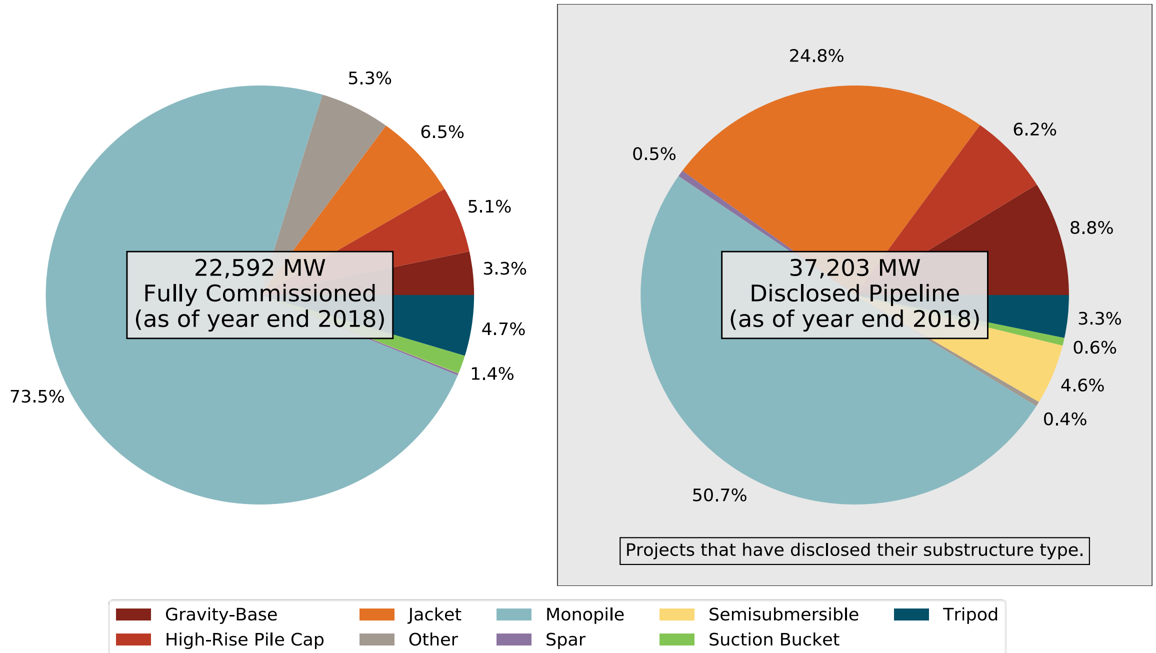


Figure 25. Offshore wind substructure technology trends in 2018[51]

Looking into the future, on the right side of Figure 25, developers have indicated they plan to increase the use of jackets by roughly fourfold. This change corresponds to projects being developed in deeper water depths and increased manufacturing options for jackets. Gravity-base foundations are also slowly increasing their market penetration because they do not require pile driving during installation, which eliminates underwater noise and potential negative impacts to marine mammals. Floating foundations are required for projects in water deeper than approximately 60 m and are discussed later in the report.

4.4 Electrical and Power System Technology

4.4.1 Array Cables and Substations

Buried, insulated, three-core copper cables are typically used for subsea array collector systems. Occasionally, aluminum cables are used as well. The array cables[52] are designed to meet the requirements on physical strength, flexibility, and temperature characteristics of the offshore site. Array cables also incorporate fiber-optic cables, plant control, and communications. Power conductor sizes for array cables are selected based on their current carrying capacity and location in a string of turbines. Array cable cross sections at the end of the string can be as small as 150 mm^2, and cables close to the substation can be 800 mm^2 or larger.

As shown in Figure 26, 42% of new intra-array cables energized in 2018 were supplied by Nexans, whereas JDR Cable Systems supplied 32.1% and Prysmian supplied 16.1%. These shares were calculated by counting the number of grid-connected turbines in each wind power plant during 2018 (WindEurope 2019).

[51] High-rise pile caps are offshore wind foundations that use a group of piles to support a flat, stable pad. The wind turbine tower is then installed on top of the pad. These foundations are primarily found in the Chinese market and deployed in shallow waters.
[52] Array cables are electrical cables that connect individual turbines to each other and an offshore substation or transmission cable.

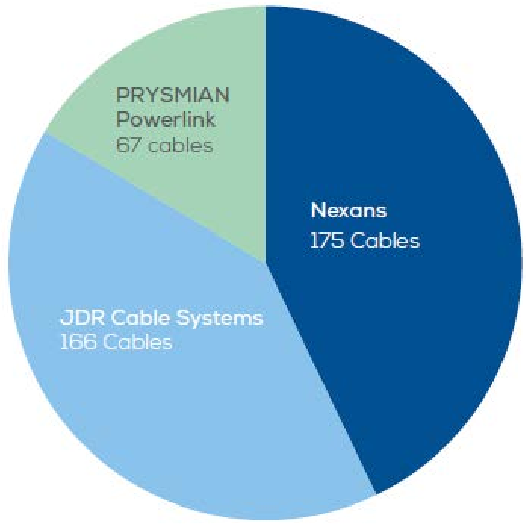


Figure 26. Number of turbines energized by supplier in 2018. *Chart courtesy of WindEurope 2019*

With the commissioning of the Aberdeen Bay offshore wind power plant in 2018, Nexans has now supplied two new offshore wind plants with its new 66-kilovolt (kV) cable technology (Nissum Brending Vind in Denmark and Aberdeen Bay in the United Kingdom). As rated power capacity of offshore wind turbines continues to grow, project developers and operators are increasing use of 66-kV cable technology instead of the conventional 33 kV. In 2018, there were three projects that used 66-kV array cables versus only one project in 2017. Operation at a higher voltage offers important life cycle cost-efficiency benefits, such as the possibility of reducing the number of offshore substations, decreasing the overall length of installed cables, and minimizing electric losses (Nexans 2018). During 2018, the advantages of 66-kV technology have been demonstrated by Nexans in three pilot projects: the Blyth Offshore Demonstrator (United Kingdom), Nissum Bredning Vind (Denmark), and Aberdeen Bay (United Kingdom) wind power plants. All these projects are currently connected to the grid and generating power. Nexans has also supplied a range of products and accessories including 66-kV sea cables (array and export cables), power cable accessories (e.g., equipment bushings, connectors, coupling connectors, surge arresters, dead-end receptacles, junction cabinets), GPH connection technology, and preassembled cables (Nexans 2018).

Continued development of several offshore projects in Southeast Asia has created new market opportunities for the undersea cable industry. For example, Formosa 1 is an offshore wind power plant being developed near Miaoli, Taiwan, by Formosa Wind Power Co in partnership with Macquarie Capital Group Limited, Ørsted, and Swancor Renewable. The 130-MW wind power plant will be Taiwan's first commercial-scale offshore wind project (Power Technology 2018). In 2018, JDR Cable Systems delivered 21 km of interarray cable, 13 km of export cable, and an additional 16 km of land cable to transmit power from the shore to the local substation. The 33-kV cables were manufactured at JDR's facility in Hartlepool, United Kingdom, before being shipped to Taiwan for installation by Jan De Nul. The project is targeted for completion in 2019 (JDR 2019).

4.4.2 Export and Land-Based Interconnect

The electrical grid connection contributes significantly to the cost of an offshore wind power plant. It includes both offshore and land-based infrastructure and connects the wind power plant to the land-based electricity grid. AC offshore substations contain the common busbar for cable termination, protection, and switchgear, transformers that step up the voltage from a 33-kV or 66-kV array level to a 132- to 220-kV export level, and reactive power compensation. There is normally more than one AC substation in a large wind power plant, thereby providing a higher level of reliability and redundancy in the electrical system to reduce the impact of a single point of failure. Similarly, DC offshore substations contain an AC busbar, protection, and switchgear; AC transformers; HVDC power electronic station; and DC terminals.

Typically, the AC export cables use conductor cores ranging from 600 mm^2 to 1,200 mm^2, although larger cross sections are possible. Various types of armoring can be used depending on seabed conditions, amount of vessel traffic, and water depth.

In terms of export cables in 2018, eight export cables manufactured by NKT Group were energized, representing 53.3% of the annual market. Prysmian, Ls Cable & System, and JDR Cable Systems each had about a 13.3% share, and Nexans represented the remaining 6.7%, as shown in Figure 27 (WindEurope 2019). When calculating these shares in Germany, the export cables are considered to be the cables connecting the offshore wind power plants to the land-based grid, whereas in other countries the export cables are considered to be the high-voltage, alternating-current cables only. Note that these market shares were calculated by considering only the export cables in operating wind power plants.

According to Market Research Consulting, the global submarine cable market accounted for $6.31 billion in 2017 and is expected to reach $25.56 billion per year by 2026 (Market Research Consulting 2018). Such growth is expected because of rising demand in both offshore wind and oil and gas operations. Increasing demand for HVDC submarine power cables is also one of the major electrical supply chain trends for offshore wind observed during the forecast period. By geography, several regions in Europe are dominating the offshore power cable market because of rapid growth in numbers of offshore wind projects and rising demand for intercountry submarine power transmission links. Some key players in the submarine power cable market include Furukawa Electric, General Cable Corporation, Hengtong Group, Hydro Group, KEI Industries, LS Cable & System, Nexans, NKT Holding, Prysmian Group, Sumitomo Electric Industries, Tele-Fonika Kable S.A, ZTT International Limited, and TE Subcom.

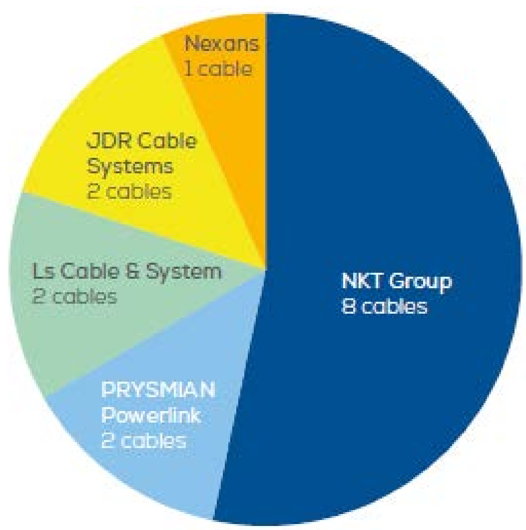


Figure 27. Share of energized export cables by supplier in 2018. *Chart courtesy of WindEurope 2019*

4.4.3 Transmission, Grid Integration, and Storage

As the role of wind energy grows in the U.S. power grid, there is increased interest and requirement for it to provide essential reliability services. These services are critical to maintaining the reliability and stability of the grid, and historically were provided by large synchronous generators, mainly from fossil-fueled and hydroelectric generators (Denholm, Sun, and Mai 2019).

In 2018 and early 2019, as state offshore wind policy commitments grew from near 5 GW to 20 GW by 2035, the challenge of integrating this amount of electricity into the existing land-based grid has begun to resonate as a high priority among the many developers, utilities, and state energy organizations (Business Network for Offshore Wind 2019). For some states like Massachusetts, New York, and New Jersey, injecting this amount of offshore wind represents up to 30% of their current electricity supply, which is likely to have significant impacts to the land-based grid and transmission system that have not been fully quantified. In the next year, the topic of offshore wind grid integration and grid planning is likely to gain more attention.

In most of today's power systems, wind (both offshore and on land) and solar generation still have a limited impact on grid operation because other generation sources can be dispatched. As the share of variable renewable generation becomes a major fraction of the total generation, electricity systems will need more flexibility services that can be potentially provided by the rapid response capabilities of electricity storage. The shift toward large-scale integration of energy storage into the power systems operation will need to be part of the energy planning process.

In 2018, Masdar and the Norwegian company Equinor (formerly Statoil) installed, and started testing, a new battery system designed to store electricity generated by the 30-MW Hywind Scotland, the world's first commercial-scale floating wind power plant. This battery energy storage system (BESS) project coupled with the offshore wind power plant is the first of its kind in the world. The goal of the project is to evaluate the capabilities of advanced storage technologies to optimize the release of electricity from renewable energy plants to transmission grids—from both a technical and commercial perspective. A conceptual diagram of interconnection between the offshore wind power plant located at a short distance from the shore and the land-based BESS is shown in Figure 28 (Equinor 2018b).

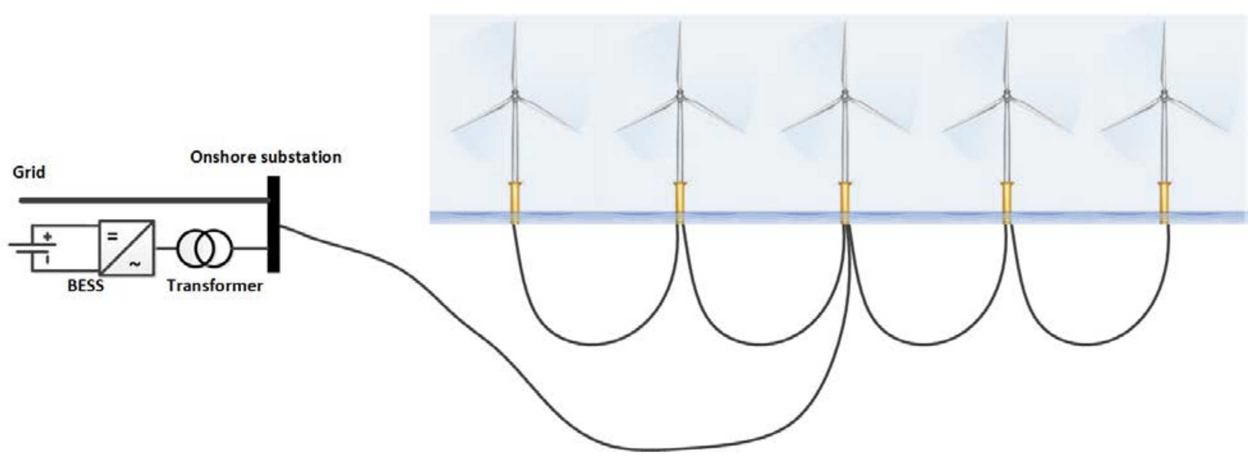


Figure 28. Near-shore offshore wind power plant operating with the land-based BESS. *Illustration by NREL*

The BESS technologies can provide a wide range of utility-controlled and self-directed services (Benson 2018).

4.5 Floating Technology Trends

Floating wind energy technology is advancing rapidly. Based on the resource capacity, the prospect for significant future deployment potential of floating wind seems similar to fixed-bottom wind but there are many technology challenges that must still be solved. Some of these unique technology challenges for floating wind are discussed in this section.

4.5.1 Floating Wind Turbines

Like fixed-bottom technology, developers of floating offshore wind projects generally want to use the largest commercial offshore turbines available on the market. For example, WindFloat Atlantic in Portugal is planning to install three MHI Vestas V164-8.4 MW turbines, and the Kincardine project in Scotland is installing five MHI Vestas V164-9.5 MW turbines (Froese 2018; 4C Offshore 2019; Davidson and Weston 2018). The motivation is the same for both floating and fixed-bottom foundations: project costs are lower with larger turbines. To date, all offshore wind turbines used in floating applications have been designed for fixed-bottom applications. Therefore, the market information for turbines on fixed-bottom foundations applies directly to floating systems. Floating-specific turbines have not yet been designed but conceptual engineering studies suggest a greater value proposition for lightweight turbine components, which may help reduce overall system weight. Because the floating wind pipeline is still small, the demand for these floating-specific offshore wind turbines is not high enough for OEMs to take the turbine development risk. More certainty in a large future floating wind market will be needed to motivate the first generation of customized floating wind turbines.

4.5.2 Floating Support Structures

The cost of a floating offshore wind project depends on the characteristics of the support structure it uses. The cost of the support structure itself is important, but so is the support structure's ability to help lower costs in other parts of the system, such as by enabling serial fabrication, inshore assembly, and commissioning, and by minimizing expensive offshore labor, including O&M. In addition, the coupled hydrodynamic-aerodynamic design of the floating system is the primary method for protecting the turbine from excessive loads and accelerations, especially under extreme conditions. Most floating projects in the pipeline plan to use semisubmersible substructures (see Table 11) because inherently, semisubmersible floating foundations have a shallow draft and are stable even after the turbine is installed. This allows for a full assembly and commissioning at quayside, and allows the full system to be towed from an inshore assembly port to an offshore station without the use of heavy-lift installation vessels.

Figure 29 shows a capacity-weighted average of the substructure choices for all floating projects in the NREL OWDB at the end of 2018.

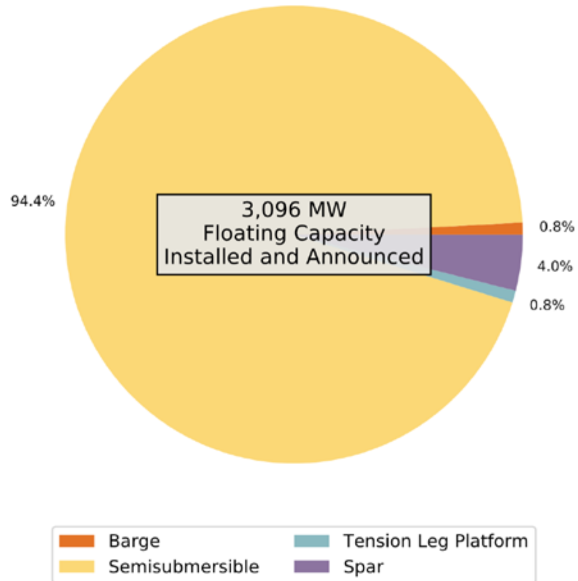


Figure 29. Capacity-weighted average of floating substructure selection for the global pipeline

The chart shows that 94% of projects in the floating wind pipeline plan to use semisubmersible substructures. Approximately 4% use or plan to use spar technology, like the substructures deployed by Equinor on the first commercial floating wind project, shown in Figure 30 (Equinor 2018a). The remaining substructures are tension leg platforms and barges.

As the industry deploys the next generation (second generation) of technology, new hybrid floating platform design concepts are being introduced that have desirable characteristics like the semisubmersible. In 2018, Stiesdal Offshore Technologies introduced the TetraSpar floater, which has a stable buoyant floating substructure with low draft to allow for inshore assembly but uses a flexible cable system to deploy a ballast weight at sea. The design incorporates a tubular steel base with a suspended underwater tetrahedral counterbalance. Innogy and Shell have partnered with Stiesdal to build a single turbine demonstration project in Norway that plans to use a 3.6-MW Siemens Gamesa turbine (Weston 2019). In November 2016, SBM Offshore won a contract to deliver three floating platforms for the 24-MW Provence Grand Large pilot wind energy project in the French Mediterranean. The SBM tension leg platform substructure design is unique because it is stable before attaching the mooring lines—an uncommon characteristic and one of the major drawbacks of conventional tension leg platforms. Both the TetraSpar and the SBM tension leg platform represent hybrid platform technologies that could challenge conventional semisubmersible technology for cost competitiveness and possible future market share. Figure 31 shows both designs.

Figure 30. A 6-MW floating wind turbine in Equinor's 30-MW array near Peterhead, Scotland, supported by a spar buoy floating platform. *Photo courtesy of Walt Musial, NREL*

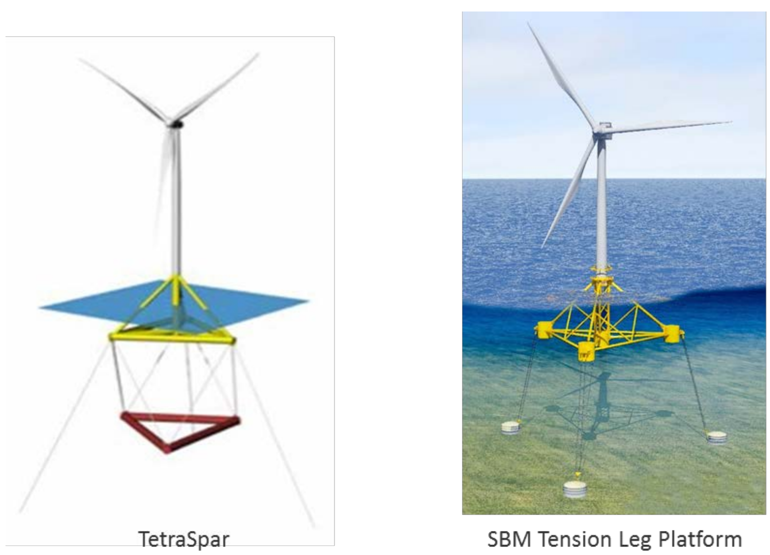


Figure 31. Second-generation floating wind concepts of alternative hybrid substructures. *Images courtesy of Stiesdal Offshore Technologies (left) and SBM Offshore (right)*

One concern for floating projects in the United States and likely other parts of the world is the design of mooring systems for the depth characteristics of the U.S. Outer Continental Shelf.

In the eastern United States, it is likely that floating technology could open large areas in the 60−100-m depth range for offshore wind development. Although this water depth is deep by fixed-bottom wind turbine standards, for floating, these depths are shallower than typical floating oil and gas rigs and are generally unique to offshore wind. Shallow water means shorter mooring lines, which act as shock absorbers to absorb hydrodynamic loading. If they are not long enough or heavy enough, platform loads could increase. New mooring system designs are needed to enable floating technology at shallow water depths. New designs are emerging already to allow projects to be sited in these water depths (4C Offshore 2019b). Conversely, because of the steep shelf on the Pacific Coast, floating projects will be located at sites with water depths up to 1,000 m or more. In these waters, the optimization of deeper water moorings is a different technology challenge because project developers are likely to be encouraged to reduce the footprint of their anchor circle and generally shorten the length of their mooring lines to minimize the impact to other users of the sea. In 2018, DOE and NYSERDA formed the National Offshore Wind R&D Consortium to address technical issues affecting developers in the United States and released a solicitation calling for engineering solutions to shallow and deep-water mooring design issues (NYSERDA 2019).

4.5.3 Electrical Power Systems

Floating turbines allow greater distances from shore, which can have several impacts on cost including the design of subsea electrical cabling and system configuration (e.g., consideration of HVDC) as well as logistical challenges during the project's construction and operation phases (e.g., transport time, effective length of working day).

Floating offshore wind platforms are constantly moving with the waves and winds acting on the structure. As a result, the attachment point for the electric cable is in motion as well. For a fixed-bottom foundation, this attachment point is firmly secured. The dynamic nature of floating platforms will require developers and cable manufacturers to develop dynamic cable designs to ensure that cyclic loads and bends on the cable will not compromise the system. This approach is important for turbine systems as well as possible floating substations. In March 2019, Prysmian announced that it had developed a specialized submarine cable system specifically designed for floating offshore wind applications. The company plans to test their new cable on the 24-MW Provence Grand Large Demonstration in France (T&D World 2019).
JDR, a supplier of subsea power cables and umbilical cables to the global offshore energy industry, has been selected by WindPlus as the preferred cable supplier for the Windfloat Atlantic 25-MW floating wind power plant. The project—located off the coast of Viana de Castelo, Northern Portugal—will be the industry's first application of dynamic cables operating at 66 kV with V164 floating wind turbine generators (WireTech 2019).

In April 2019, the Carbon Trust announced the five winners of its dynamic export cable competition as a part of the Floating Wind Joint Industry Project, which aims to accelerate and support the development of commercial-scale floating wind power plants. The project is a collaboration between industry partners EnBW, ENGIE, Eolfi, E.ON, Equinor, Innogy, Kyuden Mirai Energy, Ørsted, ScottishPower Renewables, Shell, Vattenfall, and Wpd, with support from the Scottish government (Carbon Trust 2019).

4.5.4 Targeted Research in the United States

The U.S. offshore wind industry is poised for substantial deployment of over 10 GW of electric-generating capacity over the next decade, but with only 30 MW operating there is some uncertainty about the transfer of largely European-based technology to the United States. The physical and economic characteristics of U.S. sites, supply chains, and offshore resources may present unique issues that would require additional research conducted outside the scope of individual commercial projects. To help address this concern, a new national technical research consortium was formed in 2018 with the purpose of conducting new technology research to benefit the end users (developers) of the U.S. market. Under an open funding opportunity, DOE committed

$20.5 million in 2018 to NYSERDA to form a National Offshore Wind R&D Consortium. The corporation agreed to match the DOE contribution and launched a funding organization to make research and development awards on prioritized topics that will support developers in achieving their near-term deployment and cost targets. The first solicitation was released by NYSERDA on March 29, 2019, and the first awards are expected in 2019. As the organization matures, NYSERDA envisions that the consortium will become a nonprofit entity with a self-sustaining mission that extends well beyond the initial 4-year time frame (NYSERDA 2019).

5 Cost and Pricing Trends

The PPA and price schedule agreed upon between Vineyard Wind LLC and Massachusetts electric distribution companies in July 2018 offers the first market-based reference point for the price and cost of commercial-scale (800 MW) offshore wind generation in the United States. It suggests that the Vineyard Wind project off Massachusetts falls within the price range of European offshore wind projects, with an expected start of commercial operation between 2022 and 2023. This PPA was established against the backdrop of continued price and commensurate cost reductions in major offshore wind markets from 2016 to 2018. Section 5.1 provides a discussion of price trends for fixed-bottom projects, including an analysis of the PPA price point for the Vineyard Wind project. Section 5.2 summarizes LCOE trends for fixed-bottom projects, with subsections on the constituent parts of LCOE (i.e., CapEx [Section 5.2.2], turbine costs [Section 5.2.3], operational expenditures (OpEx) [Section 5.2.4], and financing [Section 5.2.5]. Section 5.3 summarizes cost trends for floating technology.

5.1 Fixed-Bottom Pricing Trends

Figure 32 shows (adjusted) strike prices from recent offshore wind auctions held in Germany, the United Kingdom, the Netherlands, Denmark, and the United States, for projects to be commissioned between 2017 and 2025.

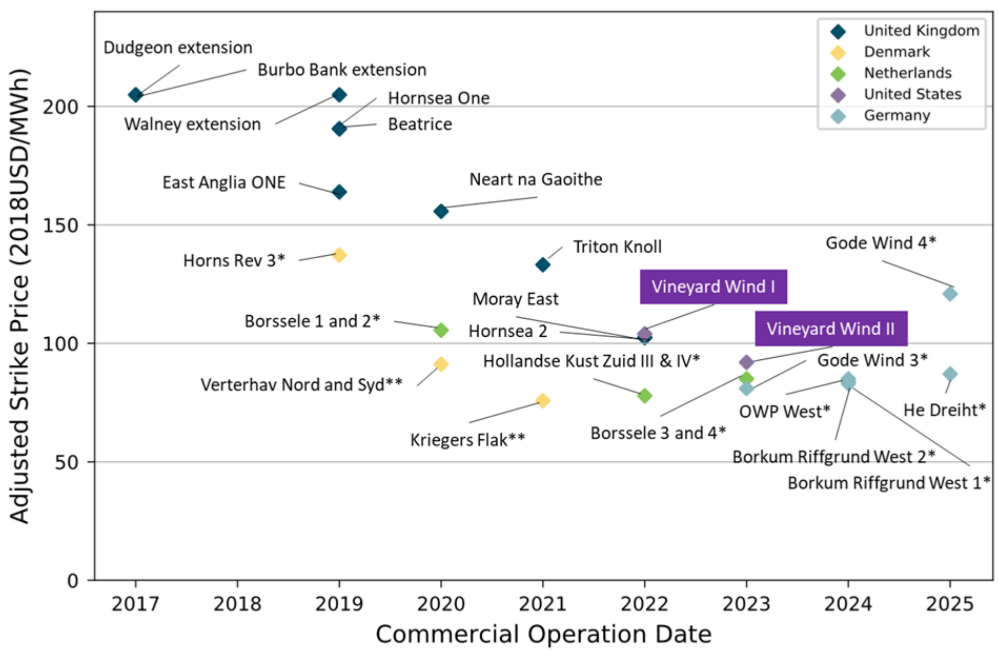


Figure 32. Adjusted strike prices from U.S. and European offshore wind auctions. *Reprinted from Beiter et al. (2019)*

Notes: *Grid and development costs added; **Grid costs added and contract length adjusted; includes data for commercial-scale projects only

The winning auction prices (commonly referred to as "strike prices")[53] that are shown in the figure were adjusted by NREL for contract length, grid connection, and revenue mechanism for an "all-in" price

[53] The strike price for an offshore wind project from an auction is usually the lowest bid price at which the offering can be sold. The strike price usually covers a specific contract term for which the project will be paid for the energy (and possibly other products or attributes) produced. The offeror of that

comparison (see Musial et al. 2017 for a more detailed description).[54] These adjustments were made to account for differences in project scope. For example, under German award terms, the project developer is only responsible for expenditures related to intra-array cabling and the offshore substation but not for the rest of the export cable system. Adjustments were made to the German projects to add the expected cost of the export cable and land-based grid connection back into the price.

The data suggest a trend of declining price levels from approximately $200/MWh (2017–2019 COD) to approximately $75/MWh for projects with a 2024–2025 COD.[55] These reductions in the prices for procuring offshore-wind-produced electricity were achieved through a combination of favorable siting characteristics; increased project size; continued optimization of technology and installation processes; improved market, regulatory, and auction design structures; increased competition within the supply chain; favorable macroeconomic trends; and strategic market behavior.

5.1.1 Vineyard Wind PPA (Lease OCS-A-0501) Analysis

On July 31, 2018, Vineyard Wind LLC and the Massachusetts electric distribution companies submitted a 20-year PPA for 800 MW of offshore wind generation and renewable energy certificates to the Massachusetts Department of Public Utilities for review and approval. The Vineyard Wind/Massachusetts PPA established a contract for procurement of electricity from two 400-MW facilities that enter commercial operation in 2022 (facility 1)[56] and 2023 (facility 2), respectively, at a specified pricing schedule (Massachusetts Department of Public Utilities 2018a, 2018b). Key contractual terms and project filings from the Vineyard Wind LLC Draft Environmental Impact Assessment (Vineyard Wind 2018a), construction and operations plan (Vineyard Wind 2018b), and the independent evaluator report (Peregrine Energy 2018) are shown in Table 12.

The documented first-year price for delivery of offshore wind generation and renewable energy certificates under the Vineyard Wind/Massachusetts PPA is $74/MWh (2022$) for facility 1 (400 MW) and $65/MWh (2023$) for facility 2 (400 MW), but these prices do not reflect all of the revenue that the project will generate, and are therefore lower than the data shown in Figure 32. To allow for a more accurate comparison with the adjusted European auction prices, Beiter et al. (2019) calculated a levelized PPA price, accounted for revenue streams outside of the PPA,[57] and excluded U.S. tax benefits (i.e., election of the investment tax credit [ITC]). The resulting (adjusted) PPA price was estimated to be $98/MWh (2018$).

Although this (adjusted) “all-in” price level of $98/MWh is significantly higher than the reported first-year PPA prices, the data in Figure 32 show that the project costs are in line with European project bids for the same time frame. This suggests that the generally anticipated price (and cost) premium for the nascent U.S. offshore wind industry in comparison to offshore wind projects in the established European markets might be much less pronounced than has widely been expected by many analysts. Earlier cost analyses estimated LCOE between $120/MWh and $160/MWh for a commercial-scale offshore wind project built in the northeastern

---

strike price is awarded the rights to develop a particular parcel under predetermined conditions set in the tender offer that may vary by country or market. The strike price should not be confused with levelized cost of energy, which may be calculated using different financing and cost assumptions.

[54] In general, these adjusted costs are higher than the unadjusted strike prices but still reflect a steep decline in price for European offshore wind projects installed out to the 2025 COD.

[55] Note that many of the projects shown in Figure 32 with future CODs have not yet reached the financial investment decision, and some caution is appropriate when determining whether these projects will reach COD.

[56] Vineyard Wind LLC has recently reported its intent for both facilities to be in operation by the end of 2022, ahead of the commercial operation date indicated on initial fillings (Vineyard Wind 2018c).

[57] One of the revenue streams outside of the PPA considered is sales into the ISO-New England (ISO-NE) Forward Capacity Market. Note that in its capacity auction FCA #13 held on February 4, 2018, Vineyard Wind did not qualify for the renewable technology resource exemption, which allows a resource to be exempt from the ISO-NE minimum-offer price rule. Vineyard Wind participated in the ISO-NE substitution auction and secured 54 MW of capacity. ISO-NE filed tariff changes on November 30, 2017, to allow offshore wind resources located in federal waters, including Vineyard Wind, to qualify for renewable technology resource treatment in future auctions. These tariff changes were approved by the Federal Energy Regulatory Commission on January 29, 2019 (ISO Newswire 2019).

United States in the early 2020s (see e.g., Beiter et al. 2017; Musial et al. 2016; Maness et al. 2017; Kempton et al. 2016).

Table 12. Vineyard Wind LLC/EDC PPA Contract Terms[58]

	PPA 1	PPA 2	Notes	Source
Capacity [MW]	400	400	N/A	a, b
Commercial operation date	January 15, 2022	January 15, 2023	N/A	a, b
Delivered product	Energy and renewable energy certificates		N/A	a, b
First-year PPA price [$/MWh]	74 $2022/MWh	65 $2023/MWh	N/A	a, b
PPA duration [years]	20		N/A	a, b
Escalation factor [%]	2.5		N/A	a, b
Vineyard Wind LLC Project Filings				
Wind speed [m/s]	9.3		Simple average of the entire Vineyard Wind lease area	c
Net capacity factor [%]	45		Average capacity factor reported by Vineyard Wind; assumed to be net capacity factor	d
Average water depth [m]	42		The construction and operations plan indicates water depths in the northern half of the lease area range from 35 to 49 m; 42 m is the average	d
Substructure type	Monopiles		Vineyard Wind has indicated that it prefers to use monopiles but may deploy jackets for up to 400 MW of capacity depending on seafloor conditions	d
Turbine rating [MW	8		Turbine rating will range between 8 and 10 MW	d
Export cable length [km]	69.2		Generator lead line proposal selected by buyer (Vineyard Wind LLC procures all cables from turbine to point of interconnection); point of cable landfall: New Hampshire Avenue	e
Land-based cable length [km]	9.65		Generator lead line proposal selected by buyer (Vineyard Wind LLC procures all cables from turbine to point of interconnection); interconnection point: Barnstable	e
O&M port distance [km]	60		O&M port: Vineyard Haven	d

[58] These terms are derived from the PPA contract between NSTAR Electric Company d/b/a Eversource Energy and Vineyard Wind LLC; similar contract terms apply to the other electric distribution companies that have separate contracts with Vineyard Wind LLC.

Installation port distance [km]	92		Installation port: New Bedford Commerce Terminal	d
ITC [%]	18	18	Assumes safe harbor provision through expense of 5% of the overall project cost by the end of 2018 (facility 1) and 2019 (facility 2)	f

Source: Reprinted from Beiter et al. (2019)

a Massachusetts Department of Public Utilities (2018a)
b Massachusetts Department of Public Utilities (2018b)
c Musial et al. (2017)
d Vineyard Wind (2018b)
e Vineyard Wind (2018a)
f Peregrine Energy (2018)

The following is a set of factors that may help explain how Vineyard Wind may have been able to achieve lower-than-expected prices, which are on par with the European price reductions shown in Figure 32:

- The ability to import major technology components from Europe and Asia (e.g., nacelles, blades, cables)
- Favorable offtake conditions for electricity produced by offshore wind in the United States (e.g., relatively low merchant risk compared to the terms of recent European tenders)
- Use of state-of-the art technology solutions expected from early U.S. projects (e.g., Vineyard Wind LLC has announced its intent to procure the V164-9.5 MW turbine [MHI Vestas 2018])
- Project size of 800 MW that is comparable to large European projects
- Developer's experience with installing and operating offshore wind plants globally
- Successful demonstration of offshore wind technology at the Block Island Wind Farm may have lowered some risk perceptions
- Strategic bidding by tender participants for entry into emerging U.S. market (e.g., to gain "first-mover" advantages)
- U.S. market pipeline visibility and growing state policies (see Section 2)
- Industry consolidation as evidenced by Deepwater Wind's acquisition by Ørsted in December 2018
- Intensified competition within the global and U.S. supply chain and among bidders.

This price signal from the Vineyard Wind/EDC PPA could be indicative of subsequent procurement prices of U.S. commercial-scale offshore wind generation in the 2020s. However, a combination of factors determines future price and cost levels (Musial et al. 2016). Massachusetts legislation H.4568 requires future offshore wind generation procured under its capacity mandate of 1,600 MW[59] to produce a price below the Vineyard Wind LLC/EDC PPA contract price.[60] This will require additional cost reductions amid a tax environment that is expected to become less favorable with the ITC phase-out underway (see Section 5.2.6). It is also possible that the Vineyard Wind LLC/EDC PPA price could have benefited from one-time effects, such as strategic

[59] Massachusetts legislation H.4568 mandates the procurement of 1.6 GW of offshore wind capacity by 2027.
[60] The Massachusetts legislature is considering a change to this requirement, which would adjust the procurement price of the previous solicitation for the availability of federal tax credits, inflation, and incentives (amendment 280 to H.3800; H.3801).

bidding behavior among market entrants to gain first-mover advantages for subsequent U.S. offshore wind tenders.

Beyond Vineyard Wind, there is only a limited number of price signals from U.S. projects but their project sizes are smaller than 250 MW. The prices for these small-to-medium size projects are shown in Section 2.4.

5.1.2 European Auction Results and Outlook

Major offshore wind auctions were held in Germany and the Netherlands during quarter 1 (Q1) and Q2 of 2018. Auction activity ceased during the second half of 2018. Table 13 lists the auctions held in European markets during 2018. These were described in greater detail in the *2017 Offshore Wind Technologies Market Update* (Beiter et al. 2018), as they all took place in early 2018.

Table 13. Offshore Wind Auctions During 2018

<table>
<tr><th>Project</th><th>Country</th><th>Auction</th><th>Award Date</th><th>Capacity (MW)</th><th>Auction Price (2016$/MWh)</th><th>Adjusted Auction Price Estimate (2016$/MWh)</th></tr>
<tr><td>Borkum Riffgrund West 1</td><td rowspan="2">Germany</td><td rowspan="2">Second Auction (§ 26 WindSeeG)</td><td rowspan="2">04/27/18</td><td>420</td><td>0</td><td>~79</td></tr>
<tr><td>Gode Wind 4</td><td>132</td><td>118</td><td>~115</td></tr>
<tr><td>Hollandse Kust Zuid III and IV</td><td>Netherlands</td><td></td><td>03/19/18</td><td>700</td><td>0</td><td>~74</td></tr>
<tr><td colspan="7">Note: For more details on these auctions, see Beiter et al. (2018).</td></tr>
</table>

In Germany, no further auction activity is expected for a 3-year period after conclusion of the country's first two rounds of auctions held under the §26 *Offshore Wind Act* (*WindSeeG*) during 2017–2018. Although the German coalition government signaled it may hold an extra tender, it has not formally proposed another auction round to date ahead of 2020 (Foxwell 2018a). Industry groups have requested to "advance grid expansion and optimization and reduce regulatory hurdles for sector coupling" (German Offshore Wind Energy Foundation 2019). After awarding Hollandse Kust Zuid I and II projects (700–750 MW) on March 19, 2018, in a zero-subsidy bid, no additional tender was conducted during 2018 in the Netherlands. Tenders for Hollandse Kust (zuid) wind farms III and IV (700 MW) are scheduled to be held in March 2019 with awarded projects expected to commercially operate by 2023. The United Kingdom will continue its tender activity with a third contract-for-difference allocation round ("AR3") in May 2019. The tender budget is specified at £ 60 million, with a delivery cap of 6 GW.[61] The last award in the United Kingdom was made during its contract-for-difference 2 round in 2017 ("AR2"). After inactivity during 2018, Denmark has selected the location of a new offshore wind facility (800 MW) off Nissum Fjord to be auctioned during 2019 with a COD between 2024 and 2027.

[61] Note that various technologies can bid under the United Kingdom tender scheme, including (but not limited to) offshore wind. However, in previous auctions, offshore wind was awarded the largest share.

5.2 Fixed-Bottom Offshore Wind Cost Trends

5.2.1 Levelized Cost of Energy

Offshore wind is among the renewable energy technologies that has experienced a rapid cost decline in recent years. It is commonly expected that this cost reduction trend will continue globally and will be realized in the United States as the market emerges. Figure 33 provides a survey of LCOE estimates and projections for fixed-bottom technologies from a variety of research organizations and consultancies.

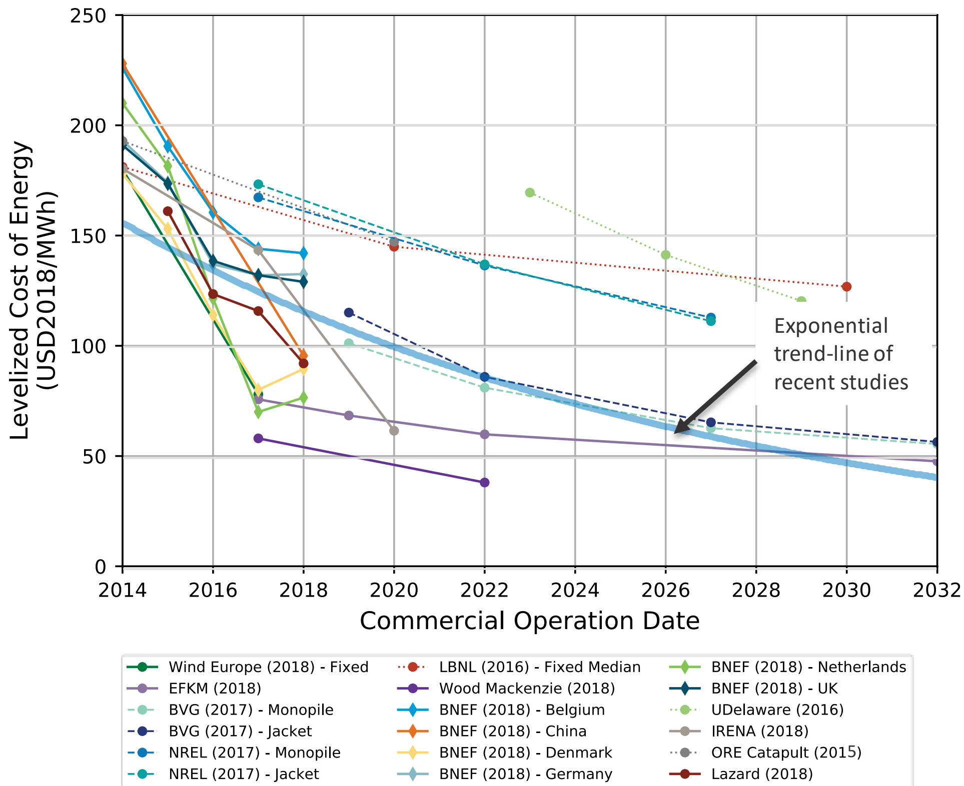


Figure 33. Global LCOE estimates for fixed-bottom offshore wind[62]

Sources: WindEurope (2018), Danish Ministry of Energy, Utilities and Climate (2018), Valpy et al. (2017), Beiter et al. (2017), Wiser et al. (2016), Barla (2018), BNEF (2018b, 2018c), Kempton et al. (2016), IRENA (2018), ORE Catapult (2015), and Lazard (2018)

In Figure 33, the 2018 cost projections are shown in solid lines, whereas earlier studies are plotted with dashed lines. The wide blue trend line represents an exponential fit of the most recent data from studies published in 2018, as well as Valpy et al. (2017) projections, which extend to 2032. This trend line suggests a decrease from LCOE levels of about $120/MWh in 2018 to $50/MWh by 2030. The trend line is meant to serve as a visual reference to focus on the most recent cost projections.

Projections informed by a learning curve approach offer a complementary method for forecasting future cost reductions (Wiser et al. 2016). Based on industry growth projections, the cumulative capacity of the global industry is likely to experience approximately three doublings, or a total growth of eight times its current

[62] "LBNL" in the figure refers to Berkeley Lab

capacity, by 2030. IRENA (2018) estimates a learning rate for offshore wind of approximately 14% per doubling over the period 2010–2020, which would indicate possible LCOE reductions of over 35% based on industry growth projections of 154–193 GW globally by 2030 (see Section 3.2.3).

5.2.2 Capital Expenditures

CapEx are the single largest contributor to the life cycle costs of offshore wind power plants and include all expenditures incurred prior to the COD. Figure 34 shows the reported CapEx over time for operational projects as well as for those in various stages of the near-term project pipeline globally. Each bubble represents the cost estimate (in terms of $/kW) for a single project and bubble size represents the project's capacity.

After a period of increasing project CapEx until 2014 (Musial et al. 2017), an industry trend of declining CapEx has developed, with a capacity-weighted average CapEx of $4,350/kW in 2018 globally. WindEurope reported a European project CapEx of $2,870/kW in 2019, a 45% reduction since 2015 (Brindley 2019). Reported project data suggest a gradual decline of CapEx to levels in the range of $2,500–$4,000/kW between 2020 and 2030. The underlying data for Figure 34 include considerable variation of CapEx within a given year. For projects with a COD in 2018, CapEx ranges from approximately $2,470/kW (Jiangsu Luneng Dongtai project, China [200 MW]) to $6,500/kW (Galloper project, United Kingdom [353 MW]) among projects with capacities greater than 100 MW. Several factors may possibly explain the variation in CapEx within a given year and over time (Smith, Stehly, and Musial 2015), including:

- Varying spatial conditions (e.g., water depth, distance to port, point of interconnection, and wave height of sites that affect technical requirements of installing and operating a wind farm)
- Project size
- Different levels of supply chain shortages (e.g., components, vessels, and skilled labor)
- Changing prices for commodities and energy
- Macroeconomic trends, such as fluctuating exchange rates
- A change in the appreciation of the costs and risks associated with offshore wind project implementation, which reflects in pricing strategies from equipment suppliers and installation contractors.

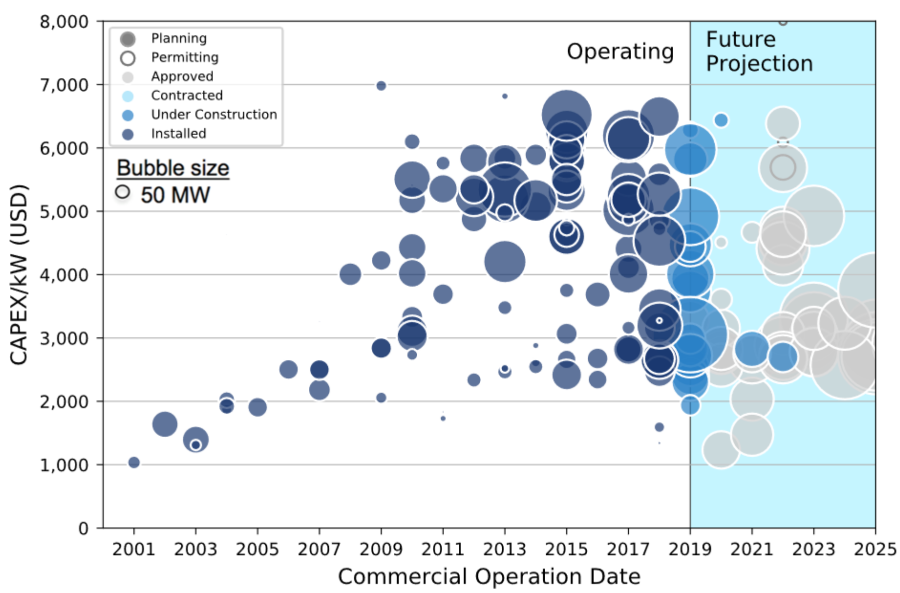


Figure 34. Capital expenditures of global offshore wind projects by commercial operation date and project capacity

Note: Only projects with CapEx greater than $800/kW included.

Note that only limited CapEx data are available for any given year before 2010 and after 2025. As a result of this relatively small sample, and the projects' early planning stages in which firm contracts for capital equipment have yet to be executed, the level of confidence is relatively low for some years.

CapEx has been reported for 67,185 MW of global offshore wind projects. Figure 34 shows the announced costs for 123 installed projects (20,198 MW), 21 projects (7,198 MW) that have started construction, 14 projects (4,848 MW) that have secured financial close, 56 projects (34,009 MW) that have received regulatory approval, 5 projects (575 MW) in the permitting process, 1 project (300 MW) that is still in the planning phase, and 8 projects (58 MW) that are decommissioned. These CapEx data have some uncertainty for various reasons: 1) the CapEx data are normally self-reported by developers and difficult to verify independently, 2) there is limited transparency into the financial impact of cost overruns, and 3) it is often unclear whether the reported CapEx fully captures the total cost of installing the project and connecting it to the grid.[63] When viewed together, though, these data can provide insight into the long-term cost trends. Generally, greater confidence can be placed in cost estimates that are in more mature stages of the project life cycle (i.e., costs for projects that have reached the financial investment decision are typically more accurate than for a project that has not yet received permits); however, preliminary estimates provide insight into developer expectations about cost trends.

5.2.3 Wind Turbine Cost

Offshore turbine costs are estimated to be between 30% and 45% of the total CapEx. Typically, turbine price data come from turbine supply agreements that are negotiated for each project, but because of their proprietary nature these data are very limited. Turbine prices may vary considerably among specific projects. Some of the factors in turbine pricing include delivery costs to the staging port, warranty period (typically 5 years), availability guarantees, project order size, turbine attributes (e.g., turbine rating and drivetrain topology), market competition, timing, and specific strategic market behavior (e.g., first-mover advantages, customer retention). Turbine CapEx has declined rapidly over the last few years, which has led to a considerable spread in price estimates found in publicly available literature sources. Figure 35 shows turbine CapEx estimates published between 2016 and 2019, which illustrate considerable variation yet a general trend of price decline in turbine CapEx between 2010 and 2030.

[63] For example, it is unclear if the announced capital expenditure values include soft costs, such as construction, financing, insurance, or fees.

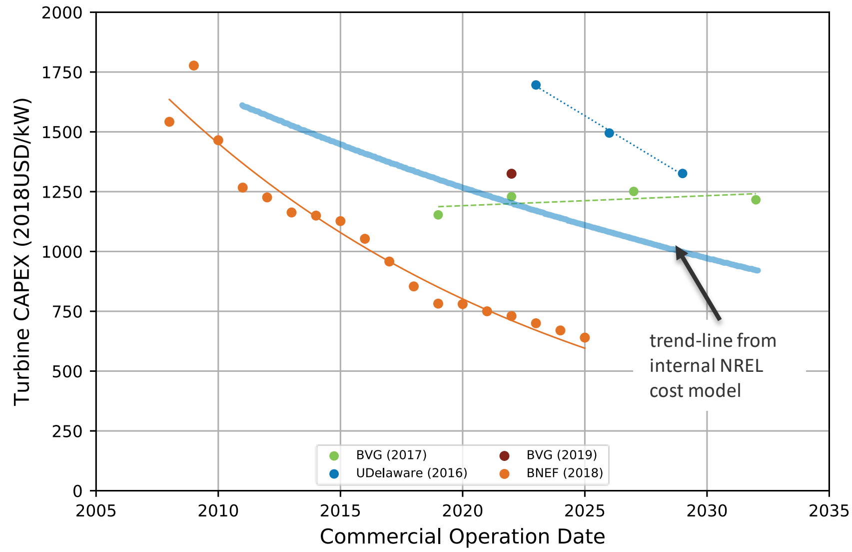


Figure 35. Turbine CapEx trend estimates

Sources: Valpy et al. (2017),[64] Kempton et al. (2016), BVG Associates (2019), and BNEF (2018e)

Available cost studies indicate that turbine CapEx could range between $800/kW and $1,200/kW in 2018–2019. BNEF (2018d) numbers were the lowest and estimate a reduction trend reaching $640/kW by 2025. Valpy et al. (2017) illustrates the impact from larger turbine ratings of 6 MW (2019), 10 MW (2022), and 12 MW (2027 and 2032) on turbine CapEx. The increase in turbine CapEx from Valpy et al. (2017) is found to be relatively small on a $/kW basis, which would allow for a significant decrease of total system costs on a $/MWh basis. Kempton et al. (2016) estimated considerably higher turbine CapEx from their 2016 study but show a similar cost reduction rate as BNEF (2018d).

The highest commercially available turbine rating is expected to grow from 9.5 MW in 2018[65] to 15 MW or higher over the next decade (see Section 4), which presents one of the primary areas for future cost reduction (e.g., Wiser et al. 2016). Using higher-rated turbines for a given project size reduces the number of turbines to be installed and serviced, effectively decreasing the unit costs for balance-of-station ($/kW) and O&M activities ($/kW/year). In addition, consultation with industry experts and turbine manufacturers suggests that higher turbine rating may not necessarily result in an increase in turbine CapEx ($/kW). Turbine manufacturers have reportedly been able to increase turbine rating without increasing the unit cost of the turbine ($/kW). Through continued innovations, such as the use of lightweight materials, advanced manufacturing methods, systemwide load control, and economies of scale in production and delivery, turbine manufacturers may be able to offset other cost increases (such as specific mass increases) caused by upscaling. Some evidence of this trend might be found in a review of the GE Haliade-X technical specifications by Pondera Consult, which reports only a slight increase in specific mass for the Haliade-X turbine at 68.8 tonnes per megawatt (t/MW)—including the nacelle, blades, and hub—compared to the Vestas V164-8MW specific mass of 62.5 t/MW. This

---

[64] Note: In contrast to the other sources, this estimate from Valpy et al. (2017) explicitly includes the impact from an increase in turbine rating (over time) on turbine CapEx ($/kW) (i.e., from turbine ratings of 8 MW [2018] up to 12 MW ([2027 and 2032]).

[65] MHI Vestas V164-9.5 MW turbine.

emerging trend in turbine lower mass/cost growth must be further validated but could provide a further economic motivation for upscaling to larger turbines (de Vries 2019).[66]

5.2.4 Operational Expenditures

OpEx cover all costs incurred after COD—but before decommissioning—that are required to operate the project and maintain turbine availability to generate power. These expenditures are generally thought to contribute between 20% and 30% to life cycle costs for offshore wind projects, depending on site characteristics. The strongest drivers are distance from the O&M port, accessibility limits related to local meteorological ocean conditions (e.g., wave height), and turbine rating (i.e., fewer, larger turbines suggest lower O&M costs per megawatt). To optimize the balance between OpEx and availability, operators adopt different logistical strategies for individual projects depending on site conditions (DNV GL 2013). OpEx for offshore wind projects are subject to considerable uncertainty because of a lack of empirical data. Although wind project owners commonly report CapEx, they rarely report OpEx.

5.2.5 Financing

In contrast to fossil-fueled power plants (e.g., natural gas or coal), variable costs of offshore wind plants are relatively small, and most lifetime costs are incurred up-front through CapEx for the development and construction of a project. These up-front expenditures generally require investment volumes of more than $1 billion for utility-scale projects (>200 MW).[67] The financing rate of a project, commonly expressed in terms of the weighted-average cost of capital,[68] has considerable impact on lifetime project costs (i.e., LCOE) because it determines the annual debt service and equity repayment for the initial (CapEx) investment.

During 2018, offshore wind projects in Europe and Asia continued to access low-cost capital, consistent with a broader trend of declining equity and debt rates for renewable energy asset financing in recent years. Nearly $12 billion was invested in new European offshore wind capacity (4.2 GW) during 2018, which comprised 24% of the total investment in new power generation assets in Europe.[69] Although the total investment volume is lower compared to the levels between 2015 and 2016, installed capacity levels were considerably higher "as a result of cost reductions and sector maturity, particularly for offshore wind" (Brindley 2019). In Europe, project finance dominated offshore wind investment transactions during 2018 with a share of 77%. This drastically reverses the trend of widespread balance-sheet financing from previous years and reflects growing comfort with the risks associated with constructing and operating an offshore wind plant, as well as the entry of smaller developers who can take advantage of a favorable lending market (Brindley 2019). Table 15 depicts financing conditions typical for European offshore wind projects between 2006 and 2018 (Guillet 2018). The share of debt in European project financing has been consistently at or above 70% since 2012, including in 2018. Brindley (2019) reports debt share of up to 90% for European offshore wind financing in 2018, exceeding those of land-based wind farms. These financing terms are generally expected to carry into 2019 (Brindley 2019).

Table 14. Typical Financing Conditions for European Offshore Wind Projects

Year	Debt-to-Equity Ratio	Pricing[70] (Basis Points)
2006–2007	60:40	150–200

[66] Note that the described trend between turbine rating and turbine CapEx may only apply to a certain range of turbine ratings.
[67] For instance, the 800-MW Vineyard Wind project has a reported investment volume of approximately $2 billion (Renewables Now 2018).
[68] Weighted-average cost of capital is the average cost of all sources of capital based on the percentage contribution to the total capital structure.
[69] Major offshore wind projects that reached their financial investment decision were Moray East and Triton Knoll (both in the United Kingdom) and Borssele III and IV (the Netherlands).
[70] Basis points are indicated above the London Interbank Offer Rate. One basis point is equal to 1/100 of a percent and 100 basis points equals 1%.

2009–2011	65:35	300–350
2012–2013	70:30	200–250
2014–2015	70:30	200–250
2016–2017	75:25	150–225
2018	70:30	120–175

Source: Reprinted from Guillet (2018)

Note: Year 2008 not available from source.

Debt

Debt rates for global offshore wind financing remain at historically low levels, ranging between 3% and 4% for 15-year debt terms (Guillet 2018). Debt maturity (post completion) ranged between 10 and 18 years, depending (among other factors) on the length and structure of the offtake conditions. These debt terms correspond to land-based wind financing in the United States (Wiser and Bolinger 2018). Consultation with industry experts suggests that debt financing rates for commercial-scale offshore wind projects will be similar to commercial-scale projects in the United States.

Equity

Driven by high demand for relatively predictable long-term cash flow and technology characteristics that are increasingly well-understood, equity rates for offshore wind have decreased in recent years. A greater variety of equity investor classes seems to be comfortable with the risk profiles of offshore wind, such as pension and insurance funds. Further, equity refinancing of operational projects has become more prevalent in established offshore wind markets. During 2018, the debt refinancing volume was nearly $10 billion for four European offshore wind farms completing their construction phase (Brindley 2019).

Emerging information for the U.S. market suggests that European financing terms are generally applicable to a U.S. project finance context. In the United States, it is generally expected that several different types of entities will participate in the financing of commercial-scale offshore wind projects, including commercial banks, export credit agencies, and institutional investors (e.g., pension funds, insurance funds, and infrastructure investors). The engagement of Copenhagen Infrastructure Partners in the Vineyard Wind project may indicate that major international infrastructure investors recognize the potential of the U.S. offshore wind market. A similar motivation might apply to the market entry of major oil and gas corporations as well as supply chain companies (i.e., manufacturers and marine contractors) acting as offshore wind investors globally and in the United States.

Important U.S.-specific financing considerations include, but are not limited to:

- **Tax Credits**. Offshore wind projects in the United States may currently elect the ITC or production tax credit. It is commonly expected that U.S. offshore wind projects will have a preference to elect the ITC; however, choosing between election of the ITC versus the PTC depends on a number of financial and legal considerations influenced by the anticipated energy production and operational risks. Pursuant to the Consolidated Appropriations Act, 2016 (P.L. 114-113), these tax credits are on a phase-down schedule (Table 15), thereby limiting the number of offshore wind projects that are expected to benefit from these tax provisions. Some large-scale projects have reportedly grandfathered their election of the ITC/production tax credit by commencing "physical work of a significant nature" on the facility or by incurring at least 5% of the total cost of the facility under the ITC phase-down rate schedule (Deloitte 2017). During 2018, some concerns were raised whether large-scale projects, such as the 800-MW

Vineyard Wind project, would be able to raise unprecedented volumes of tax equity financing for a single project of up to $600 million (Deepwater Wind 2018). Financial close of the Vineyard Wind project is expected during 2019 and will allow for a better understanding of whether enough tax equity is available at these investment levels. Election of these tax credit provisions influences the optimal financing structure of an offshore wind project with a higher share of equity and back-leveraged (i.e., the loan is collateralized by the sponsor's equity in the project), so that the benefits from the tax incentive can be fully utilized. As a result of the tax credit phase out, optimal offshore wind financing structures are expected to be impacted (i.e., lower equity share).

Table 15. ITC Phase-Down Rate Schedule

Construction Start Before	Applicable ITC Rate
1/1/2017	30%
1/1/2018	24%
1/1/2019	18%
1/1/2020	12%
On or after 1/1/2020	0%

Source: Reprinted from Deloitte (2017)

- **Installation and operation contingencies**. Consultation with industry experts suggests that early commercial-scale U.S. projects might expect higher contingency levels relative to the established European offshore wind markets. These serve to account for less experience in U.S. offshore wind power plant installation and operation with the risk of incurring delays and interruptions in the supply chain, marine logistics, and permitting processes.
- **Offtake mechanisms**. Current U.S. offtake mechanisms (Section 2.4.1) are generally seen as attractive to global offshore wind developers because of their relatively low merchant price exposure. Higher uncertainty in revenue streams and declining margins in established offshore wind markets in Europe and Asia might have been primary factors in yielding the high bid prices for lease areas auctioned during 2018.
- **Permitting**. In the United States, a federal, state, and local permit to construct and operate a wind power plant is not included in a lease award. This might introduce additional risk from legal action, permitting delays, and stranded assets compared to acquiring a fully permitted lease area.[71]

The Vineyard Wind PPA pricing suggests that there is only a small premium for "new market" risk (Beiter et al. 2019). Consultation with industry experts suggests that investors are available for the different types of risk profiles of each project phase (e.g., developers, private equity, independent power producers, utilities, tax equity, green banks, export credit agencies, manufacturers). A variety of financial vehicles could be utilized to mitigate the risk exposure of early projects, including tax incentives, bonus appreciation, loan guarantees, and financial hedging products. Coincident with the phase out of tax credits over the next few years, high RPS requirement levels are starting to take effect in coastal states, which might mitigate some of the lost tax benefits.

[71] For instance, in past German offshore wind auctions, prepermitted lease areas were awarded.

5.3 Floating Cost Trends

Although still in the precommercial phase of maturity, floating wind technology has gained greater mainstream recognition over the past year, partially because of Equinor's successful deployment and operation of the Hywind II pilot project near Peterhead, Scotland. Today, floating wind is generally considered a viable technology for the future of offshore wind. Figure 36 depicts LCOE trends estimated by various research organizations and consultancies that show a reduction from levels from above $175/MWh (2018) to $70/MWh (2030).

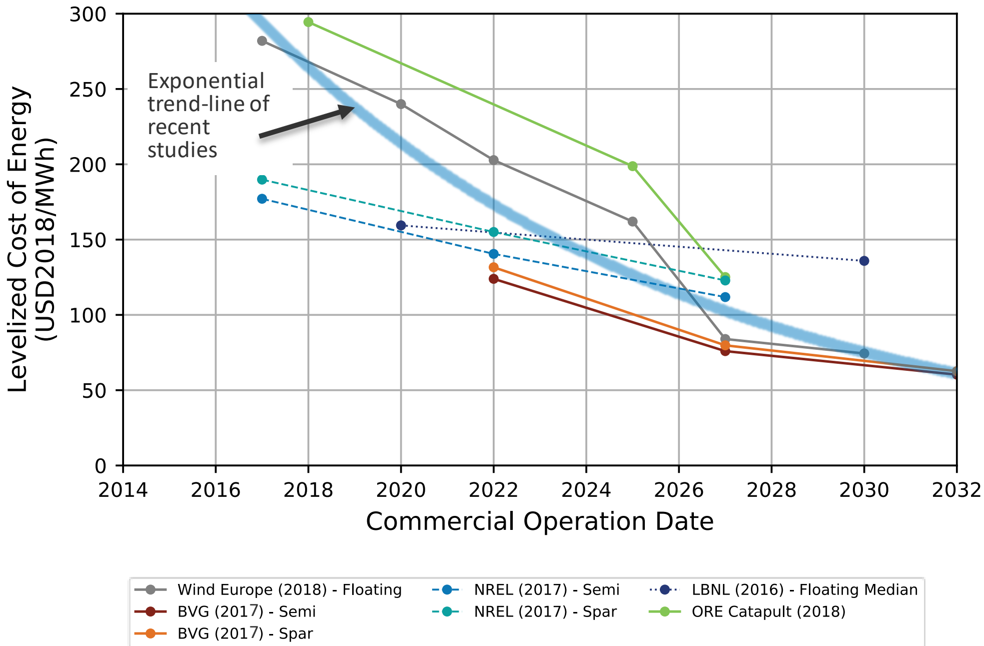


Figure 36. Global LCOE estimates for floating technology[72]

Sources: WindEurope (2018), Hundleby et al. (2017), Beiter et al. (2017), Wiser et al. (2016), ORE Catapult (2018)[73]

Note that the number of sources for floating wind cost is smaller than for the fixed-bottom trends. These estimates, except for those provided by ORE Catapult (2018) prior to 2027, assume commercial-scale floating wind plants and learning curve benefits commensurate with a mature industry. The blue trend line represents an exponential fit of the most recent studies from 2018. This trend line is meant to serve as a visual reference to focus attention on the most recent cost projections. Cost estimates assuming a commercial-scale floating project size, published prior to 2018, predict higher costs than those published more recently. This might reflect more accurate cost data and new data on anticipated fixed-bottom cost reductions that are applicable to floating systems, as well as increased optimism that technical challenges can be overcome.

The anticipated cost reductions between 2015 and 2030 are related to an expected floating deployment trajectory that spans from existing single-turbine demonstration projects (2015–2017) to multiple-turbine demonstration projects (2017–2022), and finally, to medium- to full-scale commercial projects (early to late 2020s). Globally, there is currently a wide range of floating technology concepts under consideration that are at the multiturbine demonstration phase.

[72] "LBNL" in the figure refers to Berkeley Lab

[73] Estimates from ORE Catapult (2018) were converted from £2012 to $2018 using 2012 exchange rates and applying a cumulative U.S. inflation factor of 9.4% for the period 2012–2018. The ORE Catapult (2018) estimates reflect demonstration (2018), precommercial (2025), and commercial status (2027).

The cost of floating wind technology is currently based on a small set of data from the first phase of prototypes and projects in the design or construction phase. Generally, the potential for cost reduction is high because early-stage technology advances usually result in significant cost reductions. In addition, technological and commercial developments from fixed-bottom wind systems might translate to floating wind systems. Cost estimates from NREL's geospatial analysis (Beiter et al. 2016; Gilman et al. 2016) indicate that floating costs may show a steeper rate of cost reduction than fixed-bottom systems, with the potential for cost parity over the next 10 years. The basis for technology-specific cost reduction potential comes from a range of factors, including (but not limited to) the ability of floating systems to:

- Leverage cost reductions, innovations, and experience from fixed-bottom systems
- Utilize existing supply chains
- Optimize using lighter components and increased modularity
- Reduce the number and complexity of construction steps at sea (e.g., by assembling the turbine and substructure at quayside)
- Automate production and fabrication of the floating platforms
- Access higher wind speeds sufficient to outweigh the higher O&M and installation costs associated with greater distances to shore and harsher meteorological conditions.

For a more detailed discussion of possible methods to reduce the cost of floating systems, see Beiter et al. (2016).

Primary Database Sources

- 4C Offshore. 2018. Offshore Wind Farms Intelligence. http://www.4coffshore.com/windfarms/request.aspx?id=owfdb.

- 4C Offshore. 2019. Global Offshore Wind Farms Intelligence. http://www.4coffshore.com/windfarms/request.aspx?id=owfdb.

- Bloomberg New Energy Finance. 2018. Renewable Energy Project Database. https://about.bnef.com/.
- MAKE Consulting. 2018. Global Offshore Wind Power Project Database. http://www.consultmake.com/research/databases.

- WindEurope. 2019. *Offshore Wind in Europe: Key trends and statistics 2018*. February 2019. https://windeurope.org/about-wind/statistics/offshore/european-offshore-wind-industry-key-trends-statistics-2018/.

References

The 100 Percent Clean Energy Act of 2018. Senate Bill No. 100. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB100.

4C Offshore. 2017. "Siemen's 8-megawatt wind turbine up and running." January 30, 2017. https://www.4coffshore.com/news/siemens-8-megawatt-wind-turbine-up-and-running-nid5241.html.

4C Offshore. 2018. Offshore Wind Farms Intelligence. http://www.4coffshore.com/windfarms/request.aspx?id=owfdb.

4C Offshore. 2019a. "Ørsted suspends Taiwan developments." January 21, 2019. https://www.4coffshore.com/news/%C3%B8rsted-suspends-taiwan-developments-nid11111.html.

4C Offshore. 2019b. "Kincardine Offshore Windfarm Project Offshore Wind Farm." https://www.4coffshore.com/windfarms/kincardine-offshore-windfarm-project-united-kingdom-uk2h.html.

Adwen GmbH. 2019. "Adwen (company)." Accessed April 26, 2019. https://en.wikipedia.org/wiki/Adwen_(company).

Barla, Sashi. 2018. "Global Wind Turbine Technology Trends." Market Report. Wood Mackenzie.

Bay State Wind. 2018. "Bay State Wind plans more than $2 million in environmental research grants." Press Release. April 10, 2018. https://baystatewind.com/News/2018/04/Bay-State-Wind-plans-more-than-2-million-in-environmental-research-grants.

Beiter P., W. Musial, A. Smith, L. Kilcher, R. Damiani, M. Maness, S. Sirnivas, T. Stehly, V. Gevorgian, M. Mooney, G. Scott. 2016. *A Spatial-Economic Cost Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030* (Technical Report). NREL/TP-6A20-66579. National Renewable Energy Laboratory (NREL), Golden, CO (US). www.nrel.gov/docs/fy16/66579.pdf.

Beiter P., W. Musial, A. Smith, L. Kilcher, R. Damiani, M. Maness, S. Sirnivas, T. Stehly, V. Gevorgian, M. Mooney, G. Scott. 2016. *A Spatial-Economic Cost Reduction Pathway Analysis for U.S. Offshore Wind Energy*

Development from 2015–2030 (Technical Report). NREL/TP-6A20-66579. National Renewable Energy Laboratory (NREL), Golden, CO (US). www.nrel.gov/docs/fy16/66579.pdf.

Beiter, Philipp, Walter Musial, Levi Kilcher, Michael Maness, and Aaron Smith. 2017. *An Assessment of the Economic Potential of Offshore Wind in the United States from 2015 to 2030* (Technical Report). NREL/TP-6A20-67675. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy17osti/67675.pdf.

Beiter, Philipp, Paul Spitsen, Jake Nunemaker, Tian, Walter Musial, Eric Lantz, and Vahan Gevorgian. 2018. *2017 Offshore Wind Technologies Market Update*. Washington, D.C.: U.S. Department of Energy Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/wind/downloads/2017-offshore-wind-technologies-market-update.

Beiter, Philipp, Paul Spitsen, Walter Musial, and Eric Lantz. 2019. *The Vineyard Wind Power Purchase Agreement: Insights for Estimating Costs of U.S. Offshore Wind Projects* (Technical Report). National Renewable Energy Laboratory (NREL), Golden, CO. NREL/TP-5000-72981. https://www.nrel.gov/docs/fy19osti/72981.pdf.

Benson, J. 2018. "Future Grid - Sun, Wind and BESS." Accessed April 22, 2019. https://www.energycentral.com/c/cp/future-grid-sun-wind-and-bess.

Bloomberg New Energy Finance (BNEF). 2018a. 2H 2018 Offshore Wind Market Outlook. https://about.bnef.com/.

BNEF. 2018b. "Current LCOE by Technology." https://www.bnef.com/core/lcoe?tab=Current%20LCOE%20by%20Technology.

BNEF 2018c. "Historic LCOEs: 2H 2018." https://www.bnef.com/core/lcoe?tab=Historic%20LCOE.

BNEF. 2018d. "First Big U.S. Offshore Wind Farm Offers $1.4 Billion to Customers." Accessed November 2018. https://www.bloomberg.com/news/articles/2018-08-01/first-big-u-s-offshore-wind-offers-1-4-billion-to-customers.

BNEF. 2018e. "2H 2018 Wind Turbine Price Index." Accessed February 1, 2019. https://www.bnef.com/core/.

(BOEM) Bureau of Ocean Energy Management. 2018. "Renewable Energy Path Forward on the Atlantic." Request for Information. https://www.boem.gov/Renewable-Energy-Path-Forward.

BOEM. 2019a. "Massachusetts Leases OCS-A 0500 (Bay State Wind) and OCS-A 0501 (Vineyard Wind)." Accessed April 2019. https://www.boem.gov/commercial-wind-leasing-offshore-massachusetts/.

BOEM. 2019b. "New York Bight." Accessed June 2019. https://www.boem.gov/NY-Bight/.

BOEM. 2019c. "California Activities." Accessed June 2019. https://www.boem.gov/California/.

BOEM. 2019d. "Hawaii Activities" Accessed June 2019. https://www.boem.gov/Hawaii/.

BOEM 2019e. BOEM Environmental Studies. Accessed June 2019. https://www.boem.gov/Renewable-Energy-Environmental-Studies/.

Business Network for Offshore Wind. 2019. "Leadership 100 Work Plan." June 3, 2019. https://www.offshorewindus.org/wp-content/uploads/2019/06/L100WhitePaperJun.3.2019.pdf.

Brindley, Guy. 2019. *Financing and investment trends. The European Wind Industry in 2018*. WindEurope. https://windeurope.org/wp-content/uploads/files/about-wind/reports/Financing-and-Investment-Trends-2018.pdf.

BVG Associates. 2018a. *Offshore wind in Virginia: A vision*. September 2018. https://files.vasierraclub.org/oswvision.pdf.

BVG Associates. 2018b. *The Virginia advantage: The roadmap for the offshore wind supply chain in Virginia*. https://static1.squarespace.com/static/5b3cf461d274cb109aa488d8/t/5c23e225562fa7be221fe841/1545855531929/BVGA-20802-Report-r2-final-20181227.pdf.

BVG Associates. 2019. "Guide to an Offshore Wind Farm." Published on behalf of The Crown Estate and the Offshore Renewable Energy Catapult. https://www.thecrownestate.co.uk/media/2860/guide-to-offshore-wind-farm-2019.pdf.

Carbon Trust. 2019. "Carbon Trust's Floating Wind Joint Industry Project reveals winners of dynamic export cable competition." April 17, 2019. https://www.carbontrust.com/news/2019/04/winners-dynamic-export-cable-competition.

Commonwealth of Massachusetts. 2018. An Act to Advance Clean Energy (Bill H. 4857). 190th General Court of Massachusetts. August 9, 2018. https://malegislature.gov/Bills/190/H4857.

Composites World 2014. "Vestas 8-MW turbine begins operation." February 3, 2014. https://www.compositesworld.com/news/vestas-8-mw-turbine-begins-operation.

Connecticut General Assembly. 2019. House Bill 7156. June 6, 2019. https://www.cga.ct.gov/asp/cgabillstatus/cgabillstatus.asp?selBillType=Bill&which_year=2019&bill_num=7156.

The Crown Estate. 2018. "The Crown Estate shares further detail on plans for Round 4, including proposed locations to be offered for new seabed rights." Press Release. November 16, 2018. https://www.thecrownestate.co.uk/en-gb/media-and-insights/news/2018-the-crown-estate-shares-further-detail-on-plans-for-round-4-including-proposed-locations-to-be-offered-for-new-seabed-rights/.

Davidson and Weston. 2018. "Principle Power joins Senvion's 10MW project." *Windpower Offshore*. May 4, 2018. Accessed May 2018. https://www.windpoweroffshore.com/article/1463807/principle-power-joins-senvions-10mw-project.

Danish Ministry of Energy, Utilities and Climate. 2018. "Note on technology costs for offshore wind farms and the background for updating CAPEX and OPEX in the technology catalogue datasheets." https://ens.dk/sites/ens.dk/files/Analyser/havvindsnotat_translation_eng_final.pdf.

Deepwater Wind. 2018. "Case 18-E-0071 – In the Matter of Offshore Wind Energy. Comments of Deepwater Wind, LLC." http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId=%7BE296F037-4F08-4529-8892-7295F236F80E%7D.

Deloitte. 2017. "2017 Deloitte Renewable Energy Seminar." https://www2.deloitte.com/us/en/pages/energy-and-resources/events/deloitte-energy-and-resources-conferences-and-training-seminars.html.

Denholm, Paul, Yinong Sun, and Trieu Mai. 2019. *An Introduction to Grid Services: Concepts, Technical Requirements and Provision from Wind* (Technical Report). National Renewable Energy Laboratory (NREL), Golden, CO. NREL/TP-6A20-72578. https://www.nrel.gov/docs/fy19osti/72578.pdf.

de Vries, E. 2012. "Close up - Alstom Haliade 6MW prototype." *Windpower Monthly*. July 11, 2012. https://www.windpowermonthly.com/article/1140792/close---alstom-haliade-6mw-prototype.

de Vries, E. 2019. "Haliade-X Uncovered: GE Aims for 14MW." WindPower Offshore, March 4, 2019. https://www.windpoweroffshore.com/article/1577816/haliade-x-uncovered-ge-aims-14mw.

Deign, J. 2019. "China Set to Overtake UK as Offshore Wind Leader by 2021." *Greentech Media*. January 31, 2019. https://www.greentechmedia.com/articles/read/uk-set-to-lose-offshore-wind-crown-to-china-by-2021#gs.4ef3uj.

DNV GL. 2013. "A Guide to UK Offshore Wind Operations and Maintenance." London, UK: Scottish Enterprise and The Crown Estate. http://www.hi-energy.org.uk/Downloads/General%20Documents/guide-to-uk-offshore-wind-operations-and-maintenance.pdf.

DOE (U.S. Department of Energy). 2018. Tethys Database. https://tethys.pnnl.gov/.

DOE. 2019. "Offshore Wind Advanced Technology Demonstration Projects." Accessed April 29, 2019. https://www.energy.gov/eere/wind/offshore-wind-advanced-technology-demonstration-projects.

Durakovic, A. "North Carolina Governor Proposes Offshore Wind Study." *OffshoreWIND.biz*. March 12, 2019. https://www.offshorewind.biz/2019/03/12/north-carolina-governor-proposes-offshore-wind-study/.

Dvorak, P. 2017. "Inching toward 10 MHI Vestas unwraps a 9.5-MW design." *Windpower Engineering*. August 2017. https://www.windpowerengineering.com/design/inching-toward-10-mhi-vestas-unwraps-9-5-mw-design.

Energy Information Administration. 2019. "Maryland State Profile and Energy Estimates." Accessed April 2018. https://www.eia.gov/state/?sid=MD.

Equinor. 2018a. "World class performance by world's first floating wind farm." February 15, 2018. Accessed May 2018. https://www.statoil.com/en/news/15feb2018-world-class-performance.html.

Equinor. 2018b. "Equinor has installed Batwind - the world's first battery for offshore wind." June 27, 2018. https://www.equinor.com/en/news/26june2018-equinor-has-installed-batwind.html.

Espérandieu, M. 2018. "État des lieux des projets éoliens au large des côtes françaises." Mer et Marine. December 6, 2018. https://www.meretmarine.com/fr/content/etat-des-lieux-des-projets-eoliens-au-large-des-cotes-francaises.

European Commission. 2019. "State aid: Commission approves support for four floating demonstration offshore wind farms in France." European Commission Press Release. February 25, 2019. http://europa.eu/rapid/press-release_IP-19-1412_en.htm.

Eversource Energy. 2019. "Ørsted and Eversource Enter 50-50 Partnership Agreement on Key Offshore Wind Assets in the Northeast." Boston, February 8, 2019. Accessed July 2019. https://www.eversource.com/content/docs/default-source/investors/orsted-partnership-agreement.pdf?sfvrsn=736bcb62_0.

Fingersh, L., M. Hand, A. Laxson. 2006. "Wind Turbine Design Cost and Scaling Model" National Renewable Energy Laboratory (NREL), NREL/TP-500-40566. https://www.nrel.gov/docs/fy07osti/40566.pdf.

Foxwell, David. 2018a. "Germany back-tracks on commitment to offshore wind auction." *Offshore Wind Journal.* November 1, 2018. https://www.owjonline.com/news/view,germanybacktracks-on-commitment-to-offshore-wind-auction_55731.htm.

Foxwell, D. 2018b. "20-GW reference gives German offshore wind industry greater cheer." *Offshore Wind Journal*. December 4, 2018. https://www.owjonline.com/news/view,20gw-reference-gives-german-offshore-wind-industry-greater-cheer_56109.htm.

Foxwell, D. 2018c. "Senvion super-turbine could one day be capable of 16MW." *Offshore Wind Journal*. July 23, 2018. https://www.rivieramm.com/news-content-hub/senvion-super-turbine-could-one-day-be-capable-of-16-mw-23945.

Foxwell, D. 2019. "Ørsted awards crew transfer vessel contract for US market." *Offshore Wind Journal*. May 9, 2019. https://www.owjonline.com/news/view,rsted-awards-crew-transfer-vessel-contract-for-us-market_57772.htm.

Froese, M. 2018. "MHI Vestas to supply turbines for WindFloat Atlantic Floating Offshore Wind." *Windpower Engineering & Development*. September 10, 2018. https://www.windpowerengineering.com/business-news-projects/mhi-vestas-to-supply-turbines-for-windfloat-atlantic-floating-offshore-wind/.

Froese, M. 2019a. "Responsible Offshore Science Alliance launches to advance research on fisheries and offshore wind." *Windpower Engineering & Development*. April 9, 2019. https://www.windpowerengineering.com/business-news-projects/responsible-offshore-science-alliance-launches-to-advance-research-on-fisheries-offshore-wind/.

Froese, M. 2019b. "Equinor promotes collaboration between offshore wind and fishing industries." *Windpower Engineering & Development*. February 27, 2019. https://www.windpowerengineering.com/business-news-projects/equinor-promotes-collaboration-between-offshore-wind-and-fishing-industries/.

GE (General Electric). 2018a. "GE announces Haliade-X, the world's most powerful offshore wind turbine." March 1, 2018. Accessed May 2018. https://www.genewsroom.com/press-releases/ge-announces-haliade-x-worlds-most-powerful-offshore-wind-turbine-284260.

GE. 2018b. "Haliade-X Offshore Wind Turbine Platform." Accessed May 2018. https://www.ge.com/renewableenergy/wind-energy/turbines/haliade-x-offshore-turbine.

German Offshore Wind Energy Foundation. 2019. "Expansion of Offshore Wind Energy Successfully Continued in 2018 - Industry Sector Calls for Rapid Increase of Expansion Targets." https://www.offshore-stiftung.de/en/expansion-offshore-wind-energy-successfully-continued-2018-industry-sector-calls-rapid-increase.

Gilman, P., B. Maurer, L. Feinberg, A. Duerr, L. Peterson, W. Musial, P. Beiter, J. Golladay, J. Stromberg, I. Johnson, D. Boren, A. Moore. 2016. *National Offshore Wind Strategy; Facilitating the Development of the Offshore Wind Industry in the United States*. DOE/GO-102016-4866. Washington, D.C.: U.S. Department of Energy Office of Energy Efficiency & Renewable Energy; U.S. Department of the Interior. https://energy.gov/sites/prod/files/2016/09/f33/National-Offshore-Wind-Strategy-report-09082016.pdf.

Graré, V., F. Kühn, F. Küster, A. Schlosser. 2018. "The offshore-wind industry's moment of reckoning." McKinsey & Company. https://www.mckinsey.com/business-functions/sustainability/our-insights/the-offshore-wind-industrys-moment-of-reckoning?reload.

Guillet, Jerome. 2018. "Who will fund U.S. Offshore Wind–and on what terms?" Presented at the Offshore Wind Implementation Summit, Teaneck, New Jersey, September 7. https://green-giraffe.eu/presentations/who-will-fund-us-offshore-wind-%E2%80%93-and-what-terms.

Hill, J. 2018. "How To Typhoon-Proof Offshore Wind Turbines." *CleanTechnica*. October 7, 2018. https://cleantechnica.com/2018/10/07/how-to-typhoon-proof-offshore-wind-turbines.

Hill, J. 2019. "Japanese Offshore Wind To Hit 4 Gigawatts In 2028." *CleanTechnica*. February 19, 2019. https://cleantechnica.com/2019/02/19/japanese-offshore-wind-to-hit-4-gigawatts-in-2028.

House Bill 226: Maryland Offshore Wind Energy Act of 2013. General Assembly of Maryland. Accessed May 2018. http://mgaleg.maryland.gov/2013RS/bills/hb/hb0226E.pdf.

Hundleby, Giles, Kate Freeman, Andy Logan, and Ciaran Frost. 2017. "Floating Offshore: 55 Technology Innovations That Will Have Greater Impact on Reducing the Cost of Electricity from European Floating Offshore Wind Farms." KiC InnoEnergy and BVG Associates. http://www.innoenergy.com/new-floating-offshore-wind-report-55-technology-innovations-that-will-impact-the-lcoe-in-floating-offshore-wind-farms/.

International Electrotechnical Commission (IEC) 2019a. IEC 61400-1 Edition 3, *Wind turbines*—Part 1: *Design requirements.* https://www.iec.ch/dyn/www/f?p=103:23:27965083281002::::FSP_ORG_ID,FSP_LANG_ID:1282,25/.

IEC 2019b. IEC 61400-3 Edition 2, *Wind turbines*—Part 3: *Design requirements for offshore wind turbines.* https://www.iec.ch/dyn/www/f?p=103:23:27965083281002::::FSP_ORG_ID,FSP_LANG_ID:1282,25/.

International Renewable Energy Agency (IRENA). 2018. *Offshore innovation widens renewable energy options: Opportunities, challenges and the vital role of international co-operation to spur the global energy transformation*. Brief to G7 policymakers. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_offshore_wind_brief_G7_2018.pdf.

ISO Newswire. 2019. "An Update on Vineyard Wind's Participation in FCA #13." February 8, 2019. http://isonewswire.com/updates/2019/2/8/an-update-on-vineyard-winds-participation-in-fca-13.html.

Jacobsen, S. 2018. "Offshore wind power firms see Taiwan as a battleground to expand in Asia." Reuters. Accessed April 2018. https://www.reuters.com/article/us-taiwan-windpower/offshore-wind-power-firms-see-taiwan-as-a-battleground-to-expand-in-asia-idUSKBN1I11IV.

JDR. 2019. "JDR Wins Second Offshore Wind Contract For Major Project In Taiwan." http://www.jdrcables.com/jdr-wins-second-offshore-wind-contract-for-major-project-in-taiwan/.

Kempton, W., S. McClellan, and D. Ozkan. 2016. *Massachusetts Offshore Wind Future Cost Study*. Technical Report. Special Initiative on Offshore Wind. University of Delaware. https://www.ceoe.udel.edu/File%20Library/About/SIOW/MA-Offshore-Wind-Future-Cost-Study-rev-4-April-16.pdf.

Krueger, A. D., G. R. Parsons, and J. Firestone. 2011. *Valuing the Visual Disamenity of Offshore Wind Projects at Varying Distances from the Shore*. University of Delaware, Land Economics. 87 (2): 268–283, ISSN 0023-7639; E-ISSN 1543-8325. https://works.bepress.com/george_parsons/7/.

Lazard. 2018. "Levelized Cost of Energy Analysis, Version 12.0." https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf.

Lefevre-Marton, N., Saharia, R, Sellschop, R., and Tai, H. 2019. "Scaling the US East Coast offshore wind industry to 20 gigawatts and beyond." April 2019. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/scaling-the-us-east-coast-offshore-wind-industry-to-20-gigawatts-and-beyond?reload.

Lillian, B. 2019. "Equinor Wind US Joins Effort To Protect Whales in New York Bight." *North American Wind Power*. April 9, 2019. https://nawindpower.com/equinor-wind-us-joins-effort-to-protect-whales-in-new-york-bight.

Linklaters LLP. 2019. "Korea Offshore Wind: Looking Ahead." Lexology. January 7, 2019. https://www.lexology.com/library/detail.aspx?g=32b9bb3f-1e68-4967-9b08-e71160308bdd.

Maness, Michael, Ben Maples, and Aaron Smith. 2017. *NREL Offshore Balance-of-System Model* (Technical Report). National Renewable Energy Laboratory (NREL), Golden, CO. NREL/TP-6A20-66874. https://www.nrel.gov/docs/fy17osti/66874.pdf.

Market Research Consulting. 2018. *Submarine Power Cable – Global Market Outlook (2017-2026)*. https://www.researchandmarkets.com/reports/4592698/submarine-power-cable-global-market-outlook.

Maryland General Assembly. 2019. Senate Bill 516. May 25, 2019. http://mgaleg.maryland.gov/2019RS/bills/sb/sb0516e.pdf.

Massachusetts Department of Energy Resources. 2019a. *Request for Proposals For Long-Term Contracts for Offshore Wind Energy Projects*. May 23, 2019. https://macleanenergy.files.wordpress.com/2019/05/83c-ii-rfp_finalpackage.pdf.

Massachusetts Department of Energy Resources. 2019b. *Offshore Wind Study*. May 31, 2019. https://www.mass.gov/files/documents/2019/05/31/OSW%20Study%20-%20Final.pdf.

Massachusetts Department of Public Utilities. 2018a. "Offshore Wind Generation Unit Power Purchase Agreement Between NSTAR Electric Company d/b/a Eversource Energy and Vineyard Wind LLC (Facility 1)." July 31, 2018. Redacted. Exhibit JU-3-A. https://eeaonline.eea.state.ma.us/EEA/FileService/FileService.Api/file/FileRoom/9676522.

Massachusetts Department of Public Utilities. 2018b. "Offshore Wind Generation Unit Power Purchase Agreement Between NSTAR Electric Company d/b/a Eversource Energy and Vineyard Wind LLC (Facility 2)." July 31, 2018. Redacted. Exhibit JU-3-B. https://eeaonline.eea.state.ma.us/EEA/FileService/FileService.Api/file/FileRoom/9676523.

Mass Live. 2018. "Vineyard Wind signs $9 million lease at New Bedford Commerce Pier." October 23, 2018. https://www.masslive.com/news/2018/10/vineyard_wind_signs_9_million.html.

McClellan. 2019. "Supply Chain Contracting Forecast for U.S. Offshore Wind Power," Special Initiative on Offshore Wind White Paper. Accessed July 2019. https://www.ceoe.udel.edu/File%20Library/About/SIOW/SIOW-White-Paper---Supply-Chain-Contracting-Forecast-for-US-Offshore-Wind-Power-FINAL.pdf.

MHI Vestas. 2018. "Vineyard Wind Selects MHI Vestas as Preferred Supplier for First Large-scale Offshore Wind Project in the United States." November 27, 2018. http://www.mhivestasoffshore.com/vineyard-wind-selects-mhi-vestas-as-preferred-supplier/.

Mills, J. 2019. "An Order Concluding the Maine Wind Advisory Commission and Wind Permit Moratorium." Office of the Governor. February 14, 2019. https://www.maine.gov/governor/mills/sites/maine.gov.governor.mills/files/inline-files/EO%20Wind.pdf.

Musial, W., Z. Parker, J. Fields, G. Scott, and C. Draxl. 2013. *Assessment of Offshore Wind Energy Leasing Areas for the BOEM Massachusetts Wind Energy Area* (Technical Report). National Renewable Energy Laboratory (NREL), Golden, CO. NREL/TP-5000-60942. http://www.nrel.gov/docs/fy14osti/60942.pdf.

Musial, W., D. Heimiller, P. Beiter, G. Scott, and C. Draxl. 2016. *2016 Offshore Wind Energy Resource Assessment for the United States* (Technical Report). National Renewable Energy Laboratory (NREL), Golden, CO. NREL/TP-5000-66599. http://www.nrel.gov/docs/fy16osti/66599.pdf.

Musial, W., P. Beiter, P. Schwabe, T. Tian, T. Stehly, P. Spitsen. 2017. *2016 Offshore Wind Technologies Market Report* (Technical Report). Washington, D.C.: U.S. Department of Energy Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/sites/prod/files/2017/08/f35/2016%20Offshore%20Wind%20Technologies%20Market%20Report.pdf.

New Jersey Board of Public Utilities. 2018. Docket No. Q018080843. December 18, 2018. https://www.bpu.state.nj.us/bpu/pdf/boardorders/2018/20181218/12-18-18-8H.pdf.

New Jersey Board of Public Utilities. 2019. *2019 Annual Report on New Jersey Offshore Wind and the Implementation of Executive Order No. 8*. NJ BPU. January 31, 2019. https://www.bpu.state.nj.us/bpu/pdf/publicnotice/2019%20ANNUAL%20EO8%20REPORT%2002082019%20FNL%20V2.pdf.

New Jersey State Legislature. 2018. "A3723." May 23, 2018. Accessed May 2018. http://www.njleg.state.nj.us/bills/BillView.asp?BillNumber=A3723.

New York State. 2019a. "2019 State of the State Budget Address." New York State Governor Andrew M. Cuomo. https://www.ny.gov/programs/2019-state-state-budget-address.

New York State. 2019b. *Climate Leadership and Community Protection Act*. June 18, 2019. https://www.nysenate.gov/legislation/bills/2019/s6599.

New York State Energy Research and Development Authority (NYSERDA). 2019. "National Offshore Wind R&D Consortium Research Solicitation (PON 4124)." https://portal.nyserda.ny.gov/CORE_Solicitation_Detail_Page?SolicitationId=a0rt000000beASkAAM.

Nexans. 2018. "Cable supplies for the world's first 66 KV offshore windfarms." September 2018. https://www.nexans.com/newsroom/news/details/2018/09/Supply-of-cables-for-the-first-66kv-offshore-windfarms.html.

National Oceanic and Atmospheric Administration (NOAA). 2019a. "Northeast Regional Ocean Council Data Portal." https://www.northeastoceancouncil.org/quick-links/.

NOAA. 2019b. "Mid-Atlantic Ocean Data Portal." http://portal.midatlanticocean.org/about-us/.

offshoreWIND.biz. 2018a. "Shell, EDF Acquire US Wind's New Jersey Lease Area." December 20, 2018. https://www.offshorewind.biz/2018/12/20/shell-edf-acquire-us-winds-new-jersey-lease-area/

offshoreWIND.biz. 2018b. "Poland Sets 8GW by 2035 Offshore Wind Goal." November 8, 2018. https://www.offshorewind.biz/2018/11/08/poland-sets-8gw-by-2035-offshore-wind-goal/.

ORE Catapult. 2015. "Cost Reduction Monitoring Framework: Summary Report to the Offshore Wind Programme Board." ORE Catapult and The Crown Estate.

https://ore.catapult.org.uk/app/uploads/2018/02/Cost-Reduction-Monitoring-Framework-2015.-Summary-report-to-the-OWPB.pdf.

ORE Catapult. 2018. "Macroeconomic Benefits of Floating Offshore Wind in the UK." Glasgow, UK: Crown Estate Scotland. https://www.crownestatescotland.com/maps-and-publications/download/219.

Orrell, A., N. Foster, S. Morris, J. Homer, D. Preziuso, R. Poehlman. 2019. *2018 Distributed Wind Market Report* (Technical Report). Washington, D.C.: U.S. Department of Energy Office of Energy Efficiency & Renewable Energy. https://energy.gov/eere/wind/downloads/2018-distributed-wind-market-report

Ørsted. 2018. "Ørsted acquires Deepwater Wind and creates leading US offshore wind platform." Ørsted Press Release. August 10, 2018. https://orsted.com/en/Company-Announcement-List/2018/10/1819975.
Ørsted. 2019. "TEPCO and Ørsted sign MOU to work jointly on offshore wind projects."

Ørsted Press Release. January 18, 2019. https://orsted.com/en/Media/Newsroom/News/2019/01/TEPCO-and-Orsted-sign-MoU-to-work-jointly-on-offshore-wind-projects.

Peregrine Energy. 2018. "Independent Evaluator Report: On the Solicitation, Evaluation, and Bid Process Under Section 83C of the Green Communities Act." Accessed September 2018. https://eeaonline.eea.state.ma.us/EEA/FileService/FileService.Api/file/FileRoom/9685211.

Power Engineering. 2005. "REpower 5 MW turbines to power Borkum West offshore wind park." September 7, 2005. https://www.power-eng.com/articles/2005/09/repower-5-mw-turbines-to-power-borkum-west-offshore-wind-park.html.

Power Technology. 2018. "Formosa 1 Offshore Wind Farm." https://www.power-technology.com/projects/formosa-1-offshore-wind-farm/.

Quest Floating Wind Energy. 2019. "What Will Float in South Korea's Newly Announced Project." March 5, 2019. https://questfwe.com/what-will-float-in-south-koreas-newly-announced-project/.

Ragheb, M. 2019. *Modern Wind Generators*. http://mragheb.com/NPRE%20475%20Wind%20Power%20Systems/Modern%20Wind%20Generators.pdf.

Recharge News. 2018. "Chinese wind power faces switch to competition from 2019." *Recharge News*. June 5, 2018. https://www.rechargenews.com/wind/1504927/chinese-wind-power-faces-switch-to-competition-from-2019.

Renewables Now. 2018. "Vineyard Wind Faces Rhode Island Permitting Setback." November 22, 2018. https://renewablesnow.com/news/vineyard-wind-faces-rhode-island-permitting-setback-report-634128/.

Reuters. 2018. "France cuts tariffs on controversial offshore wind projects." Reuters. June 20, 2018. https://www.reuters.com/article/us-france-windpower-offshore/france-cuts-tariffs-on-controversial-offshore-wind-projects-idUSKBN1JG1N8.

Rhode Island Coastal Resources Management Council. 2019. "Agreements to Establish RI Fishermen's Future Viability Trust." February 21, 2019. http://www.crmc.ri.gov/windenergy/vineyardwind.html.

Richard, C. 2019. "MHI Vestas in line to supply first V174 turbines." *Windpower Offshore*. February 2019. https://www.windpoweroffshore.com/article/1525372/mhi-vestas-line-supply-first-v174-turbines.

Saltzberg, R, and B. Dowd. 2019. "RODA and Ørsted Strengthen Dialogue." *Martha's Vineyard Times*. January 18, 2019. https://www.mvtimes.com/2019/01/18/roda-orsted-strengthen-dialogue/.

Siemens. 2013. *Fact Sheet: The new SWT-6.0; The next-generation offshore wind turbine. Status: February 2013*. https://www.siemens.com/press/pool/de/feature/2013/energy/2013-01-rotorblade/factsheet-6mw-e.pdf.

Siemens. 2019. "Siemens Gamesa launches 10 MW offshore wind turbine; annual energy production (AEP) increase of 30% vs. predecessor." https://www.siemensgamesa.com/en-int/newsroom/2019/01/new-siemens-gamesa-10-mw-offshore-wind-turbine-sg-10-0-193-dd.

Skopljak, N. 2019a. "Vineyard Wind Commits to Whale Protection." January 24, 2019. https://www.offshorewind.biz/2019/01/24/vineyard-wind-commits-whale-protection/.

Skopljak N. 2019b. "Vineyard Wind Seeks Whale Protection Tech." May 22, 2019. https://www.offshorewind.biz/2019/05/22/vineyard-wind-seeks-whale-protection-tech/.

Skopljak, N. 2019c. "Spain's First Offshore Wind Turbine Goes Into Operation" March 18, 2019. https://www.offshorewind.biz/2019/03/18/spains-first-offshore-wind-turbine-goes-operation.

Smith, Stehly, and Musial. 2015. *2014-2015 Offshore Wind Technologies Market Report* (Technical Report). National Renewable Energy Laboratory (NREL), Golden, CO. NREL/TP-5000-64283. https://www.nrel.gov/docs/fy15osti/64283.pdf.

Snieckus. 2018. "Senvion offshore turbine will be 12MW+ model." *Recharge News*. June 19, 2018. https://www.rechargenews.com/wind/1515084/senvion-offshore-turbine-will-be-12mw+-model.

Stehly, T., D. Heimiller, G. Scott. 2017. *2016 Cost of Wind Energy Review* (Technical Report). National Renewable Energy Laboratory (NREL). Golden, CO. NREL/TP-6A20-70363. Accessed May 2018. https://www.nrel.gov/docs/fy18osti/70363.pdf.

Stehly, T., P. Beiter, D. Heimiller, G. Scott. 2018. *2017 Cost of Wind Energy Review* (Technical Report). National Renewable Energy Laboratory (NREL). Golden, CO. NREL/TP-6A20-72167. https://www.nrel.gov/docs/fy18osti/72167.pdf.

Sununu, C.T. 2019. "BOEM Renewable Energy Task Force for New Hampshire." Office of the Governor. January 2, 2019. https://www.governor.nh.gov/news-media/press-2019/documents/20190107-boem-offshore.pdf.

T&D World. 2019. "Prysmian to Develop Submarine Cable System for Floating Offshore Wind Farm." March 20, 2019. https://www.tdworld.com/renewables/prysmian-develop-submarine-cable-system-floating-offshore-wind-farm.

University of Delaware. 2016. "Massachusetts Offshore Wind Future Cost Study." March 2016. https://www.ceoe.udel.edu/File%20Library/About/SIOW/MA-Offshore-Wind-Future-Cost-Study-FINAL-14-Mar-16.pdf.

University of Delaware's Special Initiative for Offshore Wind. 2019. *Supply Chain Contracting Forecast for U.S. Offshore Wind Power*. March 2019. https://www.ceoe.udel.edu/File%20Library/About/SIOW/SIOW-White-Paper---Supply-Chain-Contracting-Forecast-for-US-Offshore-Wind-Power-FINAL.pdf.

United States Department of Labor Bureau of Statistics. 2019. "Overview of BLS Statistics on Inflation and Prices." https://www.bls.gov/bls/inflation.htm.

United States Treasury Bureau of Fiscal Service. 2019. "Treasury Reporting Rates of Exchange." https://www.fiscal.treasury.gov/reports-statements/treaury-reporting-rates-exchange/current.html.

Valpy, B. G. Hundleby, K. Freeman, A. Roberts, A. Logan. 2017. *Future renewable energy costs: Offshore wind; 57 technology innovations that will have greater impact on reducing the cost of electricity from European offshore wind farms*. InnoEnergy and BVG Associates. http://www.innoenergy.com/wp-content/uploads/2014/09/InnoEnergy-Offshore-Wind-anticipated-innovations-impact-2017_A4.pdf.

Vineyard Wind LLC. 2018a. *Vineyard Wind Offshore Wind Energy Project: Draft Environmental Impact Statement* (EEA#15787). https://www.boem.gov/Vineyard-Wind-EIS/.

Vineyard Wind. 2018b. "Plugging into a new industry." April 1, 2018. Accessed May 2018. https://www.vineyardwind.com/in-the-news/2018/4/1/plugging-into-a-new-industry.

Vineyard Wind. 2018c. "Project Update: Vineyard Wind Submits Supplemental Draft Environmental Impact Report for Additional Public Comment." September 4, 2018. https://www.vineyardwind.com/news-and-updates/2018/9/4/project-update-vineyard-wind-submits-supplemental-draft-environmental-impact-report-sdeir-for-additional-public-comment.

Vineyard Wind. 2018d. "Project Update: Vineyard Wind Submits Supplemental Draft Environmental Impact Report for Additional Public Comment." September 4, 2018. https://www.vineyardwind.com/news-and-updates/2018/9/4/project-update-vineyard-wind-submits-supplemental-draft-environmental-impact-report-sdeir-for-additional-public-comment.

de Vries, E. 2019. "Haliade-X Uncovered: GE Aims for 14MW." WindPower Offshore, March 4, 2019. https://www.windpoweroffshore.com/article/1577816/haliade-x-uncovered-ge-aims-14mw.

Walton, R. 2018. "FERC advances transmission line to serve Massachusetts' offshore wind industry." Utility Dive. Accessed May 2018. https://www.utilitydive.com/news/ferc-advances-transmission-line-to-serve-massachusetts-offshore-wind-indus/517125/.

Weston, D. 2019. "Steisdal's TetraSpar demo gets go-ahead." *Wind Power Offshore*. February 13, 2019. https://www.windpoweroffshore.com/article/1525677/stiesdals-tetraspar-demo-gets-go-ahead.

WindEurope. 2018. *Floating Offshore Wind Energy; A Policy Blueprint for Europe*. https://windeurope.org/wp-content/uploads/files/policy/position-papers/Floating-offshore-wind-energy-a-policy-blueprint-for-Europe.pdf.

WindEurope. 2019. *Offshore Wind in Europe: Key trends and statistics 2018*. February 2019. https://windeurope.org/about-wind/statistics/offshore/european-offshore-wind-industry-key-trends-statistics-2018/.

Windpower Monthly. 2018. "Who will pay for 15MW turbine?" March 2018. https://www.windpowermonthly.com/article/1457880/will-pay-15mw-turbine.

WireTech. 2019. "JDR selected as preferred cable supplier for Windfloat Atlantic project." http://www.wiretechworld.com/jdr-selected-as-preferred-cable-supplier-for-windfloat-atlantic-project/.

Wiser, R. M. Bolinger, G. Barbose, N. Darghouth, B. Hoen, A. Mills, J. Rand, D. Millsteing, K. Porter, K. Fisher, N. Disanti, F. Oteri. *2018 Wind Technologies Market Report*. Lawrence Berkeley National Laboratory. https://www.energy.gov/eere/wind/downloads/2018-wind-technologies-market-report

Wiser, R., K. Jenni, J. Seel, E. Baker, M. Hand, E. Lantz, A. Smith. 2016. *Forecasting Wind Energy Costs & Cost Drivers. The Views of the World's Leading Experts*. LBNL-1005717. Lawrence Berkeley National Laboratory. http://eta-publications.lbl.gov/sites/default/files/lbnl-1005717.pdf.

Wiser, Ryan, and Mark Bolinger. 2018. "2017 Wind Technologies Market Report." DOE/EE-1798. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. https://emp.lbl.gov/sites/default/files/2017_wind_technologies_market_report.pdf.

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

2018 **Offshore Wind Technologies Market Report**

For more information visit,
energy.gov/eere/wind

DOE/GO-102019-5192 • August 2019

Front cover photo from
Dennis Schroeder, NREL
Back cover photo from
Walt Musial, NREL

Oregon Offshore Wind Site Feasibility and Cost Study

Walter Musial,[1] Philipp Beiter,[1] Jake Nunemaker,[1] Donna Heimiller,[1] Josh Ahmann,[2] and Jason Busch[3]

1 National Renewable Energy Laboratory
2 Parametrix
3 Pacific Ocean Energy Trust

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5000-74597
October 2019

Oregon Offshore Wind Site Feasibility and Cost Study

Walter Musial,[1] Philipp Beiter,[1] Jake Nunemaker,[1]
Donna Heimiller,[1] Josh Ahmann,[2] and Jason Busch[3]

1 National Renewable Energy Laboratory
2 Parametrix
3 Pacific Ocean Energy Trust

This report is available from the Bureau of Ocean Energy Management by referencing OCS Study BOEM 2019-046.

Suggested Citation
Musial, Walter, Philipp Beiter, Jake Nunemaker, Donna Heimiller, Josh Ahmann, and Jason Busch. 2019. *Oregon Offshore Wind Site Feasibility and Cost Study*. NREL/TP-5000-74597. nrel.gov/docs/fy20osti/74597.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5000-74597
October 2019

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of the Interior, Bureau of Ocean Energy Management. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Acknowledgments

This study was funded by the U.S. Department of the Interior, Bureau of Ocean Energy Management Pacific Region, through interagency agreement number M14PG00038 modification 007 with the U.S. Department of Energy National Renewable Energy Laboratory (NREL). The authors would like to thank the many people who contributed to the content of this report including the Bureau of Ocean Energy Management staff: Sara Guiltinan, Necy Sumait, Doug Boren, Joan Barminski, and Whitney Hauer, as well as other bureau team members for their thoughtful reviews, comments, and suggestions.

We also want to thank the NREL contributors including Tiffany Byrne, who coordinated the project schedule and deliverables at NREL, and Donna Heimiller, Caroline Draxl, and Mike Optis, for their contributions to the content of the maps, analysis, and expert consultation in writing this report. Technical editing was provided by Sheri Anstedt. Any errors or omissions are the sole responsibility of the authors.

Principle Power, Inc. was instrumental in supporting the cost analysis for this study and cooperating with NREL to assess the cost impact of project size. Specifically, the authors would like to thank Aaron Smith, Kevin Banister, and Loris Canizares for their individual contributions.

In addition, the authors would especially like to recognize the technical advisory committee for this project, which was led by Jason Busch of the Pacific Ocean Energy Trust. These advisors also provided extensive support in the peer review of this document. The advisory committee members include:

- Jason Busch–Pacific Ocean Energy Trust (committee chair)
- Adam Schultz–Oregon Department of Energy
- Andy Lanier–Department of Land Conservation and Development
- Bryson Robertson–Pacific Marine Energy Center, Oregon State University
- Crystal Ball–Bonneville Power Administration
- John Schaad–Bonneville Power Administration
- Jimmy Lindsay–Portland General Electric
- Mike Starrett–Northwest Power and Conservation Council
- Rebecca O'Neil–Pacific Northwest National Laboratory.

In particular, the contributions of John Schaad with the Bonneville Power Administration and Mike Starrett of the Northwest Power and Conservation Council were invaluable in helping us connect the wind resources with the power use patterns of the Oregon region.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

List of Acronyms

AEP	annual energy production
BOEM	Bureau of Ocean Energy Management
BPA	Bonneville Power Administration
CapEx	capital expenditures
COD	commercial operation date
DC	direct current
DOE	U.S. Department of Energy
DTU	Technical University of Denmark
FCR	fixed charge rate
GIS	geographic information system
GW	gigawatt
GWh	gigawatt-hour
km	kilometer
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelized cost of energy
m	meter
MW	megawatt
MWh	megawatt-hour
nm	nautical miles
NCF	net capacity factor
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
OCS	Outer Continental Shelf
O&M	operation and maintenance
OpEx	operational expenditures
ORCA	Offshore Regional Cost Analyzer
POET	Pacific Ocean Energy Trust
TWh	terawatt-hour

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Executive Summary

To accomplish any significant deployment in the Pacific region, and specifically in Oregon, floating wind energy technologies will be required. These technologies are needed because 97% of the 62 gigawatts of available technical offshore wind energy resource in Oregon is in water depths greater than 60 meters (m). Although floating offshore wind energy technology is still in a nascent stage of development, it is advancing toward commercialization in both Europe and Asia.[1]

The objectives of this study are to:

- Provide the Bureau of Ocean Energy Management (BOEM) and the state of Oregon with cost data based on geospatial site-specific data to allow for consideration of floating offshore wind in the state's future energy portfolio
- Inform Oregon's long-term energy planning activities, which could determine how offshore wind might contribute to future energy supplies.

In this study, we draw from the following data sources:

- Proprietary industry data on floating component costs and pilot-scale costs
- Commercial auction price points and costs from fixed-bottom offshore wind projects
- Published literature and press information
- Oregon geospatial data from resource and regulatory management agencies
- Semi-structured interviews with subject matter experts
- Cost modeling tools at the National Renewable Energy Laboratory (NREL)
- Other offshore wind industry data sources (e.g., Hundleby et al. 2017)
- Geographical and wind resource databases such as NREL's Wind Integration National Dataset (WIND) Toolkit, which includes mesoscale meteorological data covering much of North America
- Utility-supplied (Bonneville Power Administration [BPA]) transmission and energy use information
- Previous studies performed by NREL for BOEM (e.g., Musial et al. 2016a).

The work performed in the study focused on assessing the present and future costs of floating offshore wind technology deployment in the state of Oregon at commercial scale. The study was performed by NREL and its subcontractors and was funded by BOEM. The study builds off a previous report published by NREL in December 2016, titled "Potential Offshore Wind Energy Areas in California: An Assessment of Locations, Technology, and Costs" (Musial et al. 2016a)— also funded by BOEM—which estimated LCOE for floating offshore wind in California at \$100/megawatt-hour (MWh)[2] or less by the year 2030.

Since 2016, when the California cost study was conducted, the technologies for both fixed-bottom and floating offshore wind have progressed at a rapid rate, technologically and

[1] The first multiturbine commercial floating wind project was commissioned in Scotland in 2017 by Equinor.
[2] All cost estimates in this report are denoted in \$2018, unless indicated otherwise.

economically. Based on this progress, several new elements that were not available for the California study are included in this Oregon study. Some of these new considerations include:

- Recent European strike price data, which show a decline of about 65%, relative to 2017, for projects expected to be commissioned by 2025 (Beiter et al. 2017)
- New U.S. price data as well as analysis of the executed Vineyard Wind power purchase agreement, a planned fixed-bottom project in Massachusetts (Beiter et al. 2019)
- Lower finance costs derived from recent data indicating more favorable terms with higher debt shares (Green Giraffe 2016)
- Updates to the NREL Offshore Regional Cost Analyzer (ORCA) model, which provide a longer modeled time horizon through 2032 (previously 2027, extrapolating to 2030)
- Larger turbine power capacity, up to 15 megawatts (MW) within the modeling time horizon of 2032 (General Electric 2018; Hundleby et al. 2017)
- Lower turbine costs per kilowatt (kW); adjusted to reflect current market data and machine growth
- Lower unit costs for floating platforms, in part due to scaling to larger platform sizes, and further systemwide cost reductions due to lower anticipated labor at sea and commissioning time requirements (Villaespesa et al. 2015; Melis et al. 2016).

Pacific Ocean Energy Trust (POET), under subcontract with NREL, convened an advisory committee to help ensure that the study assumptions were sound, that it addressed the key questions reflecting the interests of Oregon, and provided a peer review of the study report. The advisory committee was made up of energy system and development experts in Oregon, including the Oregon Department of Energy and Department of Land Conservation & Development, Northwest Power and Conservation Council, BPA, Portland General Electric, Pacific Marine Energy Center, and Pacific Northwest National Laboratory.

A study site selection team comprising POET and POET's graphical information system subcontractor, Parametrix, defined five study sites that are geographically dispersed offshore Oregon where commercial-scale offshore wind projects are technically viable. NREL and BOEM provided guidance to the study site selection team on technical criteria and minimum site size for commercial-scale viability. The selected study sites were reviewed by the advisory committee. It is important to note that the study site selection process was conducted to model potential cost. This study was not a stakeholder engagement or a marine spatial planning effort to create wind energy areas under BOEM's leasing process and the hypothetical sites have not been vetted by ocean user communities. Any actual wind energy planning effort on the Outer Continental Shelf would require comprehensive stakeholder engagement and analysis of all relevant data for siting.

Figure ES-1 shows an offshore wind speed map of Oregon with the five selected study sites. The sites reflect the physical differences in wind speed; in particular, a strong north-south gradient.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

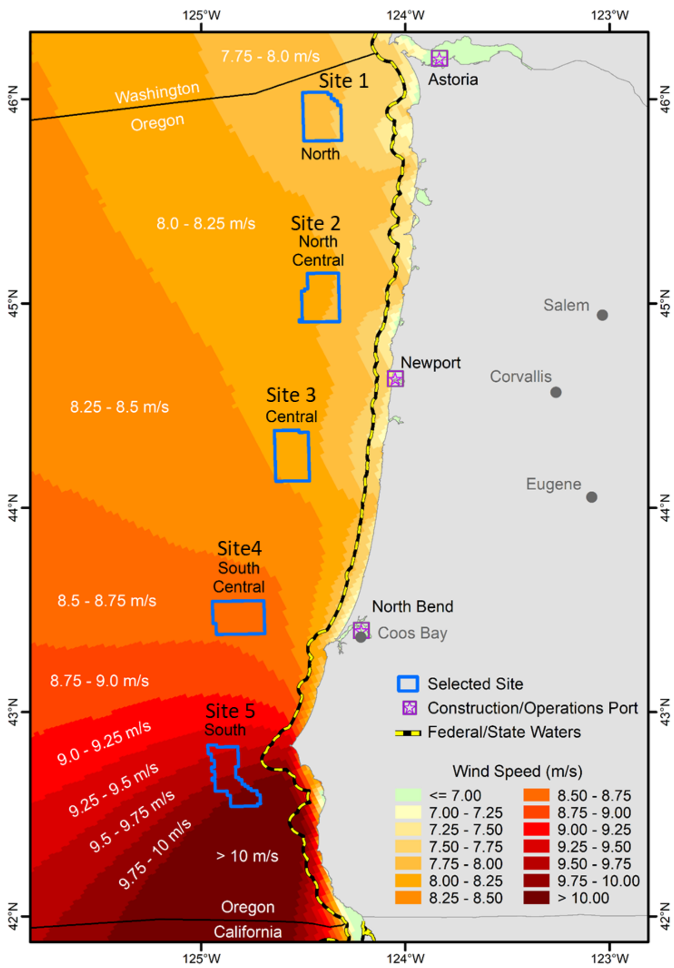


Figure ES-1. Average offshore wind speed map for Oregon at a 100-m elevation for five study sites from NREL's WIND Toolkit database

Table ES-1 shows the turbine technology assumptions for the expected available commercial technology in four reference years: 2019, 2022, 2027, and 2032. Technology assumptions are based on industry trends ascertained by following the rapidly changing technology advancements and through discussions with experts in the industry. Generally, we assume that the technology specified will be available for commercial development 2 years prior to the reference year.

Table ES-1. Technology Assumptions for Oregon Offshore Wind Cost Analysis

Commercial Operation Date	2019	2022	2027	2032
Turbine Rated Power (MW)	6	10	12	15
Turbine Rotor Diameter (m)	155	178	222	248
Turbine Hub Height (m)	100	114	136	149
Turbine Specific Power (Watts/m^2)	318	401	310	311
Substructure Technology	Semisubmersible	Semisubmersible	Semisubmersible	Semisubmersible

Note that technology assumptions for this study from Table ES-1 are based on semisubmersible substructures, but other substructure technology types could be applicable and competitive over

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

our time frame.[3] As the market matures, the design that can deliver an optimal balance between costs, risk, and value will be favored.

Power curves that represent each reference year's turbine technology were created by NREL using turbine design tools. Turbine growth was estimated from literature research and tracking industry progress. A key assumption is that 15-MW turbines will be available by 2030—the year when projects commissioned in 2032 will achieve financial closure.

Gross annual energy production for each of the five sites was calculated using 7 years of wind speed data (2007–2013) from the WIND Toolkit created by NREL. We applied wake losses, electrical losses, downtime, and other losses for all five sites to obtain net capacity factors for each reference year.

NREL analyzed floating offshore wind costs at each of the five sites using an upgraded version of the ORCA model assuming a 600-MW wind power plant[4] is built at each location.

The modeling results estimate that levelized cost of energy (LCOE) range from $74 MWh to $53/MWh in Oregon for floating wind technology in 2032. These results are based on assessments for all five sites using a conceptual NREL-designed 15-MW wind turbine in a 600-MW array. These costs reflect lower LCOE than the previous California study conducted by NREL for BOEM because of new industry data and modeling assumptions that support reduced capital expenditures and operational expenditures. The wide range in data reflect the range of wind speeds between the north and the south sites. Figure ES-2 shows these LCOE data plotted for all five sites and for all 4 years, along with their corresponding exponential curves fit to the data. Table ES-2 shows the LCOE data used to make these plots along with data for the corresponding capital expenses, operational expenses, and net capacity factors for each curve.

[3] The pipeline for floating wind systems shows that 94% of proposed floating projects are using semisubmersibles. Therefore, we chose semisubmersibles as the substructure to be modeled in the Oregon cost analysis.

[4] A wind power plant size of 600 MW was assumed to represent a commercial-scale project and because the modeling relationships in ORCA are calibrated for this plant size. Note that while some U.S. projects are planned for smaller project sizes (e.g., US Wind [248 MW] and Skipjack [120 MW]), several recent projects planned for commercial operation in the mid-2020s exceed a project size of 600 MW (e.g., Vineyard Wind [800 MW] and Ocean Wind [1,100 MW]) (Musial et al. 2019).

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

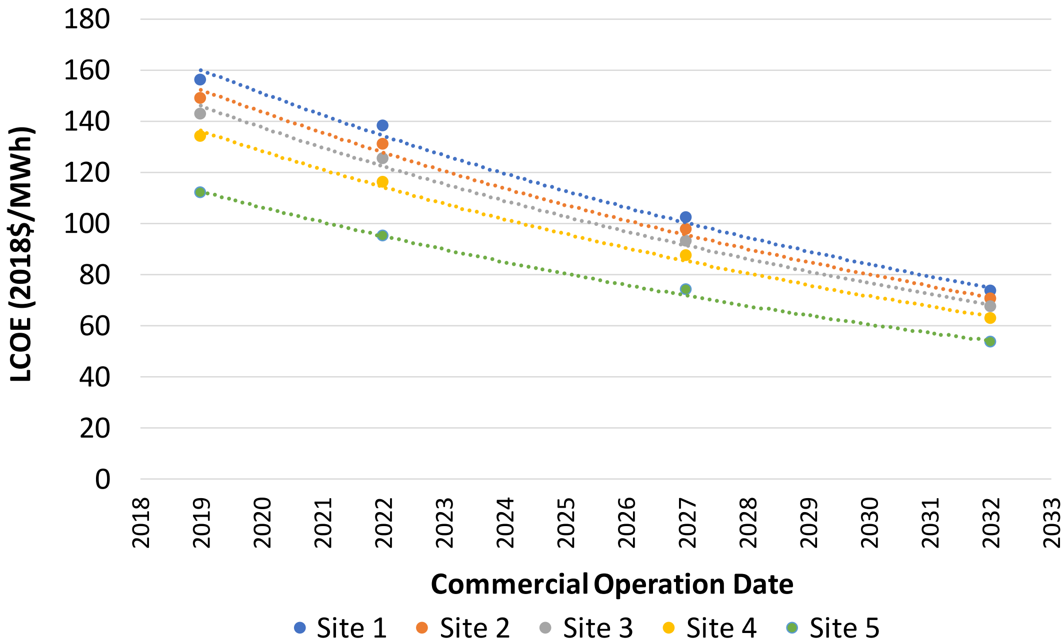


Figure ES-2. Cost trajectories for five Oregon floating offshore wind study sites

Table ES-2. Data for Oregon Cost Analysis in $2018

LCOE ($/MWh)					
Commercial Operation Date (COD)	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**
2019	156	149	143	134	112
2022	138	131	125	116	95
2027	102	97	93	87	74
2032	74	70	67	63	53
Capital Expenditures ($/kW)					
COD	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**
2019	5,180	5,177	5,213	5,229	5,150
2022	4,388	4,383	4,424	4,437	4,358
2027	3,797	3,792	3,833	3,836	3,769
2032	2,901	2,897	2,936	2,924	2,877
Operational Expenditures ($/kW/year)					
COD	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**
2019	126	126	125	128	132
2022	89	89	89	90	93
2027	74	74	74	75	78
2032	52	52	52	52	54
Net Capacity Factor (%)					
COD	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**
2019	36%	38%	40%	43%	51%
2022	36%	38%	40%	43%	52%
2027	38%	40%	42%	46%	53%
2032	40%	42%	44%	47%	55%

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Another part of the study was to investigate the cost variations between a pilot-scale and commercial-scale project. In 2014, Principle Power proposed a 24-MW project (WindFloat Pacific) near Coos Bay, Oregon, funded by DOE's advanced wind energy technology demonstration program. NREL compared the cost of this project to a hypothetical 600-MW commercial-scale project located at the same site (Site 4 off Coos Bay, Oregon). The cost of this project was deemed too high by utility officials, citing costs that were over three times the amount for an equivalent land-based wind project (Davis 2015). Although the unit costs were high, at the time the high cost was seen as a reflection of how expensive offshore wind was in general, rather than considering the high cost of developing and installing a smaller-scale (24-MW) project.

The LCOE comparison showed a cost approximately three times higher for the 24-MW pilot scale project than a 600-MW commercial-scale project. This cost difference reflects technology improvements assumed to be realized since the WindFloat Pacific was originally proposed, such as larger turbines that are assumed to be available in a decade, but mostly reflects the capital and operation cost economies of scale that allow fixed-cost items to be spread over the entire project cost. The LCOE for the pilot-scale project was calculated to be $197/MWh, whereas the LCOE of the commercial-scale project was $63/MWh. The Principle Power WindFloat prototype is shown in Figure ES-3, as it is being towed to its station in Portugal.

Figure ES-3. Principle Power semisubmersible with mounted turbine. *Photo courtesy of Principle Power, Inc.*

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Table of Contents

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

List of Figures

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

List of Tables

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

1. Introduction

The work performed in this study assessed the present and future costs of floating offshore wind technology deployment in the state of Oregon at commercial scale. It is widely recognized that floating offshore wind energy technology will be necessary to enable significant offshore wind deployment in the Pacific region. The study was performed by the National Renewable Energy Laboratory (NREL) and its subcontractors and funded by the Bureau of Ocean Energy Management (BOEM). It was based, in part, on assumptions and analysis from an NREL report titled "A Spatial-Economic Cost-Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030" (Beiter et al. 2016), which supported the "National Offshore Wind Strategy" (Gilman et al. 2016). The strategy builds on the previous DOE Wind Vision Study Scenario of 86 gigawatts (GW) of offshore wind deployed by 2050 in the United States. Under the Wind Vision scenario, 20% (17.2 GW installed capacity) of the nation's total offshore wind in 2050 comes from the Pacific coastal states (DOE 2015), which will require the development of floating wind technologies. Although most offshore development to date has been in depths of 50 meters (m) or less, 97% of Oregon's offshore wind resource is in water depths greater than 60 m, where floating wind is assumed to be more economically attractive. Floating offshore wind technology is still in its nascent stage of development but is advancing toward commercialization in both Europe and Asia.[5]

In this report, we use available floating prototype costs, pilot-scale costs, and commercial-scale costs from fixed-bottom offshore wind projects to model and analyze the cost of floating wind for five hypothetical wind sites in Oregon using specific geographical and utility grid information.

In December 2016, NREL published a report, titled "Potential Offshore Wind Energy Areas in California: An Assessment of Locations, Technology, and Costs" (Musial et al. 2016a) funded by BOEM. This report estimated that future cost reductions could enable levelized cost of energy (LCOE) levels for floating offshore wind in California at \$100/megawatt-hours (MWh)[6] or less by the year 2030. However, the Musial et al. (2016a) analysis (hereafter referred to as the "California study") was performed with a higher degree of uncertainty because fewer floating turbines had been deployed globally and the most recent price data from European offshore wind projects were not known. Recent winning auction strike prices[7] in Europe indicate tender price declines of up to 65% for fixed-bottom projects with commercial operation in the 2025 timeframe compared to those in 2017. These cost declines in Europe and advancements in floating wind technology provide new data that can help validate and advance current floating offshore wind cost models. For this Oregon cost study, the impacts of the recent European offshore wind auction prices on U.S. fixed-bottom projects, and the degree to which fixed-bottom technology cost reductions may transfer/apply to floating offshore wind technology, were

[5] The first multiturbine commercial-scale project was commissioned in Scotland in 2017 by Equinor.
[6] All cost estimates in this report are denoted in \$2018, unless indicated otherwise.
[7] The strike price for an offshore wind project from an auction is usually the lowest bid price at which the offering can be sold. The strike price usually covers a specific contract term for which that strike price will be paid for the energy produced. The offeror of that strike price is awarded the rights to develop a particular parcel under predetermined conditions set in the tender offer that may vary by country or market.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

investigated and incorporated into the NREL Offshore Regional Cost Analyzer (ORCA) model. In addition, because not all cost components of a fixed-bottom system can be transferred to floating systems, we identified key differences in the cost structure of fixed-bottom and floating offshore wind technologies and assessed the major cost items unique to floating technology independently through industry consultations and accessing component-level proprietary data.

This report provides BOEM and the state of Oregon with cost information for five spatially explicit study sites to allow for consideration of floating offshore wind in the state's future energy portfolio. The data may also inform Oregon's long-term energy planning activities, which could determine how offshore wind might contribute to future energy supplies.

1.1 Oregon Offshore Wind Advisory Committee

Pacific Ocean Energy Trust (POET), under subcontract with NREL, convened an advisory committee to help ensure that the study assumptions were sound, that it addressed the key questions reflecting the interests of stakeholders in Oregon, and it provided peer review of the study report. The committee was made up of energy system and development experts in Oregon, including the Oregon Department of Energy and Department of Land Conservation and Development, Northwest Power and Conservation Council, Bonneville Power Administration (BPA), Portland General Electric, Pacific Marine Energy Center, and Pacific Northwest National Laboratory.

The members and affiliations of the advisory committee are:

- Jason Busch–POET (committee chairman)
- Adam Schultz–Oregon Department of Energy
- Andy Lanier–Department of Land Conservation and Development
- Bryson Robertson–Pacific Marine Energy Center–Oregon State University
- Crystal Ball–BPA
- John Schaad–BPA
- Jimmy Lindsay–Portland General Electric
- Mike Starrett–Northwest Power and Conservation Council
- Rebecca O'Neil–Pacific Northwest National Laboratory

POET engaged the advisory committee in the following activities for this study:

- Compilation of geospatial data from resource and management agencies on infrastructure, environmental resources, and ocean uses in the state and federal waters off the coast of Oregon to inform study site selection
- Compilation of geospatial data on onshore infrastructure in Oregon, including possible grid connections and ports, to inform the study site selection
- Initial study webinar on November 1, 2018
- Review of study site selection team's criteria, considerations, and five candidate study sites
- Compilation of load characteristics for diurnal and seasonal variations at locations near points of interconnection; these data helped identify possible coincidence of the load with the wind resource

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

- Compilation of systemwide electric load data for the state of Oregon to evaluate the maximum offshore wind in-state capacity requirements under high renewable-energy-penetration scenarios.
- Interim study webinar on May 21, 2019
- Peer review of report.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

2. Reference Offshore Wind Study Areas

This section describes the site selection process and provides detailed geospatial analysis for each of the study sites selected to be used as inputs to the ORCA cost model.

2.1 Oregon Offshore Wind Resource

The offshore wind resources in Oregon were evaluated previously by Musial et al. (2016b) in terms of offshore wind energy nameplate capacity and energy-generating potential. The gross potential resource capacity for Oregon was found to be 508 GW, considering all the ocean area from the shoreline to the exclusive economic zone (EEZ) boundary located 200 nautical miles (nm) from shore, and from the border of California to Washington state. However, gross offshore wind resource capacity overstates the offshore wind deployment potential because most of the resource area exceeds practical technology limits of extreme water depth.

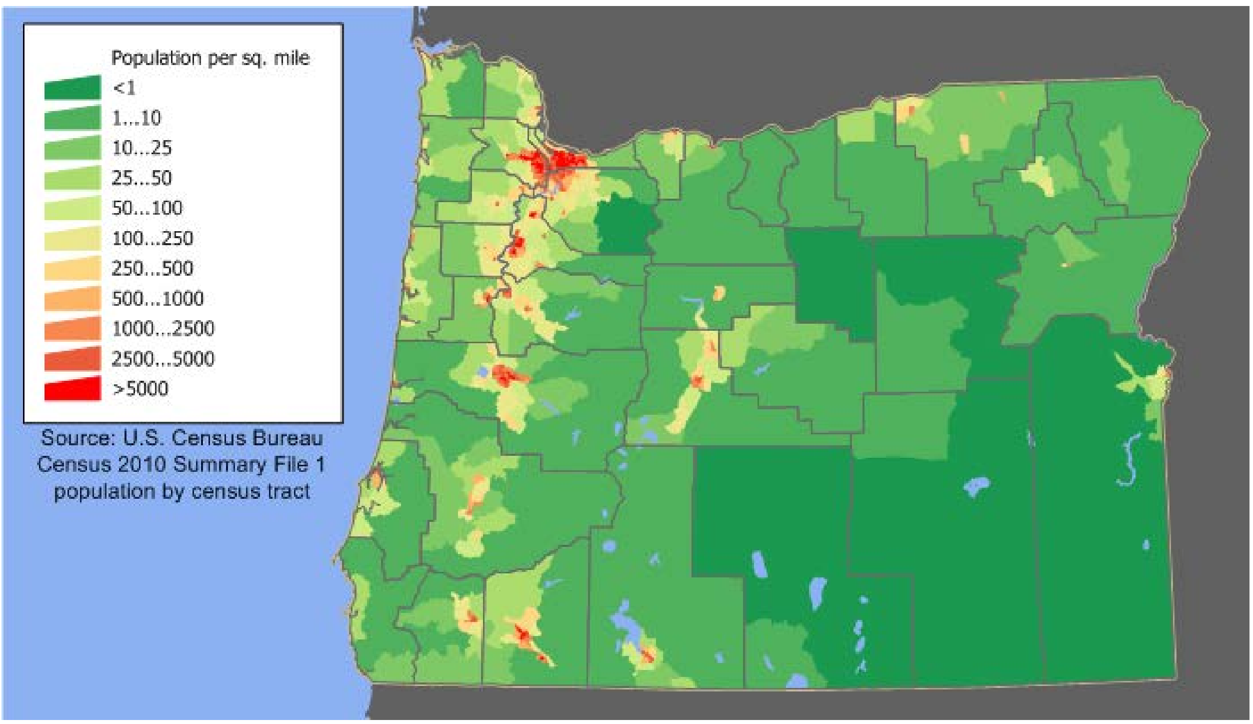


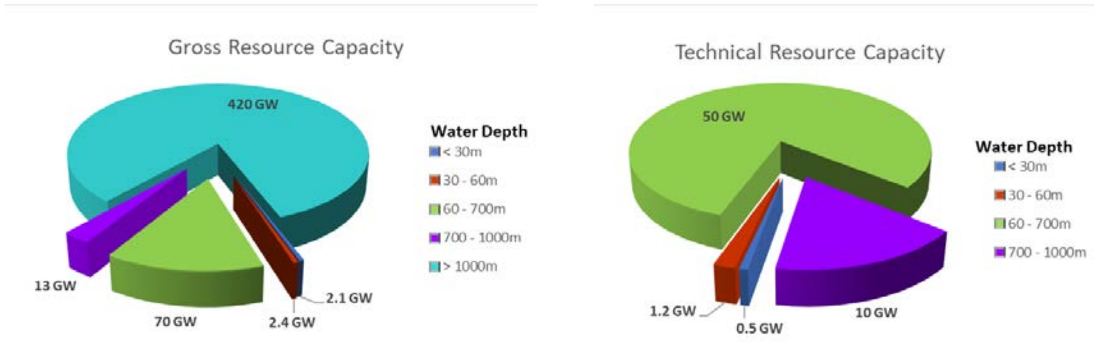
Figure 1. Oregon population density map showing the primary population centers of the Willamette Valley bounded by the coastal ranges and Cascade Mountains. *Image from PBS Learning Media 2019*

Following the methodology developed in the national resource study by Musial et al. (2016b), when water depth, low wind speeds, known sensitive environmental areas,[8] and technology constraints are considered, the gross resource potential is reduced to the "technical resource potential." The technical resource potential captures the subset of gross resource potential that

[8] These exclusions were not developed under a rigorous site-specific analysis. An estimate of the minimum amount of ocean area that would be inaccessible for offshore wind was applied to the wind resource calculation to reduce the total technical resource. These estimates do not replace a full marine spatial planning process.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

could become commercially viable using available technology or technology that is likely to become available within the timescale of this study to 2032. Therefore, the technical resource potential calculation excluded water depths greater than 1,000 m[9] and wind speeds less than 7 meters per second (m/s).[10] The technical potential calculation also excluded known sensitive environmental areas and use conflicts by approximating a percentage of the resource area to be off limits without identifying exact locations. Such exclusions (Figure 2) may be ecological preserves, certain fisheries, cable crossings, navigation lanes, closed areas, marine-protected areas, national wildlife refuges, National Park Service areas, critical habitat, and habitat areas of particular concern (e.g., Canopy Kelp) (Black & Veatch 2010).[11]



Gross Resource Capacity – 508 GW	**Technical Resource Capacity – 62 GW**

Exclusions

None	Greater than 1000 m Less than 7 m/s average windspeed 48% between 0 and 3 nautical miles 38% between 3 and 12 nautical miles 21% between 12 and 50 nautical miles

Figure 2. Comparison of Oregon gross offshore resource to technical resource potential by water depth. *Source: Musial et al. 2016b*

The technical offshore wind resource potential for Oregon was computed to be 62 GW across the entire coastline (Musial et al. 2016b). This amount corresponds to about 217 terawatt-hours (TWh)/year of potential offshore wind energy production, which is about 4.5 times the state's

[9] The 1,000 m exclusion is not a hard limit and some technology developers believe wind turbines can be placed in deeper water.
[10] All offshore sites in Oregon were found to be above the 7 meters per second cut off so low wind speed was not a factor in reducing the gross resource capacity.
[11] Black & Veatch data are not published but were provided to NREL as geographic information system data layers where shipping lanes or areas of environmental concern are located. In general, energy development would be prohibited in protected areas. Development is not necessarily prohibited in all areas of competing use, though mitigation may be required. For offshore wind energy, developers will need to work with all appropriate federal, state, and local agencies and organizations for permitting.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

total electric energy consumption (Musial et al. 2016b; Oregon Department of Energy 2019).[12] In Oregon, only 1.7 GW of technical resource capacity potential is located in waters with depths of 60 m or less.[13] Virtually all of this shallow-water offshore wind potential is in state waters, within 3 nm of the coast, where concerns relating to coastal viewsheds or wildlife may be elevated.

Globally, almost all of the offshore wind development to date has used fixed-bottom foundations in waters of 50 m or less (Musial et al. 2019); but because 97% of Oregon's viable offshore wind energy resource is located in waters with depths greater than 60 m, floating wind will likely be the dominant technology used if offshore wind is to become a part of Oregon's energy mix.

2.2 Identification of Offshore Wind Cost Study Sites

In this section, we describe the process for selecting the five sites used in the cost study. Each site represents a location where an offshore wind project would be technically feasible for the purpose of modeling potential cost. However, determining technical feasibility does not imply that the site has been deemed suitable for development. This study is not a stakeholder engagement or a marine spatial planning effort to create wind energy areas under BOEM's leasing process, and the hypothetical sites have not been vetted by ocean user communities. Any wind energy planning effort on the Outer Continental Shelf (OCS) would require comprehensive stakeholder engagement and analysis of all relevant data and information for siting.

2.2.1 Site Selection Process

A site selection team comprised of POET and POET's geographical information system subcontractor, Parametrix, defined the initial study area and five study sites offshore Oregon where commercial-scale offshore wind projects are technically viable. NREL and BOEM provided guidance to the site selection team on technical criteria and minimum site size for commercial-scale viability. The study sites selected by POET and Parametrix were reviewed by the advisory committee.

The domain considered for offshore wind study site selection in Oregon started with the technical offshore wind resource area, which includes all sites with water depths less than 1,000 m and with average wind speeds greater than 7 m/s. It comprises about 20,636 square kilometers (km^2). The study area under consideration was further reduced to eliminate all sites closer than 10 nm from shore to mitigate possible visual impacts to coastal communities, resulting in the initial study area shown in Figure 3.

---

[12] Oregon uses about 48 terawatt-hours of electricity per year.

[13] Resource capacity estimates are based on 3-MW/km^2 array power density (Musial et al. 2016b).

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

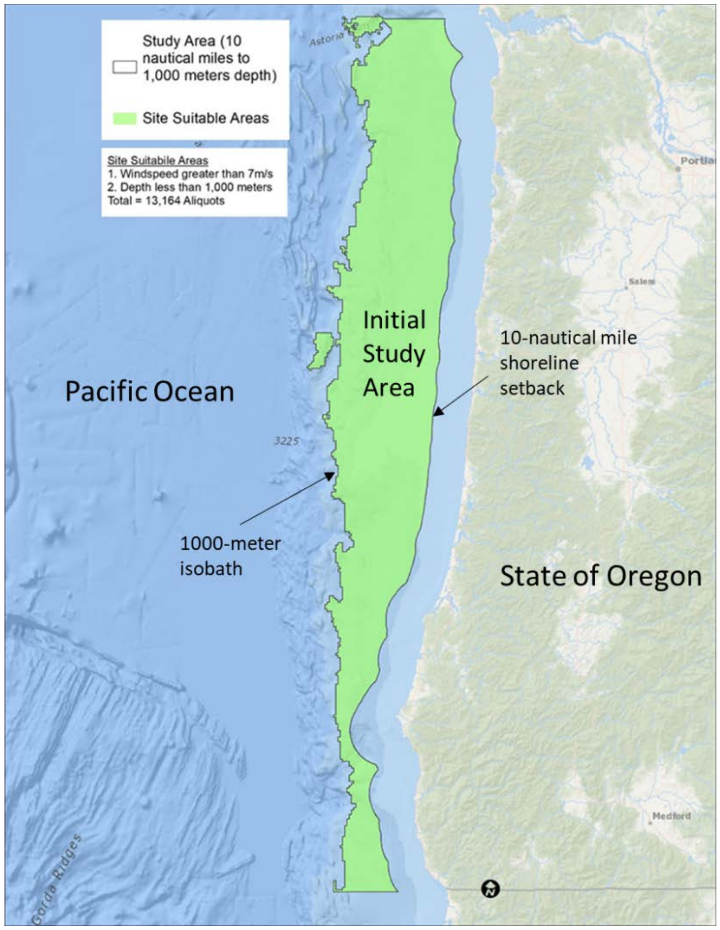


Figure 3. Initial study area defined by the study site selection team. "Site Suitable Areas" denote technical viability for the purposes of this study. *Image adapted from Parametrix*

Working within the boundaries of this initial study area, the study site selection team developed additional criteria to identify the study sites that could be used for cost analysis. These criteria were:

1. Identify five study sites that are geographically dispersed from north to south to provide contrasting economic profiles.
2. Construct study site boundaries along contiguous clusters of aliquots within the BOEM lease block grid.[14]
3. Identify an area of at least 250 aliquots for each study site, providing a total capacity of at least 1,000 MW (this allowed NREL the flexibility to model a 600-MW offshore wind power plant at each site).
4. Avoid existing subsea communication and data cables (North American Submarine Cable Association 2019).
5. Overlap one of the study sites with the WindFloat Pacific Project (west of Coos Bay, Oregon), which was proposed in 2014, as part DOE's advanced wind energy technology

[14] BOEM has divided the Outer Continental Shelf into lease blocks that are 4.8-km-by-4.8-km squares. Each lease block is subdivided into 16 1.2-km-by-1.2-km square aliquots.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

demonstration projects. This criterion is included to enable present cost analysis to be compared with earlier Principle Power, Inc. costs.

Known subsea transmission cables for communication and data are shown in Figure 4.

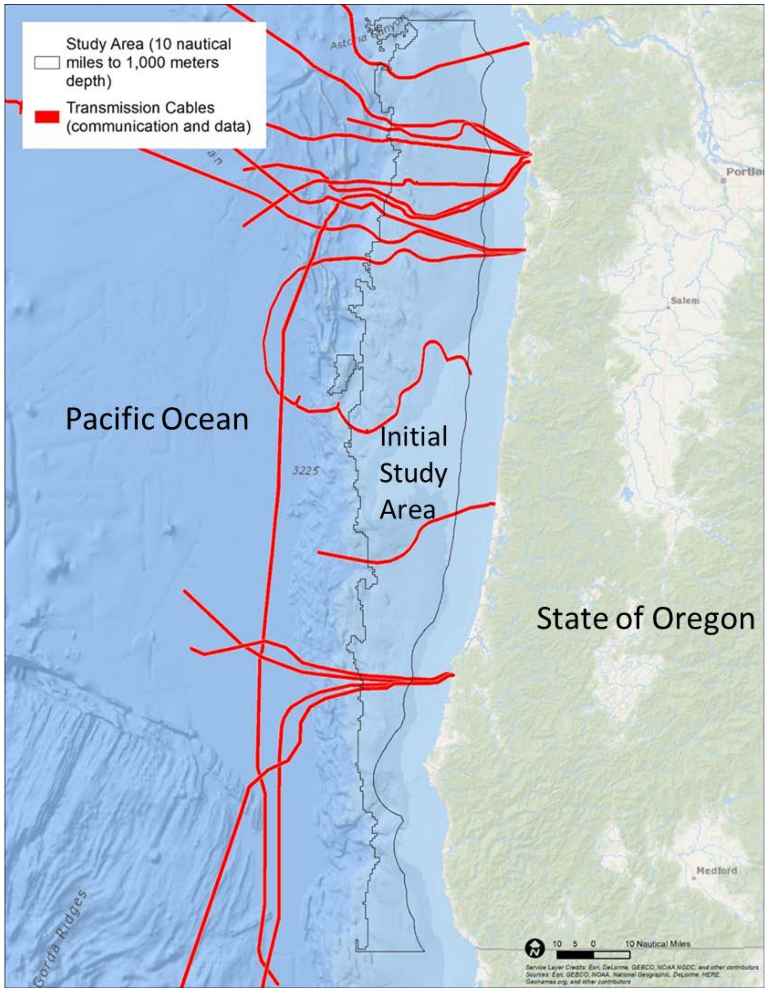


Figure 4. Subsea cable locations off the Oregon coast. *Image adapted from Parametrix*

Data on existing infrastructure, environmental resources, and ocean uses was also compiled for consideration in study site selection. These considerations included proximity to installation and service ports (Porter and Phillips 2016), proximity to land-based substations for electrical grid connection (ABB Energy Velocity Suite 2019a, 2019b), marine protected areas (National Oceanic and Atmospheric Administration [NOAA] 2019b), critical habitat and habitat conservation areas (NOAA National Marine Protected Areas Center 2019; NOAA Fisheries 2019a; NOAA Fisheries 2019b), and fishing activity (BOEM/NOAA 2013). These data were shared with the advisory committee for consideration.

Ultimately, POET, Parametrix, and the advisory committee decided to use primarily the technical viability criteria to drive site selection for the cost modeling study while acknowledging that any actual siting of wind turbines would have to have a broader purview to address potential environmental and use conflicts. The study sites' proximity to critical

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

infrastructure necessary for an offshore wind plant's operation and service—installation ports, service ports, and substations—was examined but did not drive the study site selection significantly. In general, the cost model was setup to use the closest port or grid connection available, but further analysis to understand the degree of upgrades necessary for the onshore infrastructure was beyond the scope of the study.

Possible installation ports that might provide slips for offshore wind power plant construction vessels and space for construction staging are shown in Figure 5. The ports at Astoria and Coos Bay have depths and clearances meeting the installation requirements of wind turbines. The port at Newport is not included because of the low clearance of the Yaquina Bay Bridge. Possible service ports that might support offshore wind plant operation and maintenance are shown in Figure 6 (Porter and Phillips 2016).

Figure 5. Possible installation ports on the Oregon coast. *Image adapted from Parametrix*

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

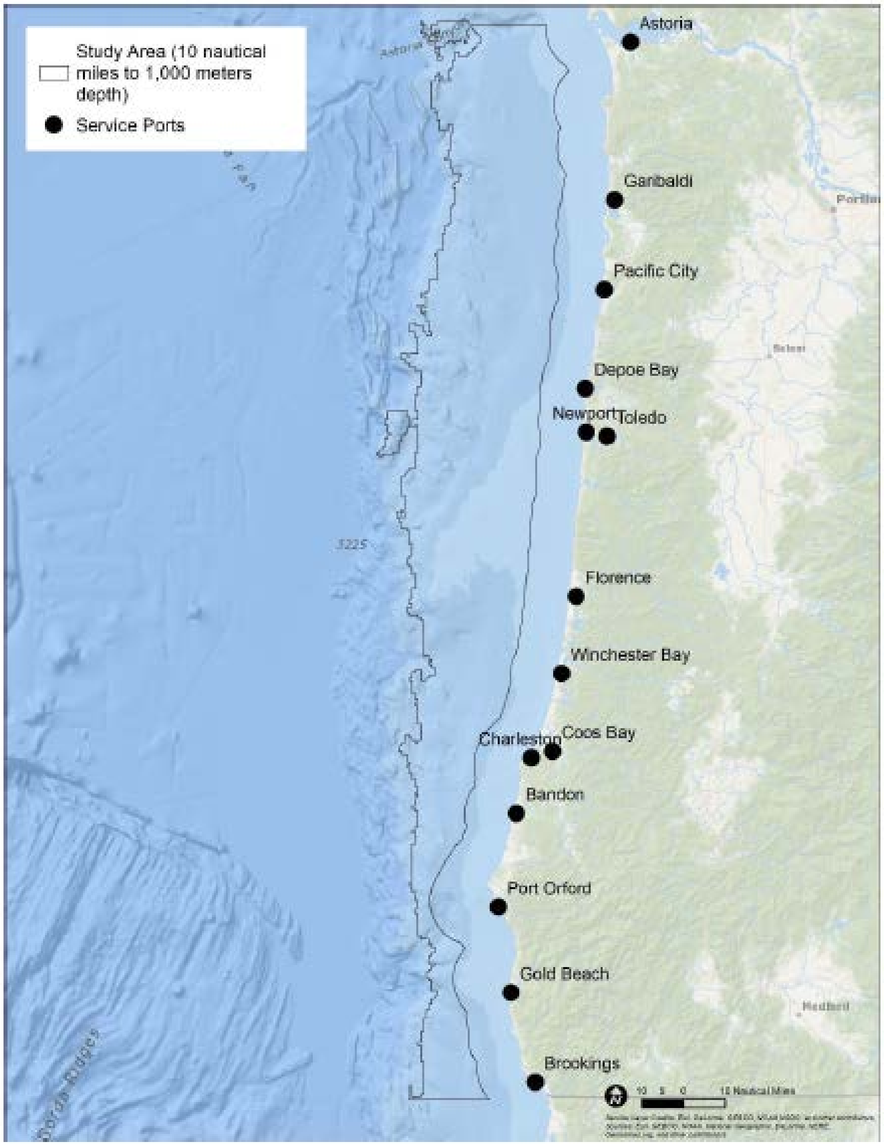


Figure 6. Possible service ports on the Oregon coast. *Image adapted from Parametrix*

To create the desired north-south geographic distribution of sites, the coastline was roughly divided into five regions: North, North Central, Central, South Central, and South, targeting one viable reference site in each. No specific boundaries were identified to separate these north-south regions, but the final sites were spaced relatively evenly down the coast. Based on the initial study area and site-selection criteria, Parametrix plotted the boundaries of the five study sites.

The study site boundaries, selection criteria geospatial data, and geospatial data for the other site selection considerations were presented to the advisory committee on November 1, 2018, via webinar. Following a multimonth review period among the site-selection team, advisory committee members, NREL, and BOEM, the study sites were finalized in February 2019. The final study sites are shown in Figure 7.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

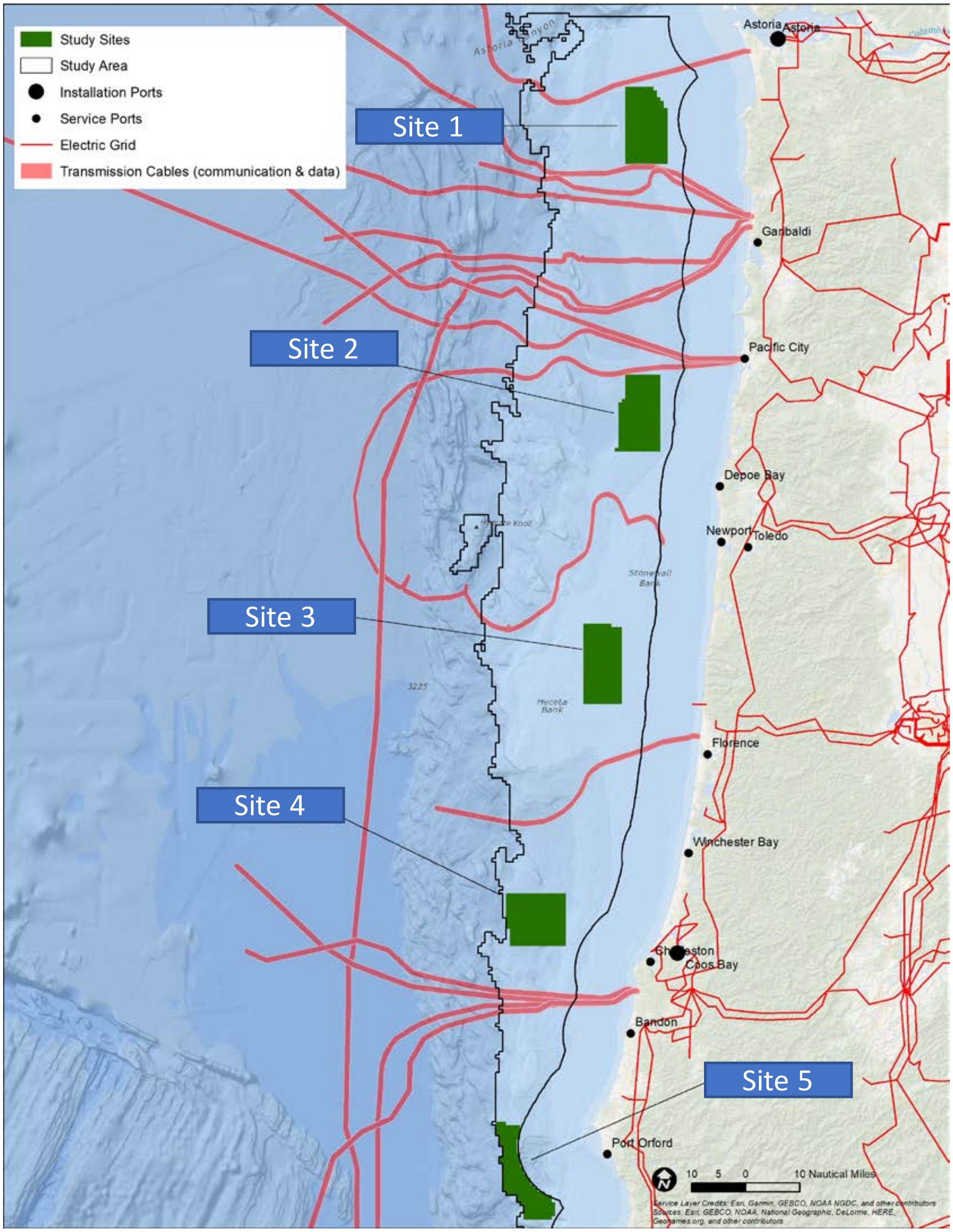


Figure 7. Final five study sites shown with existing infrastructure layers; study site 4 overlaps with the proposed pilot-scale WindFloat Pacific project. *Image adapted from Parametrix*

2.2.2 Global Site Description

Each study site has approximately 360 km^2, and together the study sites represent about 7.7% of the technical offshore wind resource area (approximately 1,800 km^2).

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Each square kilometer is roughly capable of supporting about 3 MW of offshore wind capacity, a power density that is often used to estimate generation capacity on an area basis (Musial et al. 2016b). Based on statewide energy use presented in Section 4, an ocean area of 1,800 km^2 could supply approximately 40% of Oregon's total electricity from offshore wind on a megawatt-hour basis.

Once the study site boundaries were finalized, the coordinates were transferred from Parametrix to NREL's geographic information system staff where further analysis was conducted to identify hypothetical, technically viable wind development areas for the purpose of modeling cost and to establish the inputs to the cost model. The required inputs to the cost model include distances to shore, distances to grid connections, distances to ports, wave heights, average wind speed, water depths, areas, power capacity, land-based grid distances, and other details (National Geospatial Intelligence Agency undated). Most of these input data were determined at the centroid of each study area. Distances were measured from the centroid to a geospatial infrastructure feature. Variations of site characteristics within a specific site's boundary were generally ignored. This detailed site information is presented in Table 1.

Table 1. Site-Specific Data for Offshore Wind Cost Study[15]

Site Characteristics	1 - North	2 - North Central	3 - Central	4 - South Central	5 - South
Study Site ID	1	2	3	4	5
Centroid Latitude (deg)	45.909	45.024	44.253	43.463	42.682
Centroid Longitude (deg)	-124.411	-124.412	-124.556	-124.814	-124.853
Minimum Distance to Shore–Straight Line (km)	25.62	22.91	27.85	25.40	21.23
Maximum Distance to Shore–Straight Line (km)	40.17	38.15	42.22	50.12	35.90
Mean Wind Speed (m/s)	7.8	8.03	8.17	8.65	9.84
Min, Mean, Max Significant Wave Height (m)	1.47-3.82 2.52 avg	1.48-3.85 2.53 avg	1.51-3.82 2.52 avg	1.54-3.9 2.57 avg	1.58-3.89 2.58 avg
Min, Mean, Max Depth (m)	126-169 147.4 avg	159-402 279.3 avg	85-121 100.8 avg	369-846 594.7 avg	220-1013 601.7 avg
Construction Port Name	Astoria	Newport	Newport	North Bend	North Bend
Construction Port (Lat. Long)	46.2, -123.83	44.63, -124.05	44.63, -124.05	43.4, -124.22	43.4, -124.22
Centroid Distance to Construction Port-–Straight Line (km)	55.20	52.30	58.20	48.78	95.42
Centroid Distance to Construction Port–Avoids Land (km)	61.91	54.86	58.20	57.45	95.42

[15] Note that the maximum depth for study site 5 was 1,013 m, which exceeds the 1,000-m depth filter. Depth filters were based on the characteristics of the centroid of the aliquots that allowed the depth to be greater than 1,000 m along the edges.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Site Characteristics	1 - North	2 - North Central	3 - Central	4 - South Central	5 - South
Operation and Maintenance (O&M) Port Name	Astoria	Newport	Newport	North Bend	North Bend
O&M Port (Lat. Long)	46.2, -123.83	44.63, -124.05	44.63, -124.05	43.4, -124.22	43.4, -124.22
Centroid Distance to Centroid Distance to O&M Port–Avoids Land (km)	61.91	54.86	58.21	57.45	95.42
Interconnection Point Name	Cannon Beach Sub	Devil's Lake Sub	Florence Sub	Empire Sub	Gold Beach Sub
Interconnection Point (Lat. Long)	45.89, -123.95	44.96, -124.01	43.98, -124.08	43.37, -124.28	42.77, -124.47
Centroid Distance to Interconnection (Offshore until Landfall)–Avoids Land (km)	35.76	32.22	48.40	44.00	33.02
Distance Point of Cable Landfall to Interconnect (km)	1.0	0.6	5.4	1.0	1.4
Area (km^2) < 1,000-m depth	360.17	360.18	360.15	360.10	358.64
Total Potential Capacity (MW)	1,080.5	1,080.5	1,080.5	1,080.3	1,075.9

Each study site is shown on the map in Figure 8, which also shows the average annual offshore wind speeds for the state of Oregon. Note that all wind speed maps in this report were created using WIND Toolkit data (Draxl et al. 2015). The offshore wind speeds in the map were adjusted to a reference height of 100 m above the water, but for the calculation of annual energy production (Section 4) the actual hub heights of the offshore wind turbines modeled were extrapolated using an average wind shear coefficient of 0.10. Data extrapolations were based on statistical data developed by AWS Truepower (2012).

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

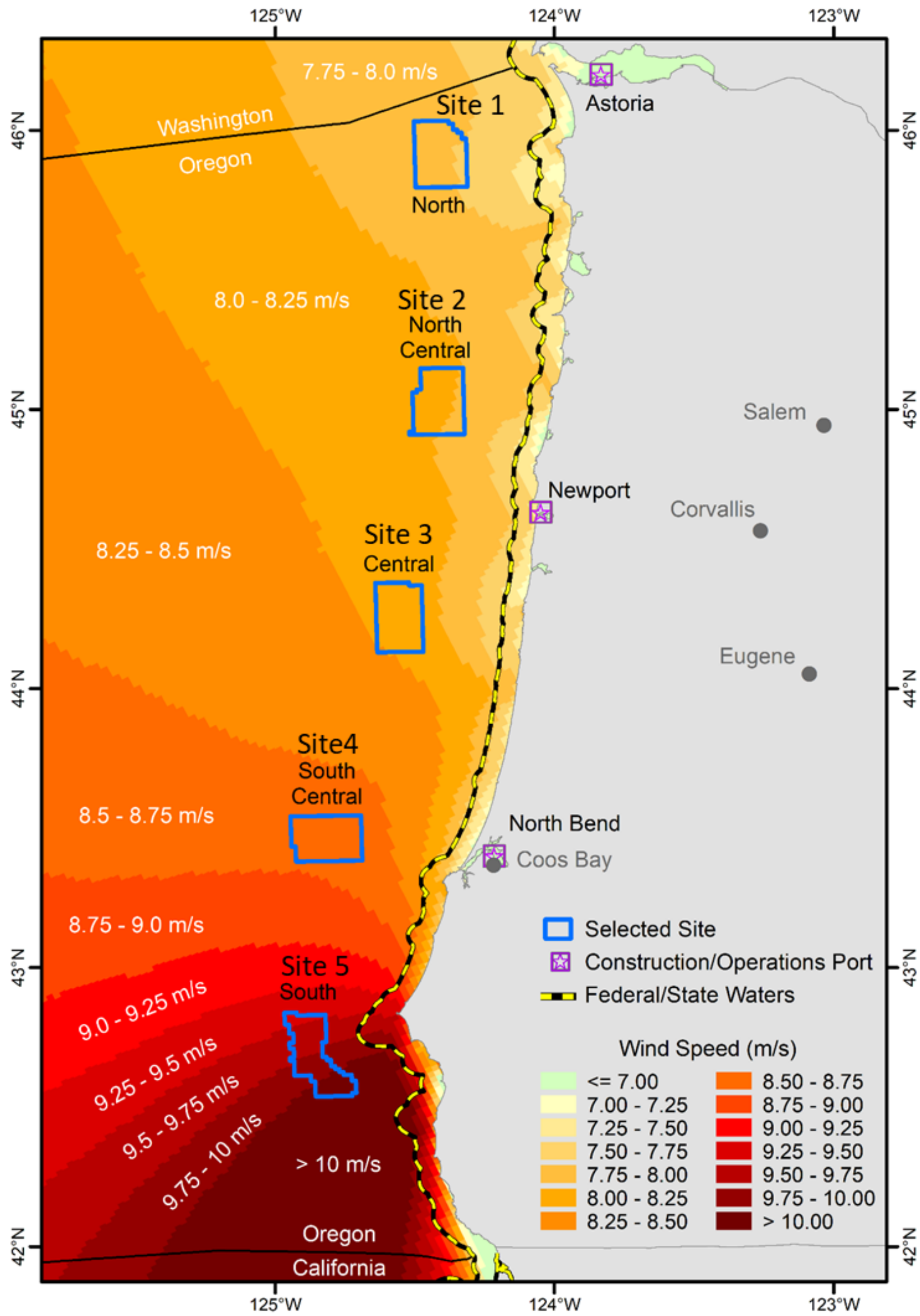


Figure 8. Average annual offshore wind speed map for Oregon at 100-m elevation for five study sites

Figure 8 shows that the best annual average wind speeds are almost 10 m/s near the California border. A strong north-south gradient diminishes these averages to below 8 m/s near the Washington State border. Figure 9 shows the wind direction frequency plots (wind roses) for each of the study sites.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

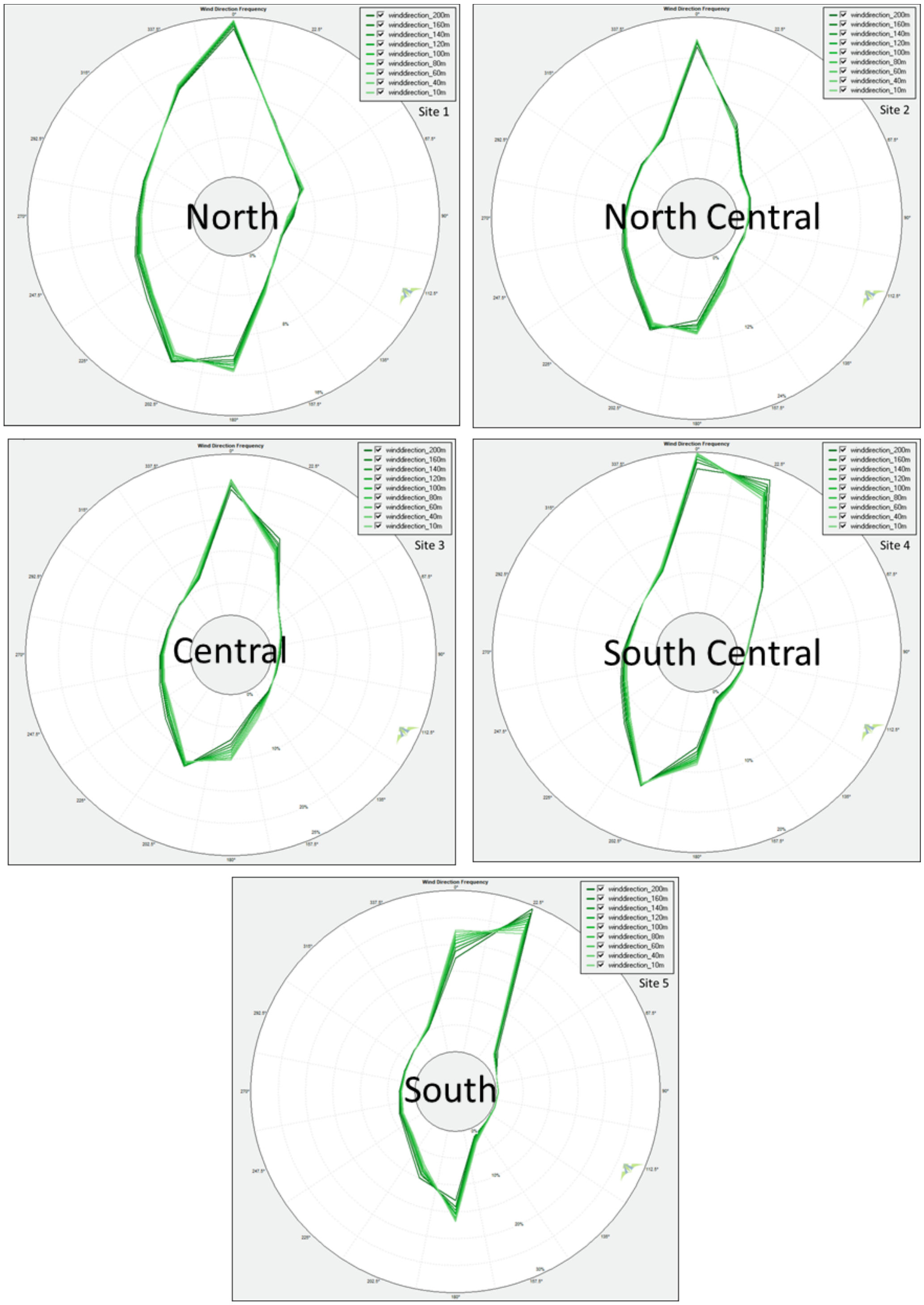


Figure 9. Wind direction frequencies (wind roses) for each of the study sites selected for elevations from 10 m to 200 m

The plots show data for elevations ranging from 10 m to 200 m, where wind turbines operate. These wind roses all indicate a strong north-south prevailing wind component that is consistent for all study sites, and generally parallel to the coastline.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Figure 10 shows the bathymetry of the coastal regions in the technical offshore wind resource area showing the five study sites. The plot indicates the steep Pacific shelf, which makes most of the area of the OCS deeper than 1,000 m. The bathymetry of each study site is shown in more detail in Section 2.3.

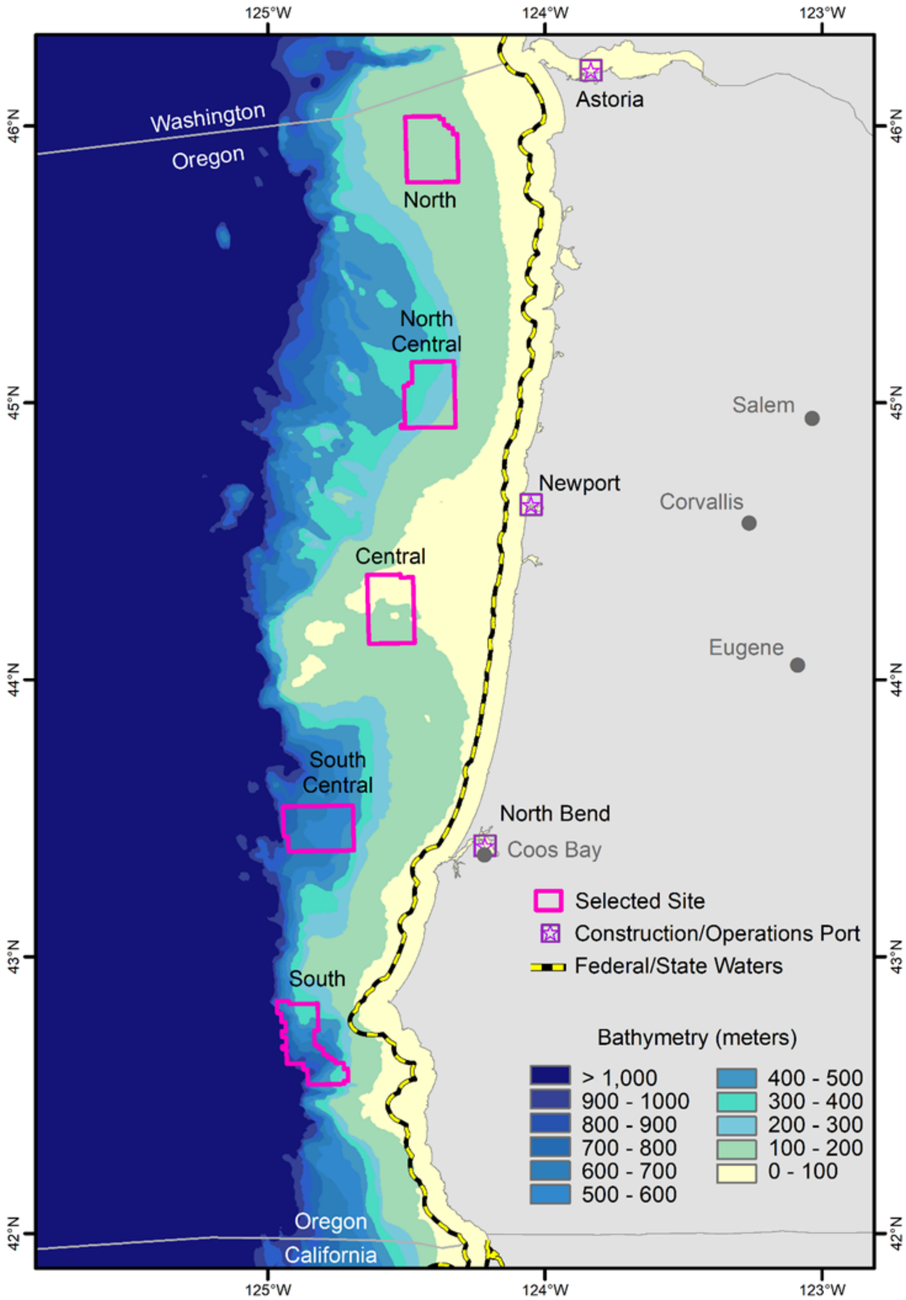


Figure 10. Ocean bathymetry map of Oregon showing the five study sites used for the cost analysis

Figure 11 provides a layout of the political boundaries for the Oregon OCS showing the five study sites. The map indicates the key nautical distance boundaries including the federal/state waters boundary at 3 nm and the EEZ boundary at 200 nm. It also shows the designated state

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

boundaries on the north and south sides. In addition, the 1,000-m isobath is shown (in purple), indicating a soft limit to the depth at which offshore wind turbines might become more challenging.

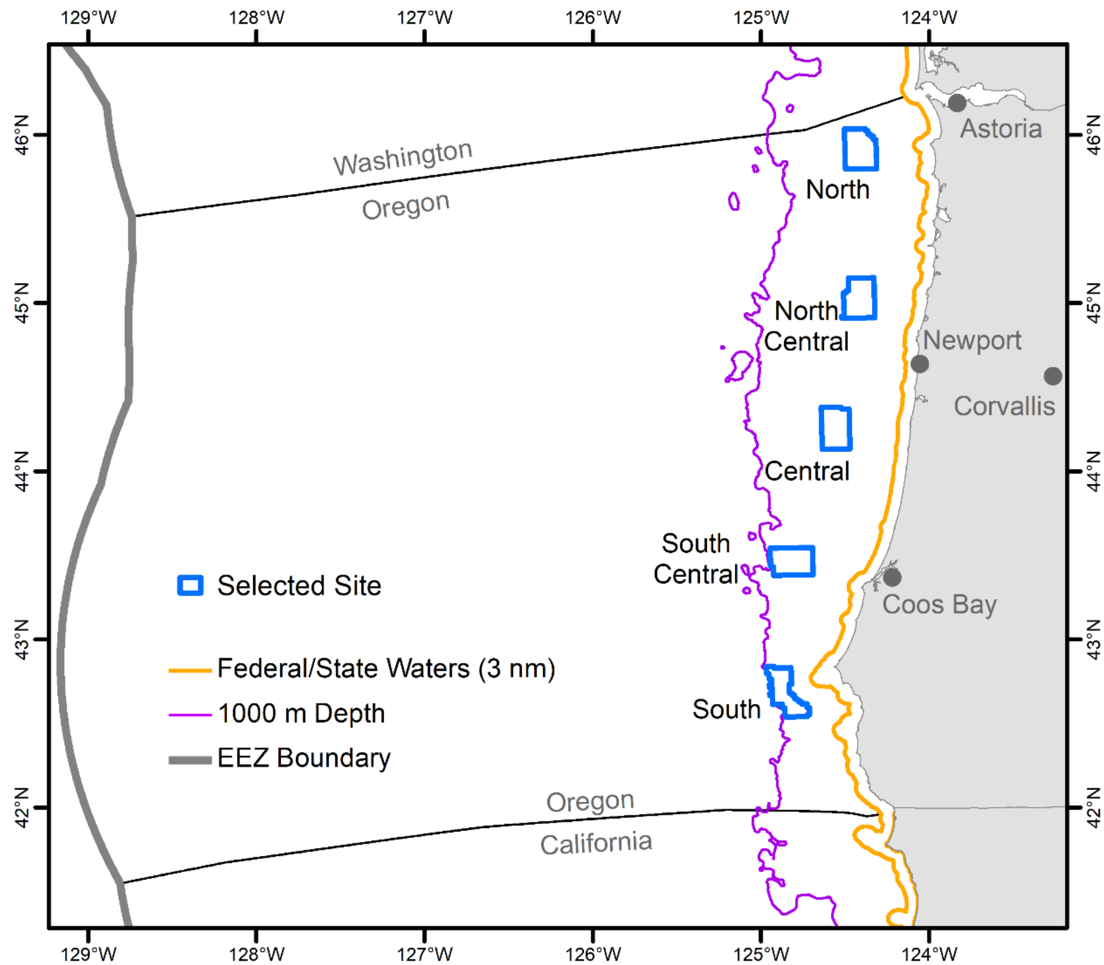


Figure 11. OCS political boundaries for Oregon showing the study sites used for cost analysis and the 1,000-m isobath

Figure 12 shows the five study sites and the known cable locations that exist on the seabed and the substations and transmission access assumed for the grid connection and cable length (ABB Energy Velocity Suite 2019a, 2019b). All substations chosen for this study were based mostly on proximity to the site; no analysis was done to assess the capacity of the transmission system to receive the power. However, it is assumed that upgrades would be needed for these full-scale offshore wind power plants. The straight blue dashed lines in Figure 12 connect the centroid of each study site to the associated substation used in the analysis.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

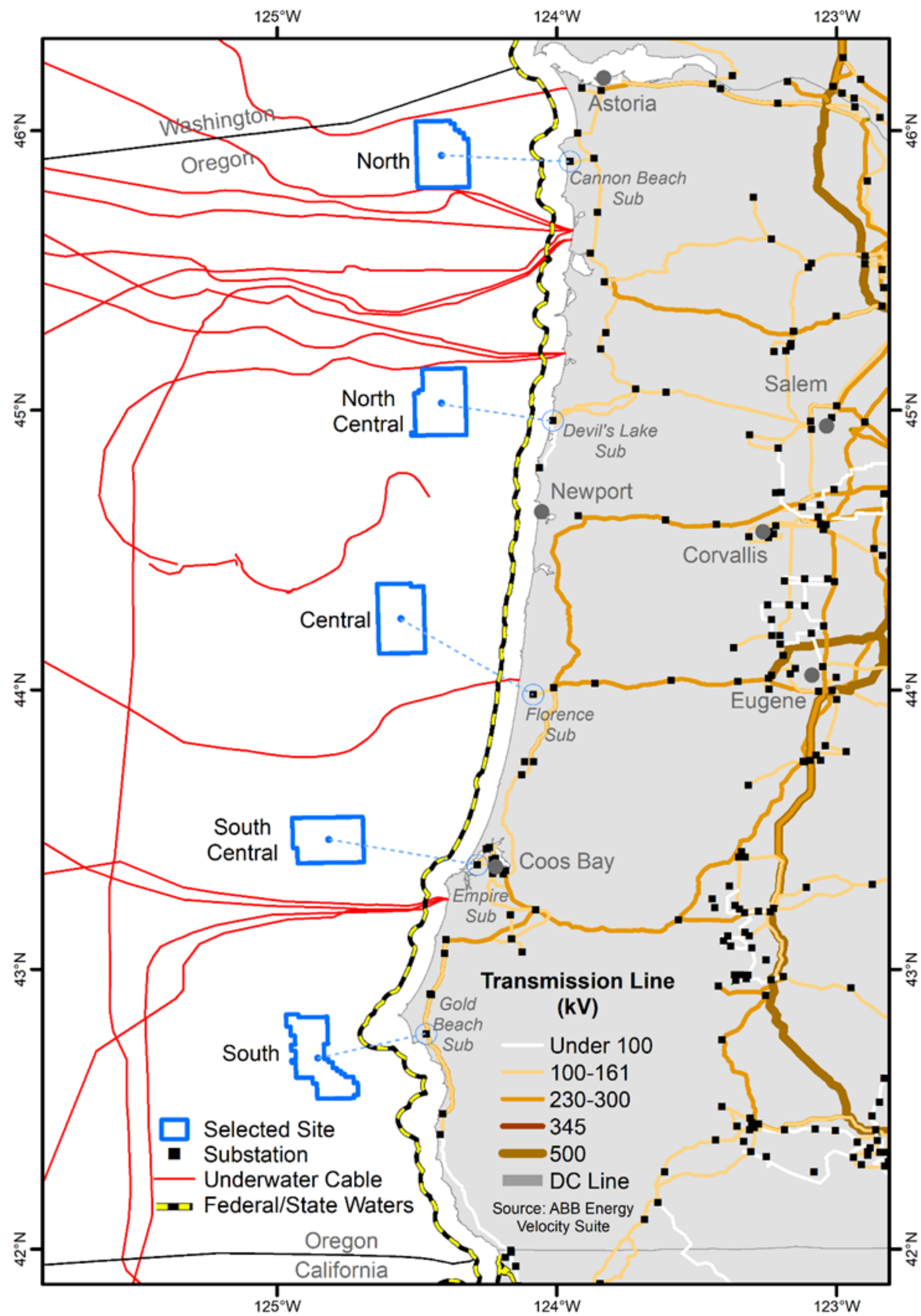


Figure 12. Map of study sites showing existing subsea cables and location of land-based substations assumed for interconnection. *Image from ABB Energy Velocity Suite*

Distance from shore is a critical siting parameter for offshore wind as it is generally considered desirable to site turbines far enough from shore so they will not have a large visual impact. However, there is no legal distance-from-shore requirement, so siting decisions are often left to the judgment of the developers, regulators, and stakeholders. The "acceptable" setback distance will vary depending on many factors including the land-based terrain and elevation, turbine size and height, weather, proximity to populations, and demographics. An Argonne National

Laboratory study on the visual impacts of offshore wind turbines found that because of their size and height, offshore wind turbines may be visible at distances up to 26 miles (42 km). It found that, at 10 miles (16 km) wind turbines may become a major feature of the viewshed (Sullivan et al. 2012). Oregon has recorded a visual resource inventory of 142 coastal viewshed locations where the aesthetic value of certain features is to be protected (State of Oregon 2019). In 2018, BOEM issued a request for information regarding siting new wind energy areas on the East Coast of the United States that recommended new wind energy areas be at least 10 nm (18.52 km) from the shore (BOEM 2018). Although this BOEM recommendation is not legally binding, it established a reasonable cutoff for the study area in this analysis, which eliminated sites closer than 10 nm.

The minimum and maximum distances to shore were calculated as the Euclidean distance (straight line path) from any point within the study site to the mainland shore. This method of calculating distance to shore was used within the ORCA cost model to estimate costs for subsea export cables and port distances. This method was necessary because the model relied on inputs calculated all the way to the main land mass. In all cases, the site minimums are at least 10 nm (Westington and Slagle 2019; NOAA 2018).

Figure 13 shows the range of distances from the mainland shore for each of the five study sites. Note that a 10-nm reference line is indicated on the chart showing the maximum and minimum distances to shore for each of the study sites.

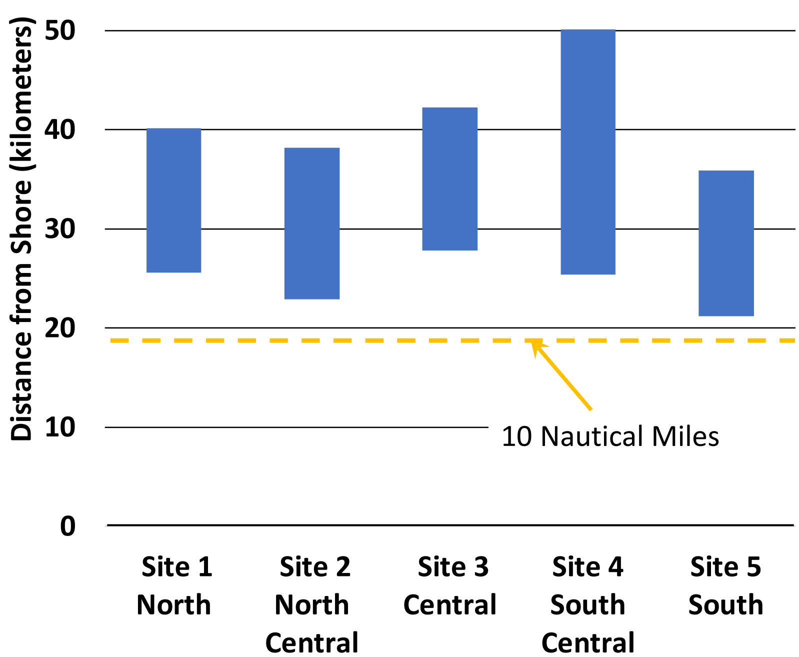


Figure 13. Distance from shore for study sites showing the minimum to maximum range

2.3 Oregon Study Sites Descriptions

The following are more detailed descriptions of each of the sites analyzed in this study. All sites were approximately the same area, but their shapes, depths, wind speeds, and geographic

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

features all varied considerably. The same turbine technologies were modeled for each site, but the technologies varied over time, as described in Section 3.

2.3.1 Site 1–North

Study site 1 is near the Washington State border and is the northernmost Oregon offshore wind site analyzed. It comprises 250 aliquots,[16] with a centroid located at 45.91 degrees latitude and -124.41 degrees longitude, as shown in Figures 14 and 15.

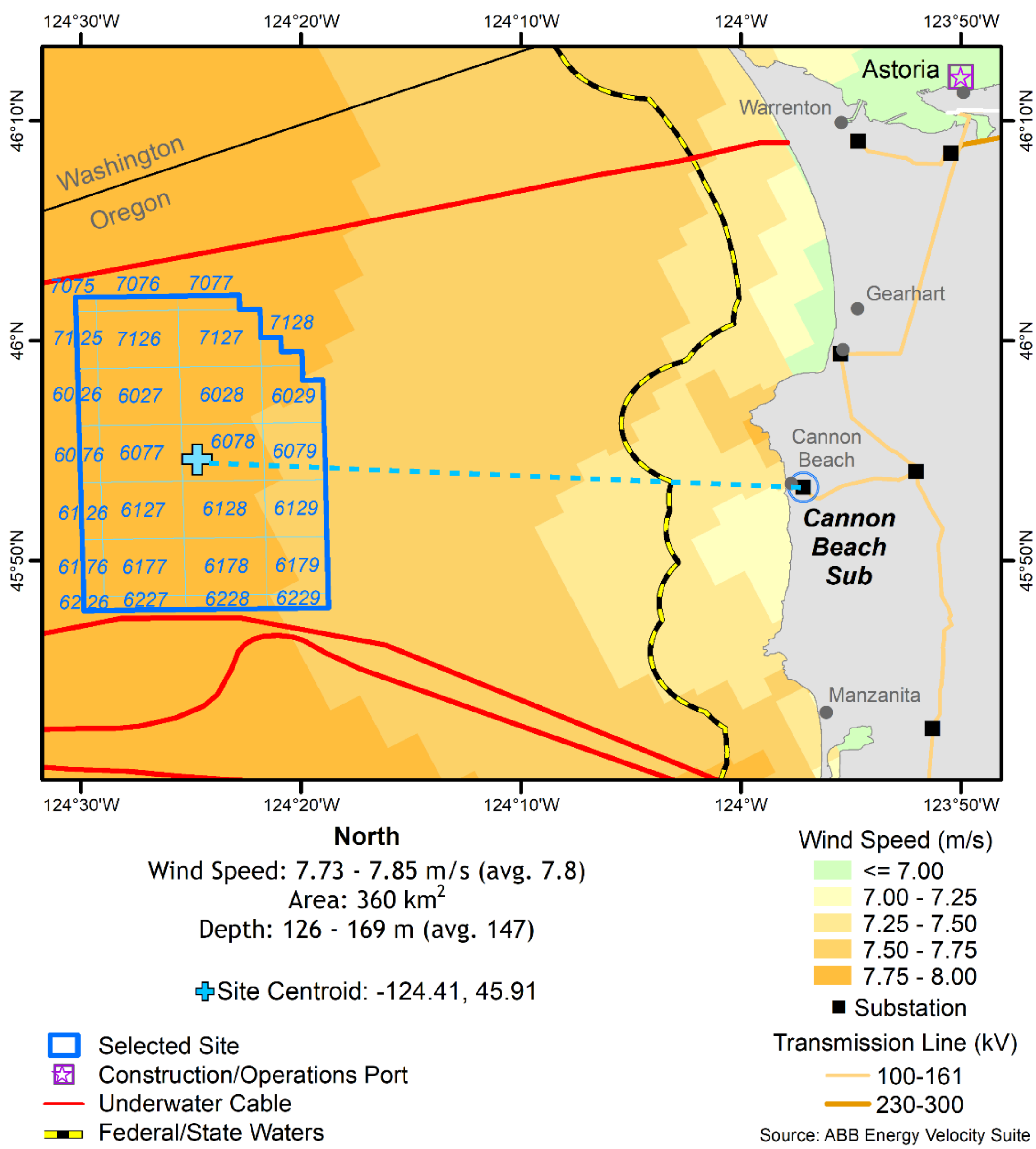


Figure 14. Annual average wind speed map of the north offshore wind study site (Site 1) at 100 m

---

[16] One aliquot is a square with dimensions of 1.2 km by 1.2 km. There are 16 aliquots in each BOEM lease block.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

The total area of this site was determined to be 360 km^2, which could support about 1,081MW of offshore wind capacity. This site has an average wind speed of 7.8 m/s; the lowest annual average wind speed of the Oregon cost study (plotted in Figure 14). The depth range for this site, plotted in Figure 15, was between 126 m and 169 m, which is relatively shallow for the Oregon OCS and within the depth range demonstrated by prototype floating support structures. The construction and operation and maintenance (O&M) ports were assumed to be located in Astoria, Oregon, which is about 62 km from the site's centroid. The grid interconnection point was assumed to be at the Cannon Beach substation, which requires a minimum run of 36 km for the export cable measured from the centroid of the site. Actual cable length varies by water depth, distance from site to point of interconnection, and competing use constraints (e.g., existing cable routes, fishing, protected areas).

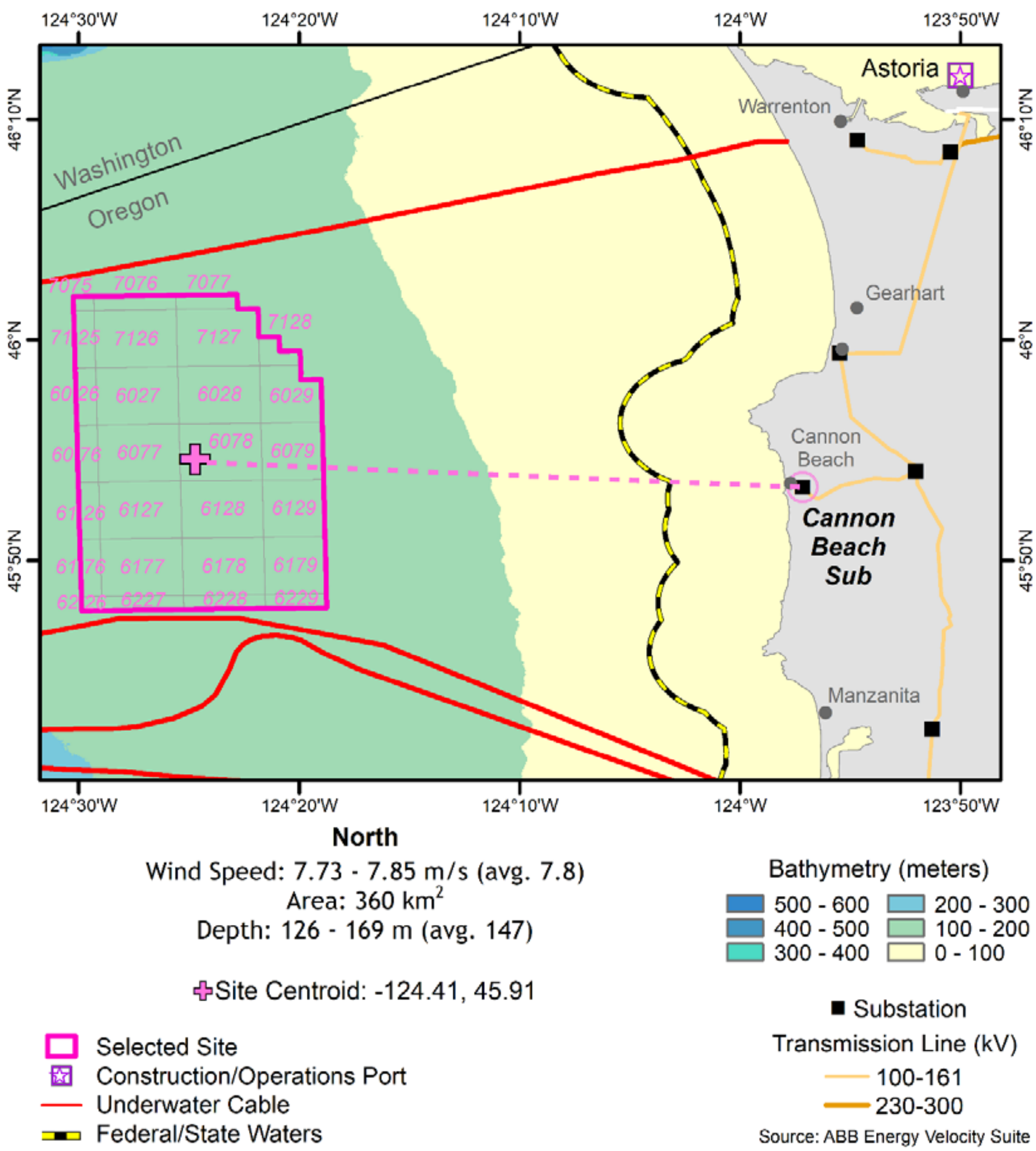


Figure 15. Bathymetry map of north offshore wind study site (Site 1)

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

2.3.2 Site 2–North Central

Study site 2 is just north of Newport, Oregon, and is named the north-central Oregon offshore wind site. It comprises 250 aliquots with a centroid located at 45.02 degrees latitude and -124.41 degrees longitude, as shown in Figures 16 and 17.

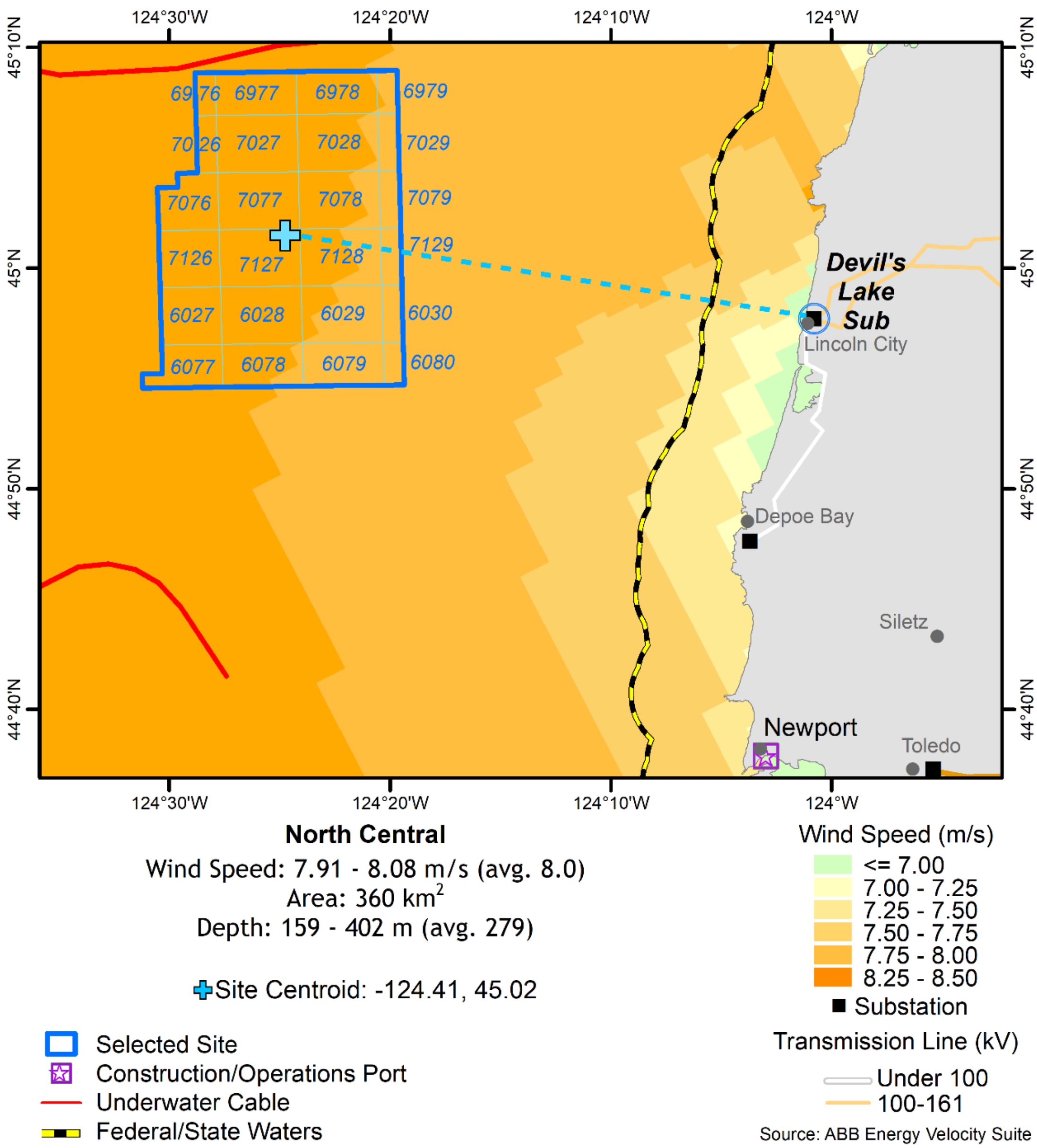


Figure 16. Annual average wind speed map of the north-central offshore wind study site (Site 2) at 100 m

The total area of this site is 360 km^2, which can support about 1,081MW of offshore wind capacity. This site has an annual average wind speed of 8.0 m/s, which is a relatively low wind site; the details of which are plotted in Figure 16. The depth range, plotted in Figure 17, is between 159 m and 402 m, indicating a sharper drop off in depth than Site 1. The construction and O&M port are assumed to be in Newport, Oregon, about 55 km from the site's centroid. The

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

grid interconnection point was assumed to be at the Devil's Lake substation, which requires a minimum run of 32 km for the export cable.

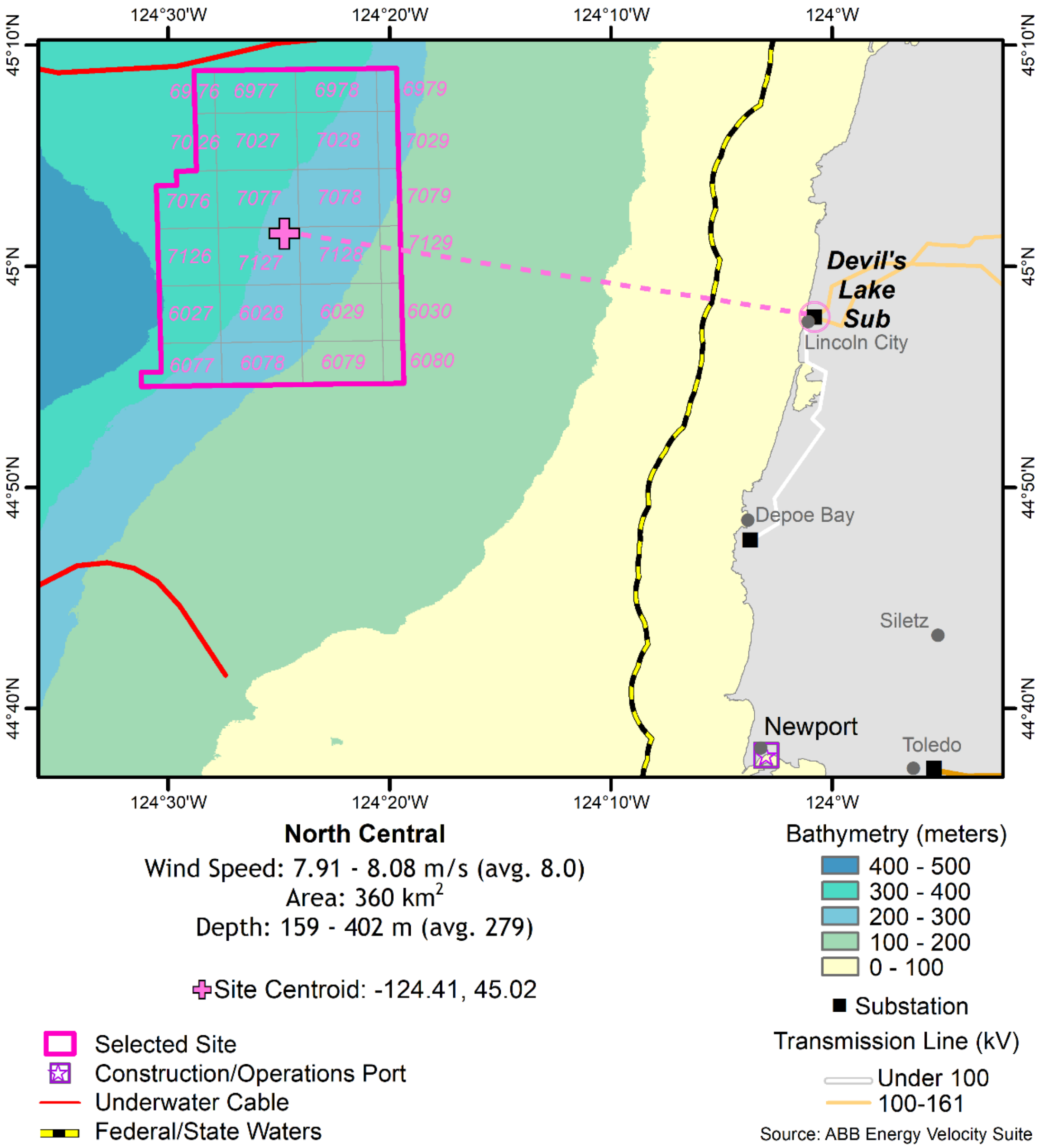


Figure 17. Bathymetry map of the north-central offshore wind study site (Site 2)

2.3.3 Site 3–Central

Study Site 3 is just south of Newport, Oregon, and is named the central Oregon offshore wind site. It comprises 250 aliquots, with a centroid located at 44.25 degrees latitude and -124.56 degrees longitude, as shown in Figures 18 and 19.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

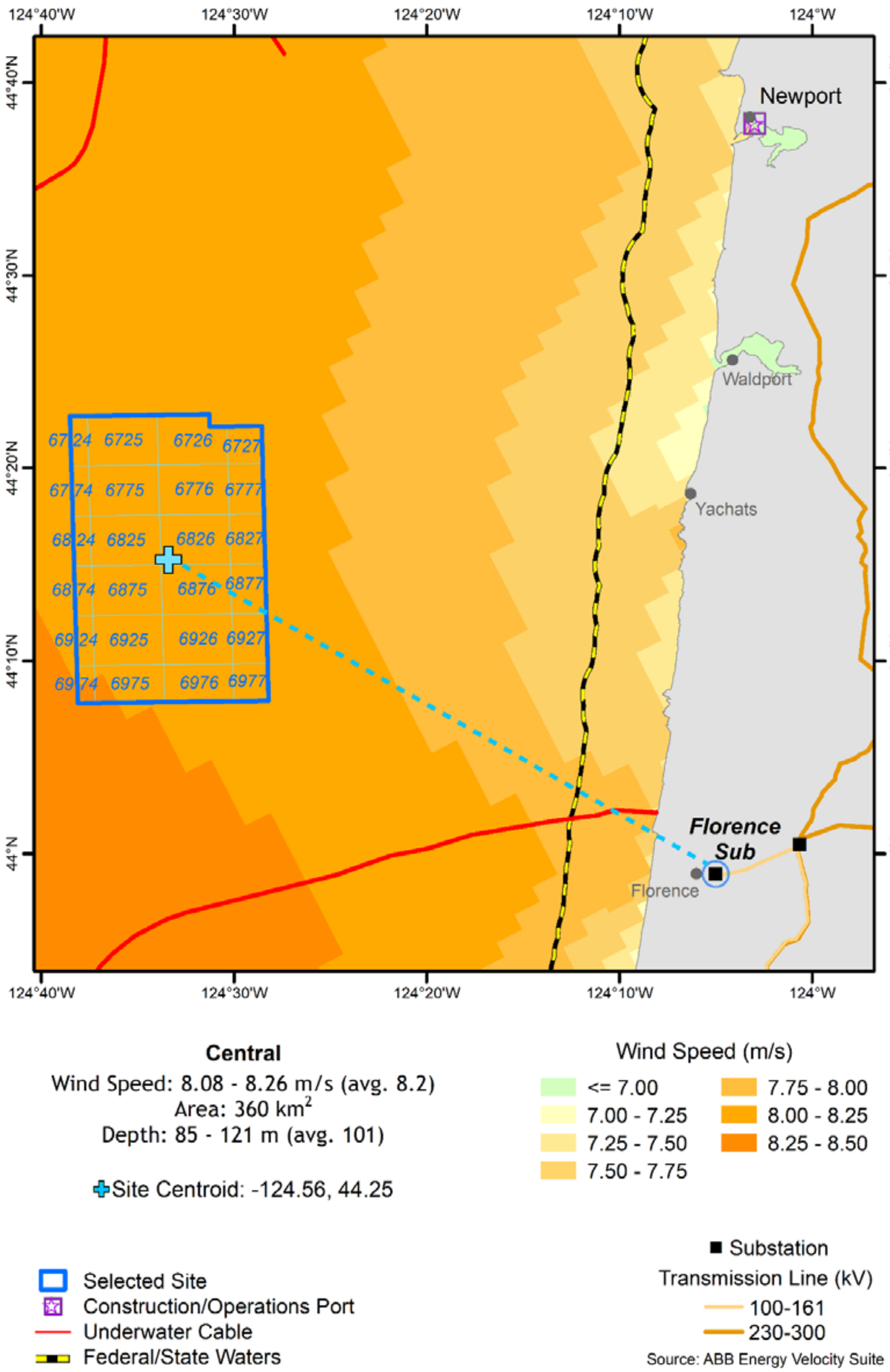


Figure 18. Annual average wind speed map of central offshore wind study site (Site 3) at 100 m

The area of this site is 360 km^2, which can support about 1,081MW of offshore wind capacity. This site has an annual average wind speed of 8.2 m/s, which is still a relatively low wind site;

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

the details of which are plotted in Figure 18. The depth range, plotted in Figure 19, is between 85 m and 121 m, making Site 3 the shallowest site in the study; located on a wider part of the shelf off Newport. The construction and O&M ports were assumed to be in Newport, Oregon, about 58 km from the site's centroid. The grid interconnection point was assumed to be at the Florence substation, which requires a minimum run of 48 km for the export cable.

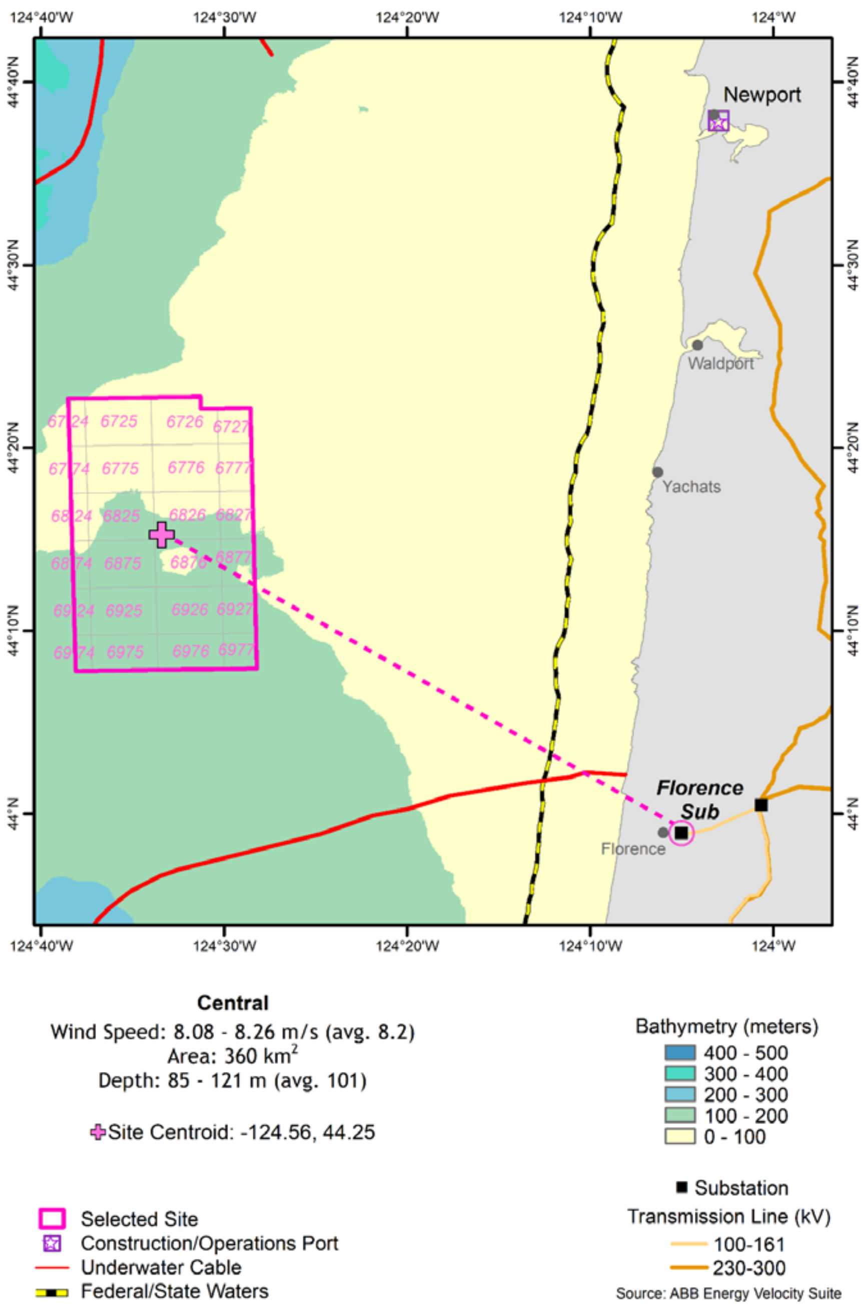


Figure 19. Bathymetry map of the central offshore wind study site (Site 3)

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

2.3.4 Site 4–South Central

Study Site 4 is near North Bend and Coos Bay, Oregon, and is designated the south-central Oregon offshore wind site. It comprises 250 aliquots with a centroid located at 44.25 degrees latitude and -124.81 degrees longitude, as shown in Figures 20 and 21.

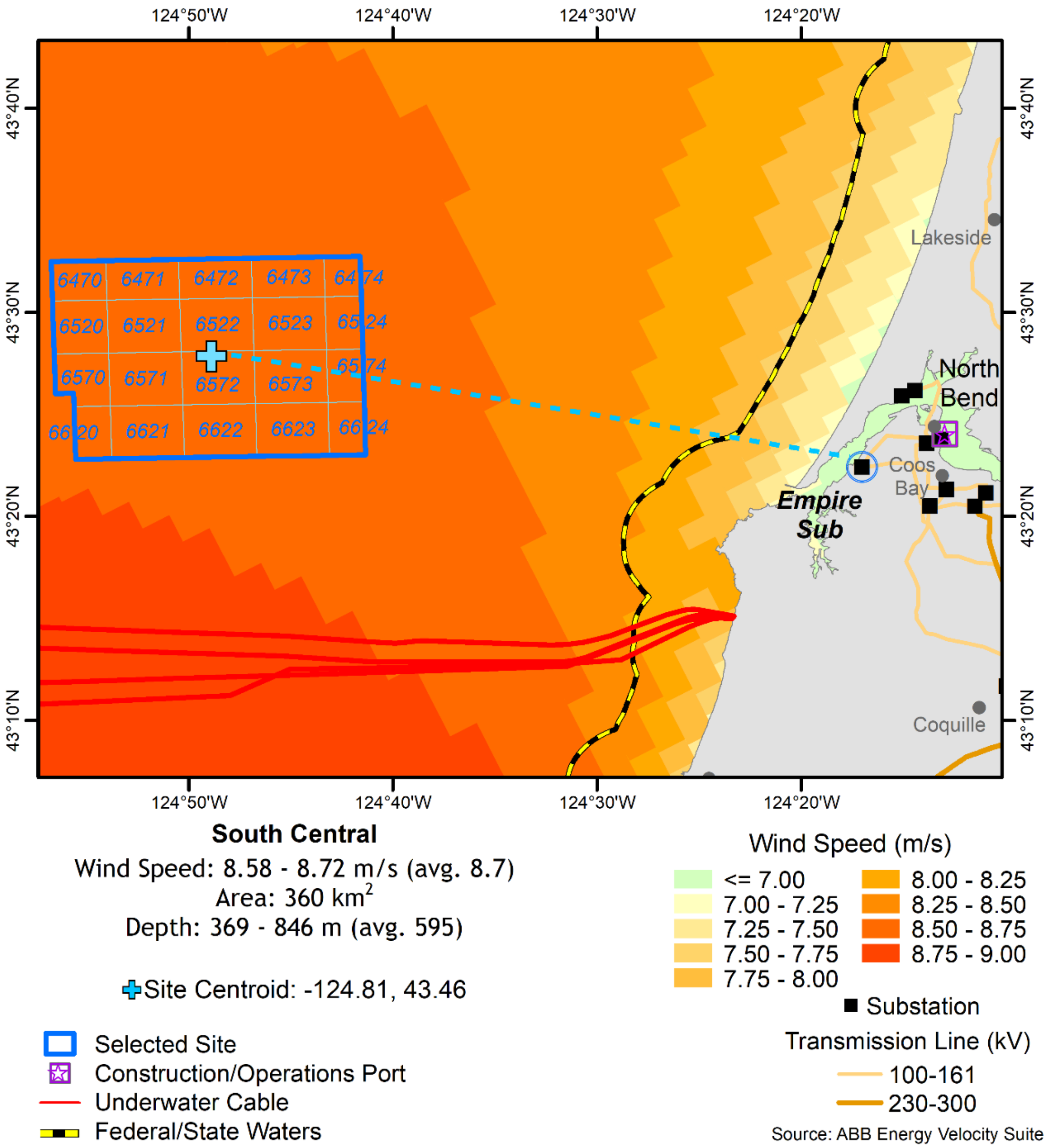


Figure 20. Annual average wind speed map of the south-central offshore wind study site (Site 4) at 100 m

The area of this site is 360 km^2, which can support about 1,081 MW of offshore wind capacity. This site has an annual average wind speed of 8.7 m/s, which is a moderate wind site; the details of which are plotted in Figure 20. The depth range, plotted in Figure 21, was between 368 m and 846 m, indicating much greater depths than the northern sites. The construction and O&M ports were assumed to be in North Bend, Oregon, about 57 km from the site's centroid. The grid

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

interconnection point was assumed to be at the Empire substation, which requires a minimum run of 44 km for the export cable. This site is also geographically co-located with the site of WindFloat Pacific (Banister 2017; DOE 2019). It is used to illustrate the cost benefits of larger project scales in Appendix A, comparing the 24-MW project to a full-scale 600-MW commercial project at the same site.

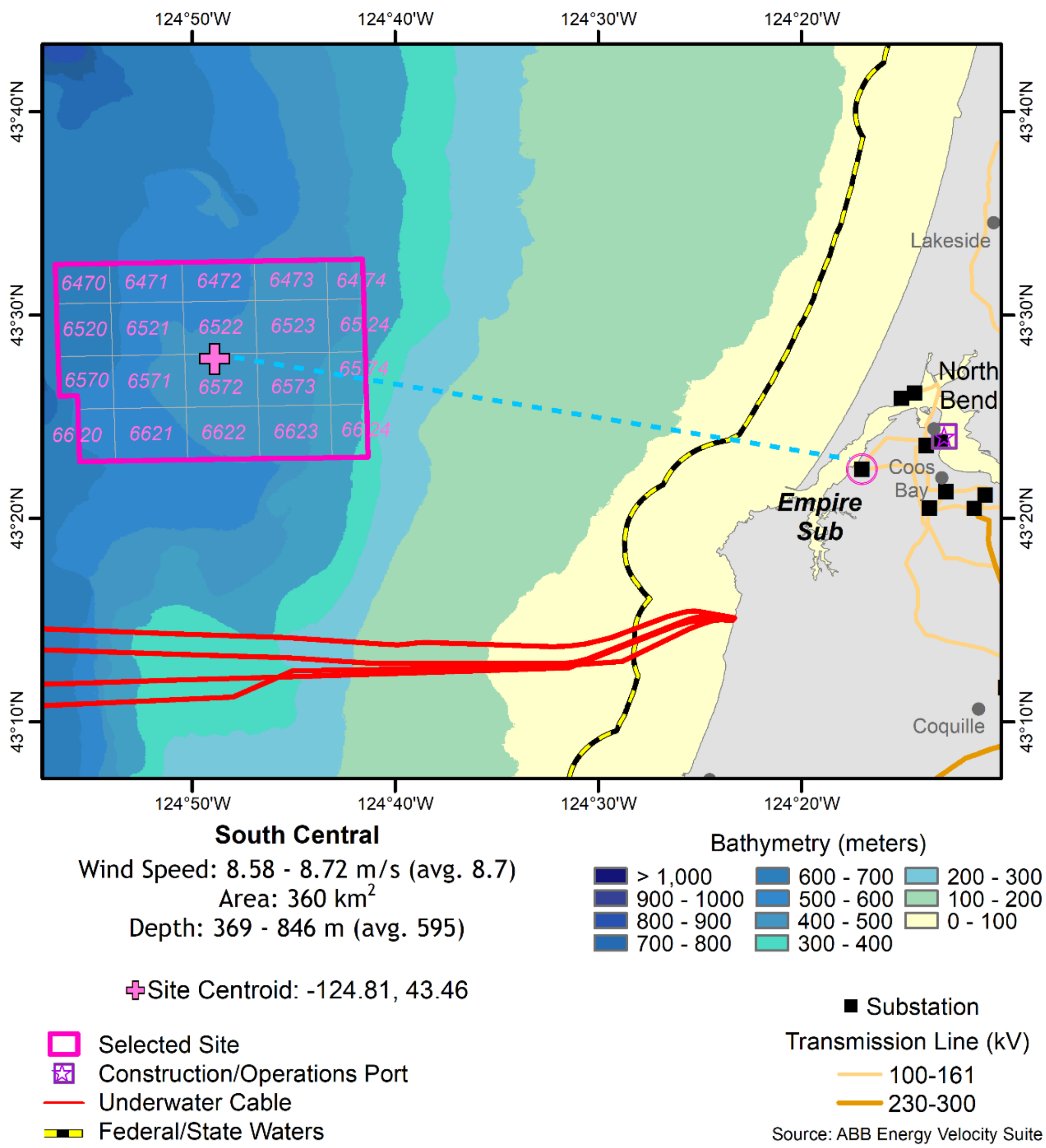


Figure 21. Bathymetry map of the south-central offshore wind study site (Site 4)

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

2.3.5 Site 5–South

Study Site 5 is south of North Bend and Coos Bay, Oregon, and is named the south Oregon offshore wind site. It comprises 249 aliquots with a centroid located at 42.68 degrees latitude and -124.85 degrees longitude, as shown in Figures 22 and 23.

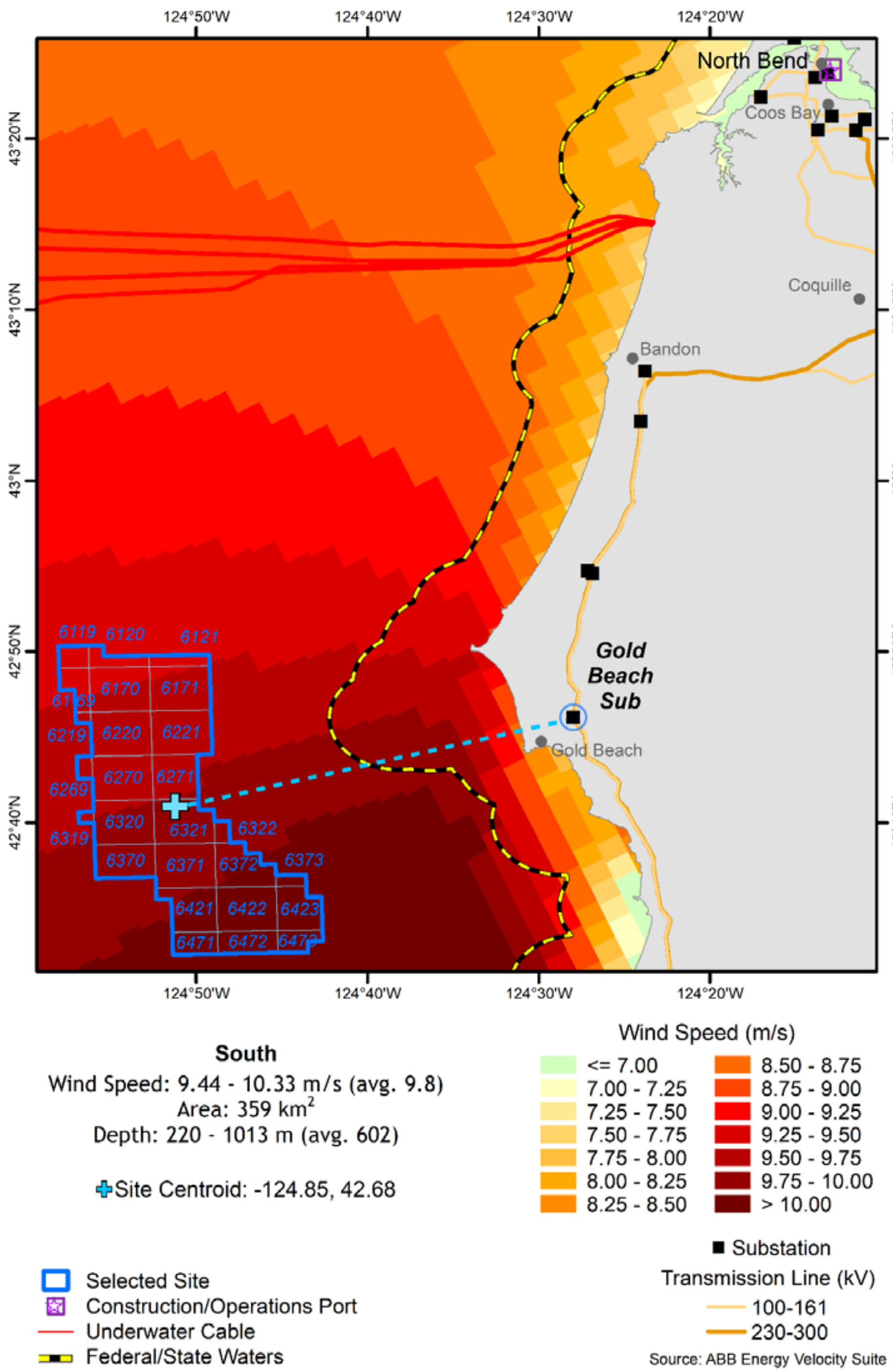


Figure 22. Annual average wind speed map of the South offshore wind study site (Site 5) at 100 m

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

The area of this site is 359 km^2, which can support about 1,076 MW of offshore wind capacity. This site has an average wind speed of 9.8 m/s, which is a relatively high wind site and the best energy-producing site in this study. These wind speeds are plotted in Figure 22. The depth range, plotted in Figure 23, falls between 220 m and 1,013 m, indicating a sharp drop off and the greatest depth range of all the sites. The construction and O&M ports were assumed to be in North Bend, Oregon, which is about 95 km from the site's centroid. The grid interconnection point was assumed to be at the Gold Beach substation, which requires a minimum run of 32 km for the export cable.

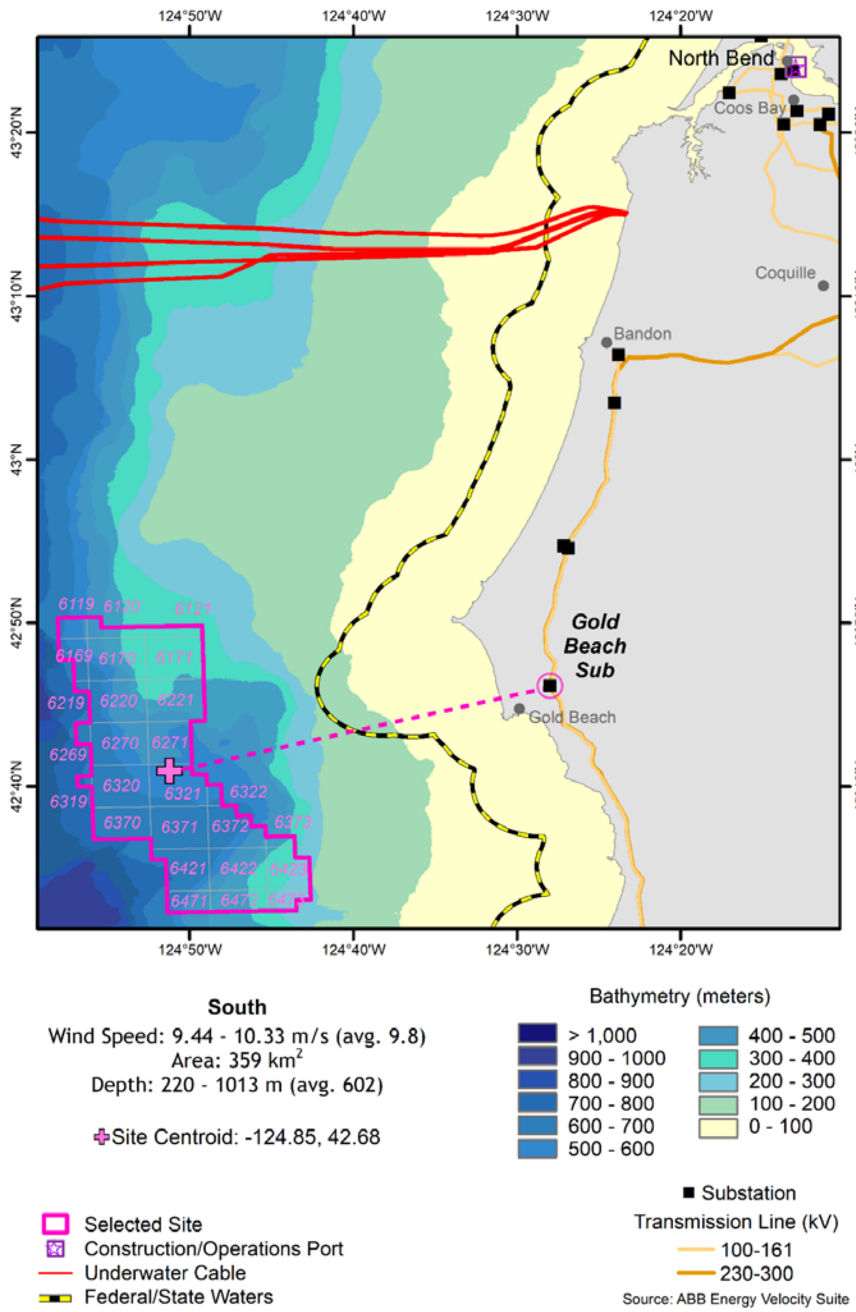


Figure 23. Bathymetry map of the south offshore wind study site (Site 5)

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

3. Offshore Wind Technology Assumptions

The time frame of this study extends through 2032 but focuses on 4 years when a new wind project reaches a commercial operation date (COD) to assess progress and evaluate cost: 2019 (estimated from industry prototype data), 2022 (modeled), 2027 (modeled), and 2032 (modeled). The primary technical assumptions are based on turbine size and floating platform technology, although there are many second-order technology assumptions that are explained in greater detail in Section 5.

3.1 Current State of Floating Offshore Wind

From the bathymetry distribution of the Oregon technical offshore wind resource shown in Figure 2, approximately 97% of Oregon's offshore wind resource is in waters with depths greater than 60 m, indicating that floating wind technology should be considered as the primary technology option for large-scale offshore wind deployment in Oregon.

Globally, floating offshore wind is driven largely by the prospect of expanding areas viable for offshore wind development beyond conventional fixed-bottom depths. In the United States, over 58% of the total technical offshore wind resource is in water depths greater than 60 m, and in Europe the floating resource area is 80% of the total (Musial et al. 2016b; Wind Europe 2018). The development of floating offshore wind technology is emerging quickly as a result of experience and knowledge gained from pilot-scale projects in Europe and Asia. At present, most demonstration-scale projects are still under development but are expected to be in operation by 2022. Their operation and experience will inform cost-effective commercial-scale floating wind development that may be deployed as early as 2025.

At the end of 2018, there were eight floating offshore wind projects installed around the world representing 46 MW of capacity. Five projects (37 MW) were installed Europe and three (9 MW) in Asia. There were an additional 14 projects representing 200 MW that are currently under construction or have achieved either financial close or regulatory approval. Two projects (488 MW) had advanced to the permitting phase of development, and another 14 are in the early planning stages (4,162 MW). Overall, by the end of 2018, there were approximately 4,888 MW of floating offshore wind capacity in the operational and development pipeline ranging from small-scale, single-turbine prototypes (2009–2015), to multiturbine demonstration projects (2016–2022), and commercial-scale projects that have already been proposed (Musial et al. 2019). Some of these proposed commercial projects are in U.S. waters off the coasts of California and Hawaii (BOEM 2019a, 2019b), though BOEM has not issued leases for any projects in these states as of the date of report publication.

Figure 24 illustrates three archetypes for floating wind turbine substructure technology being developed. Many variations of these archetypes exist. Each of these substructure archetypes have evolved or been adapted from oil and gas production platforms.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

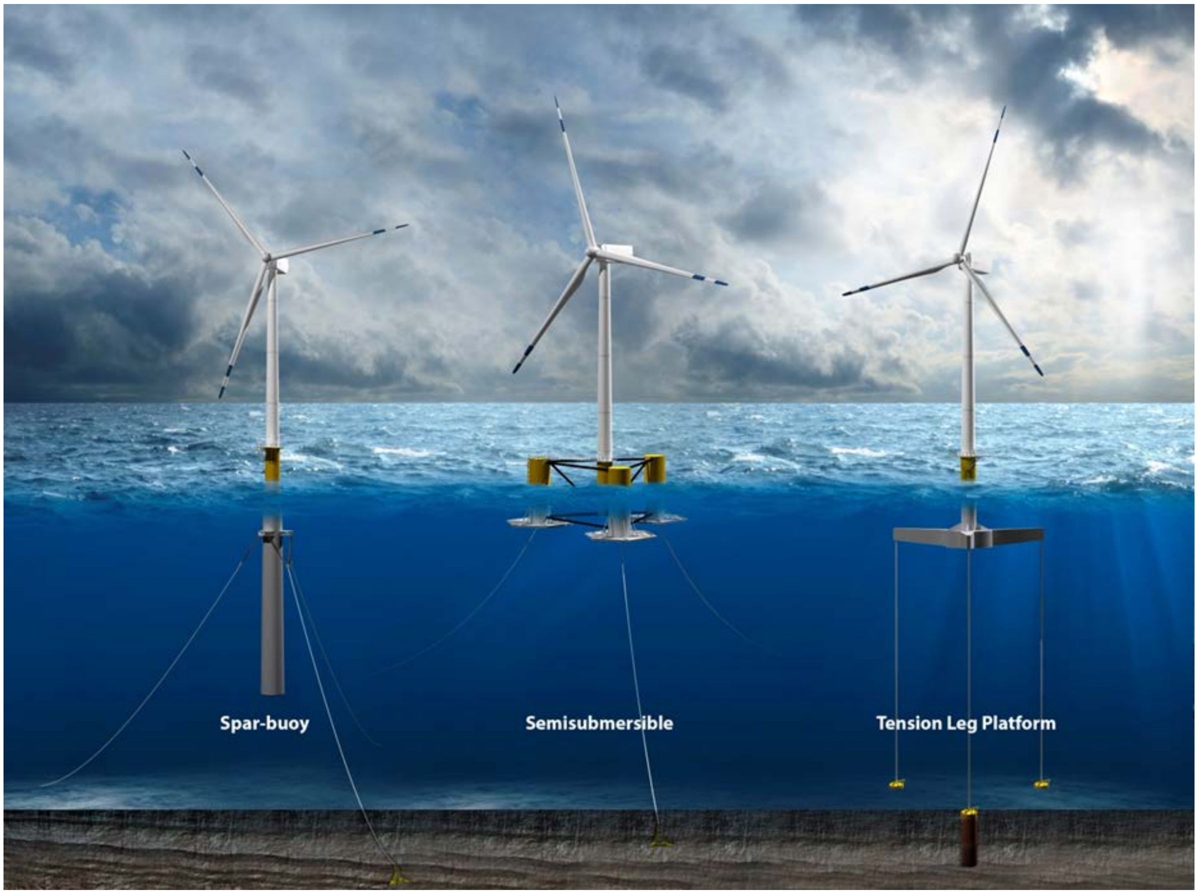


Figure 24. Substructure archetypes for floating offshore wind systems including the spar buoy, semisubmersible, and tension leg platform. *Illustration by Josh Bauer, NREL*

All these concepts have advantages and disadvantages. The semisubmersible design depends primarily on buoyancy and water plane area to maintain static stability. It has the key advantage of being stable enough to support a wind turbine before connecting the mooring lines. Because of its shallow draft, the system can be fully assembled at quayside and towed to its open-ocean operating site with a minimal amount of expensive labor at sea. Semisubmersibles can also be disconnected from their moorings at sea and towed to shore for maintenance at quayside to avoid expensive lift vessels that may otherwise be required for some repairs of major components. Commercial applications include the Kincardine Offshore Wind Farm (Scotland), which delivered first power in September 2018. The spar buoy is stabilized by ballast and has a deeper draft (i.e., the substructure penetrates farther below the water surface) that avoids surface wave action (Musial and Ram 2010). A 30-MW pilot-scale floating project, the world's first commercial floating wind power plant, was deployed by Equinor in October 2017 off Peterhead, Scotland, using spar technology. The deep draft of the spar required Equinor to assemble the wind turbine systems at sea in a sheltered deep-water area, which is rarely found in most coastal regions. This unique assembly requirement adds cost and may not be scalable to larger projects or to parts of the world where deep-water assembly is not available.

One example of a promising hybrid between the spar buoy and semisubmersible substructures has been proposed by Stiesdal, known as the TetraSpar. The TetraSpar relies on a deployable

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

ballast weight that can be secured near the surface to stabilize the system in a low-draft state for assembly and load-out at quayside, and subsequently lowered at the project site for stable operation (Weston 2019).

The tension leg platform gets its static stability from mooring-line tension. Therefore, it is generally unstable until the mooring lines are attached. It can be difficult to deploy but is stable once installed. The unstable deployment challenge makes it difficult to assemble at quayside and may increase expensive labor at sea. New concepts are under development to lower labor at sea and promise lower deployment and assemble costs. One concept comes from a Dutch company, SBM Offshore, which has won a contract to deliver three floating tension leg platforms for the 24-MW Provence Grand Large pilot wind energy project in the French Mediterranean in November 2016. The SBM tension leg platform substructure is unique because its buoyancy system is at the surface during assembly and stabilizes the system to enable turbine installation before attaching the mooring lines.

The optimum platform configuration for a given project depends on site-specific variables, such as bathymetry, soil conditions, competing use constraints, and availability of vessels and infrastructure. All three substructure archetypes could be suitable for waters in Oregon, but semisubmersibles are currently dominating the early start of the floating wind industry. Recent unsolicited lease requests submitted to BOEM in California and Hawaii propose to use the semisubmersible type foundation (BOEM 2016a; 2016b). The pipeline for floating wind systems shows that 94% of proposed floating projects are using semisubmersibles. Therefore, semisubmersibles were chosen as the substructure to be modeled in the Oregon cost analysis. The early dominance of the semisubmersible substructure in the market, however, does not preclude other platform concepts from gaining future market share. As the market matures, the design that can deliver an optimal balance between costs, risk, and value will be favored.

3.2 Technology Assumptions

Based on NREL's engineering experience with turbine and substructure technology advancement and detailed research on economic market trends, an increasing turbine size was assumed for this study for each of the four focus COD years: 2019, 2022, 2027, and 2032.

One of the major technology cost drivers for floating wind is the introduction of larger turbines. Increasing turbine size has historically led to reduced balance-of-system (e.g., elements of the offshore wind plant other than the turbine) and O&M costs per megawatt. Recent industry cost declines can, in part, be attributed to the use of larger offshore-specific wind turbines (Beiter et al. 2018). Current market data indicate that the trend toward larger machines is likely to continue. Vestas has recently released its 9.5-MW and 10-MW wind turbines to the offshore market with the first commercial deployments now underway (MHI Vestas 2018). In addition, GE and Siemens Gamesa have announced the introduction of a 12-MW and 10-MW turbine for commercial availability in 2022 (General Electric 2018; Siemens Gamesa 2019).

Table 2 describes the major technology assumptions for the modeling and results described later.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Table 2. Technology Assumptions for Oregon Offshore Wind Cost Analysis

Commercial Operation Date	2019	2022	2027	2032
Turbine Rated Power (MW)	6	10	12	15
Turbine Rotor Diameter (m)	155	178	222	248
Turbine Hub Height (m)	100	114	136	149
Turbine Specific Power (Watts/m^2)	318	401	310	311
Substructure Technology	Semisubmersible	Semisubmersible	Semisubmersible	Semisubmersible

We assume that by 2022, the industry would be able to deploy a 10-MW turbine with a 178-m rotor. This is a reasonable assumption because these turbines are available commercially today (MHI Vestas 2019). In 2027, we assume that 12-MW commercial wind turbines could be deployed in large-scale projects in Oregon. GE reports that the first prototype 12-MW turbine is being installed in 2019, and it will be available to the market in 2022. In 2032, we assume that a 15-MW turbine will be available. Some turbine manufacturers including GE are already planning turbines as large as 15 MW. These assumptions account for the fact that the turbine must be on the market at financial close; 2 years before COD. Although there is some uncertainty associated with the commercial availability of turbine designs currently in planning phases, the assumed turbine size trajectory is considered conservative. Developers tend to utilize the latest available turbine technology for new projects and have factored in these future turbine designs of up to 15 MW in their current planning process for future projects. Note that the Musial et al. (2016a) California study used even more conservative assumptions in estimating turbine growth; a major differentiator between these two studies and reflection of the rapid technology innovation pathway that the industry has pursued in recent years. Appendix C contains a baseline cost analysis that uses the technology assumptions from Musial et al. (2016a) to calculate the cost at each of the five Oregon sites.

Table 2 also describes another technology trend toward larger rotors and lower specific power ratings, a trend observed in the evolution of land-based turbines.[17] Tower height offshore is expected to increase only enough to accommodate longer blade lengths, thereby maintaining tip clearances of about 25 m with the flat-water surface. For fixed-bottom offshore wind turbines, increases in turbine size require a commensurate upsize in turbine installation vessels. This study assumes that large floating turbines will enable full-system assembly in a port or sheltered assembly areas with stable tow-out to sea, relaxing most large vessel constraints.

Power curves were developed by NREL for each of the turbines indicated in Table 2, except for the 2022 10-MW power curve, which comes from the Danish Technical University's (DTU) 10-MW reference turbine. These power curves are shown in Figure 25 with the corresponding data provided in Appendix C (Table C.1).[18] The power curves reflect modest performance improvements based on energy capture over the next decade. In general, the power curves have a slightly more aggressive power coefficient than current industry turbines by about 2% based on historical performance improvements observed over the last decade. However, the assumed

[17] A wind turbine's specific power is the ratio of its nameplate capacity rating to its rotor-swept area. All else being equal, a decline in specific power should lead to an increase in capacity factor.
[18] Note that the "DTU Reference 10-MW" turbine has a rated power of 10.64 MW but is labeled here as a 10-MW turbine.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

performance improvements are considered conservative compared to historical advances realized by land-based wind (Wiser et al. 2016).

The power curves embody typical features included in all variable-speed pitch-controlled wind turbine power curves today. Cut-in wind speeds reach around 3 m/s when the turbine begins to produce power and enters Region 2 of the power curve. The power increases with wind speed until it reaches its rated power level at about 11 m/s.[19] At rated power, power production levels off and is pitch-regulated (Region 3) to maintain constant power until cut-out wind speed is reached at about 25 m/s. At cut-out, the turbine is automatically shut down by feathering the blades to a zero-power position.

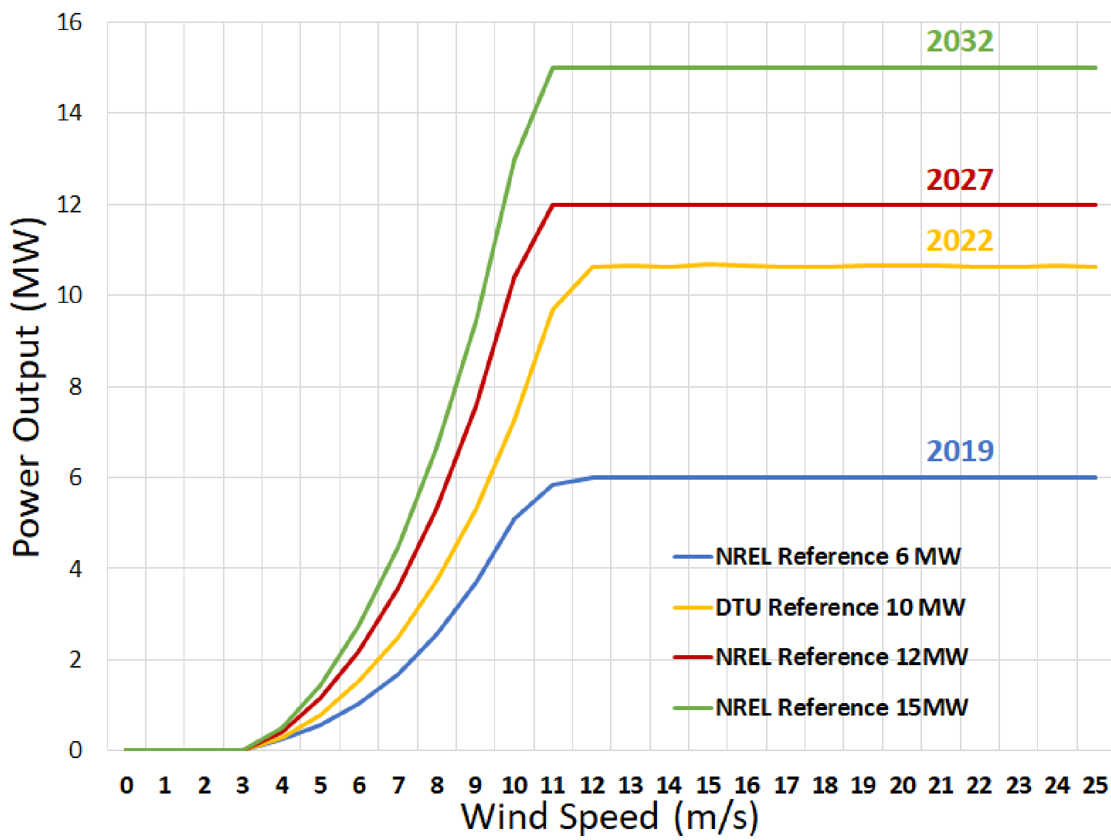


Figure 25. Offshore wind turbine power curves corresponding to 2019, 2022, 2027, and 2032[20]

These power curves were corrected empirically in the shoulder region of the power curve near rated power (between Region 2 and 3), to roll off power gradually when transitioning to Region 3 (the regulated level power state between rated power and cut-out) to represent the actual behavior of turbine power curves in turbulent wind flow. These curves were validated by comparison with proprietary power curves from operating wind turbines.

[19] The part of the power curve between cut-in and rated power is called Region 2. The part of the power curve where the pitch system is maintaining rated power is called Region 3.
[20] Note: 1 megawatt = 1,000 kilowatts

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

The DTU 10-MW power curve was chosen because the reference turbine is well-documented, publicly available, and representative of turbine technology that could be deployed in 2022. It has a smaller rotor and higher specific power rating than the next generation of 10- to 12-MW turbines (Bak 2013).

4. Electricity Production and Use

4.1 Overview of Energy Analysis Methodology

Net annual energy production (AEP_{net}) has more impact on cost of energy than any other variable in the LCOE equation. AEP calculations were carried out for all five study sites assuming a 600-MW commercial-scale wind power plant. These results were used as an input to the final cost analysis. A plant size of 600 MW was assumed to represent a commercial-scale project. Accordingly, NREL's cost modeling relationships in ORCA are calibrated for this plant size. Note that although some U.S. projects are planned for smaller project sizes (e.g., US Wind [248 MW] and Skipjack [120 MW]), several recent projects planned for commercial operation in the mid-2020s exceed a project size of 600 MW (e.g., Vineyard Wind [800 MW] and Ocean Wind [1,100 MW]) (Musial et al. 2019). The net annual energy production was calculated for each of the turbines in their respective COD year. Each turbine was assumed to be operating in a 600-MW array located around the centroid of each of the five study sites described in Section 2. Using hourly wind speed data (described in Section 4.4.1), the gross AEP was first calculated. It was then adjusted to account for wake losses, electrical losses, and a range of other losses associated with turbine inefficiencies and reliability issues to arrive at the net capacity factor (NCF) and AEP_{net}.

In addition, this section provides an assessment of the diurnal and seasonal offshore wind energy generating potential and compares these diurnal wind characteristics to average load profiles within the Bonneville Power Administration (BPA). These temporal resource characteristics can play a key role in understanding how well offshore wind energy will integrate with other variable generating sources on the grid.

4.2 Wind Resource Data Source

In recent years, NREL introduced the high-resolution Wind Integration National Dataset (WIND)Toolkit database, which is now being implemented as the primary data set for offshore resource assessment in the continental United States. The WIND Toolkit database, which was developed under DOE funding, is owned and maintained by NREL. It is based on modern mesoscale dynamics, physics, and input data sets, and is a time series product available at a 5-minute resolution (Draxl 2015).

The WIND Toolkit database consists of a wind resource and forecast data set with a 2-by-2-km grid and 20-m vertical resolution from the surface to a 200-m elevation. It includes meteorological and power data for every 5 minutes. The database is based on simulations from seven complete years of data between 2007 and 2013 from the open-source Weather Research and Forecasting mesoscale model, developed and maintained by the National Center for Atmospheric Research. The state-of-the-art Weather Research and Forecasting model is used globally by tens of thousands of users. It is updated at least twice annually to incorporate the latest research and development advancements.

The offshore wind resource is uniquely different from its land-based counterpart because of a range of physical phenomena resulting from the air-sea and land-sea boundaries, including coastal low-level jets, radiative cooling at the top of marine stratocumulus clouds, variable surface conditions (e.g., waves), coastal circulations (e.g., sea breezes) and internal boundary layers. The inability to account for these complex phenomena can introduce errors in the estimates of the wind speed and power resource (i.e., wind power plant energy production, diurnal ramping, and so on). Recent comparisons by NREL another more dated UL data set, which was formally used as the primary wind resource data set, indicate differences and uncertainty that are difficult to resolve with the present state-of-the-art in offshore wind resource characterization over broad state and regional levels. Although the present WIND Toolkit data set does not fully account for uncertainty, it is currently the best data set available in the public domain. Gridded Weather Research and Forecasting modeled offshore wind data and metadata are available on NREL's Wind Prospector at https://maps.nrel.gov/wind-prospector.

4.3 Diurnal and Monthly Resource Characteristics

From the WIND Toolkit data set described earlier, the average diurnal wind speed was calculated for each of the five study sites. These data are shown in Figures 26 and 27 for the months of January and July. The plots in Figure 26 show the average January diurnal variations for each study site using data from 2007 to 2013. The figure shows that for the month of January, the variations are virtually flat over the day. Also, the figure shows that the variations between study sites are the lowest for this month. In other words, given the large annual average wind speed range across the five study sites, the January data show that all five study sites are relatively close in their diurnal range, as well as their average wind speed, with all five study sites grouped between 9 and 10 m/s.

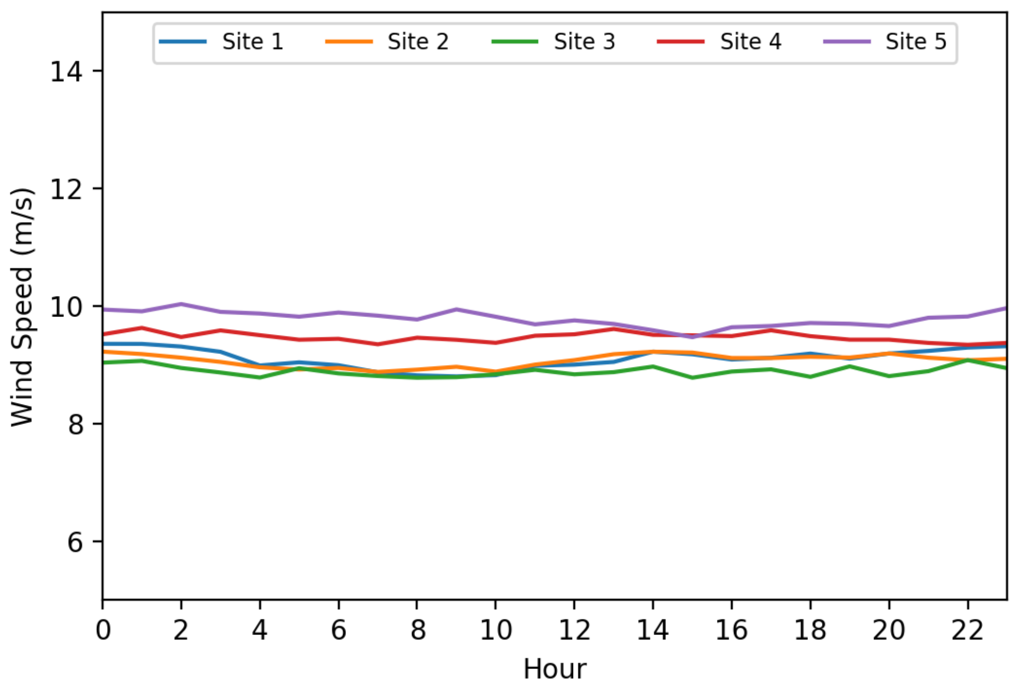


Figure 26. Diurnal average wind speed for five Oregon study sites in the month of January

Figure 27 shows significantly different behavior. The diurnal range for July indicates pronounced cyclic variations of 1 m/s to 2 m/s during a 24-hour period, with peak winds occurring in the middle of the night between 11 p.m. and 2 a.m. The peak winds are later in the night for the more northern sites. The figure also shows a strong separation based on absolute

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

wind speed that reveals the strong north-south average wind speed gradient, with Site 5 showing wind speeds 5 m/s greater than Site 1 in the north.

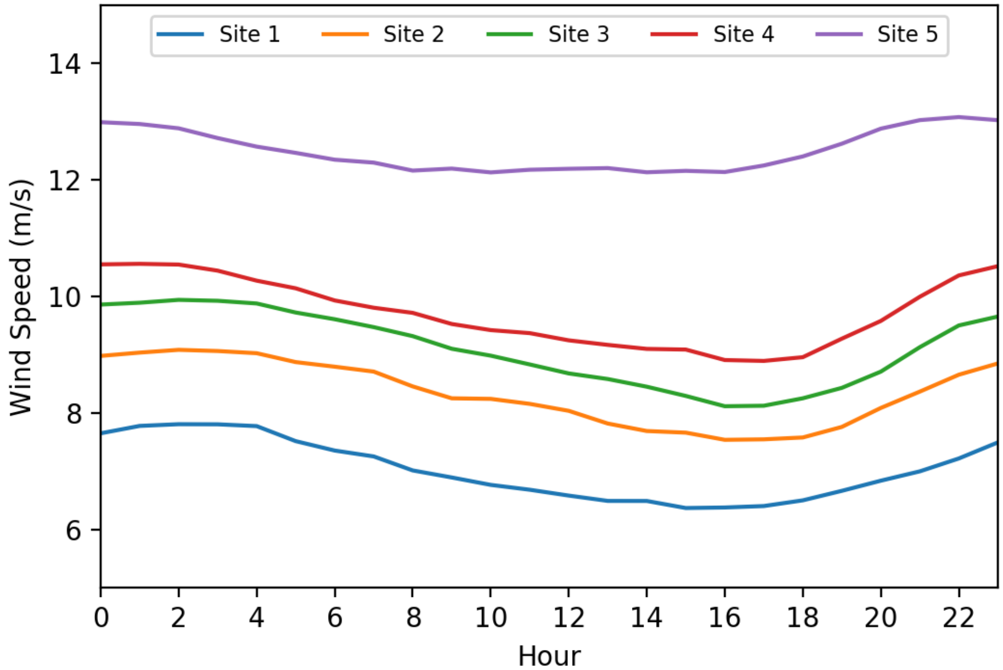


Figure 27. Diurnal wind speed for five Oregon study sites in the month of July (0 = midnight)

Figure 28 shows the average monthly distribution of all five study sites over a 12-month period.

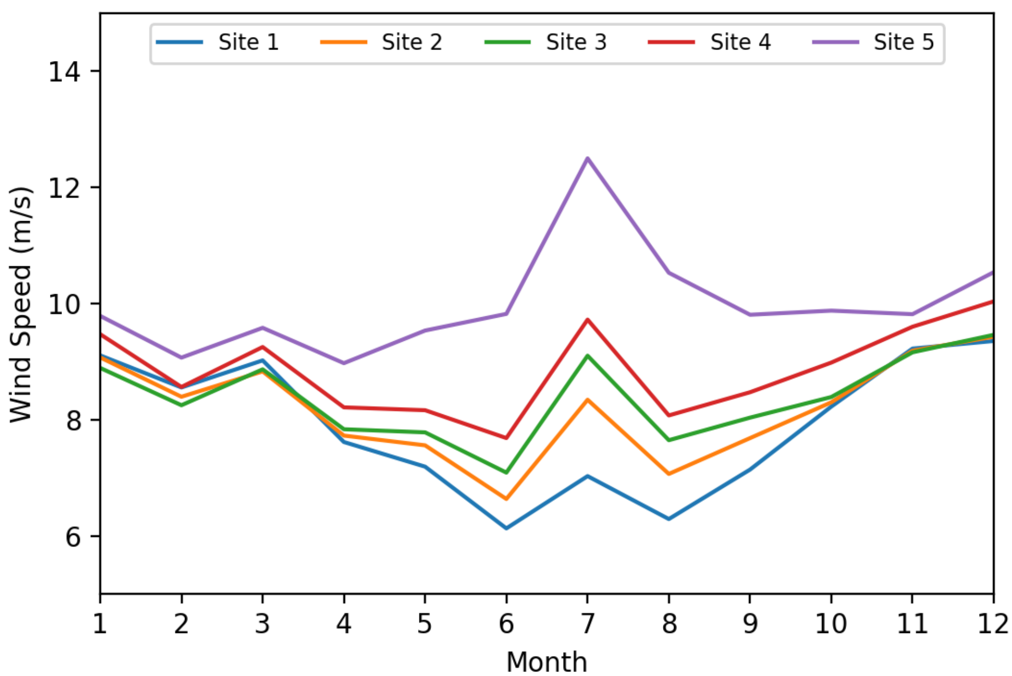


Figure 28. Average monthly wind speed at five Oregon study sites (January = 1)

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

The data in Figure 28 show that the summer months have a much wider variation from site to site in average wind speed. This geographic variation in average wind speeds during this time suggests that the north-south wind speed gradient is more pronounced in the summer months.

This apparent winter/summer characteristic wind pattern was investigated further by NREL atmospheric scientists. The average monthly wind speed data for each month in the 7-year wind time series was plotted in Figure 29 for Site 5 only. This figure shows observable variability from year to year. Note that red dots have been placed on the average wind speeds for the month of July in each year to illustrate the range. In this example, the average wind speed in July varied between approximately 9.6 m/s in 2007 and 13.7 m/s in 2013. This variability could indicate a high degree of uncertainty and that a longer record of wind speeds is needed.

Appendix B has the diurnal wind characteristic by month for each of the five study sites.

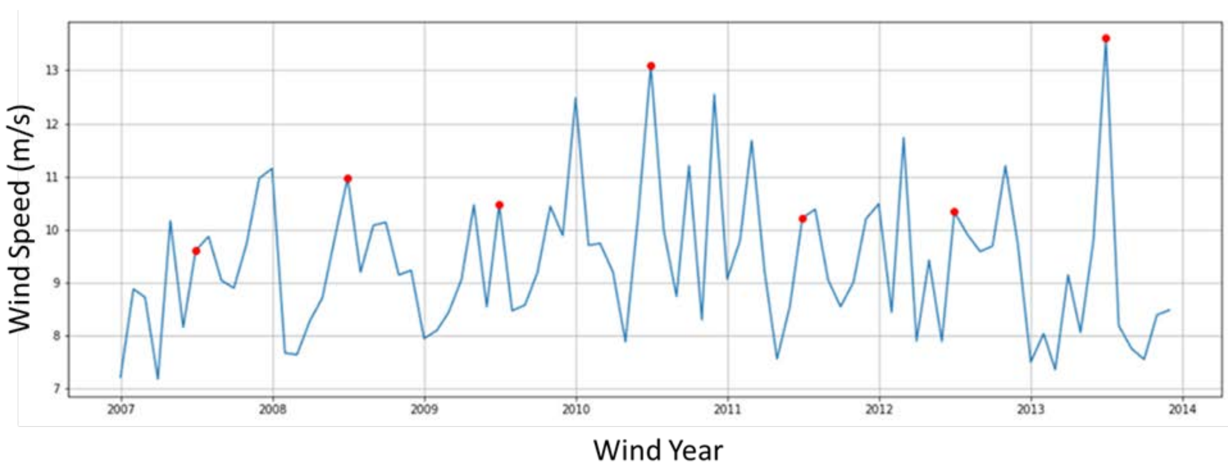


Figure 29. Monthly average wind speeds for Site 5 in southern Oregon for the entire WIND Toolkit data record

4.4 Annual Energy Production

4.4.1 General Methodology

Seven-year WIND Toolkit hourly time series were used in combination with the power curves shown in Figure 25 to calculate the gross energy production.[21] The 7-year data record was averaged to obtain a typical year. The gross AEP was calculated for a generic 600-MW wind power plant and was assumed to be constant for each model year from 2019 through 2032. The sum of the energy produced by a single turbine during 8,760 hours (1 year) was multiplied by the number of turbines in the 600-MW array in each model year.[22] The gross capacity factor was calculated by dividing the gross AEP by the maximum energy that the 600-MW power plant

[21] The gross AEP is defined as the energy that the wind plant would produce at a given site without losses and is based only on the power curves in Figure 25 and the WIND Toolkit wind speed time series.
[22] For instance, in 2019, there are one hundred 6-MW turbines; in 2022, there are sixty 10-MW turbines; in 2027, there are fifty 12-MW turbines, and in 2032, there are forty 15-MW turbines.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

could produce.[23] These values are shown in Table 3 for each of the model years, respectively. AEP_{net}[24] is determined by applying loss estimates to the calculated gross AEP. The losses account for the reduction in power delivery to the grid as a result of site conditions and wind plant inefficiencies (Section 4.4.2). NCF is the net AEP divided by the maximum energy the wind power plant can produce, running continuously at rated power without losses or inefficiencies.

Table 3. Gross Capacity Factors, Losses, Net Capacity Factors, and AEP_{net} for Oregon Sites

6 MW 2019					
100-m Hub Height	Site 1	Site 2	Site 3	Site 4	Site 5
Gross Capacity Factor	43.48%	46.26%	47.20%	50.68%	59.74%
Total Losses	16.78%	18.09%	15.91%	15.73%	14.71%
Net Capacity Factor	36.18%	37.89%	39.69%	42.71%	50.95%
AEP_{net} (GWh)	1,902	1,991	2,086	2,245	2,678
10 MW 2022					
114-m Hub Height	Site 1	Site 2	Site 3	Site 4	Site 5
Gross Capacity Factor	42.85%	45.90%	47.08%	50.98%	61.12%
Total Losses	16.63%	17.93%	15.77%	15.59%	14.58%
Net Capacity Factor	35.72%	37.67%	39.65%	43.03%	52.21%
AEP_{net} (GWh)	1,877	1,980	2,084	2,262	2,744
12 MW 2027					
136-m Hub Height	Site 1	Site 2	Site 3	Site 4	Site 5
Gross Capacity Factor	46.15%	49.10%	50.39%	53.94%	62.49%
Total Losses	16.58%	17.88%	15.72%	15.54%	14.53%
Net Capacity Factor	38.50%	40.32%	42.47%	45.55%	53.41%
AEP_{net} (GWh)	2,023	2,119	2,232	2,394	2,807
15 MW 2032					
149-m Hub Height	Site 1	Site 2	Site 3	Site 4	Site 5
Gross Capacity Factor	47.77%	50.82%	52.28%	55.87%	64.54%
Total Losses	16.32%	17.60%	15.47%	15.30%	14.30%
Net Capacity Factor	39.97%	41.88%	44.19%	47.32%	55.31%
AEP_{net} (GWh)	2,101	2,201	2,323	2,487	2,907

4.4.2 Energy Loss Estimates and Assumptions

Total energy loss estimates for model years 2019, 2022, 2027, and 2032 are provided in Table 3. Losses account for differences between the annual energy output of the turbines operating at the site without obstruction, inefficiencies, or downtime, and the actual electricity delivered to the grid. Losses were generally assessed using standard industry assumptions (AWS Truepower

[23] Maximum energy production is the nameplate rating of 600 MW x 8,760 hours/year.

[24] AEP_{net} can be thought of as the energy delivered to the land-based grid at the substation.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

2014). For this analysis, energy losses were divided into generic and site-specific losses. Generic losses (i.e., environmental and technical losses) were held constant for all sites over time. Site-specific losses (i.e., wake, electrical resistance, and availability losses) varied among the study sites. The loss percentages were applied to the gross AEP to compute the net AEP for each model year. Environmental losses include energy lost because of surface roughness created by contamination or erosion on the blades, lightning damage, or shutdowns caused by extreme temperatures. Technical losses include inefficiencies caused by issues such as drivetrain wear or pitch system imbalance. Site-specific losses include energy lost as a result of turbines operating in the wake of other turbines, electrical losses caused by the transmission of the electricity in the array and to shore, and turbine availability issues that are driven by O&M accessibility limitations from the prevailing wave environment, as well as general turbine reliability.

4.4.2.1 Generic Losses

The generic losses include 1% for energy lost as a result of icing or blade soiling, which can be more significant in land-based applications. The 1% loss may be high for offshore sites in Oregon where ice or soiling accumulations on blades would be rare. In addition, generic losses include 0.5% for low/high temperature shutdowns, 0.1% for lightning losses, 1% losses as a result of hysteresis, 0.1% for onboard equipment (parasitic load), and 0.1% for rotor misalignment loss across all turbines. These standard industry assumptions for generic losses should be further assessed in actual AEP calculations, but are considered representative of industry progress expected over the next decade.

4.4.2.2 Site-Specific Losses

Site-specific losses include wake losses, electrical losses, and availability losses. Each was calculated by considering the spatial conditions at each reference site (e.g., electrical losses vary with distance to the point of grid interconnection and water depth).

Wake losses for a 6-MW wind turbine array were computed in an earlier study using the NREL Offshore Wind Cost Model (Beiter et al. 2016). They were calculated for the major United States offshore wind resource areas using Openwind, a software program developed by AWS Truepower (AWS Truepower 2010). For this analysis, we used these wake loss results for the Oregon OCS using a 6-MW turbine array. As described by Beiter et al. (2016), turbines were arranged in 10-by-10 arrays with 7-rotor diameter spacing[25] and were derived as a function of wind speed, with wind speed steps of 1 m/s estimated for wind speed ranges between 5 and 30 m/s. The analysis did not consider the likely possibility that more optimized array configurations than the modeled 10-by-10 square array could be implemented to lower losses further at each site. As such, the 10-by-10 square array loss calculations would overstate losses if a more efficient array layout is used. Electrical losses were derived using PSCAD, a general-purpose time domain simulation tool for studying transient behavior of electrical networks. We developed parametric equations that capture electrical losses as a function of distance from the site to the point of interconnection and water depth (i.e., total cable length). We calculated availability through a series of runs within the ECN O&M tool, which varies by distance to

[25] Rotor diameter is typically used as the primary measure for turbine separation in an array. This spacing means that there are 7 rotor diameters of distance between individual towers. For example, the 6-MW turbine has a diameter of 155 m, which means that there would be 7 x 155 m, or 1,085 meters of distance between individual towers.

O&M port and wave regime. Availability losses are particularly severe in the Oregon wave climate relative to other parts of the United States. These conditions would likely hinder turbine access (such as in the European North Sea or the U.S. Northeast) initially. Therefore, turbine availability is likely to be lower at first (Beiter et al. 2016). Over time, new O&M strategies for turbine access are likely to mitigate some of these turbine access issues and help restore availability to more normal industry values (Beiter et al. 2016).

To account for future innovations that might decrease losses in future model years (i.e., 2022, 2027, and 2032), this study derived cost reduction potentials from Hundleby et al. (2017) (as shown in Table 5). These include loss improvements achieved through a set of innovations, such as:[26]

- Multivariable optimization of array layouts, allowing for better consideration of design criteria trade-offs between wake effects, array cable costs, substructure, consenting, and installation and O&M costs
- Advanced wind resource characterization by using improved virtual and remote data sources to better model wake effects
- Improved sea condition monitoring, which can inform optimal substructure selection and, as a result, improved O&M accessibility (i.e., higher availability)
- Use of DC power take-off, which eliminates the need for AC power conversion and reduces associated electrical losses
- New turbine configurations, which are specific to design drivers of offshore wind, such as down-wind turbines and DOE Atmosphere to Electrons' innovations
- Introduction of direct-drive superconducting drivetrains, which reduces electrical resistance in the generator and losses
- Continuously variable drivetrains, which increase reliability and thereby reduce availability losses
- Improvements in blade design standards, which can deliver improved aerodynamic performance through the use of more advanced tools and modeling techniques resulting in a reduction of losses from technical issues related to blades.

These innovations (and related cost reductions) were associated with model years 2022, 2027, and 2032 in alignment with Hundleby et al. (2017), considering the degree of commercial readiness of an innovation and the market share. The latter accounts for the compatibility of different innovations, as some innovations cannot be combined (e.g., because of different assembly methods).

4.4.3 Net Capacity Factor

Figure 30 shows the net capacity factors resulting from the Oregon AEP analysis. The figure shows that NCF increases steadily from 2019 to 2032 as larger turbine technology increases unit energy production because of taller towers, lowers electrical losses as a result of shorter cable runs, and increases availability over time. The figure shows the NCF for each of the five study

[26] A subset of all innovations related to losses are shown here. See Hundleby et al. (2017) for the full set of innovations related to loss reductions and a detailed discussion.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

sites, which indicates the increase in NCF geographically from north to south. This increase in NCF can be attributed almost exclusively to higher average wind speeds found in the south.

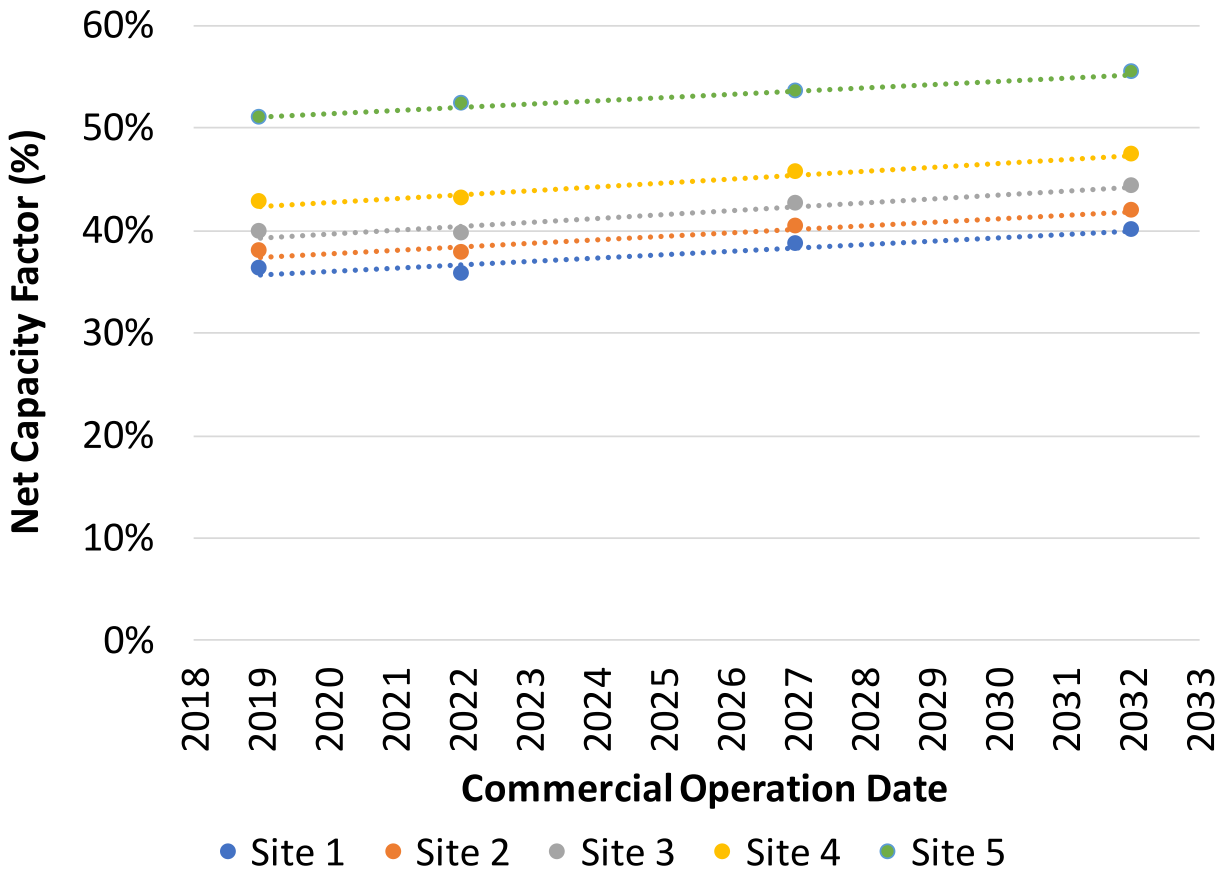


Figure 30. Estimated net capacity factors for Oregon

4.5 Oregon Electric Energy Use

4.5.1 State Electric Energy Profile

Oregon used a total of 48,157,378 MWh of electricity per year averaged over the period from 2014 through 2016 according to the Oregon Department of Energy (Oregon 2019). Based on electricity sales, this breaks down to 40.47% from hydroelectric facilities, 31.89% from coal, 16.58% from natural gas, 6.48% from land-based wind, 3.25% from nuclear, and the remaining 1.33% from a miscellaneous assortment of biomass, solar, and other sources, as shown in Figure 31.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

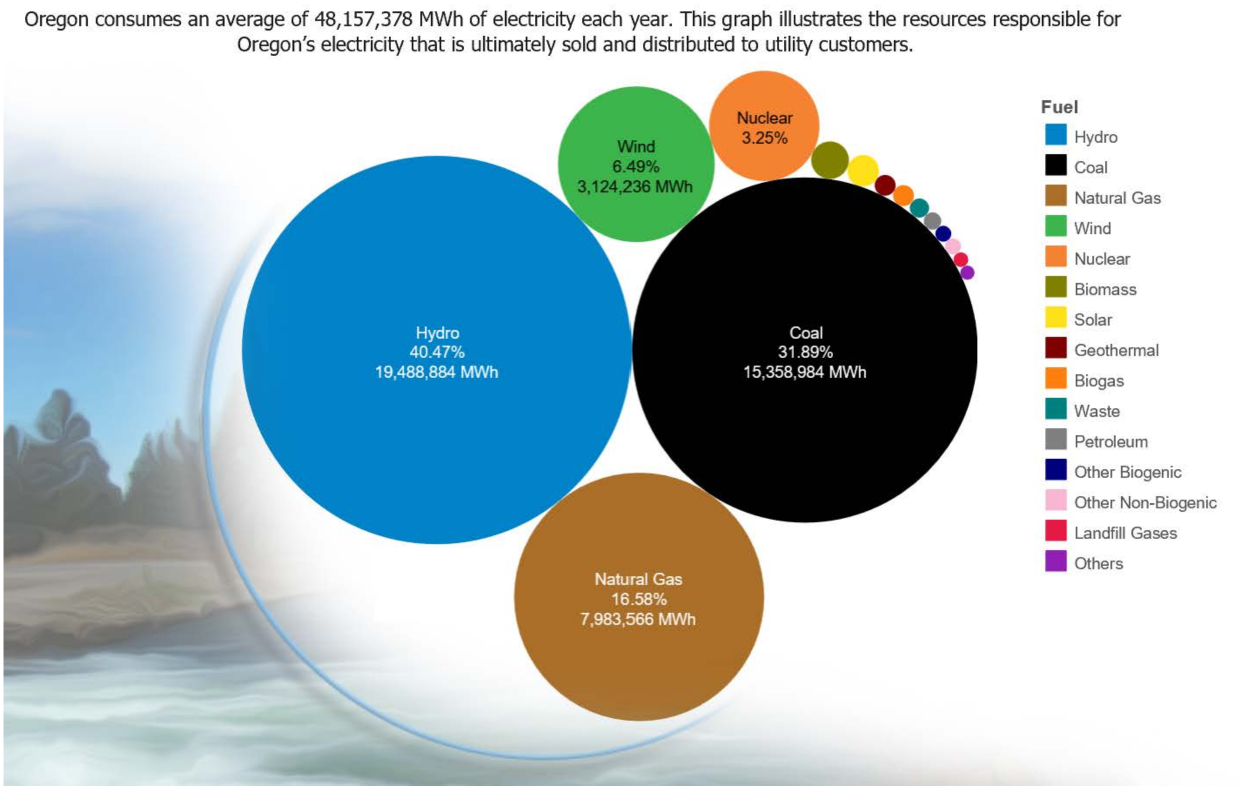


Figure 31. Fuels used to generate electricity in Oregon. *Image from the Oregon Department of Energy (2019)*

4.5.2 Oregon Utility Grid and Transmission

In Oregon, the BPA, in coordination with local electric utilities, markets wholesale electricity from over 30 hydroelectric plants, one nuclear plant, and several other power plants. The BPA is a nonprofit federal power marketing administration with service territory that covers much of the Pacific Northwest including Idaho, Oregon, Washington, western Montana, and small parts of eastern Montana, California, Nevada, Utah, and Wyoming (BPA 2019). BPA is part of DOE, but is self-funded through electric sales and services. It serves nearly 3 million customers, owns about one-third of its generation, and operates and maintains about three-fourths of the high-voltage transmission in its service territory. Figure 32 shows the BPA service territory in relationship to the state of Oregon and the rest of the continental United States.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

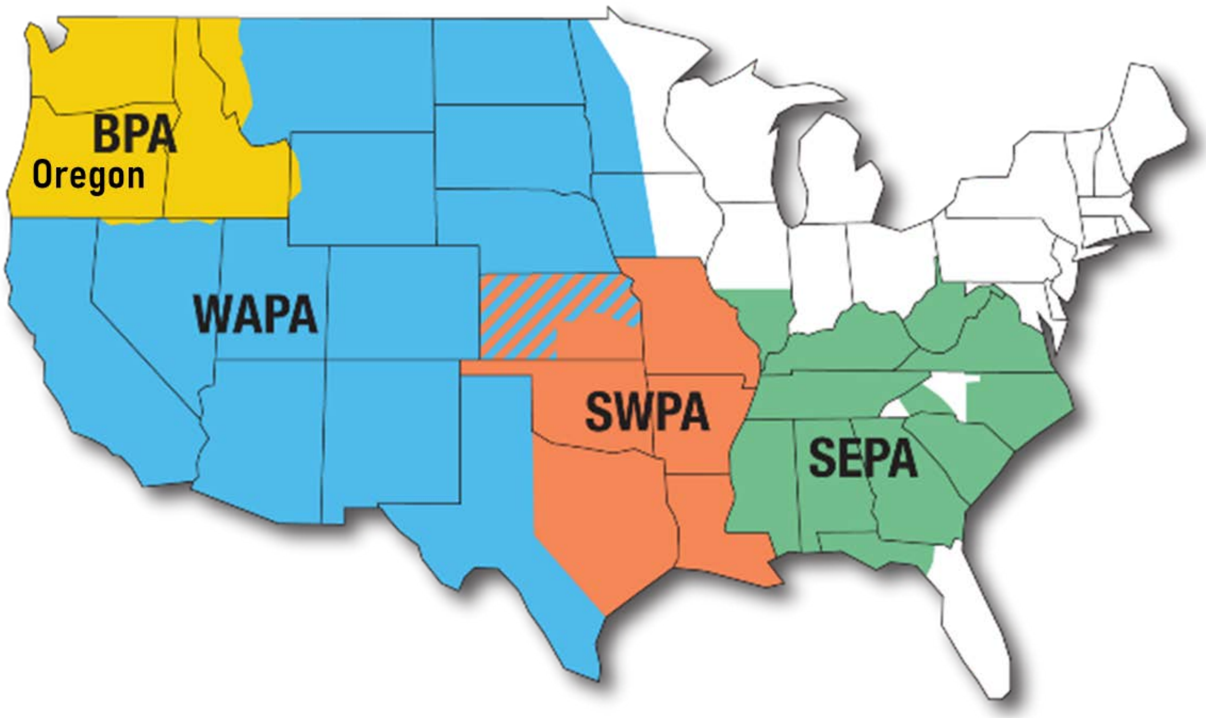


Figure 32. BPA service territory shown in relation to the state of Oregon[27]

Although comparisons to the state's energy consumption and energy targets are often made to inform political decisions and metrics, it is difficult to describe the impact that offshore wind might have on the land-based utility grid without a regional discussion that includes the wider boundaries of the BPA service territory.

With the regional aspect of the BPA in mind, the delivery of electric power in Oregon is defined and constrained by several geographic features. As shown in Figure 1, the coastal mountain range separates a narrow strip of rural coastal communities from the central Willamette Valley, where most of Oregon's 4.91 million people reside. Power flows from the Willamette Valley over the coastal range via seven east-west transmission pathways, as shown in Figure 33. As the right side of the figure shows, the net power flow is toward the sea to serve the coastal communities. The red arrows indicate the net power flow direction, and the numbers annotated in blue indicate the quantity of power flowing based on average summer and winter values, respectively. The figure also provides the locations of the major substations and potential offtake points for power delivered by possible future offshore wind plants. These target areas are indicated by the green ovals in the figure. One key point to observe from Figure 33 is if power were injected from an offshore wind or marine energy power plant, a significant change in these flow directions would be likely. This power flow disruption would impact the grid system and

[27] Western Area Power Administration (WAPA), South Western Power Administration (SWPA), Southeast Power Administration (SEPA).

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

could have potential benefits for BPA by possibly reducing requirements for transmission expansion in the eastern part of the state.

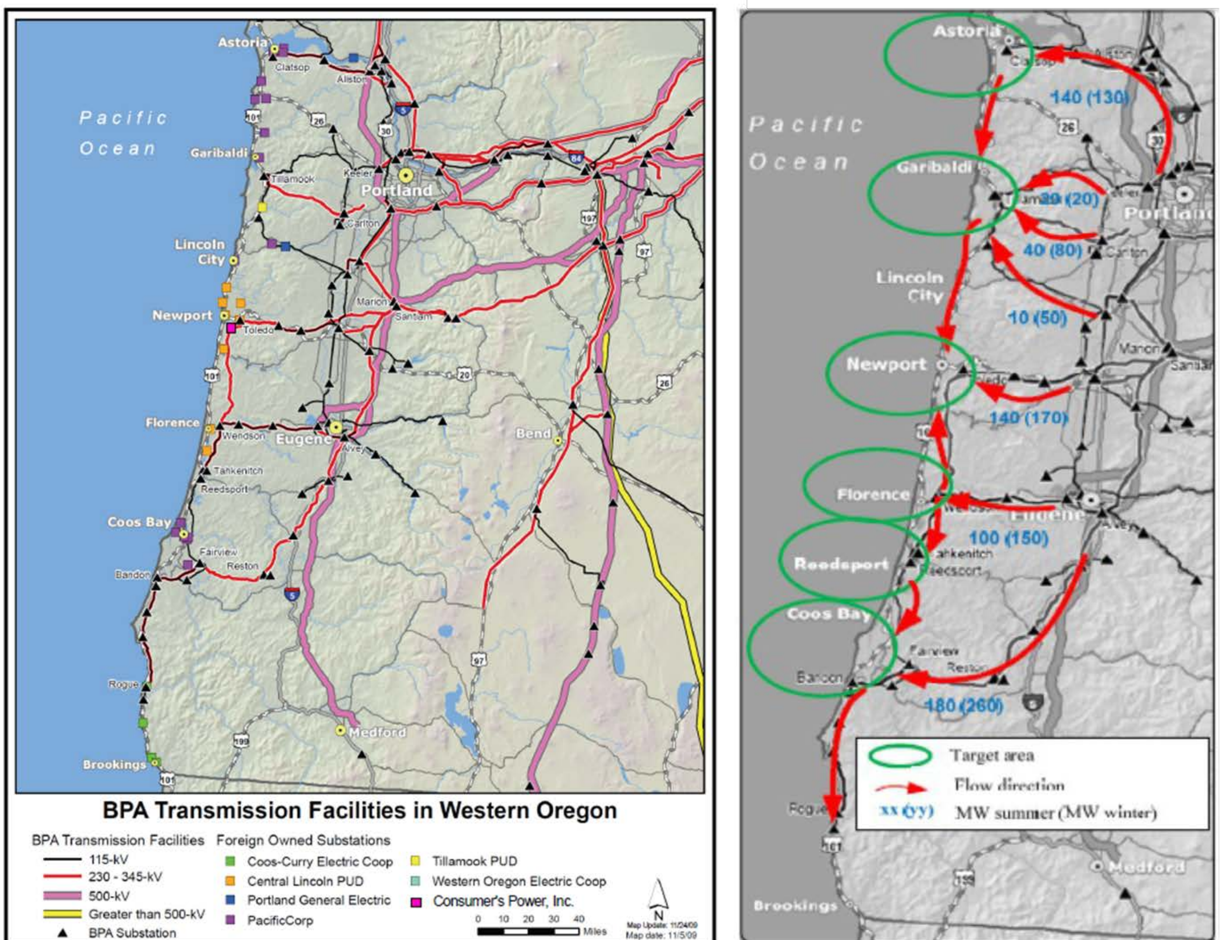


Figure 33. Transmission facilities in Oregon. *Image source: BPA*

The effect of offshore wind on the land-based grid could also have other consequences, but those impacts are beyond the scope of this study. It is recommended that future work investigate the cost impacts on the entire system at different levels of offshore wind penetration.

Figure 34 shows a sample of hourly electricity consumption for the southwest region of Oregon, representative of the load in the vicinity of Site 5. The plot shows the power flow over the calendar year of 2018 (8,760 hours). Note that the wide scatter of the plotted data indicates the diurnal range of energy use showing 365 days of variation. For 2018, the plot shows a peak load in February and the minimum demand (and less day/night variation) for the year in July and throughout the summer. It is notable that July has the strongest winds at Site 5, although the load is lowest during this period.

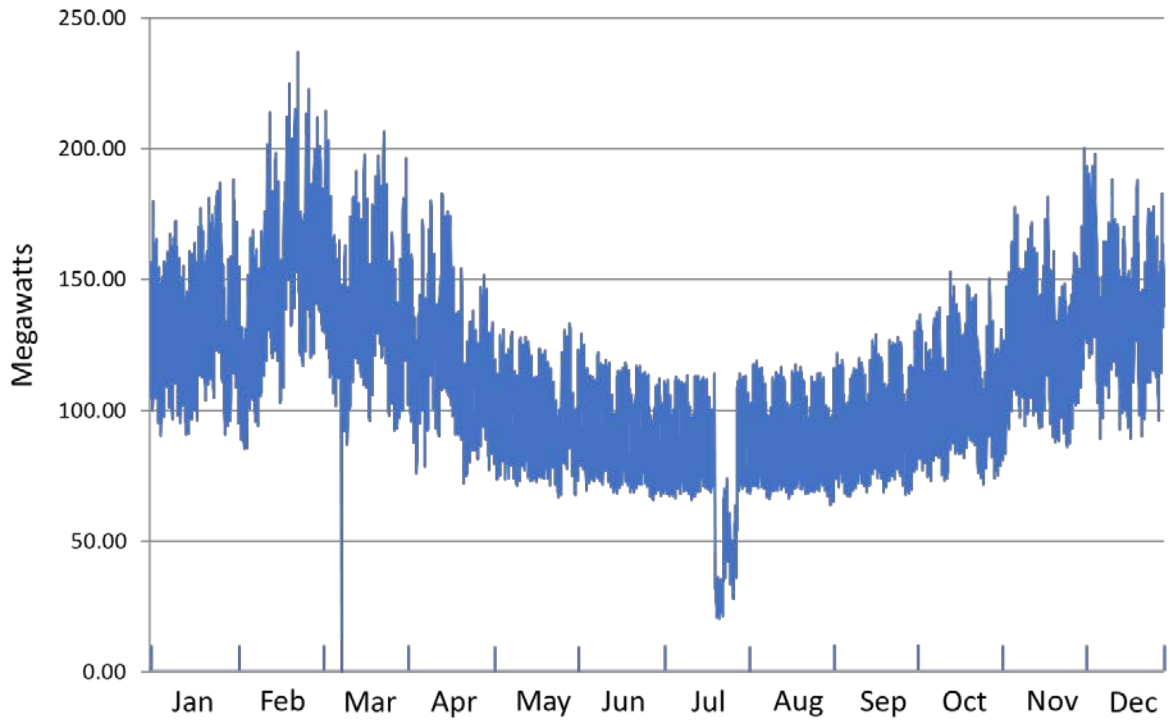


Figure 34. Hourly electricity load for southwest Oregon for 2018

Figure 35 shows the winter and summer diurnal load profiles for locations representative of Site 5 in southwestern Oregon. Note that the characteristics of the two load profiles differ significantly. The winter profile shows a double peak corresponding to increased morning loads electric demand, with a similar magnitude peak in the early evening.

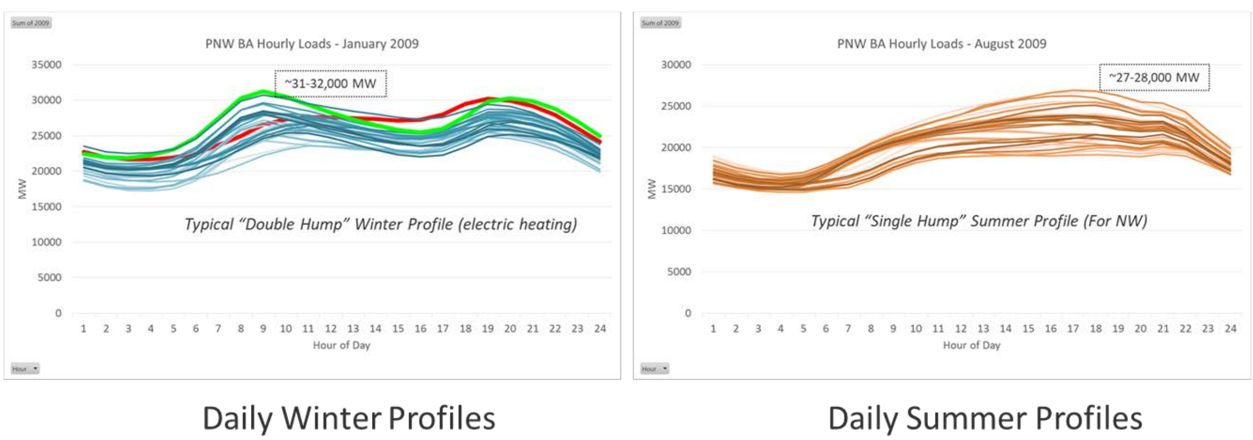


Figure 35. Winter (left) and summer (right) electricity load profiles for the 2009 season in southwest Oregon representative of Site 5. *Data source: Northwest Conservation Council*

Note that Figure 35 shows a characteristic morning peak (green curve) and a characteristic evening peak (green curve) for the same month. The pattern depends on the day of the week and

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

weather systems. For example, in winter, Mondays often have a higher morning peak because businesses have been kept cooler over the weekend and need to catch up. The summer load characteristics show a single peak in the evening, absent the morning peak seen in the winter.

4.5.3 Maximum Offshore Wind Build Scenario

The five study sites modeled in this study provide a visualization of what offshore wind might look like in the state of Oregon. One key question is what is the maximum amount of offshore wind that could be delivered to the Oregon grid in a long-term renewable energy conversion scenario, such as a hypothetical 100% renewable energy scenario?

If all the thermal plants were to eventually retire (Roberts 2019), approximately 25,000 gigawatt-hours (GWh)/year would be needed to replace them. If this generation were replaced by 100% renewable energy sources, offshore wind could be a component of the future mix. If offshore wind provided 80% of that replacement generation, a total of 20,000 GWh/year would be needed. Assuming a net capacity factor of 43%, approximately 5 GW of offshore wind capacity would be needed to generate this quantity of electricity, or approximately the area represented by the five study sites.

Of course, there are many caveats to this simple characterization of offshore wind potential:

- This maximum buildout scenario is purely hypothetical and is intended to provide an order of magnitude approximation for how much offshore wind could potentially be needed.
- The electric energy consumption of 48,157 GWh/year today does not reflect possible load growth that is likely to increase this requirement significantly.
- Generation from offshore wind into coastal regions may be limited by the transmission capacity over the coastal range, in turn limiting the installed capacity potential.
- The area required for 5 GW of offshore wind might be as much as 1,750 km^2, which would involve extensive stakeholder engagement and coordination.
- Other renewables, such as land-based wind and solar, might prove to be more economically attractive, especially in the eastern part of the state.
- The possibility that Oregon could export energy to Washington or California could change the scenario assumptions considerably.

5. NREL Cost Modeling Approach

NREL's ORCA model was used to assess the five study sites identified in Section 2. This section provides details about the model, its underlying and evolving spatial cost relationships, and assumptions. All cost estimates in this report are denoted in $2018, unless indicated otherwise.

One of the primary enhancements applied to the model for this study was to capture the dynamic economic changes experienced by the offshore wind industry over the past 4 years, which have led to market price reductions of over 65% in European auctions for fixed-bottom offshore wind projects reaching commercial operations near 2025. By 2017, it became clear that European markets were consistently driving prices downward, but U.S. market observers believed that because of market immaturity and lack of an established U.S. supply chain, it might take several years for low European prices to be realized in the United States. In 2018, the first U.S. commercial price point was established with the negotiation of a power purchase agreement (PPA) for the 800-MW Vineyard Wind project in Massachusetts. This price point fell within the price range of similar European projects for the same COD. A detailed assessment of the Vineyard Wind price was conducted by NREL for the purpose of tuning the ORCA model and developing a more thorough understanding of the underlying assumptions used for modeling the major cost components of offshore wind systems (Beiter et al. 2019).

Because we expect many major aspects of fixed-bottom costs for offshore wind to be directly related to the future cost of commercial floating systems, the analysis of Vineyard Wind's PPA price was foundational in informing the new model assumptions for floating wind in this report. However, there are several elements in the cost breakdown structure developed by Beiter et al. (2016) for a floating project that are not found in fixed-bottom offshore wind systems. These floating-specific cost elements were assessed individually in the cost breakdown structure, and through market research and consultation with floating offshore wind developers input values were assigned directly in the ORCA model for the 2019 COD year.

Projected cost reductions between 2018 and 2032 are derived from Hundleby et al. (2017) and were assigned to model years 2022, 2027, and 2032 (COD) in ORCA. These reductions represent updated cost projection trends from earlier NREL cost studies (e.g., Beiter et al. 2016; Musial et al. 2016a).

At the time that the 2016 California study was conducted the new European auction price market data and the Vineyard Wind fixed-bottom price insights were not available. In addition, recent advancements made by developers in engineering and documenting floating-specific components at larger scales (e.g., 15-MW substructures) were not known. These additions have been incorporated into this 2019 Oregon study. In 2018, new European cost studies on floating wind were published, which can be generally verified at a high level (Hundleby et al. 2017; WindEurope 2018).

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

5.1 Cost of Energy

The ORCA model follows the general definition of LCOE described in Beiter et al. (2016):

$$LCOE = \frac{(FCR*CapEx) + OpEx}{AEP_{net}}$$

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

Further details about the bottom-up method for calculating CapEx, operational expenditures (OpEx), and AEP_{net} from spatial parameters and financial parameters, such as the fixed charge rate (FCR),[28] are documented in Beiter et al. (2016). The assumptions developed for this model and the major cost reduction categories and relationships are discussed in Section 5.3.

5.2 NREL's Offshore Regional Cost Analyzer Model

ORCA was developed and is maintained by NREL with funding from DOE and was used in this analysis. ORCA was designed to capture the cost and geographic variations of offshore wind across the United States. The model was developed in 2015 to enable the geospatial cost of offshore wind in U.S. waters (for both fixed bottom and floating) to be assessed over time and was documented in detail by Beiter et al. (2016, 2017) and Maness et al. (2017). It was also used to perform the cost analysis in support of the 2016 "National Offshore Wind Strategy" (Gilman 2016). It is being further developed as a tool to evaluate the cost impact of technical innovation and assess regional offshore wind costs over time as the industry evolves. The model is primarily a "bottom-up" tool, which calculates offshore wind cost by summing the individual component costs of the wind power plant system. Therefore, its accuracy is highly dependent on the accuracy of the cost inputs it receives. With costs changing rapidly over the past few years, new information is needed continuously to maintain accurate results. NREL modelers update ORCA when new data become available, but at any given moment, some offshore wind cost areas may be better represented than others.

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

---

[28] The fixed charge rate is used to approximate the average annual payment required to cover the carrying charges on an investment and tax obligations.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Variable costs refer to categories of expenditures that have distinct relationships with spatial parameters. For example, installation costs are expected to vary with logistical distances (e.g., distance from port to site), water depth, and prevailing meteorological ocean conditions.

Cost multipliers vary in general with total project cost to reflect the complexity of certain cost items. For instance, engineering and management costs incurred from financial close through commercial operations are applied as a percentage of capital expenditures (CapEx).

5.3 Cost Modeling Methodology for Oregon

This section describes the cost analysis methods and assumptions for the results described in Section 6.

5.3.1 Overview of Oregon Analysis Method

The cost modeling methodology was broken into several steps. First, we developed a baseline cost using the 2016 California technology and cost modeling assumptions (Musial et al. 2016a) for the five Oregon study sites. In parallel to the baseline analysis, we made structural changes to ORCA to allow for larger turbines up to 15 MW (previously 10 MW was the maximum), and to extend the time frame to 2032 (previously 2027). Both the turbine technology and time extension had considerable impacts on cost.

Developers of semisubmersible technologies were consulted to obtain floating system component costs. These results are not revealed in this report because of their proprietary nature, but generally came from internal engineering designs or from vendor quotes. These data were modified using methods of averaging to avoid disclosure and applied to ORCA for this analysis.

The upgraded ORCA model was run using the new technology and economic assumptions, and cost data described earlier for the five Oregon study sites. The primary model inputs are CapEx, OpEx, and AEP_{net} (Section 4). The primary output from ORCA is the LCOE for each of the five sites.

The scope of this study does not allow for a detailed analysis of the value of offshore wind to the Oregon electricity grid, but the data provided on Oregon energy use profiles and grid capacity in Section 4 may establish an initial basis for future work in this area.

5.3.2 Baseline Cost Modeling

The cost of floating wind in Oregon was calculated in ORCA using the same assumptions initially applied for the 2016 California study, but with the site characteristics for the five Oregon study sites. The purpose of the baseline analysis was to establish a reference for comparison of this study to the 2016 California study. In addition, the baseline analysis was used to initially verify proper model function by comparing Oregon study sites directly to the 2016 California LCOE values. These baseline data are presented in Appendix C-2. They generally verify proper model behavior, showing LCOE values and average annual wind speeds that are similar to the California study. The 2030 extrapolated baseline LCOE values range from $120/MWh at Site 1 to $91/MWh at Site 5. The wide range in baseline LCOE can be attributed mostly to the average annual wind speed gradient, which is over 2 m/s from north to south.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

5.3.3 Application of Fixed-Bottom Market Data

Floating offshore wind technology is in a precommercial phase, with multiturbine arrays being deployed and under development globally, but at a smaller scale than is cost effective. The largest array to date was commissioned in October 2017 by Equinor off Peterhead, Scotland, and used five 6-MW turbines on floating spar platforms. Commercial-scale floating arrays, 10 times larger or more, are proposed for the mid-2020s (Beiter et al. 2018). The limited cost data available for the few small-scale floating projects deployed to date are not sufficient to represent future commercial-scale floating offshore wind project development. Generally, a commercial-scale project has the benefits of economies of scale and more favorable procurement and financing terms.

The uncertainty in estimating LCOE for commercial floating offshore wind was managed by (1) using cost data from fixed-bottom projects and technology, which share many technological and logistical aspects of floating offshore wind projects, (2) scaling the emerging cost data from precommercial to commercial-scale project size using established relationships from the existing offshore wind (and related) industries, and (3) conducting bottom-up assessments of the technological and logistical aspects unique to floating offshore wind. This study has combined these three approaches to estimate the LCOE of the five Oregon study sites.

Common cost characteristics that are shared between commercial-scale fixed-bottom and floating technology are shown in Table 4.[29]

Table 4. Common LCOE Elements Between Commercial-Scale Fixed-Bottom and Floating Offshore Wind Systems

Category	Major Cost Element	Common Cost Elements
Turbine	Turbine	Common
Balance of System	Development and Project Management	Common
	Substructure	Floating-Specific
	Foundation	Floating-Specific
	Port, Staging, Logistics, and Transport	Floating-Specific
	Turbine Installation	Floating-Specific
	Substructure Installation	Floating-Specific
	Array Cable	Floating-Specific
	Export Cable	Common
	Offshore Substation	Common
	Onshore Grid Connection	Common
Soft Costs	Soft Costs (Insurance, Contingencies, Construction, Finance)	Common
Financing	Financing Terms	Common
Energy Production	Capacity Factor	Common
Operation and Maintenance	Operations	Common
	Maintenance	Floating-Specific

[29] Note that Table 4 is a simplification; even when a cost element is common to fixed-bottom and floating technology, there are substantive differences that may affect actual costs.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Expenditures for those fixed-bottom cost elements expected to be applicable to floating offshore wind systems were analyzed and calibrated toward recent industry and market developments. Costs for fixed-bottom systems have experienced a rapid decline globally beginning in 2015. These reductions in costs are also reflected in declining auction prices, as shown in Figure 36. Available cost estimates for global fixed-bottom projects were used to estimate LCOE for the Oregon sites, where certain fixed-bottom project cost categories were used to estimate floating offshore wind system costs (see Table 4). These include financing terms reported for European fixed-bottom systems, turbine CapEx, development and project management, and soft costs.

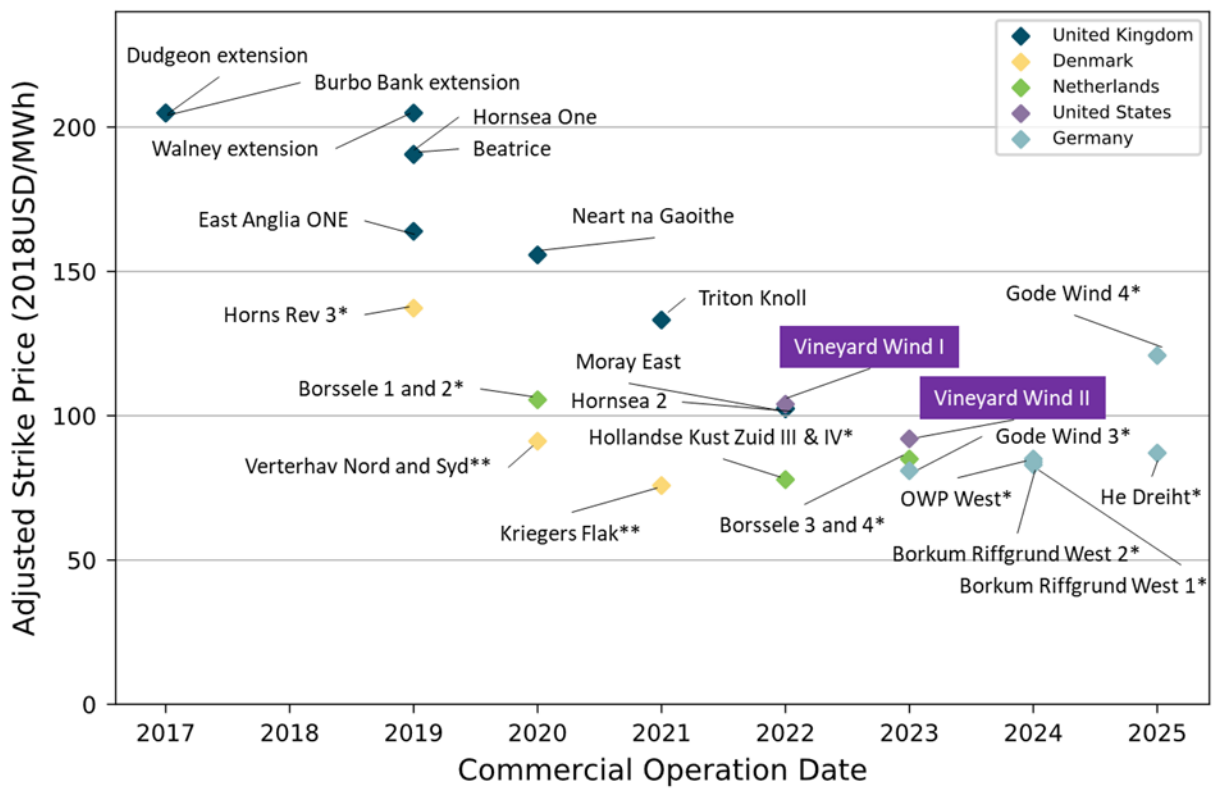


Figure 36. Adjusted strike prices from European offshore wind auctions. *Source: Beiter et al. (2019)*

Although most of the data points shown in Figure 36 are from jurisdictions outside of the United States, the recent PPA and price schedule agreed upon between Vineyard Wind LLC and Massachusetts electric distribution companies in July 2018 offers an indicative and first market-based reference point for the price and cost of commercial-scale offshore wind generation in the United States. The first year PPA price for delivery of offshore wind generation and renewable energy certificates for the Vineyard Wind LLC project was reported to be \$74/MWh (\$2022)[30] for facility 1 (400 MW) and \$65/MWh (\$2023) for facility 2 (400 MW). This price level suggests that the Vineyard Wind project off Massachusetts generally falls within the price (and

[30] All dollars are reported in \$2018, unless indicated otherwise.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

by extension, cost) range of European offshore wind projects, with an expected start of commercial operation of 2022 and 2023, respectively.

We derived the estimated (unsubsidized) cost from the PPA price of Vineyard Wind, accounting for the entire 20-year price schedule and the complete set of expected revenue sources and available tax benefits, (documented in detail in Beiter et al. [2019]), using the following steps:

- Calculate the present value of the revenue from delivery of electricity and renewable energy certificates under the negotiated PPA price schedule
- Account for the value of the Investment Tax Credit to derive an LCOE that is subsidy-free
- Consider the revenue from the project's ability to participate in the ISO-New England Forward-Capacity Market
- Discount all revenue to 2018 dollars.

This analysis estimated that the reported first year PPA price should be adjusted upward by 24 $/MWh for facility 1 and by $33/MWh for facility 2, giving a composite levelized revenue of energy of $98/MWh ($2018) for the combined facilities (800 MW). In Figure 36, these are shown as Vineyard Wind I and II adjusted strike prices for the separate facilities. The levelized revenue of energy provides a reference point for cost estimates of fixed-bottom technology.

From Figure 36, the adjusted Vineyard Wind price levels are in line with the European offshore wind project prices having the same COD. This result suggests that the cost structures and financing terms from European offshore wind projects to be commissioned in the early to mid-2020s would be applicable to Vineyard Wind, and possibly to other early commercial-scale projects in the United States, without a substantial cost penalty resulting from U.S market and supply chain immaturity.

For the five Oregon study sites, the detailed Vineyard Wind PPA levelized revenue of energy analysis detailed in Beiter et al. (2019) allowed for validation of several cost elements in the ORCA model including financing terms, total CapEx and OpEx, turbine CapEx, export system cable costs, and lease area price.

Turbine CapEx in 2019 was reduced from previous estimates of about $1,600/kilowatts (kW) to $1,300/kW (informed by Efstathiou [2018] and Hundleby et al. [2017]), decreasing over time in ORCA to $900/kW by 2032.

Export system cable costs in 2019 were reduced by 25% compared to Beiter et al. (2016) to account for recent cost reductions caused by low-cost material use (i.e., higher aluminum content), lower commodity prices, and cost reductions resulting from an antitrust case against an international cable cartel (Chee 2018).

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

The lease price assumed for the five Oregon study sites was $50 million, roughly corresponding to the price paid by Equinor for its New York lease area in 2016 (Musial et al. 2019).[31] For floating wind, it is not yet known what the cost of securing a lease will be because no auctions have taken place yet in areas with floating technology options.

Finance terms were calibrated to correspond to recent literature estimates (Guillet 2018) and validated through industry consultation. A 7.1% FCR (nominal) was assumed for model years 2019-2032 (COD) (see Table 5). This FCR assumes a commercial-scale floating project that can access similar financing conditions as current European and U.S. fixed-bottom projects planned for commercial operation in the early to mid- 2020s (i.e., similar risk profiles for installation and operation, power offtake, and macroeconomic conditions).

Table 5. Assumed Financing Conditions for Oregon Sites in Model Years 2019–2032

Category	Value
FCR[a] (Nominal) (After Tax)	**7.1%**
FCR[a] (Real) (After Tax)	5.3%
WACC[b] (Nominal) (After Tax)	5.4%
WACC[b] (Real) (After Tax)	2.9%
Capital Recovery Period	30
Share of Debt	75%
Debt Rate (Nominal)	4.4%
Equity Return (Nominal)	12.0%
Tax Rate	26.0%
Inflation	2.5%
CRF[c] (Nominal) (After Tax)	6.8%
CRF[c] (Real) (After Tax)	5.0%
Project Finance Factor	105%
Depreciation Basis	100%
Depreciation Schedule	5-year MACRS[d]
Present Value of Depreciation	86%

[a] Fixed Charge Rate
[b] Weighted Average Cost of Capital (WACC)
[c] Capital Recovery Factor
[d] Modified Accelerated Cost Recovery System (MACRS)

[31] Note that in its latest auction, BOEM awarded three offshore wind lease areas off Massachusetts in December 2018 at a lease sale price record of $135 million each; more than tripling the previous record of $42 million paid for the New York lease area sale in 2016 (Musial et al. 2019).

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

5.3.4 Floating-Specific Costs

For cost elements unique to floating offshore wind, we obtained data from floating offshore wind developers and industry literature for the base year of 2019. An example of these data for a substructure, foundation, and array cable system is shown in Table 6. These expenditures, representative of Oregon Site 4,[32] for substructure and foundation, are over 10% lower than the cost estimates from Beiter et al. (2016), reflecting the continued technology improvements achieved in the floating sector. In Table 6 and Appendix A, the cost estimates for substructure and foundation are combined into one item because of limited data resolution. A full disclosure of the data used to model cost in this area cannot be disclosed due to nondisclosure agreements with industry.

Table 6. Floating-Specific Cost Assumptions (Shown for Site Conditions of Coos Bay [Site 4] and 2019)

Category	Unit	Cost	Source
Substructure and Foundation	$/kW	1,361	Consultation with industry
Array Cable System	$/kW	330	Consultation with industry

5.3.5 Temporal Cost Reductions

ORCA's treatment of cost reduction potentials that result from technology innovation and supply chain maturity are described in detail in Beiter et al. (2016). These cost reduction potentials were derived from Hundleby et al. (2017) and associated with model years 2022, 2027, and 2032, respectively. The Hundleby et al. (2017) framework considered the degree of commercial readiness of an innovation and its "market share" for a given year. The degree of market share accounts for the compatibility of different components, as some innovations cannot be combined with innovations on a mating subassembly if they correspond to different system architectures (e.g., different assembly methods, different drivetrain configurations). The assumed cost reductions for major cost categories are based on an expert elicitation conducted by Hundleby et al. (2017). These cost reductions are shown in Table 7 as a percent reduction by cost category.[33] All cost categories show a net reduction in cost relative to the base values of 2019. All percentage values are cumulative in comparison to the 2019 baseline.

Some examples of these innovations include advanced materials in rotor designs that both lower loads and cost, but also increase AEP_{net} over time; new drivetrains that can reduce systems weight and increase efficiency; high-voltage power systems that can collect and distribute power from the turbines to a land-based offtake point at lower cost; high reliability systems that require less maintenance, coupled with better access to turbines at sea and increased availability (Hundleby et al. 2017).

---

[32] Installation CapEx is not included in Table 6 because of the proprietary nature of the data.

[33] The floating innovation and cost reduction assessment used in Beiter et al. (2016) was originally derived from an expert elicitation conducted by BVG Associates (Valpy et al. 2014) in combination with NREL research and analysis (for discussion, see Beiter et al. 2016). BVG Associates recently published an updated assessment for floating technology (Hundleby et al. 2017) that covers the period 2017–2032 (COD). This recent study from Hundleby et al. (2017) was used to derive innovation areas and their associated cost reduction potential.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Table 7. Assumed Cost Reductions Applied in ORCA by Cost Category All Values are Cumulative in Comparison to the 2019 Baseline)

COD	2019	2022	2027	2032
Development	0.00%	3.79%	6.68%	11.75%
Rotor Nacelle Assembly	0.00%	0.61%	9.45%	25.00%
Substructure	0.00%	0.77%	11.92%	31.52%
Foundation	0.00%	0.61%	9.47%	25.06%
Array Cable System	0.00%	14.12%	25.97%	46.81%
Export Cable System	0.00%	14.83%	27.34%	49.36%
Turbine Installation	0.00%	0.05%	8.02%	21.20%
Substructure & Foundation Installation	0.00%	0.09%	14.11%	37.33%
Operations	0.00%	22.32%	28.27%	41.93%
Maintenance	0.00%	24.76%	31.41%	46.69%
Gross AEP	0.00%	1.63%	2.19%	5.03%
Total Losses	0.00%	0.09%	1.19%	2.74%
CapEx	0.00%	6.76%	16.17%	32.67%
OpEx	0.00%	9.16%	14.84%	27.89%
AEP	0.00%	1.75%	2.40%	5.72%

Note: Reductions for CapEx, OpEx, and losses are shown with a positive sign; performance improvements (AEP) are shown with a positive sign.

Source: Derived from Hundleby et al. (2017) estimates.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

6. Results of Oregon Cost Analysis

ORCA was run to estimate the cost of floating wind in Oregon at the five study sites identified in Section 2. This section covers the LCOE results of that analysis and describes the high-level inputs for CapEx and OpEx and how the model expects them to change over time.

6.1 Oregon Floating Cost Scenarios

The scenarios modeled and major new assumptions are generally summarized by the following:

- European strike price declines of 65% for offshore wind projects being commissioned from 2016 to 2025 were used to adjust cost categories common to both fixed and floating technologies (Musial et al. 2019)
- The price point from the Vineyard Wind PPA allowed us to validate that U.S. cost levels may correspond to European market costs (Beiter et al. 2019). No market cost adjustments from the Atlantic to the Pacific were assumed for a mature floating commercial market on the West Coast by 2030
- An FCR of 7.1% (nominal) was assumed across all model years (2019–2032) based on Vineyard Wind PPA analysis and industry reporting (Green Giraffe 2016; Beiter et al. 2019); this FCR assumes a commercial project scale
- ORCA cost projections were extended to 2032 (in previous assessments [e.g., Musial et al. 2016a], these were limited to 2027 and extrapolated to 2030)
- Turbine power capacity was accelerated; 12-MW turbines were assumed to be on the market in 2025, and 15-MW turbines were assumed to be on the market by 2030 (General Electric 2018; Hundleby et al. 2017)
- A decrease in turbine capital costs per kilowatt ($/kW) was modeled as turbine rating increases
- Optimized floating platform designs that realize lower component cost per kilowatt and provide more systemwide benefits to reduce labor at sea and commissioning time were used (Villaespesa et al. 2015; Melis et al. 2016).

Figure 37 shows the results of the Oregon offshore wind scenarios for each of the five study sites ranging from 2019 through 2032. The LCOE values indicate that floating costs vary widely across the five sites, as indicated by the spread between the five curves. The values shown on the plot are also given in Table 9.

The ORCA cost model predicts that LCOE will range from $74/MWh at the north site to $53/MWh at the south site by 2032, assuming forty 15-MW turbines are deployed in a 600-MW array. In the 2027 scenario, 12-MW turbines are modeled, and the cost range varies from $102/MWh in the North to $74/MWh in the South. No commercial deployments are expected in the 2022 reference year modeled.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

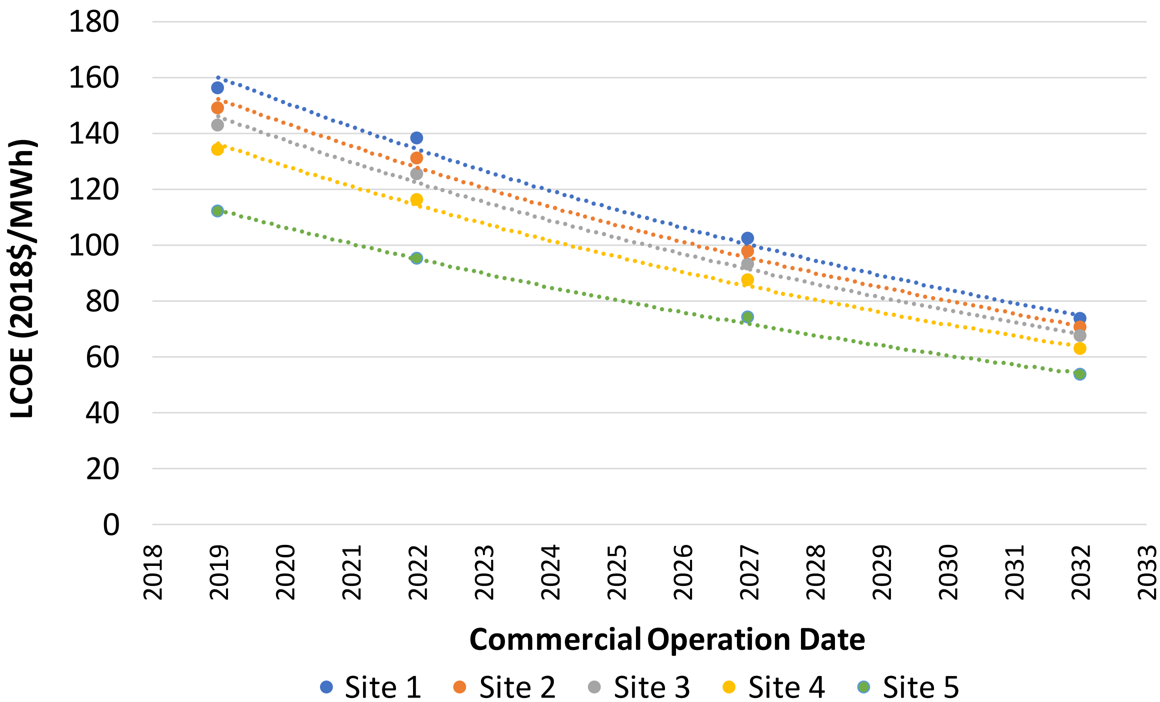


Figure 37. Cost trajectories for five Oregon floating offshore wind study sites

Table 8. Data for Oregon Cost Analysis in $2018

LCOE ($/MWh)					
Commercial Operation Date (COD)	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**
2019	156	149	143	134	112
2022	138	131	125	116	95
2027	102	97	93	87	74
2032	74	70	67	63	53
Capital Expenditures ($/kW)					
COD	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**
2019	5,180	5,177	5,213	5,229	5,150
2022	4,388	4,383	4,424	4,437	4,358
2027	3,797	3,792	3,833	3,836	3,769
2032	2,901	2,897	2,936	2,924	2,877
Operational Expenditures ($/kW/year)					
COD	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**
2019	126	126	125	128	132
2022	89	89	89	90	93
2027	74	74	74	75	78
2032	52	52	52	52	54
Net Capacity Factor (%)					
COD	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**
2019	36%	38%	40%	43%	51%
2022	36%	38%	40%	43%	52%
2027	38%	40%	42%	46%	53%
2032	40%	42%	44%	47%	55%

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Figure 38 shows the CapEx associated with the LCOE cost reductions plotted in Figure 37. As CapEx is a major component of the LCOE equation in Section 5.1, LCOE reductions can be attributed largely to declines in CapEx, which decrease from about $5,200/kW to $2,900/kW between 2019 and 2032. The CapEx are not influenced significantly by the geospatial site characteristics for the Oregon sites. Although the studied sites are located in considerably different water depths, the impact on CapEx for floating offshore wind systems is relatively small because of the limited influence on foundation and installation expenditures. As Figure 38 shows, CapEx has similar values for all sites at each year over time. This result is expected because all five sites have similar distances to grid connections, service, and construction ports; have similar average sea states; use the same turbines; and have the same size and configuration for their wind power plants.

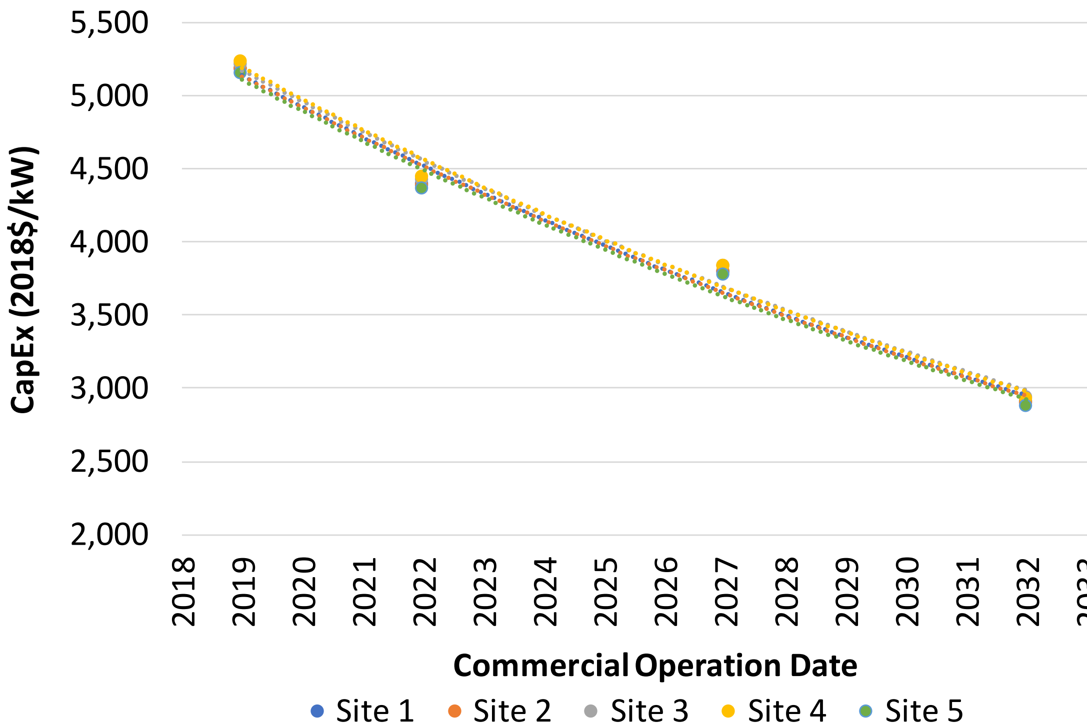


Figure 38. CapEx trajectories for five Oregon floating offshore wind study sites

Similarly, the OpEx decline for all five sites over time, as shown in Figure 39. Site 5 shows a slightly higher OpEx because of higher sea states and shorter weather windows, but OpEx levels decline at all five sites from $130/kW/year in 2019 to approximately $55/kW/year in 2032. These modeled declines can be attributed to improvements in turbine reliability, mature O&M strategies that can be adapted from fixed-bottom systems, better turbine accessibility resulting from vessel transfer improvements, innovations in remote diagnostic sensing, inspection and condition monitoring, and decreased dependence on expensive service vessels.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

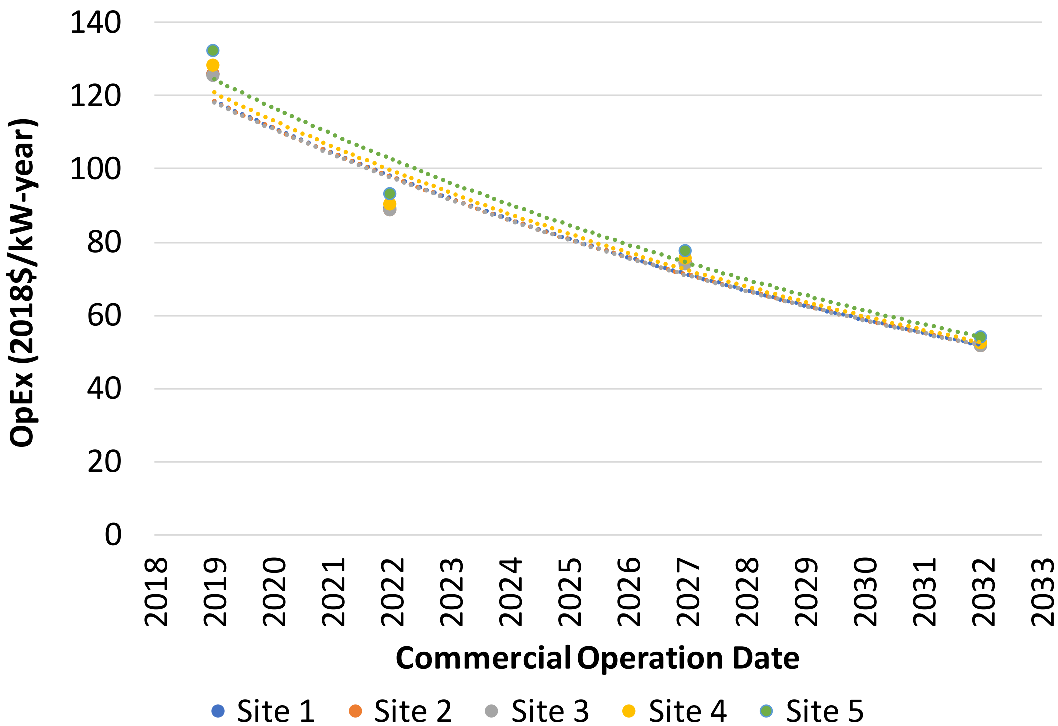


Figure 39. OpEx trajectories for five Oregon floating offshore wind study sites

6.2 Caveats and Limitations

Key limitations and corresponding caveats associated with ORCA modeling are discussed in detail in Beiter et al. (2016). These limitations and caveats relate to the general uncertainties associated with the availability of cost data, the timing of expected innovation (and associated cost reduction) trajectories, and macroeconomic factors (e.g., commodity prices, exchange rates). Some additional caveats associated with the current model and the Oregon modeling assumptions include the following:

- European strike prices are only approximations to project costs. Most of the activity associated with the lower auction strike prices seen over the past 4 years and that are plotted in Figure 36 relate to projects that have been bid but not yet built. It is not known how many of the projects in Figure 36 will get built and if they can be built for costs lower than the reported bid prices.
- One price point for Vineyard Wind may not accurately reflect the future U.S. market trend. The analysis performed by NREL provides some confidence that Vineyard Wind PPA prices can be translated for comparison with European projects, but more project data are needed to support the conclusion that U.S. projects will not be subject to a premium as a result of market immaturity.
- Common elements between floating and fixed-bottom offshore wind systems may not translate directly at the same cost (e.g., turbines may need some customization before installing them on a floating platform). Some costs may change from fixed-bottom to floating systems but are not accounted for in this analysis.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

- Floating cost assumptions do not include an Atlantic-to-Pacific adjustment. The supply chains in the Pacific may have different constraints and advantages, such as better access to Asian markets, that have not been accounted for.
- Floating-specific component costs based on vendor quotes and production cost estimates may not represent actual costs when built. Most floating cost data have higher uncertainty because values are based on production cost estimates rather than realized costs.
- Wind resource estimates from the WIND Toolkit are the best available but have not been validated against observations and have associated uncertainty. Better resource data is needed to verify AEP assumptions.
- Grid connections in Oregon may prove to be difficult when injecting 600 MW of power at a single location. Transmission upgrades may be necessary to deliver the power but may be challenging and costly. Conversely, some grid system costs may potentially be avoided by using offshore wind development to reduce congestion in some locations, but understanding these issues is beyond the scope of this study.
- Turbine growth may be hindered by unforeseen technology issues. For example, 15-MW wind turbines will be technologically challenging, and their development is not a certainty.
- ORCA is undergoing upgrades related to balance of system and O&M, and its characterization of turbine scaling and AEP profiles. All of these model elements require further development.
- Research is needed to further validate key assumptions of this study, particularly to evaluate the degree to which learning and supply chain expertise from the U.S. Atlantic Coast and Asia (and the fixed-bottom industry) can be leveraged for building a robust floating offshore wind supply chain along the Oregon and Pacific Coast. As more data become available about the evolving technology and cost trajectory of the global and U.S. floating wind industry, costs will need to be calibrated.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

7. Summary and Conclusions

This study focused on assessing the present and future costs of floating offshore wind technology deployment in the state of Oregon at commercial scale. The study was performed by NREL and funded by BOEM. The study builds off a previous report published by NREL and BOEM in December 2016, titled "Potential Offshore Wind Energy Areas in California: An Assessment of Locations, Technology, and Costs" (Musial et al. 2016a), also funded by BOEM, which estimated LCOE for floating offshore wind in California at $100/MWh or less by 2030.

Since 2016, when the California study was conducted, fixed-bottom and floating offshore wind systems have progressed at a rapid rate both technologically and economically. There are several key areas that were not considered in the California report that are now known to be important variables in estimating future costs of floating wind in general, and in Oregon specifically. Some of the major new areas that were considered in the latest version of ORCA include:

- Strike price declines by about 65% for projects being commissioned between 2017 and 2025 in European auctions for offshore wind (Beiter et al. 2017).
- A new U.S. price point for fixed-bottom offshore wind, established through analysis of the Vineyard Wind PPAs (Beiter et al. 2019).
- Lower-than-expected Vineyard Wind PPA prices, which indicate minimal cost penalties because of immature U.S. supply chains (Beiter et al. 2019).
- Finance costs were reassessed and are lower than previously anticipated based on new industry data (Green Giraffe 2016).
- NREL's cost model, ORCA, was updated to look ahead to 2032 (previously 2027, extrapolating to 2030).
- Turbine power capacity is assumed to reach 15 MW within the modeling time horizon of 2032 (General Electric 2018; Hundleby et al. 2017).
- Turbine costs per kilowatt were adjusted downward and are not expected to increase as turbine sizes grow.
- Optimized floating platform designs promise a lower component cost for platforms, and systemwide benefits to reduce labor at sea and commissioning time (Villaespesa et al. 2015; Melis et al. 2016). Platform scaling also shows favorable cost declines for larger platform sizes.

Five study sites were selected in Oregon that represent typical locations where offshore wind projects could be built and were analyzed to estimate the cost of offshore wind. This site-selection process was conducted to model potential cost. This study is not stakeholder engagement or a marine spatial planning effort to create wind energy areas under BOEM's leasing process and the hypothetical sites have not been vetted by ocean user communities. Any wind energy planning effort on the OCS would require comprehensive stakeholder engagement and analysis of all relevant data and information for siting.

We analyzed floating offshore wind costs at each of the five study sites using a version of the ORCA model and incorporating updated modeling assumptions for a 600-MW project at commercial scale.

The results of this cost study estimate that LCOE could range from $74 MWh to $53/MWh in Oregon for floating wind technology in 2032. These results are based on assessments for all five

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

sites using a conceptual NREL-designed 15-MW wind turbine. These costs reflect lower LCOE than the 2016 California study because of new cost and technology data that support lower CapEx and OpEx than was previously modeled.

We compared full-scale 600-MW project costs for a site near Coos Bay, Oregon, to a 24-MW pilot-scale Principle Power, Inc., project proposed in 2014, also off Coos Bay. The pilot-scale project costs were three times higher than the commercial-scale project using the same financing and energy production. This analysis demonstrated the benefits of building projects at commercial scale.

Overall, the prospects for offshore wind in Oregon look promising for large-scale electricity generation. Floating technology is maturing rapidly, and offshore wind can provide a carbon-free alternative electricity source in coastal regions, especially in the southern region where offshore annual average wind speeds are near 10 m/s and among the highest in the United States. However, wind resource assessments are based on single ensemble setups and validations are sparse; therefore, higher-resolution resource data are needed to lower uncertainty for investors, lawmakers, developers, and utilities that are considering offshore wind in Oregon.

There will be significant challenges for offshore wind to overcome in Oregon including optimization of floating technology, coexistence with the fishing industry, mitigating impacts to wildlife and the viewshed, and integrating with the existing land-based grid. However, offshore wind can play a long-term role in helping to meet state and regional electricity-generation goals and could be synergistic in relieving congestion at some grid locations. Future work should focus on assessing these potential impacts to allow for offshore wind development to progress in a manner that is appropriate and fair for all stakeholder communities.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

References

ABB Energy Velocity Suite. 2019a. "Electric Substations dataset (2019)." Licensed by NREL. Accessed April 2019.

ABB Energy Velocity Suite. 2019b. "Transmission Lines dataset (2019)." Licensed by NREL. Accessed April 2019.

AWS Truepower, LLC. 2010. OpenWind Theoretical Basis and Validation. http://www.awsopenwind.org/downloads/documentation/OpenWindTheoryAndValidation.pdf

AWS Truepower. 2012. "Wind Resource Maps and Data: Methods and Validation." https://www.awstruepower.com/products/maps-and-resource-data. Accessed July 2016.

AWS Truepower. 2014. *AWS Truepower Loss and Uncertainty Methods*. Memorandum. June 5, 2014. https://www.awstruepower.com/assets/AWS-Truepower-Loss-and-Uncertainty-Memorandum-5-Jun-2014.pdf.

Bak, C., Zahle, F., Bitsche, R., Kim, T., Yde, A., Henriksen, L. C., Natarajan, A. 2013. The DTU 10 MW Reference Wind Turbine. Danish Technical University. http://orbit.dtu.dk/files/55645274/The_DTU_10MW_Reference_Turbine_Christian_Bak.pdf.

Banister, Kevin. 2017. *WindFloat Pacific Project, Final Scientific and Technical Report*. United States. doi:10.2172/1339449. https://www.osti.gov/servlets/purl/1339449.

Beiter, P., W. Musial, A. Smith, L. Kilcher, R. Damiani, M. Maness, S. Sirnivas, T. Stehly, V. Gevorgian, M. Mooney, Scott G. 2016. *A Spatial-Economic Cost Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030* (Technical Report). Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-66579. https://www.nrel.gov/docs/fy16osti/66579.pdf.

Beiter, Philipp, Walter Musial, Levi Kilcher, Michael Maness, and Aaron Smith. 2017. *An Assessment of the Economic Potential of Offshore Wind in the United States from 2015 to 2030*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-67675. https://www.nrel.gov/docs/fy17osti/67675.pdf.

Beiter, Philipp, Walter Musial, and Eric Lantz. 2019. *The Vineyard Wind Power Purchase Agreement: Insights for Estimating Costs of U.S. Offshore Wind Projects* (Technical Report). Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-72981. https://www.nrel.gov/docs/fy19osti/72981.pdf.

Black & Veatch. 2010. "Technology Characterization for Renewable Energy Electricity Futures Study: GIS Database of Offshore Wind Resource Competing Uses and Environmentally Sensitive Areas." Overland Park, KS: Black & Veatch (unpublished).

Bonneville Power Administration (BPA). 2019. BPA Website https://www.bpa.gov/Pages/home.aspx.

Bureau of Ocean Energy Management (BOEM). 2018. “Renewable Energy Path Forward on the Atlantic.” Request for Information, Aug 2018. https://www.boem.gov/Renewable-Energy-Path-Forward.

BOEM. 2019a. “California Activities.” Accessed April 2019. https://www.boem.gov/California/.

BOEM. 2019b. “Hawaii Activities.” Accessed April 2019. https://www.boem.gov/Hawaii/.

Bureau of Ocean Energy Management and National Oceanic and Atmospheric Administration. 2013. “Vessel Traffic Data.” www.marinecadastre.gov.

Chee, Foo Yun. 2018. “Goldman Sachs, Prysmian, others lose challenge against EU cartel fine.” Reuters. Accessed July 2, 2019. https://www.reuters.com/article/us-eu-cartel-court/goldman-sachs-prysmian-others-lose-challenge-against-eu-cartel-fine-idUSKBN1K21DY.

Davis, C. 2015. “Without Oregon utilities nod, Coos Bay WindFloat dead in the water.” *The World*. https://theworldlink.com/news/local/without-oregon-utilities-nod-coos-bay-windfloat-dead-in-the/article_095e12ca-6d7e-53e0-a313-05181d324cf3.html.

Deepwater Wind. 2015. “Block Island Wind Farm Now Fully Financed.” Accessed July 2019. http://dwwind.com/press/block-island-wind-farm-now-fully-financed.

Draxl, Caroline, Andy Clifton, Bri-Mathias Hodge, James McCaa. 2015. “The Wind Integration National Dataset (WIND) Toolkit.” *Applied Energy*. 151(1):355-366. ISSN 0306-2619. http://dx.doi.org/10.1016/j.apenergy.2015.03.121.

Efstathiou, Jim. 2018. “First Big U.S. Offshore Wind Farm Offers $1.4 Billion to Customers.” Bloomberg New Energy Finance, August 1, 2018. https://www.bloomberg.com/news/articles/2018-08-01/first-big-u-s-offshore-wind-offers-1-4-billion-to-customers.

General Electric. 2018. “Haliade-X Offshore Wind Turbine Platform.” Accessed December 31, 2018. https://www.ge.com/renewableenergy/wind-energy/turbines/haliade-x-offshore-turbine.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Gilman, P., B. Maurer, L. Feinberg, A. Duerr, L. Peterson, W. Musial, P. Beiter, J. Golladay, J. Stromberg, I. Johnson, D. Boren, A. Moore. 2016. *National Offshore Wind Strategy: Facilitating the Development of the Offshore Wind Industry in the United States*. U.S. Department of Energy and Bureau of Ocean Energy Management. http://energy.gov/sites/prod/files/2016/09/f33/National-Offshore-Wind-Strategy-report-09082016.pdf.

Green Giraffe. 2016. "Offshore wind finance –2016 update." Presented at Energy Talk, December 8, 2016, London, England. Accessed March 2018. https://green-giraffe.eu/sites/green-giraffe.eu/files/161206_energytalk_v5_-_sent_orga.pdf.

Guillet, Jerome. 2018. "Who will fund U.S. Offshore Wind - and on what terms?" Presented at the Offshore Wind Implementation Summit, September 7, 2018, Teaneck, New Jersey. https://green-giraffe.eu/presentations/who-will-fund-us-offshore-wind-%E2%80%93-and-what-terms.

Hundleby, Giles, Kate Freeman, Andy Logan, and Ciaran Frost. 2017. "Floating Offshore: 55 Technology Innovations That Will Have Greater Impact on Reducing the Cost of Electricity from European Floating Offshore Wind Farms." KiC InnoEnergy and BVG Associates. http://www.innoenergy.com/new-floating-offshore-wind-report-55-technology-innovations-that-will-impact-the-lcoe-in-floating-offshore-wind-farms/.

Maness M., B. Maples, and A. Smith, A. 2017. NREL Offshore Balance-of-System Model (Technical Report). Golden, CO: National Renewable Energy Laboratory.NREL/TP-6A20-66874.https://www.nrel.gov/docs/fy17osti/66874.pdf.

Melis, C., C. Bauduin, A. Wattez, A. Newport, Y. Poirette, T. Perdrizet, T., et al. 2016. "Adapting tension leg technology to provide an economical solution for floating wind power." In: Offshore Technology Conference. OTC-27153-MS; 2016.

MHI Vestas. 2018. "Vineyard Wind Selects MHI Vestas as Preferred Supplier for First Large-scale Offshore Wind Project in the United States." November 27, 2018. http://www.mhivestasoffshore.com/vineyard-wind-selects-mhi-vestas-as-preferred-supplier.

MHI Vestas. 2019 "MHI Vestas To Supply Five V164-9.5 MW Turbines for Kincardine Floating Offshore Wind Park in Scotland." http://www.mhivestasoffshore.com/mhi-vestas-to-supply-five-v164-9-5-mw-turbines-for-kincardine-floating-offshore-wind-park-in-scotland.

Musial, W. and B. Ram. 2010. *Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers* (Technical Report). Golden, CO: National Renewable Energy Laboratory. NREL/TP-500-40745. http://www.nrel.gov/docs/fy10osti/40745.pdf.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Musial, Walt, Philipp Beiter, Suzanne Tegen, and Aaron Smith. 2016a. Potential Offshore Wind Energy Areas in California: An Assessment of Locations, Technology, and Costs (Technical Report). Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-67414. https://www.boem.gov/2016-074/.

Musial, W., D. Heimiller, P. Beiter, G. Scott, and C. Draxl. 2016b. *2016 Offshore Wind Energy Resource Assessment for the United States* (Technical Report). Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-66599. http://www.nrel.gov/docs/fy16osti/66599.pdf.

Musial, W, P. Beiter, P. Spitsen, J. Nunemaker, V. Gevorgian. 2019. *2018 Offshore Wind Technologies Market Report*. U.S. Department of Energy, Washington, D.C. https://www.energy.gov/eere/wind/2018-wind-market-reports#offshore.

National Geospatial Intelligence Agency. Undated. "World Port Index (2017)." Dataset. https://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0015. Accessed March 2017.

National Oceanic and Atmospheric Administration (NOAA). 2018. "State Waters and Federal Waters Boundary dataset." Produced by the NOAA Office of Coast Survey, NOAA Office of Coastal Management, BOEM Mapping and Boundaries Branch, and Department of the Interior Minerals Management Service. Distributed at http://www.nauticalcharts.noaa.gov/csdl/mbound.html. Accessed April 2019.

NOAA National Marine Fisheries Service. 2019a. "West Coast Bottom Trawl Fishing Intensity (2006-2010).https://coast.noaa.gov/digitalcoast/data. Accessed April 2019.

NOAA National Marine Fisheries Service. 2019b. "West Coast Mid-Water Trawl Fishing Intensity (2006-2010)." https://coast.noaa.gov/digitalcoast/data. Accessed April 2019.

NOAA Marine Protected Areas Center. 2019. "Marine Protected Areas." https://marineprotectedareas.noaa.gov/dataanalysis/mpainventory/mpaviewer/.

NOAA Fisheries. 2019. "Leatherback Sea Turtle Critical Habitat Map - West Coast." https://www.fisheries.noaa.gov/resource/map/leatherback-sea-turtle-critical-habitat-map-west-coast.

North American Submarine Cable Association. 2019. "Submarine Cables dataset (2015)." Distributed by the NOAA Office for Coastal Management. https://marinecadastre.gov/data. Accessed April 2019.

Oregon Department of Energy 2019. "Electricity Mix in Oregon." https://www.oregon.gov/energy/energy-oregon/Pages/Electricity-Mix-in-Oregon.aspx. Accessed June 4, 2019.

PBS Learning Media. 2019. "Population Map of Oregon." https://rmpbs.pbslearningmedia.org/resource/great-states-oregon-1.3/activity.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Porter, A., and Phillips, S. 2016. "Determining the Infrastructure Needs to Support Offshore Floating Wind and Marine Hydrokinetic Facilities on the Pacific West Coast and Hawaii." U.S. Department of the Interior, Bureau of Ocean Energy Management, Pacific OCS Region, Camarillo, CA. OCS Study BOEM 2016-011. 238 pp. https://www.boem.gov/BOEM-2016-011/.

Roberts, D. 2019. "Oregon is poised to set a cap on greenhouse gas emissions. That's a huge deal." *Vox*. June 5, 2019. https://www.vox.com/energy-and-environment/2019/6/5/18650155/climate-change-oregon-carbon-cap-trade-california.

Siemens Gamesa. 2019. "Siemens Gamesa launches 10 MW offshore wind turbine; annual energy production (AEP) increase of 30% vs. predecessor." https://www.siemensgamesa.com/en-int/newsroom/2019/01/new-siemens-gamesa-10-mw-offshore-wind-turbine-sg-10-0-193-dd.

State of Oregon. 2019. "State of Oregon Geographic Location Description: Analysis of Reasonably Foreseeable Effects of Federal Actions Related to Marine Renewable Energy Projects on Resources and Uses Occurring within the Federal Waters of the Oregon Ocean Stewardship Area." Oregon Department of Land Conservation and Development, Coastal Management Program. https://www.oregon.gov/lcd/OCMP/Documents/OCMP_MarineRenewable_GLD_final.pdf.

Sullivan, Robert G., Leslie B. Kirchler, Jackson Cothren, and Snow L. Winters. 2012. "Offshore Wind Turbine Visibility and Visual Impact Threshold Distances." .Argonne National Laboratory. http://blmwyomingvisual.anl.gov/docs/EnvPractice_Offshore%20Wind%20Turbine%20Visibility%20and%20Visual%20Impact%20Threshold%20Distances.pdf.

U.S. Department of Energy. 2015. *Wind Vision: A New Era for Wind Power in the United States*. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. DOE/GO-102015-4557. Washington, D.C. http://www.energy.gov/sites/prod/files/WindVision_Report_final.pdf. Accessed May 2019.

U.S. Department of Energy. 2019. "DOE Advanced Technology Demonstration Projects." https://www.energy.gov/eere/wind/offshore-wind-advanced-technology-demonstration-projects.

Valpy, B., P. English, Philip, A. Martínez, E. Simonot. 2014. Future renewable energy costs: offshore wind. BVG Associates and KIC InnoEnergy. Accessed June 6, 2016. http://www.kic-innoenergy.com/wp-content/uploads/2014/09/KIC_IE_OffshoreWind_anticipated_innovations_impact1.pdf.

Villaespesa, E. B., Gonzalez, C. M., Martin, N. G. K. 2015. Transportation and installation of the Tetraspar floating offshore wind turbine. Tech. Rep.; Aalborg University; Aalborg, Denmark; 2015. https://projekter.aau.dk/projekter/files/281663582/Master_Thesis.pdf.

Westington, M., and Slagel, M. 2019. "U.S. Maritime Zones and the Determination of the National Baseline." National Ocean Service (NOAA) Office of Coast Survey. http://ushydro.thsoa.org/hy07/11_01.pdf.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Weston, D. 2019. "Stiesdal's TetraSpar demo gets go-ahead." *WindPower Offshore*. February 13, 2019. https://www.windpoweroffshore.com/article/1525677/stiesdals-tetraspar-demo-gets-go-ahead.

Wind Europe. 2018. "Floating Offshore Wind Energy: A Policy Blueprint for Europe."https://windeurope.org/wp-content/uploads/files/policy/position-papers/Floating-offshore-wind-energy-a-policy-blueprint-for-Europe.pdf.

Wiser, R., K. Jenni, J. Seel, E. Baker, M. Hand, E. Lantz, A. Smith. 2016. Forecasting Wind Energy Costs & Cost Drivers. The Views of the World's Leading Experts. LBNL-1005717. Lawrence Berkeley National Laboratory. http://eta-publications.lbl.gov/sites/default/files/lbnl-1005717.pdf.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Appendix A. Principle Power Project Scaling Study

The cost of offshore wind is sensitive to technological and spatial variables, including average wind speed, turbine size, water depth, and project scale, to name a few. Project scale is difficult to demonstrate as a cost driver because the large financial investments (greater than $1 billion) needed to build an economical commercial-scale project is often prohibitive, especially for new technology. However, smaller investments at a pilot scale most often come at a higher cost per unit of energy. Nevertheless, with the nascent state of floating wind technology, it is prudent to demonstrate this new technology initially at a pilot scale.[34] However, investors will not be satisfied unless they are convinced that a lower unit cost can be achieved at commercial scale. This section examines a case study relevant to the state of Oregon for offshore wind. Principle Power, Inc., a leading offshore wind floating platform technology developer, provided detailed costs for a pilot project to the Oregon Public Utility Commission in 2014 off the coast of Coos Bay, Oregon, which were rejected because the project was deemed too expensive. Here, we compare that pilot-scale project to the cost of a commercial-scale project (e.g., 600 megawatts [MW]) in the same location using current technology (Banister 2017).

Background and Coos Bay Project Description

The National Renewable Energy Laboratory (NREL) obtained cost information from Principle Power, Inc. on their proposed 24-MW Advanced Technology Demonstration pilot project off Coos Bay, Oregon, to allow for comparison with the commercial projects analyzed in this report. Figure A-1 shows the first Principle Power, Inc. prototype being towed to its station off Portugal in 2011.

Figure A-1. Principle Power, Inc. semisubmersible with mounted turbine. *Photo courtesy of Principle Power, Inc.*

[34] A pilot scale is subjectively defined. In this report, pilot scale means the project is using state-of-the-art turbine technology but in smaller numbers, usually less than 50 MW total capacity. Pilot-scale projects are privately financed but are not economically viable without some public or private subsidies.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Offshore wind pilot-scale projects are pursued by technology developers to demonstrate the technical and economic viability of a concept design, improve engineering and related support activities, address nontechnical barriers (e.g., environmental or socio-economic issues), and collect performance, monitoring, and cost data (Banister 2017). According to Banister (2017), the WindFloat Pacific project from Principle Power was "the first floating project offshore wind array proposed in the United States and the first offshore wind project of any kind proposed off the West Coast."

The cost structure according to Banister (2017) for the WindFloat Pacific project is shown in Table A-1, converted to $2018. The 24-MW project was proposed to be sited at a water depth of 435 meters and a 30-kilometer distance from export cable landfall. This reported capital expenditure (CapEx) estimate from the WindFloat Pacific project compares to an estimated CapEx of $9,700/kilowatts (kW) for the 30-MW Block Island Wind Farm project (Deepwater Wind 2015).[35]

Table A-1. Cost Breakdown for the 24-MW Principle Power Pacific WindFloat Project

Category	Unit	Cost	Source
CapEx	$/kW	10,153	Banister (2017)
OpEx[36]	$/kW/year	243	
Net Capacity Factor	%	43%	

Because of the project's smaller capacity, the costs were higher per-unit CapEx ($/kW) and operation and maintenance ($/kW/year) than a full-scale commercial project. Commercial-scale projects leverage economies of scale by spreading fixed-cost capital and OpEx over a higher number of turbines and total installed capacity. For instance, by spreading the cost of an export system cable infrastructure over many turbines instead of just a few turbines (WindFloat Pacific used three turbines), the per-unit cost ($/kW) is much smaller. For some cost elements, these scaling effects can have several orders of magnitude difference between the pilot-scale and the commercial-scale project, especially for offshore wind projects, because they have higher upfront CapEx.

Project-Scale Cost Comparisons

Table A-2 shows the comparison between the 24-MW WindFloat Pacific project and the 600-MW project (Section 6), with a 2032 commercial operation date (COD) for the Coos Bay location (south-central; Site 4). These calculations were informed by cost information obtained from Principle Power, but the component cost data are provided by NREL and are representative of industry costs. NREL cost data from multiple sources are aggregated and presented here to allow the results to be published without revealing proprietary data. The same annual energy production and financing conditions were assumed for this comparison to focus on the scaling effects resulting from differences in plant size. Note that this comparison is made in 2032

[35]This estimate was derived by dividing the reported project financing of $290 million by the project capacity of 30 MW.
[36]Operational expenditures

(COD); therefore, these results represent the combined impact from projected cost reductions (by 2032)37 and from economies of scale (24-MW vs. 600-MW project size).

Table A-2. CapEx Estimates for 24-MW and 600-MW Project Scale in 2032 (COD)

	Project size	600 MW Project Size	24 MW Project Size	
	Unit	**$/kW**	**$/kW**	**% Difference**
1	Tower	182	250	-27%
2	RNA	839	1,536	-45%
TURBINE SUPPLY		1,021	1,786	-43%
3	Substructure	577	1,265	-54%
4	Foundation[1]	-	-	0%
SUPPORT STRUCTURE		577	1,265	-54%
5	Port, Staging, Logistics and Transport	44	868	-95%
6	Turbine Install	-	-	0%
7	Substructure Install[2]	164	300	-45%
TOTAL INSTALLATION		208	1,169	-82%
8	Array Cabling	181	181	0%
9	Export Cable	253	1,574	-84%
10	Grid Connection	7	7	0%
TOTAL ELECTRIC SYSTEM		441	1,762	-75%
11	Development	79	974	-92%
12	Lease Price	88	88	0%
13	Project Management	45	168	-73%
BALANCE OF SYSTEM		1,438	5,426	-73%
14	Insurance During Construction	28	72	-61%
15	Project Completion	28	72	-61%
16	Decommissioning	28	175	-84%
17	Procurement Contingency	132	302	-56%
18	Install Contingency	57	351	-84%
19	Construction Financing	118	686	-83%
TOTAL SOFT CAPEX		391	1,658	-76%
TOTAL CAPEX		**2,924**	**8,870**	**-67%**

		$/kW-year	**$/kW-year**	**% Difference**
1	Operations	19	64	-70%
2	Maintenance	33	109	-70%
TOTAL OPEX		**52**	**172**	-70%

		%	**%**	**% Difference**
1	Net Capacity Factor	47%	47%	0%
NET CAPACITY FACTOR		**47%**	**47%**	**0%**

		%	**%**	**% Difference**
1	WACC (nominal)	5.4%	5.4%	0%
FIXED CHARGE RATE (nominal)		**7.11%**	**7.11%**	**0%**

		$/MWh	**$/MWh**	**% Difference**
LCOE		**63**	**183**	**-68%**

[1] Expenditures for substructure and foundation are combined under the “substructure” line item because of the proprietary nature of the underlying data.
[2] Expenditures for turbine and substructure installation are combined under the “substructure installation” line item because of the proprietary nature of the underlying data.

The input data show that estimated CapEx ($/kW) is 67% lower for the 600-MW project size relative to the 24-MW project. A similar magnitude of difference (-70%) was estimated for

[37] The same cost reductions were applied to the 24-MW and 600-MW projects to estimate costs in 2032 (COD).

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

OpEx. In other words, the pilot-scale project CapEx was about three times higher than the commercial-scale project. The levelized cost of energy (LCOE) was modeled to be about three times lower for the 600-MW commercial power plant size compared to the 24-MW pilot project. Quantitatively, economies of scale from plant sizing has the largest effect on installation (-82%) and electric system (-75%) line items, as well as project development and management (-92% and -73%, respectively).

Both the pilot-scale and commercial-scale project were assumed to have the same favorable financing rates and generated power with the same net capacity factor of 44%.

Project Scaling Conclusions

In this study, we estimated the cost-scaling relationship between the 24-MW WindFloat Pacific project proposed by Principle Power in 2014 and a 600-MW project located at the same site (Site 4 off Coos Bay, Oregon). The LCOE was approximately three times higher for the 24-MW pilot-scale project. This cost difference mostly reflects the capital and operation cost economies of scale that allow fixed cost items to be spread over the entire project cost. As the comparison is made in model year 2032, the estimated costs shown in Table A-2 also represent technology improvements assumed to be realized since the WindFloat Pacific was originally proposed, such as larger turbines that are assumed to be available in a decade. The LCOE for the pilot-scale project was calculated to be $183/megawatt-hour, whereas the commercial-scale project LCOE was found to be $63/megawatt-hour.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Appendix B. Monthly Wind Resource Site Characteristics

The data in Figures B-1 through B-5 show the results of the Windographer analysis of the diurnal wind various for each month at all five study sites.

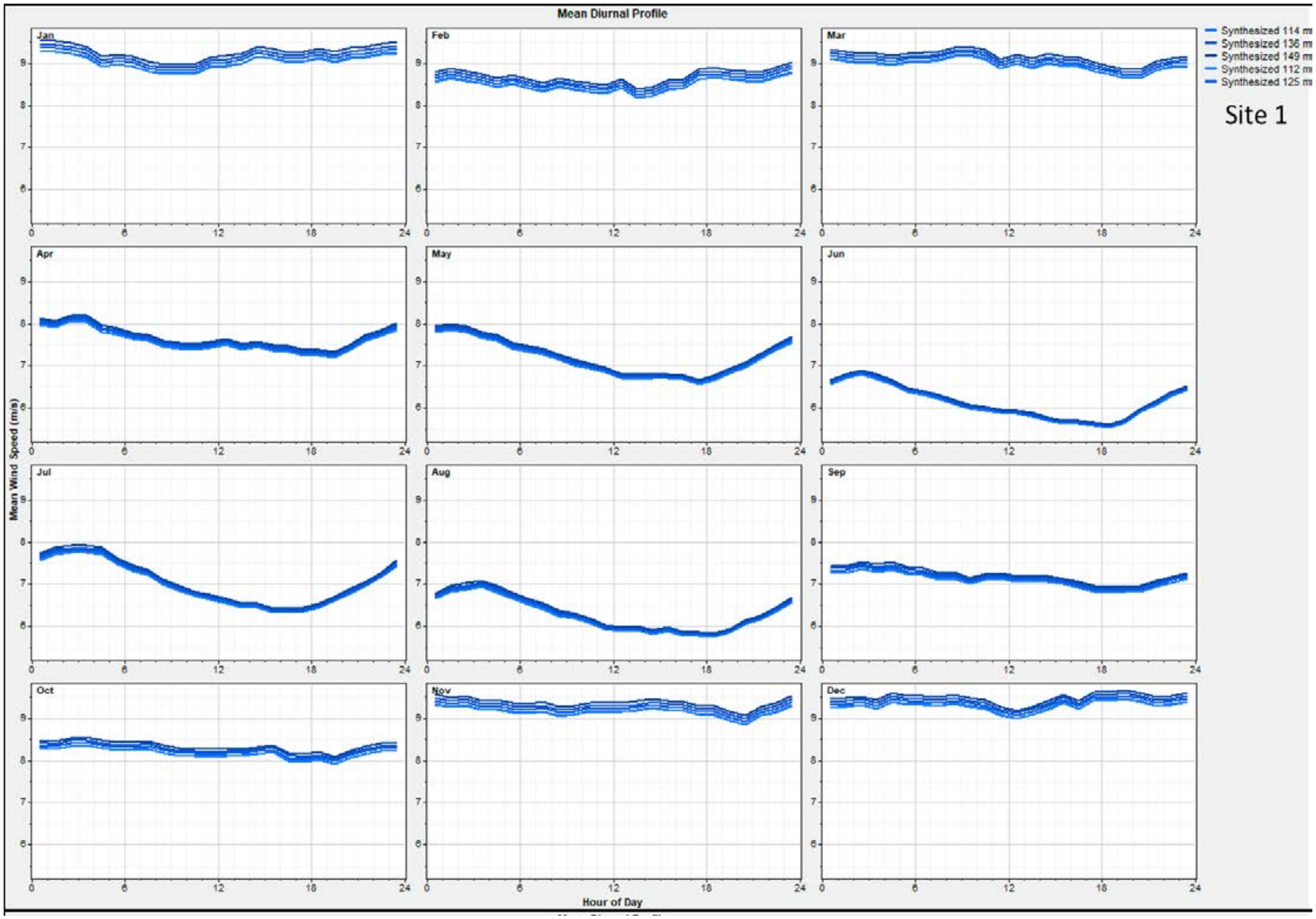


Figure B-1. Mean diurnal profiles for Site 1

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

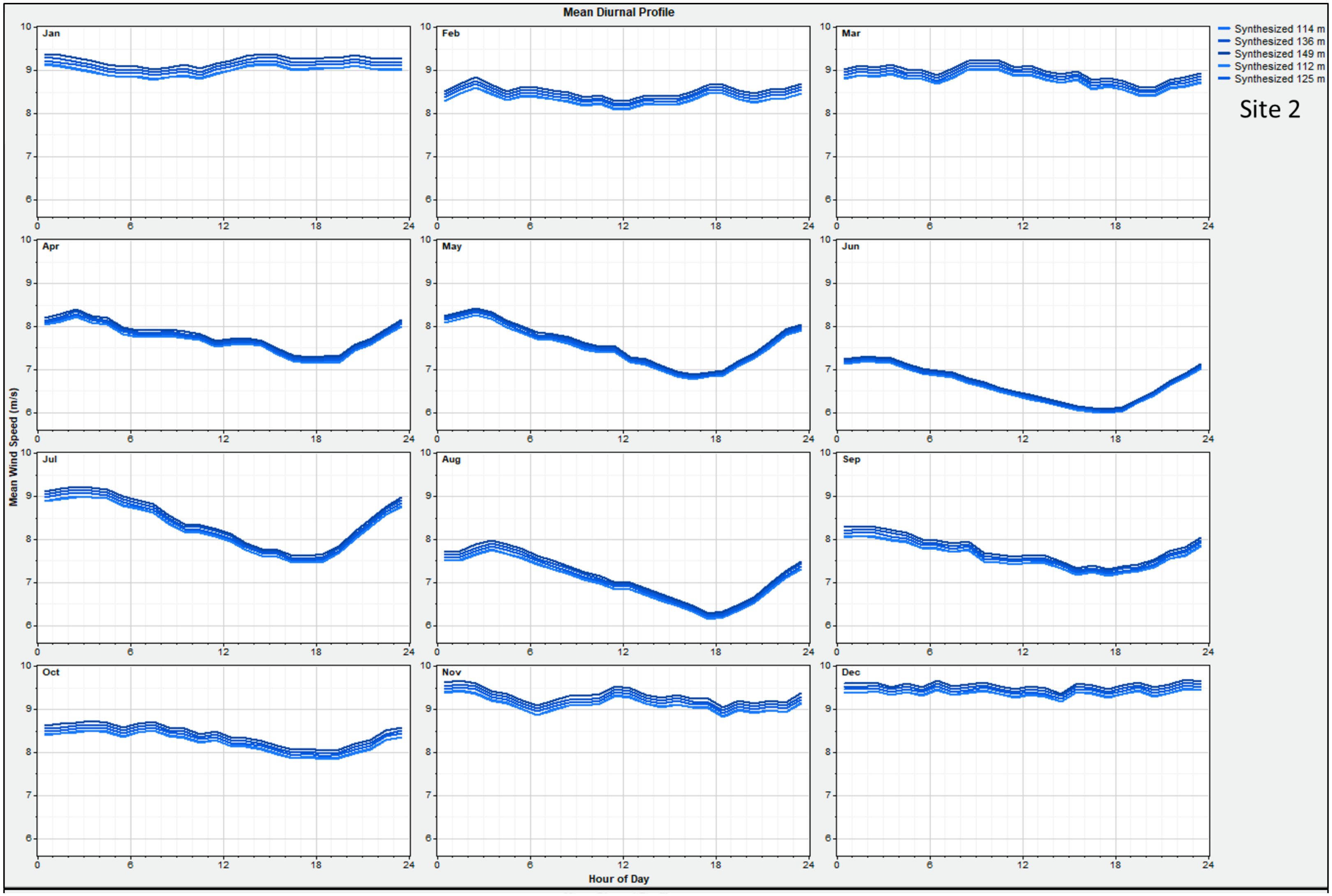


Figure B-2. Mean diurnal profiles for Site 2

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

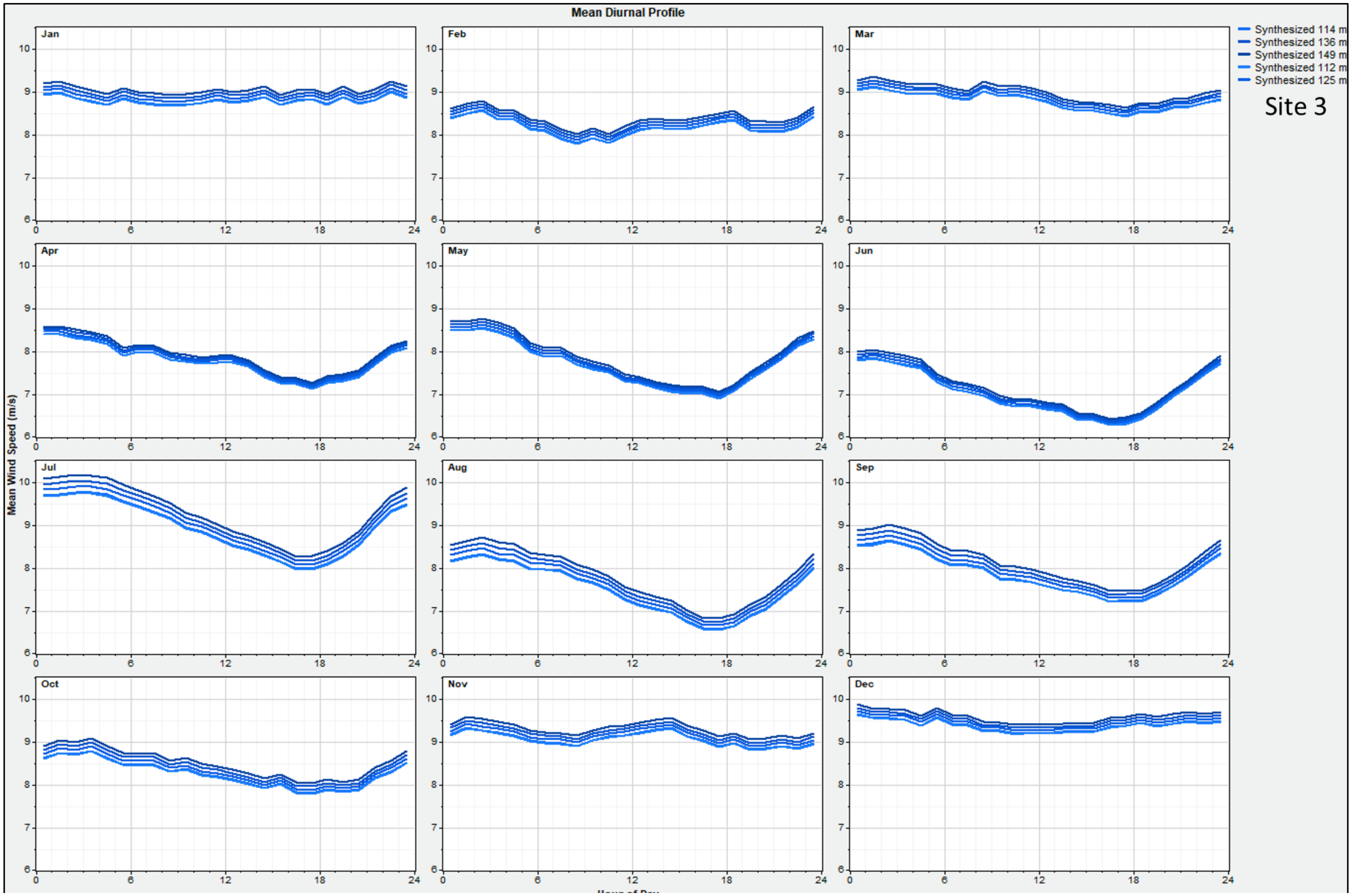


Figure B-3. Mean diurnal profiles for Site 3

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

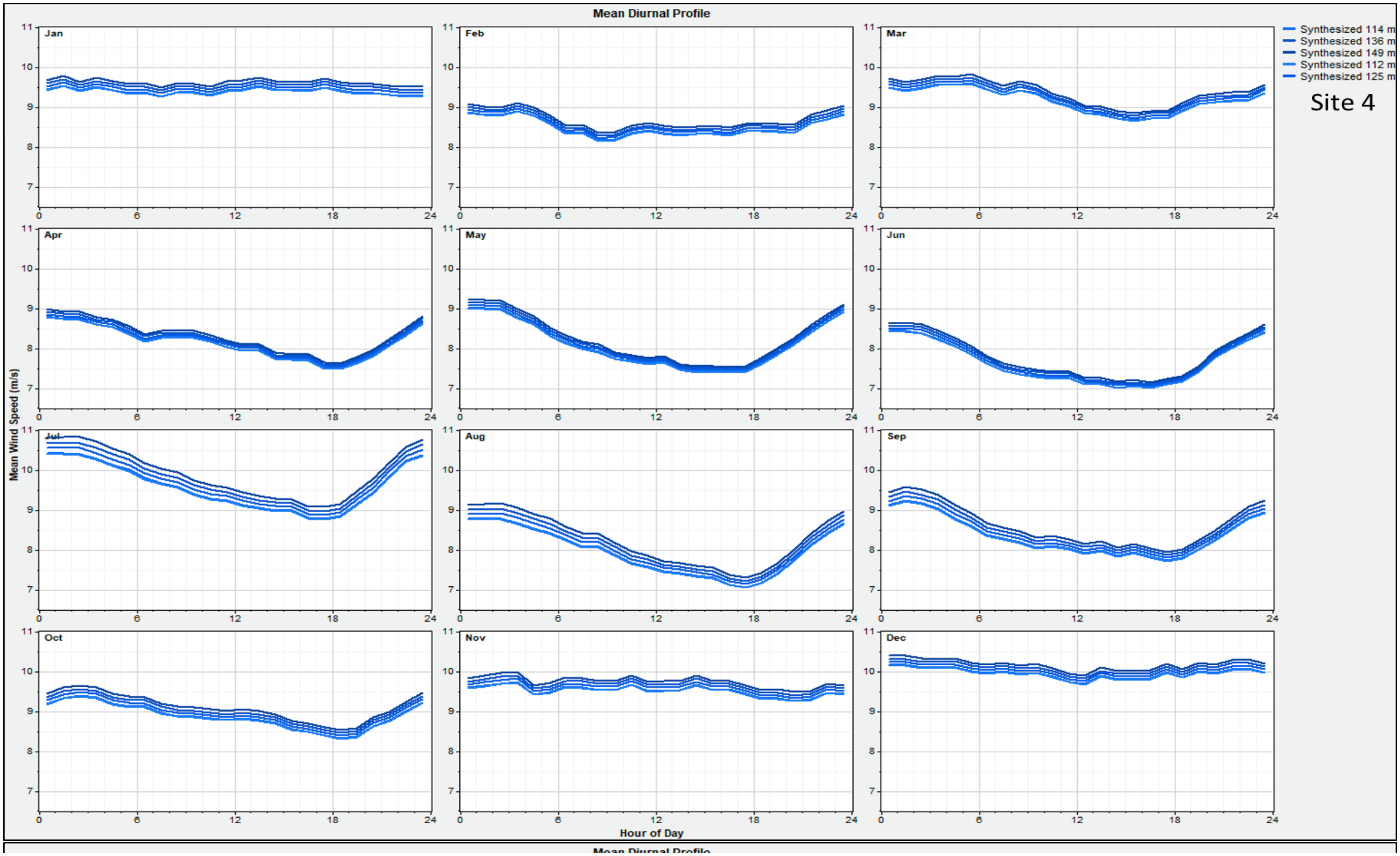


Figure B-4. Mean diurnal profiles for Site 4

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

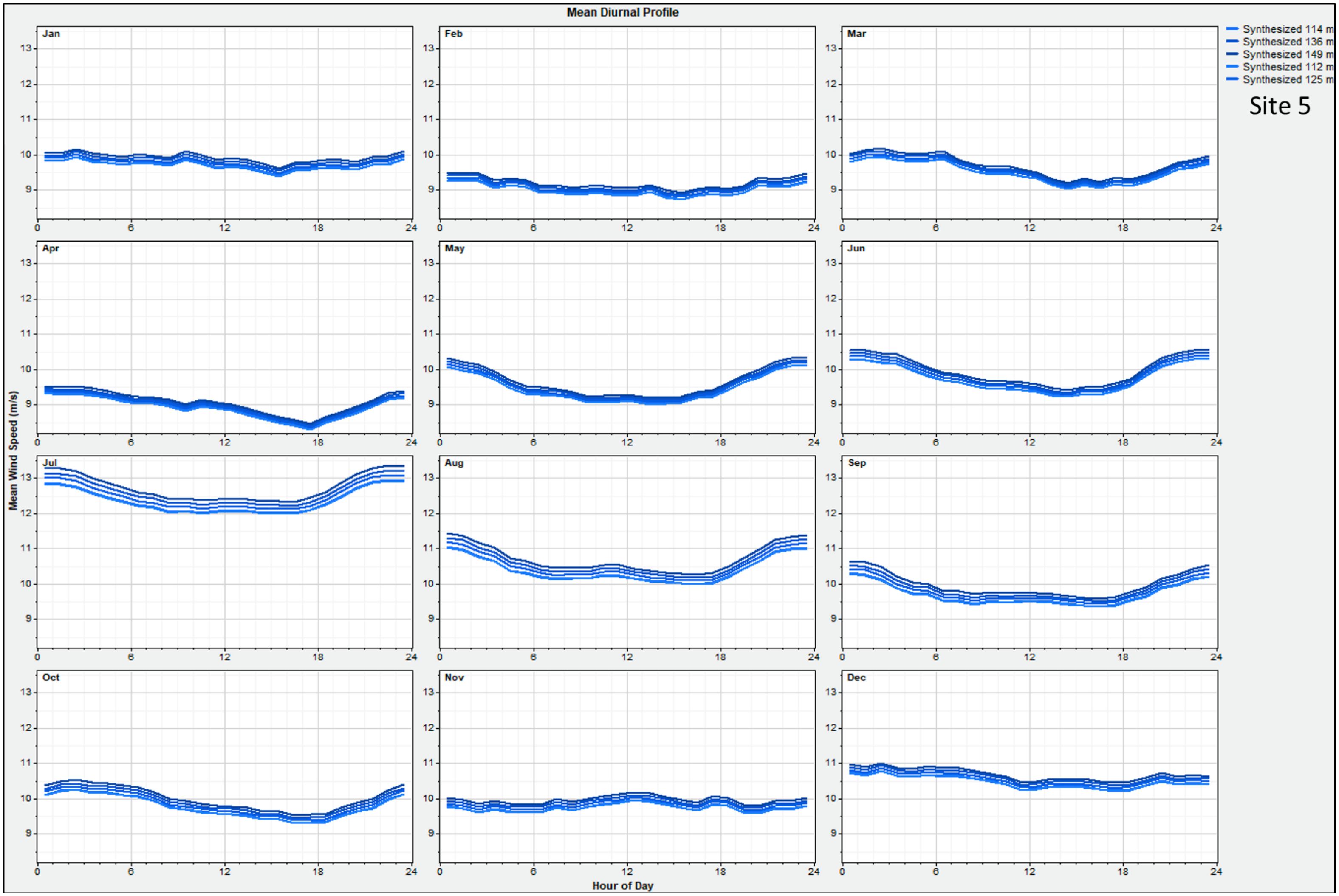


Figure B-5. Mean diurnal profiles for Site 5

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Appendix C. Baseline Cost Results

A baseline cost analysis was performed for three modeled years, representing commercial operation dates (COD) of 2015, 2022, and 2027. In addition, the resultant baseline levelized cost of energy (LCOE) values for these years were extrapolated (using an exponential curve fit) to 2030 to provide a cost estimate that can be compared to the California cost study. Using the technology assumptions in Table C-1, we modeled a 6-megawatt (MW) turbine for 2015, increasing to 8 MW in 2022, and 10 MW in 2027. Plant size was held constant at 600 MW for all model runs. A fixed charge rate (FCR) of 10.51% was used to represent 2016 financing parameters.

Table C-1. Baseline Turbine Technology Assumptions from Musial et al. (2016a)

Commercial Operations Date	2015	2022	2027
Turbine Rated Power (MW)	6	8	10
Turbine Rotor Diameter (m)	155	180	205
Turbine Hub Height (m)	100	112	136
Turbine Specific Power (W/m^2)	318	314	303
Substructure Technology	Semisubmersible	Semisubmersible	Semisubmersible

Figure C-1 shows the power curves for the baseline turbines in the Oregon cost study, which are the same as the ones used in the 2016 California study. It is important to note that the Danish Technical University turbine used to represent the 2022 technology in the primary Oregon analysis is different from the 10-MW National Renewable Energy Laboratory (NREL) reference turbine used for the 2016 California study to represent 2027 technology and the baseline analysis for this report. The NREL 10-MW turbine uses a rotor diameter of 205 m, which reflects a lower specific power of 303 W/m^2 than offshore wind rotors of today. This estimation of declining specific power is reasonable given that many land-based turbines already exist with specific power well below 300 W/m^2. However, with ultra-large offshore machines, increasing rotor diameter is one of the biggest challenges of upscaling, which makes lower specific power turbines more difficult.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

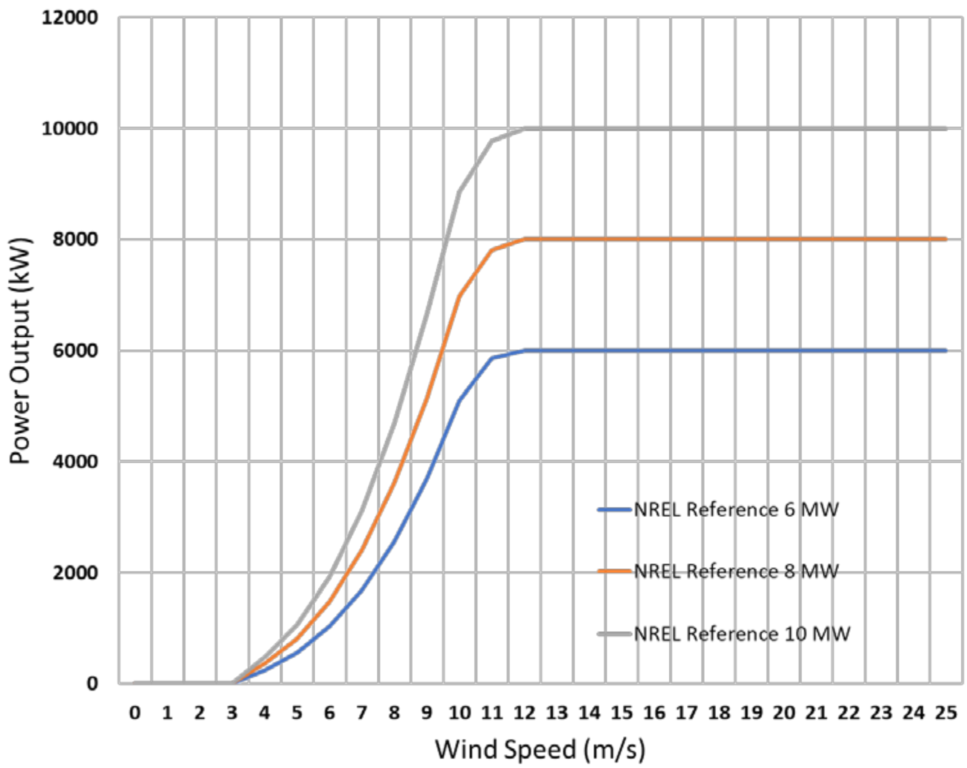


Figure C-1. Power curves for the baseline Oregon floating offshore wind study using California study assumptions for COD years 2015, 2022, and 2027. *Source: Musial et al. 2016a*

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Table C-2. Baseline Gross Capacity Factors, Losses, Net Capacity Factors, and Net Annual Energy Production (AEP_{net}) for Oregon Sites

6 MW 2017					
100-m Hub Height	Site 1	Site 2	Site 3	Site 4	Site 5
Gross Capacity Factor	43.48%	46.26%	47.20%	50.68%	59.74%
Total Losses	22.84%	24.05%	22.02%	21.86%	20.91%
Net Capacity Factor	33.55%	35.13%	36.81%	39.60%	47.25%
AEP_{net} (GWh)	1,763	1,847	1,934	2,081	2,483
8 MW 2022					
112-m Hub Height	Site 1	Site 2	Site 3	Site 4	Site 5
Gross Capacity Factor	46.35%	49.28%	50.35%	54.09%	63.01%
Total Losses	21.24%	22.37%	20.48%	20.33%	19.45%
Net Capacity Factor	36.51%	38.26%	40.04%	43.09%	50.76%
AEP_{net} (GWh)	1,919	2,011	2,104	2,265	2,668
10 MW 2027					
125-m Hub Height	Site 1	Site 2	Site 3	Site 4	Site 5
Gross Capacity Factor	50.67%	53.83%	55.10%	58.99%	68.20%
Total Losses	19.83%	20.88%	19.12%	18.98%	18.16%
Net Capacity Factor	40.63%	42.59%	44.57%	47.79%	55.82%
AEP_{net} (GWh)	2,135	2,238	2,342	2,512	2,934

The baseline cost results are plotted in Figure C-2 and shown in Table C-3.

Table C-3. Baseline Cost Results

	LCOE ($/MWh)				
	Site 1	Site 2	Site 3	Site 4	Site 5
	North	North Central	Central	South Central	South
2015	$ 242.46	$ 233.26	$ 220.81	$ 217.53	$ 181.56
2022	$ 179.35	$ 172.36	$ 163.63	$ 160.65	$ 135.61
2027	$ 136.03	$ 130.48	$ 124.26	$ 121.28	$ 103.33
2030	$ 119.54	$ 114.48	$ 109.18	$ 106.06	$ 90.53

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

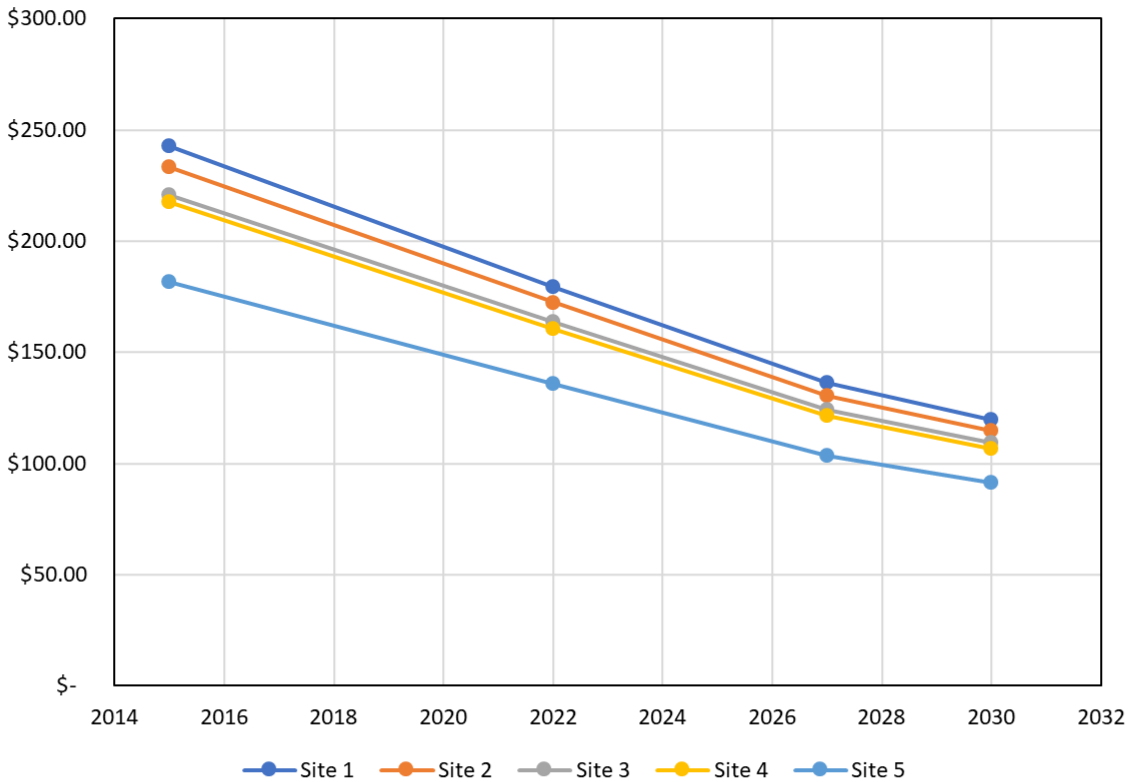


Figure C-2. Baseline cost trajectories for five Oregon floating offshore wind study sites

For the five sites in this analysis, the largest driver of LCOE is the wind speed gradient from north to south. At a 114-m hub height, based on data obtained from NREL's Wind Integration National Dataset Toolkit (Draxl 2015), the mean wind speed increases from 7.84 meters per second to 9.91 meters per second from the north to the south site.

For the 6-MW turbine (2017), LCOE varies from 242 $/megawatt-hour (MWh) at the north site and 182 $/MWh at the south site. In 2030, the extrapolated values show baseline costs that vary between $119/MWh in the north to about $90/MWh in the south. These compare to the California study, which show the Humboldt and Channel Island site costs in 2030 to be $100/MWh and $97/MWh, respectively.

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Appendix D. Power Curve Data

The data in Table D-1 are plotted for the power curves used in this report.

Table D-1. Data Used To Plot Power Curves in Figure 27 and Figure C-1

Wind Speed (m/s)	NREL Reference 6 MW	NREL Reference 8 MW	NREL Reference 10 MW	DTU Reference 10 MW	NREL Reference 12MW	NREL Reference 15MW
0	0	0	0	0	0	0
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	246	359	471	280	400	499
5	562	812	1059	799	1141	1424
6	1033	1483	1928	1533	2189	2732
7	1691	2407	3125	2506	3581	4469
8	2567	3616	4691	3731	5323	6643
9	3691	5135	6655	5312	7579	9459
10	5092	6976	8858	7287	10397	12975
11	5860	7813	9767	9698	12000	15000
12	6000	8000	10000	10639	12000	15000
13	6000	8000	10000	10649	12000	15000
14	6000	8000	10000	10639	12000	15000
15	6000	8000	10000	10684	12000	15000
16	6000	8000	10000	10642	12000	15000
17	6000	8000	10000	10640	12000	15000
18	6000	8000	10000	10640	12000	15000
19	6000	8000	10000	10653	12000	15000
20	6000	8000	10000	10646	12000	15000
21	6000	8000	10000	10644	12000	15000
22	6000	8000	10000	10641	12000	15000
23	6000	8000	10000	10640	12000	15000
24	6000	8000	10000	10644	12000	15000
25	6000	8000	10000	10636	12000	15000

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

Achievable Renewable Energy Targets

For Puerto Rico's Renewable Energy Portfolio Standard

Final Report

Agustín A. Irizarry-Rivera, Ph.D., P.E.
Department of Electrical and Computer Engineering
agustin@ece.uprm.edu

José A. Colucci-Ríos, Ph.D., P.E.
Department of Chemical Engineering
biodieselpr1@aol.com

Efraín O'Neill-Carrillo, Ph.D., P.E.
Department of Electrical and Computer Engineering
oneill@ece.uprm.edu

Project sponsored by:

Puerto Rico´s Energy Affairs Administration
Under contract number 2008-132009
October 2008 thru November 2009

Acknowledgements

This work was sponsored by the Puerto Rico Energy Affairs Administration under Contract Number 2008-132009. We are especially grateful, for his support and useful comments, to Dr. Javier Quintana Méndez Administrator of the Puerto Rico Energy Affairs Administration.

Graduate students contribution to this work was significant. The authors wish to express their gratitude to, and acknowledge the individual contribution of, the following students:

Miguel Ríos contributed to Chapter 2 Wind energy.

Franchesca Aponte and Magaby Quintero contributed to Chapter 3 Ocean energy.

Arlene Sosa, Luisa Feliciano and Johana Dumeng contributed to Chapter 4 Solar resource and solar thermal technologies.

Hillmon Ladner contributed to Chapter 5 Photovoltaic technology.

Liliana Martínez contributed to Chapter 6 Biomass and Chapter 7 Fuel Cell Technology.

Edy E. Jiménez contributed to Chapter 8 Micro hydroelectric technology.

Copyright Notice

All figures and tables in this report were created by the authors, or their student collaborators, except when otherwise noted. Adapted figures and tables are identified as such and their original sources are credited. Data or figures from public domain sources such as: United States Department of Energy (DOE), United States Geological Services (USGS), United States National Renewable Laboratory (NREL), National Oceanic and Atmospheric Administration (NOAA) and others are identified and their use conforms to the copyright policy published in their respective Internet sites.

Table of Contents

Tables

Figures

2 WIND POWER SYSTEMS

2.1 Introduction

Wind is the movement of air caused by the irregular heating of the Earth's surface. It happens at all scales, from local breezes created by heating of land surfaces that lasts some minutes, to global winds caused from solar heating of the Earth. Wind power is the transformation of wind energy into more utile forms, typically electricity using wind turbines [Gipe, 2004].

2.2 History

The first use of wind power was to make possible the sailing of ships in the Nile River some 5000 years ago. Many civilizations used wind power for transportation and other applications. The Europeans used it to crush grains and pump water in the 1700s and 1800s. The first wind mill to generated electricity in the rural U.S. was installed in 1890 [Patel 2006]. However, for much of the twentieth century there was small interest in using wind energy other than for battery charging for distant dwellings. These low-power systems were quickly replaced once the electricity grid became available. The sudden increases in the price of oil in 1973 stimulated a number of substantial

Government-funded programs for research, development and demonstrations of wind turbines and other alternative energy technologies.

In the United States this led to the construction of a series of prototype turbines starting with the 38 diameter 100kW Mod-0 in 1975 and culminating in the 97.5m diameter 2.5MW Mod-5B in 1987. Similar programs were pursued in the UK, Germany and Sweden [Burton et al. 2001]. Today, even larger wind turbines are being constructed such as 5MW units. Wind generated electricity is the fastest renewable growing energy business sector [Gipe, 2004].

Growth in the use of larger wind turbines, has made small wind turbines increasingly attractive for small applications such as, powering homes and farms. Wind power has become a very attractive renewable energy source because it is cheaper than other technologies and is also compatible with environmental preservation. To provide the reader with an idea of how has been the growth in wind energy, the installed capacity of wind has increased by a factor of 4.2 during the last five years [Mathew 2006]. The total global installed capacity of wind power systems in 2006 is approximately 73,904MW. Figure 2.1 [World Wind Energy 2007] shows the total installed in the last few years and provide a prediction for 2010. Figure 2.2 [The wind indicator 2005] shows the total wind power installed in different parts of the world.

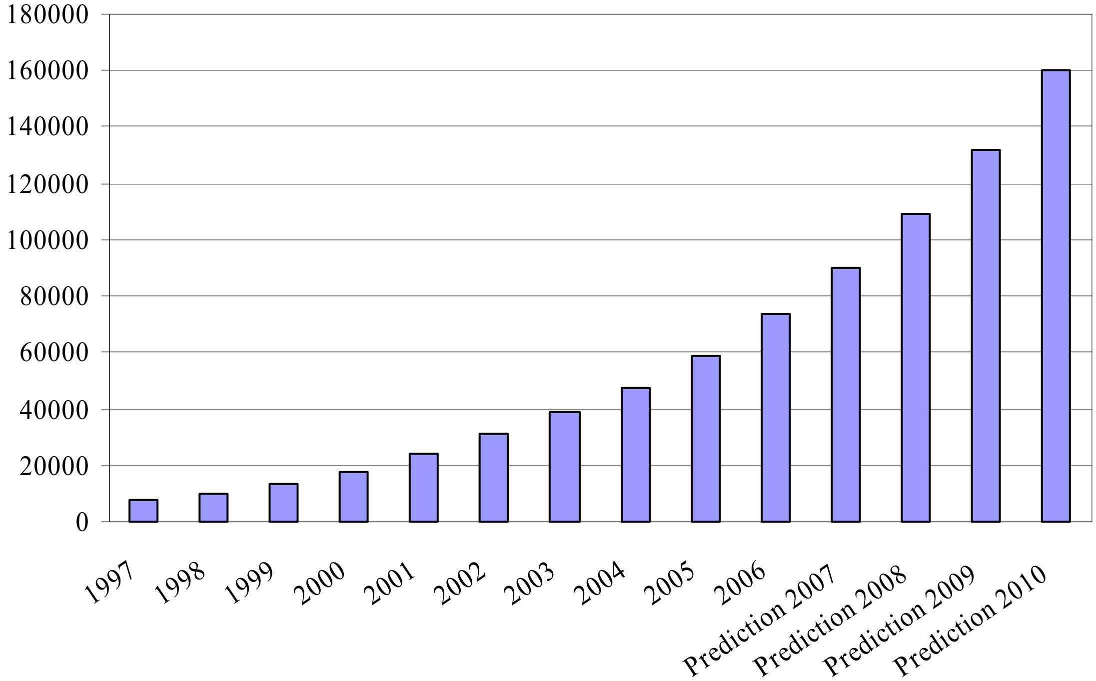


Figure 2-1 World Wind Energy – Total Installed Capacity (MW) (Adapted from [World Wind Energy])

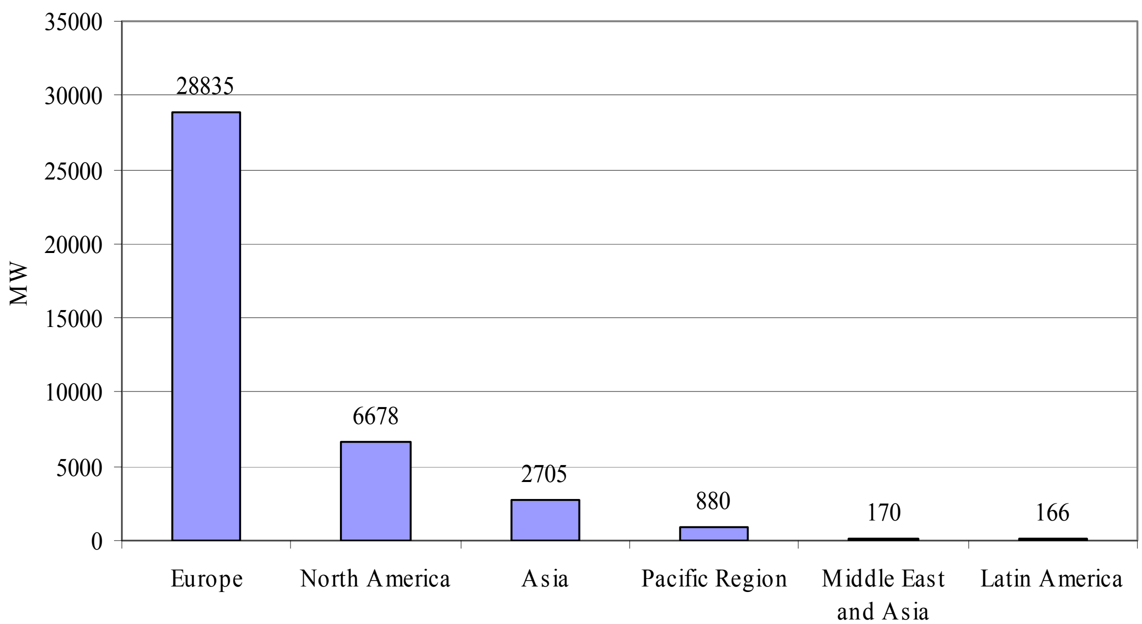


Figure 2-1 Installed Wind Energy Capacity (MW) in Different Regions (Adapted from [The Wind Indicator 2005])

2.3 Wind Turbines

A wind turbine is a machine that converts the kinetic energy from the wind into mechanical energy. If the mechanical energy is used directly by machinery, such as a pump or grinding stones, the machine is usually called a windmill. If the mechanical energy is then converted to electricity, the machine is called a wind generator [Gipe, 2004].

The modern wind turbine is a sophisticated piece of machinery with aerodynamically designed rotor and efficient power generation, transmission and regulation components. The size of these turbines ranges from a few Watts (Small Wind Turbines) to several Million Watts (Large Wind Turbines).

The modern trend in the wind industry is to go for bigger units of several MW capacity in places where the wind is favorable, as the system scaling up can reduce the unit cost of wind-generated electricity. Most of today's commercial machines are horizontal axis wind turbines (HAWT) with three bladed rotors.

While research and development activities on vertical axis wind turbines (VAWT) were intense during the end of the last century, VAWT could not evolve as a reliable alternative to the horizontal axis machines [Mathew 2006]. Figure 2.3 shows the typical vertical and horizontal wind turbines.

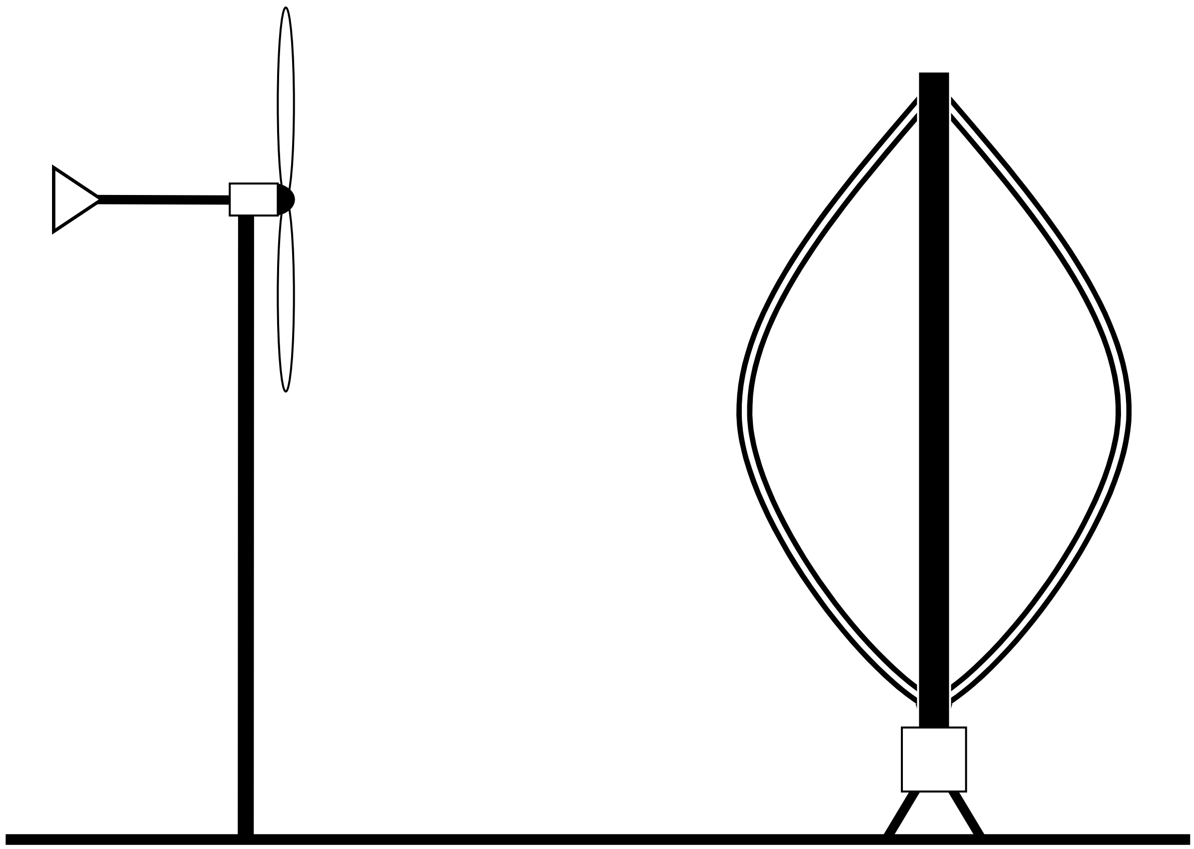


Figure 2-2 Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT)

2.3.1 Wind Turbines Components

The basic components for horizontal axis wind turbine are shown on **Figure 2-3 Components of a Wind Turbine**.

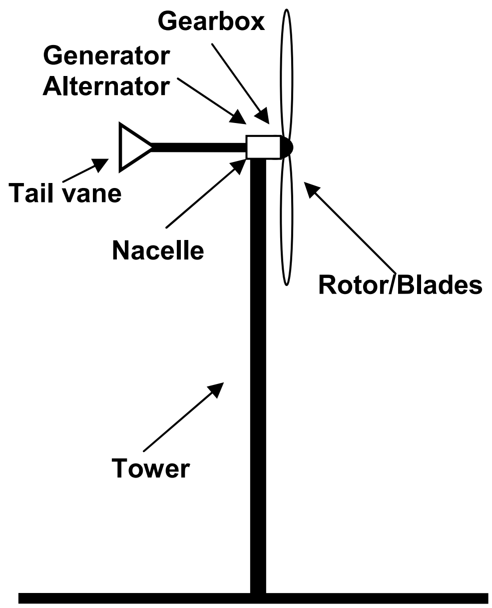


Figure 2-3 Components of a Wind Turbine

- Rotor/blades – The blades together with the hub are called the rotor. The rotor drives the generator by harnessing the kinetic energy in the wind. The blades are aerodynamically shaped to best capture the wind. The amount of energy a turbine can capture is proportional to the rotor sweep area. The blades are usually made of fiberglass, metal, reinforced plastic or wood.
- Generator/Alternator – Is the part of the turbine that produces electricity from the kinetic energy captured by the rotor. A generator produces Direct Current (DC)

power or, if in use, an alternator produces Alternating Current (AC) power, depending on the application for the turbine.

- Gearbox – Most turbines above 10 kW use a gearbox to match the rotor speed to the generator speed.
- Nacelle – Is the housing that protects the essential motorized parts of a turbine.
- Tail vane (Yaw system) – A yaw system aligns a HAWT with the wind. Most micro and mini systems use a simple tail vane that directs the rotor into the wind. In some systems, the rotor is downwind of the generator, so it naturally aligns with the wind. Some yaw systems can be offset from the vertical axis to regulate rotor power and speed by tilting the turbine slightly upward.

The following components are also usually supplied as part of a small wind turbine package:

- Control & Protection System – Control systems vary from simple switches, fuses and battery charge regulators to computerized systems for control of yaw systems and brakes. The sophistication of the control and protection system varies depending on the application of the wind turbine and the energy system it supports.
- Tower – Is the support of the small wind turbine. The wind speed increases at higher heights, meaning the higher the tower the greater the power. There are several types of towers.
    - Guyed lattice towers, where the tower is permanently supported by guy wires. These towers tend to be the least expensive, but take up a lot of space on a yard. A radio broadcast tower is a good example of a guyed lattice tower.

o Guyed tilt-up towers, which can be raised and lowered for easy maintenance and repair.

o Self-supporting towers, which do not have any guy wires. These towers tend to be the heaviest and most expensive, but because they do not require guy wires, they do not take up as much space on a yard.

2.4 Small Wind Turbines

Small wind turbines are typically used for powering houses, farms and remote locations that usually consume less than 50 kW of total capacity. For use these small turbines there must be enough wind, tall towers are allowed in the neighborhood or rural area, there enough space, the noise level of the turbine is approved and know how much electricity want to produce.

2.4.1 Small Wind Turbines Manufacturers

Today there are more than fifty manufactures of small wind turbines worldwide, and they produce more than one hundred different models [Gipe, 2004]. TABLE 2-1 and TABLE 2-2 present examples of small wind turbines available in the market today. These turbines are the most used in the United States and Europe for small wind power applications. Looking at the table we see that while larger turbine rotor area translates into more power that can be extracted from the wind and it also make the turbine more expensive. We selected a 25m tower to be used with all turbines. The prices were obtained from different manufactures in the internet during January 2008.

TABLE 2-1 Small wind turbines cost information, in US dollars

Product	Watts @ 28 mph	Turbine price	25m tower price	Turbine and tower	$/W	$/rotor area, m^2	W/m^2
SouthWest (Air X)	400	$600	$805	$1,405	$3.51	1376	392
SouthWest (Whisper 100)	900	$2,085	$805	$2,890	$3.21	834	260
SouthWest (Whisper 200)	1000	$2,400	$805	$3,205	$3.20	453	141
SouthWest (Whisper 500)	3000	$7,095	$1,157	$8,252	$2.75	497	181
SouthWest (Skystream 3.7)	1800	$5,400	$1,157	$6,557	$3.64	603	166
Aeromax Engineering (Lakota S, SC)	800	$1,591	$804	$2,395	$2.99	698	233
Bergey (BWC 1500)	1500	$4,700	$1,968	$6,668	$4.45	943	212
Bergey (BWC XL.1)	1000	$2,590	$1,968	$4,558	$4.56	929	204
Bergey (BWC Excel-R)	8100	$23,000	$2,396	$25,396	$3.14	720	230
Bornay (Inclin 250)	250	$2,151	$1,157	$3,308	$13.23	2149	162
Bornay (Inclin 600)	600	$2,726	$1,157	$3,883	$6.47	1236	191
Bornay (Inclin 1500)	1500	$3,973	$1,157	$5,130	$3.42	896	262
Bornay (Inclin 3000)	3000	$6,028	$1,968	$7,996	$2.67	744	279
Bornay (Inclin 6000)	6000	$10,070	$1,968	$12,038	$2.01	1120	558
Abundant Renewable Energy (ARE110)	2500	$11,500	$1,968	$13,468	$5.39	1323	246
Abundant Renewable Energy (ARE442)	10000	$36,000	$2,396	$38,396	$3.84	943	246
Kestrel Wind (600)	600	$1,296	$804	$2,100	$3.50	1188	340
Kestrel Wind (800)	800	$1,995	$804	$2,799	$3.50	808	231
Kestrel Wind (1000)	1000	$2,950	$1,157	$4,107	$4.11	581	141
Kestrel Wind (3000)	3000	$8,400	$1,968	$10,368	$3.46	914	265
Solacity (Eoltec)	6000	$25,200	$1,968	$27,168	$4.53	1103	244

TABLE 2-2 Small wind turbines physical data and seller

Product	Rotor Diameter (m)	Rotor Area (m^2)	Weigh lb	Voltage V	Seller
SouthWest (Air X)	1.14	1.02	13	12, 24, 48 Vdc	Alt En Store
SouthWest (Whisper 100)	2.1	3.46	47	12, 24, 48 Vdc	Infinigy
SouthWest (Whisper 200)	3	7.07	65	12, 24, 48 Vdc 230 Vac	Gaiam
SouthWest (Whisper 500)	4.6	16.62	155	12, 24, 48 Vdc 230 Vac	Alt En Store
SouthWest (Skystream 3.7)	3.72	10.87	154	120/240 AC	Southwest
Aeromax Engineering (Lakota S, SC)	2.09	3.43	35	12, 24, 48 Vdc	Aeromax Engineering
Bergey (BWC 1500)	3	7.07	168	12, 24, 36, 48, 120 Vdc	Alter System
Bergey (BWC XL.1)	2.5	4.91	75	24, 48 Vdc	Alter System
Bergey (BWC Excel-R)	6.7	35.26	1050	48 Vdc 120Ac 240Ac	Alt En Store
Bornay (Inclin 250)	1.4	1.54	93	12, 24, 48, 220 Vdc	Bornay
Bornay (Inclin 600)	2	3.14	93	12, 24, 48, 220 Vdc	Bornay
Bornay (Inclin 1500)	2.7	5.73	93	12, 24, 48, 220 Vdc	Bornay
Bornay (Inclin 3000)	3.7	10.75	276	12, 24, 48, 220 Vdc	Bornay
Bornay (Inclin 6000)	3.7	10.75	342	12, 24, 48, 220 Vdc	Bornay
Abundant Renewable Energy (ARE110)	3.6	10.18	315	48Vdc	ARE
Abundant Renewable Energy (ARE442)	7.2	40.72	1350	48Vdc	ARE
Kestrel Wind (600)	1.5	1.77	44	12, 24, 48, 220 Vdc	www.kestrelwind.co.za
Kestrel Wind (800)	2.1	3.46	66.1	12, 24, 48, 220 Vdc	www.kestrelwind.co.za
Kestrel Wind (1000)	3	7.07	88	12, 24, 48, 220 Vdc	www.kestrelwind.co.za
Kestrel Wind (3000)	3.8	11.34	397	24, 48, 220 Vdc	www.kestrelwind.co.za
Solacity (Eoltec)	5.6	24.63	450	3 phase AC	Solacity.com

2.5 Large Wind Turbines

Large wind turbines are typically used to sell power to electric utilities. Their power ranges from 100 kW up to 5 MW. For use these large turbines there must be enough wind, tall towers are allowed in the neighborhood or rural area, there enough space, the noise level of the turbine is approved and know how much electricity want to produce.

2.5.1 Large Wind Turbines Manufactures

TABLE 2-3 presents examples of large wind turbines available in the market today. These turbines are the most used in the United States and Europe for large wind power applications. From TABLE 2-3 see that while larger turbine rotor area translates into more power that can be extracted from the wind and it also make the turbine more expensive. Installed cost of these turbines ranges between 1 and 1.4 dollars per installed W. Typical costs of operation and maintenance are in the $0.01 per kWh generated.

TABLE 2-3 Examples of large wind turbines and basic data

Manufacturer	**Product**	**kW @ 28 mph**	**Watt/m^2**	**Rotor diameter (m)**	**Rotor area (m²)**	**Output voltage (V)**
Distributed Energy System	NorthWind 100	100	289	21	346.36	480
AAER Wind	A-1000	1000	378	58	2642.08	690
GE	1.5xle	1500	281	82.5	5345.62	
GE	2.5xl	2500	318	100	7853.98	
GE	3.6sl	3600	372	111	9676.89	
ACSA	A27/225	225	393	27	572.56	400
Enercon	E-33	330	377	33.4	876.16	
Enercon	E-44	900	592	44	1520.53	
Enercon	E-48	800	442	48	1809.56	
Enercon	E-53	800	364	52.9	2197.87	
Enercon	E-70	2300	581	71	3959.19	
Enercon	E-82	2000	379	82	5281.02	
Vesta Wind Systems	V52-850kw	850	400	52	2123.72	690
Vestas Wind Systems	V82-1.65MW	1650	312	82	5281.02	690
Vestas Wind Systems	V80-1.8 MW	1800	358	80	5026.55	690
Vesta Wind System	V90-1.8 & 2.0	2000	314	90	6361.73	690
Vesta Wind Systems	V80-2.0MW	2000	398	80	5026.55	690
Vesta Wins Systems	V90-3.0MW	3000	472	90	6361.73	690
Fuhrlander	FL 1500	1500	322	77	4656.63	690
Fuhrlander	FL 2500	2500	318	100	7853.98	690
Gamesa	G58-850KW	850	322	58	2642.08	690
Gamesa	G90-2.0MW	2000	314	90	6361.73	690
Nordex	N60/1300	1300	460	60	2827.43	690
Nordex	S77/1500 KW	1500	322	77	4656.63	690
Nordex	N90/2300	2300	362	90	6361.73	660
Nordex	N100/2500 KW	2500	320	99.8	7822.60	600
Suzlon	Serie 600	600	283	52	2123.72	690
Suzlon	S66-1250	1250	365	66	3421.19	600
Suzlon	S.82-1.5MW	1500	284	82	5281.02	690
Suzlon	S.88	2000	329	88	6082.12	690

2.6 Wind Turbines Efficiency and Power Curve

The theoretical limit of power extraction from wind, or any other fluid was derived by the German aerodynamicist Albert Betz. Betz law, [Betz, 1966], states that 59% or less of the kinetic energy in the wind can be transformed to mechanical energy using a wind turbine.

In practice, wind turbines rotors deliver much less than Betz limit. The factors that affect the efficiency of a turbine are the turbine rotor, transmission and the generator. Normally the turbine rotors have efficiencies between 40 to 50%. Gearbox and generator efficiencies can be estimated to be around 80% to 90%. Also efficiency of a turbine is not constant. It varies with wind speeds. Many companies do not provide their wind turbine efficiencies. Instead they provide a power curve.

A power curve is a graph that represents the turbine power output at different wind speeds values. The advantage of using a power curve is that it includes the wind turbines efficiency for all wind speeds of operation. The power curve is normally provided by the turbine's manufacture. **Figure 2-4** presents an example of a wind turbine power curve. Note that at speeds from 0 to 3.5 m/s the power output is zero. This occurs because there is not sufficient kinetic energy in the wind to move the wind turbine rotor. Normally the manufactures provide a technical data sheet where the start up wind speed of the turbine is given. In general lower start up wind speeds result in higher energy coming from the turbine.

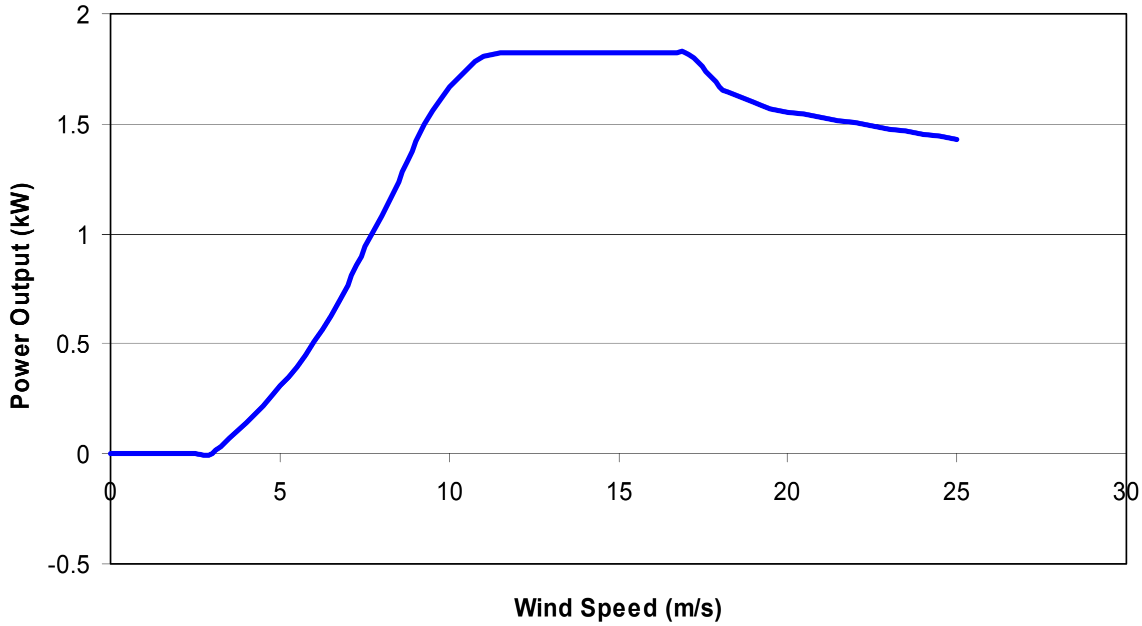


Figure 2-4 Power Curve for Wind Turbine "Sky Stream 3.7" of South West Company (Source: Data from manufacturer, plot by author)

A manufacturer may also show the power curve information in table format. The table provides the exact value of power at different wind speed. The power curve is then obtained by plotting the table values. TABLE 2-4 and TABLE 2-5 present the power curve data for different small turbines. TABLE 2-6 and TABLE 2-7 present the power curve data for different large turbines.

TABLE 2-4 Power curve values, in kW, for small wind turbines

Wind Speed m/s	SouthWest					AeroMax Engineering	Bergey		
	Air X	Whisper 100	Whisper 200	Whisper 500	Skystream 3.7	Lakota S, SC	BWC 1500	BWC XL.1	BWC Excel-R
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.01	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.05
4	0.02	0.02	0.05	0.27	0.14	0.03	0.08	0.06	0.25
5	0.03	0.06	0.15	0.55	0.31	0.07	0.15	0.12	0.70
6	0.04	0.12	0.28	0.88	0.51	0.11	0.30	0.23	1.38
7	0.07	0.19	0.44	1.26	0.77	0.28	0.45	0.38	2.18
8	0.09	0.28	0.63	1.70	1.08	0.34	0.60	0.54	3.11
9	0.13	0.39	0.78	2.18	1.42	0.41	0.80	0.70	4.26
10	0.16	0.52	0.89	2.67	1.67	0.53	1.15	0.89	5.37
11	0.20	0.66	0.96	3.07	1.80	0.64	1.30	1.06	6.63
12	0.28	0.80	0.99	3.28	1.82	0.75	1.50	1.21	7.45
13	0.35	0.90	1.00	3.33	1.82	0.90	1.60	1.24	8.09
14	0.41	0.92	1.00	3.26	1.82	1.16	1.70	1.20	8.05
15	0.44	0.91	0.99	3.13	1.82	1.28	1.60	1.15	7.92
16	0.45	0.88	0.96	2.96	1.82	1.30	0.35	1.10	7.75
17	0.35	0.85	0.93	2.77	1.82	1.25	0.35	1.05	7.51
18	0.15	0.81	0.90	2.56	1.67	1.20	0.40	0.99	7.28
19	0.15	0.77	0.85	2.33	1.60	1.10	0.40	0.94	7.11
20	0.15	0.73	0.81	2.08	1.55	1.00	0.40	0.90	6.96
21	0.15	0.69	0.77	1.76	1.53	0.98	0.40	0.85	6.73
22	0.15	0.64	0.72	1.45	1.50	0.93	0.40	0.85	6.49
23	0.15	0.60	0.68	1.13	1.48	0.90	0.40	0.85	6.26
24	0.15	0.56	0.63	0.82	1.45	0.90	0.40	0.85	6.03

TABLE 2-5 Power curve values, in kW, for small wind turbines (cont)

Wind Speed m/s	Bornay					Abundant Renewable Energy		Kestrel Wind				Solacity
	Inclin 250	Inclin 600	Inclin 1500	Inclin 3000	Inclin 6000	ARE110	ARE442	Kestrel 600	Kestrel 800	Kestrel 1000	Kestrel 3000	Eoltec
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.02	0.03	0.11	0.25	0.68	0.14	0.30	0.01	0.02	0.01	0.05	0.14
4	0.03	0.06	0.22	0.50	1.10	0.20	0.64	0.03	0.04	0.08	0.15	0.34
5	0.05	0.11	0.41	0.75	1.60	0.25	1.40	0.05	0.10	0.17	0.26	0.67
6	0.08	0.15	0.59	1.00	2.10	0.50	2.13	0.09	0.19	0.34	0.50	1.16
7	0.12	0.24	0.80	1.50	3.10	0.70	3.57	0.14	0.27	0.53	0.79	1.81
8	0.17	0.32	1.00	1.80	3.90	1.32	5.62	0.21	0.36	0.74	1.17	2.71
9	0.21	0.41	1.12	2.15	4.50	1.65	7.75	0.30	0.47	1.00	1.59	3.82
10	0.24	0.50	1.24	2.50	5.00	2.25	9.55	0.39	0.58	1.29	2.00	5.00
11	0.27	0.55	1.40	2.80	5.50	2.55	10.38	0.48	0.69	1.64	2.50	5.70
12	0.30	0.60	1.55	3.10	6.00	2.55	10.50	0.55	0.79	1.20	2.90	6.00
13	0.33	0.60	1.67	3.30	6.25	2.55	10.50	0.63	0.86	1.21	3.45	6.00
14	0.35	0.60	1.78	3.50	6.50	2.55	10.50	0.65	0.86	1.22	3.40	6.00
15	0.30	0.56	1.64	3.25	6.00	2.55	10.50	0.66	0.85	1.23	3.40	6.00
16	0.25	0.52	1.50	3.00	5.80	2.55	10.50	0.65	0.85	1.23	3.40	6.00
17	0.26	0.53	1.53	3.03	5.90	2.55	10.50	0.65	0.85	1.23	3.40	6.00
18	0.26	0.54	1.55	3.05	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00
19	0.26	0.54	1.60	3.20	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00
20	0.26	0.54	1.64	3.35	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00
21	0.26	0.54	1.65	3.38	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00
22	0.26	0.54	1.66	3.39	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00
23	0.26	0.54	1.66	3.40	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00
24	0.26	0.54	1.66	3.40	6.00	2.55	10.50	0.65	0.85	1.23	3.40	6.00

TABLE 2-6 Power curve values, in MW, for large wind turbines

Wind Speed m/s	**Suzlon**				**Nordex**				**Gamesa**		**Fuhrlander**		**Vestas Wind Systems**			
	S.88 - 2.1MW	**S.82 -1.5MW**	**S66 -1.2MW**	**Serie 600KW**	**N100/2.5MW**	**N90/2.3MW**	**S77/1.500MW**	**N60/1.3MW**	**G90-2.0MW**	**G58-850KW**	**FL 2500**	**FL 1500**	**V90-3.0MW**	**V90-2.0MW**	**V82-1.65MW**	**V52-850KW**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
4	0.01	0.00	0.04	0.00	0.05	0.04	0.04	0.03	0.08	0.08	0.10	0.03	0.05	0.05	0.03	0.04
5	0.14	0.10	0.09	0.04	0.21	0.18	0.13	0.07	0.20	0.15	0.20	0.10	0.24	0.16	0.14	0.08
6	0.31	0.26	0.15	0.10	0.43	0.35	0.24	0.13	0.36	0.24	0.48	0.24	0.40	0.33	0.31	0.12
7	0.55	0.47	0.29	0.18	0.73	0.58	0.40	0.24	0.59	0.37	0.73	0.40	0.65	0.60	0.51	0.20
8	0.84	0.71	0.45	0.25	1.11	0.87	0.60	0.38	0.90	0.53	1.08	0.60	0.95	0.88	0.76	0.30
9	1.18	0.97	0.64	0.40	1.58	1.24	0.85	0.54	1.27	0.70	1.50	0.90	1.28	1.20	1.02	0.41
10	1.54	1.22	0.83	0.47	2.02	1.62	1.11	0.70	1.63	0.80	2.08	1.16	1.65	1.63	1.29	0.55
11	1.86	1.38	1.01	0.55	2.31	2.01	1.33	0.87	1.86	0.84	2.50	1.34	2.04	1.90	1.50	0.65
12	2.04	1.44	1.15	0.59	2.46	2.23	1.48	1.02	1.96	0.85	2.50	1.45	2.45	1.98	1.64	0.76
13	2.09	1.47	1.24	0.61	2.50	2.30	1.50	1.12	1.99	0.85	2.50	1.50	2.75	2.00	1.65	0.83
14	2.10	1.50	1.25	0.61	2.50	2.30	1.50	1.25	2.00	0.85	2.50	1.50	2.90	2.00	1.65	0.85
15	2.10	1.50	1.25	0.61	2.50	2.30	1.50	1.30	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
16	2.10	1.50	1.25	0.61	2.50	2.30	1.50	1.34	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
17	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.36	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
18	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.32	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
19	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.32	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
20	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.31	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
21	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.31	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
22	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.31	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
23	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.30	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85
24	2.00	1.50	1.25	0.60	2.50	2.30	1.50	1.29	2.00	0.85	2.50	1.50	3.00	2.00	1.65	0.85

TABLE 2-7 Power curve values, in MW, for large wind turbines (cont)

Wind Speed m/s	Enercon						AAER Wind	ACSA	GE			Distributed Energy Systems
	E-82	E-70	E-53	E-48	E-44	E-33	A-1000	A27/225	3.6sl	2.5xl	1.5xle	NorthWind 100
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.03	0.02	0.04	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
4	0.08	0.06	0.08	0.03	0.02	0.01	0.03	0.01	0.10	0.05	0.08	0.01
5	0.17	0.13	0.14	0.07	0.05	0.03	0.07	0.02	0.25	0.15	0.16	0.01
6	0.32	0.24	0.23	0.12	0.10	0.06	0.14	0.03	0.45	0.39	0.30	0.02
7	0.53	0.40	0.34	0.19	0.16	0.09	0.24	0.05	0.73	0.64	0.50	0.03
8	0.82	0.63	0.48	0.28	0.24	0.14	0.36	0.08	1.10	0.99	0.73	0.04
9	1.18	0.89	0.65	0.41	0.34	0.20	0.51	0.11	1.70	1.35	1.00	0.05
10	1.66	1.22	0.74	0.56	0.47	0.25	0.67	0.15	2.18	1.90	1.25	0.06
11	1.89	1.59	0.78	0.67	0.60	0.29	0.86	0.17	2.70	2.25	1.46	0.08
12	2.00	1.90	0.81	0.75	0.71	0.32	1.00	0.21	3.18	2.42	1.50	0.09
13	2.05	2.08	0.81	0.79	0.79	0.34	1.00	0.22	3.40	2.50	1.50	0.09
14	2.05	2.23	0.81	0.81	0.85	0.34	1.00	0.23	3.55	2.50	1.50	0.10
15	2.05	2.30	0.81	0.81	0.88	0.34	1.00	0.23	3.60	2.50	1.50	0.10
16	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
17	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
18	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
19	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
20	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
21	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
22	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
23	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10
24	2.05	2.31	0.81	0.81	0.91	0.34	1.00	0.23	3.60	2.50	1.50	0.10

2.7 Wind Turbine Power

To estimate the average power generated by a wind turbine at a given site you may use the average wind speed for the site and the wind turbine power curve to estimate the average power output. The power available for a wind turbine at a specific site is:

$$P = P_c(v) * n \qquad \textbf{2-1}$$

Where P is an estimate of the expected power production at the site, $P_c(v)$ is the turbine power output from the power curve at wind speed v, and n is the number of wind turbines to be installed. The generated energy, for a given wind speed, is obtained multiplying the power produced at such speed by the time the wind blows at such speed. Total generated energy is obtained adding the energy produced at each wind speed the turbine is capable of producing electricity.

2.8 Wind Resources

Wind resource is the most important element in projecting turbine performance at a given place. The energy that can be extracted from a wind stream is proportional to the cube of its velocity, meaning that doubling the wind velocity increases the available energy by a factor of eight. Also, the wind resource itself rarely is a constant or has a steady flow. It varies with year, season, and time of day, elevation above ground, and form of terrain. Proper location of windy sites, away from large obstructions, improves wind turbine's performance.

2.8.1 Anemometer

Wind speed is measured with an instrument called an anemometer. These come in several types. The most common type has three or four cups attached to a rotating shaft. When the wind hits the anemometer, the cups and the shaft rotate. The angular speed of the spinning shaft is calibrated in terms of the linear speed of the wind. In the U.S., wind speed is reported in miles per hour or in nautical miles per hours (knots). In other countries, it is reported in kilometers per hours or meters per second. No matter what measurement system is installed, the user needs to be sure it is properly calibrated. Make note that the energy that can be extracted from the wind is proportional to the cube of its velocity, meaning bad wind speed measurements will cause an even worse estimate of power available, [Gipe, 2004].

For a small wind turbine a minimum of one year of data should be recorded and compared with another source of wind data. It is very important that the measuring equipment is set high enough to avoid turbulence created by trees, buildings or other obstructions. Readings would be most useful if they have been taken at hub height, or the elevation at the top of the tower where the wind turbine is going to be installed, [Gipe, 2004].

2.8.2 Wind Speed Height Correction

If the measurement of wind speed was not made at the wind turbine hub height it is important to adjust the measured wind speed to the hub height. This can be done using the one-seventh power law as shown in Equation 2.2, [Burton et al. 2001].

$$\frac{v(z_2)}{v(z_1)} = \left(\frac{z_2}{z_1}\right)^{\alpha} \qquad \textbf{2-2}$$

Where $v(z_2)$ is the wind speed at the desired height z_2, $v(z_1)$ is the wind speed measured at a known height z_1. α is a coefficient known as the wind shear exponent. The wind shear exponent varies with pressure, temperature and time of day. A commonly use value for α is one-seventh (1/7), approximately 0.1429.

2.8.3 Wind Resources in Puerto Rico

Puerto Rico is a mountainous, oceanic island situated between the Atlantic Ocean and the Caribbean Sea, at approximately 18º N latitude and 66º longitude. The island is approximately rectangular, 177 kilometers east to west and about 57 kilometers maximum north to south. The prevailing wind of the island comes from the northeast trade winds [Burton et al. 2001]. A collaborative effort between the US Department of Energy (DOE), the National Renewable Energy Laboratory (the Wind Powering America program and the Wind Resource Group), AWS Truewind and the Puerto Rico Energy Affairs Administration has produced a high resolution wind maps for Puerto Rico. Figure 2-5 shows the annual average wind power at 50 m for Puerto Rico [NREL 2008].

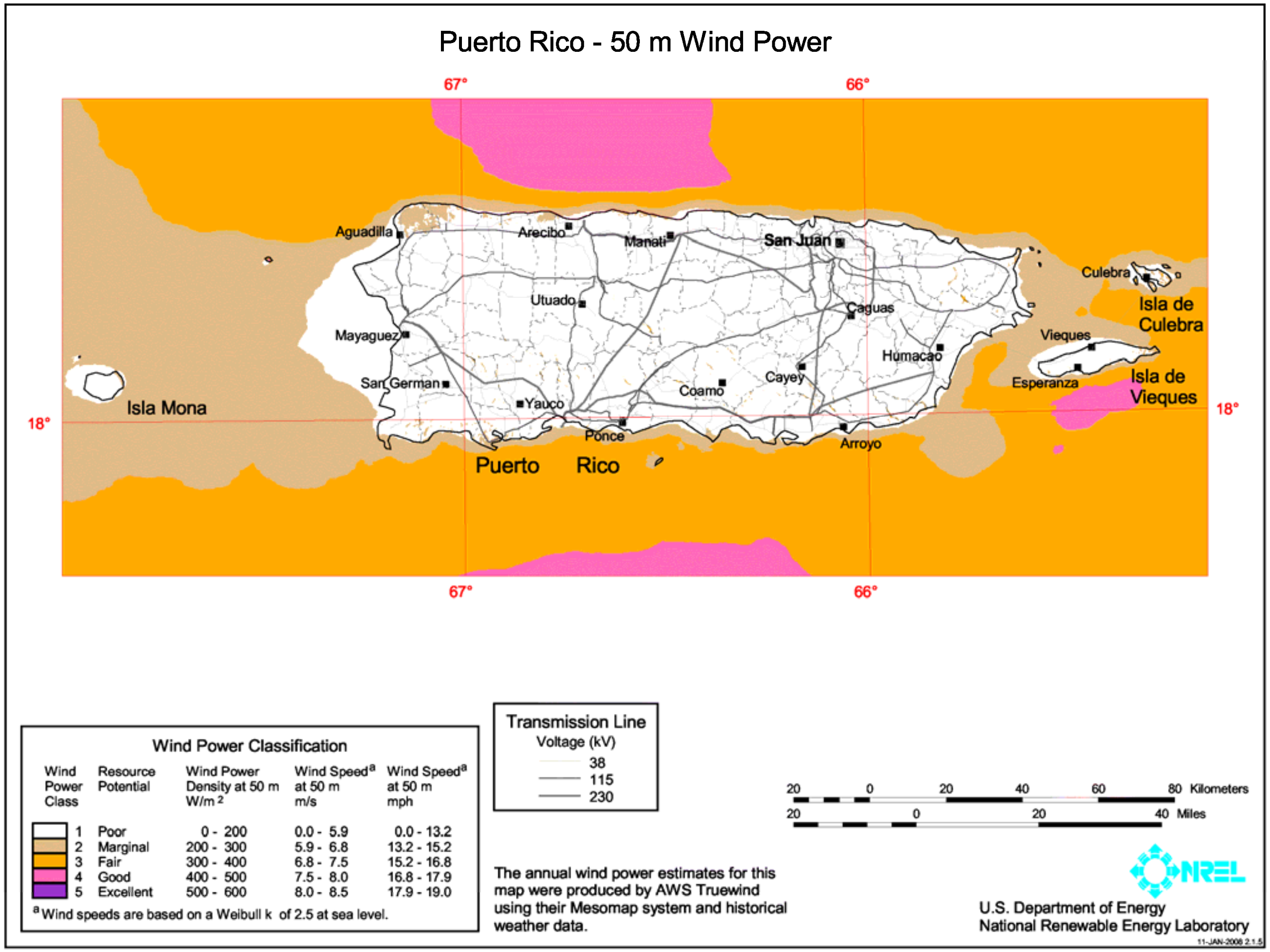


Figure 2-5 Puerto Rico annual average wind map at 50 m height [Source: NREL 2008]

The maps show estimates of wind speed. The only way to make sure the wind speed presented in the maps is correct for a given location is to use an anemometer to measure wind speed at the site. Several studies have measure wind speed in Puerto Rico. TABLE 2-8 and TABLE 2-9 present a diurnal distribution of mean wind velocity in (m/s) for several sites in Puerto Rico. TABLE 2-10 and TABLE 2-11 present monthly distribution of mean wind velocity in (m/s) for the sites shown in TABLE 2-8 and TABLE 2-9. All the data has been adjusted to a height of 25 meters from the ground.

TABLE 2-8 Diurnal distribution of mean wind velocity, m/s at 25 m above ground [Briscoe, 1966]

hour	Cape San Juan	Yunque	Gurabo Town	Viejo San Juan	Buchanan	Rio Blanco	Roosevelt Roads	Fajardo City	Catalina
1	6.35	6.25	1.21	2.42	1.45	0.68	4.70	0.63	1.02
2	6.11	6.20	1.26	2.18	1.36	0.68	4.60	0.63	1.07
3	6.45	6.20	0.92	2.13	1.45	0.63	3.97	0.63	0.97
4	6.11	6.30	1.11	2.08	1.45	0.63	4.02	0.58	1.02
5	6.06	6.25	0.97	1.99	1.41	0.68	4.07	0.58	1.02
6	6.11	6.25	1.16	2.04	1.31	0.63	4.02	0.63	1.11
7	6.25	6.45	1.07	1.94	1.16	0.63	4.02	0.63	1.31
8	6.06	6.35	1.02	2.52	1.31	0.68	4.85	0.78	1.41
9	6.11	6.06	1.11	3.64	1.70	0.78	5.62	1.16	1.45
10	6.20	5.87	1.89	4.99	2.38	1.07	6.16	1.60	1.55
11	6.11	5.82	2.62	5.87	3.01	1.21	6.45	1.74	1.60
12	6.20	5.72	3.20	6.30	3.30	1.31	6.69	1.89	1.89
13	6.35	5.67	3.34	6.69	3.49	1.41	6.59	2.18	1.89
14	6.35	5.77	3.44	6.64	3.59	1.45	6.79	2.13	1.89
15	6.50	5.87	3.44	6.30	3.49	1.26	6.59	2.08	1.94
16	6.59	5.91	3.10	6.11	3.20	1.16	6.45	2.13	1.79
17	6.59	5.77	2.67	5.67	3.10	1.02	6.01	1.70	1.50
18	6.45	6.01	2.08	5.04	2.76	0.73	5.14	1.41	1.31
19	6.54	6.11	1.41	4.17	2.28	0.63	4.65	0.78	1.11
20	6.50	6.25	1.21	3.88	1.79	0.63	4.41	0.63	1.02
21	6.54	6.30	1.31	3.10	1.41	0.58	4.31	0.68	0.97
22	6.35	6.35	0.97	3.01	1.36	0.63	4.22	0.63	1.02
23	6.59	6.30	1.11	2.62	1.26	0.58	4.27	0.78	0.97
24	6.54	5.91	0.87	2.47	1.21	0.58	4.17	0.68	1.02

TABLE 2-9 Diurnal distribution of mean wind velocity, m/s at 25 m above ground

hour/place	Aguirre [a]	Cuyón [a]	CROEM [a]	Cape San Juan [a]	Tallaboa [b]
1	2.28	5.97	4.61	6.68	2.24
2	2.18	5.86	4.51	6.52	2.27
3	2.29	5.79	4.28	6.47	2.30
4	2.28	5.59	4.43	6.43	2.34
5	2.13	5.61	4.14	6.35	2.39
6	2.16	5.59	4.09	6.20	2.42
7	2.19	5.61	3.98	6.17	2.42
8	2.29	5.61	3.83	6.27	2.37
9	3.00	5.42	3.55	6.26	3.12
10	4.37	5.10	3.70	6.26	4.15
11	5.47	4.83	4.18	6.33	4.93
12	6.06	4.61	4.44	6.39	5.51
13	6.53	4.58	4.83	6.47	5.82
14	6.69	4.67	4.99	6.49	5.82
15	6.63	4.69	4.89	6.56	5.57
16	6.38	4.72	4.75	6.53	5.18
17	5.89	4.62	4.43	6.56	4.67
18	5.30	4.70	4.21	6.49	4.03
19	4.38	4.94	4.25	6.81	3.24
20	3.32	5.23	4.30	6.95	2.62
21	2.80	5.66	4.51	6.93	2.37
22	2.58	5.94	4.41	6.96	2.22
23	2.52	6.15	4.55	6.93	2.18
24	2.46	6.11	4.59	6.71	2.20

[a] [Soderstrom, 1989]

[b] [PREPA, 1997] (original measurements at 10 m, adjusted to 25 m using 1/7 power law)

TABLE 2-10 Monthly average distribution of wind velocity, m/s at 25 m above ground [Briscoe, 1966]

Place\ Month	Cape San Juan	Yunque	Gurabo	Viejo San Juan	Buchanan	Rio Blanco	Roosevelt Roads	Fajardo	Catalina
Jan	5.50	6.16	1.43	3.20	2.40	1.07	4.85	1.45	1.04
Feb	5.40	5.21	1.70	4.44	2.52	1.04	5.65	1.41	1.91
Mar	6.30	2.13	1.94	4.70	1.74	0.99	5.74	1.53	1.96
Apr	8.36	5.43	2.04	3.95	2.59	0.92	5.91	1.43	1.58
May	7.76	7.05	1.94	1.94	0.87	0.58	5.60	0.95	1.19
Jun	6.83	8.97	2.40	4.58	2.62	0.80	5.87	0.58	0.97
Jul	8.85	7.66	2.11	4.85	2.64	0.80	6.45	0.90	1.87
Aug	7.59	6.45	2.01	5.26	1.62	0.92	5.94	1.26	1.41
Sep	4.19	6.52	1.09	3.73	2.18	0.70	3.71	0.63	1.38
Oct	6.08	7.13	1.77	3.20	2.11	0.70	4.00	1.38	0.92
Nov	3.13	5.19	1.16	3.05	1.87	0.70	3.64	1.07	0.92
Dec	6.01	5.09	1.67	4.00	1.94	0.90	4.05	1.07	0.78

TABLE 2-11 Monthly average distribution of wind velocity, m/s at 25 m above ground [Soderstrom, 1989]

Place\ Month	Aguirre	Cuyón	CROEM	Cape San Juan
Jan	3.72	5.42	3.65	6.40
Feb	3.76	4.76	5.04	6.11
Mar	3.86	5.50	4.89	6.13
Apr	3.29	4.06	4.89	6.34
May	3.81	5.05	4.38	5.68
Jun	2.95	5.40	3.57	4.90
Jul	4.69	6.72	3.16	7.11
Aug	4.72	6.35	4.20	5.76
Sep	4.37	4.76	3.54	6.76
Oct	4.45	4.33	3.42	6.76
Nov	3.36	5.61	5.74	7.76
Dec	3.11	5.84	5.74	7.01

2.9 Weather Effects

The sun causes most weather effects changes. When the sun strikes the earth, it heats the soil near the surface. In turn, the soil warms the air lying above it. Warm air is less dense than cool air, and, like a helium-filled balloon, it rises. Cool air flows in to take its place and is itself heated. The rising warm air eventually cools and falls back to the earth completing the convection cell. This cycle is repeated over and over again every day. This is how wind is created on Earth. While the sun keeps shinning the earth wind will keep flowing.

In islands, winds are stronger and more frequent along the coast because of differential heating between the land and the water. During the day, the sun warms the land much quicker than it does the surface of water. Water has higher specific heat and can store more energy without a change in temperature than can soil. The air above the land is once again warmed and rises. Cool air flows landward, replacing the warm air, creating a large convection cell. At night the flows reverse as the land cools more quickly than the water. [*Gipe* 2006]

2.9.1 Monthly Wind Variations in Puerto Rico

The average wind speeds in Puerto Rico vary by season and by month. In summer the island is windier in comparison to winter. This happens because summer is warmer than winter. Sun's rays hit the Earth at a more direct angle during summer than during winter and also because the days are much longer than the nights during the summer. During the winter, the Sun's rays hit the Earth at an extreme angle, and the days are short. These effects are due to the tilt of the Earth's axis. **Figure 2-6** shows the average monthly distribution of mean wind velocity in (m/s).

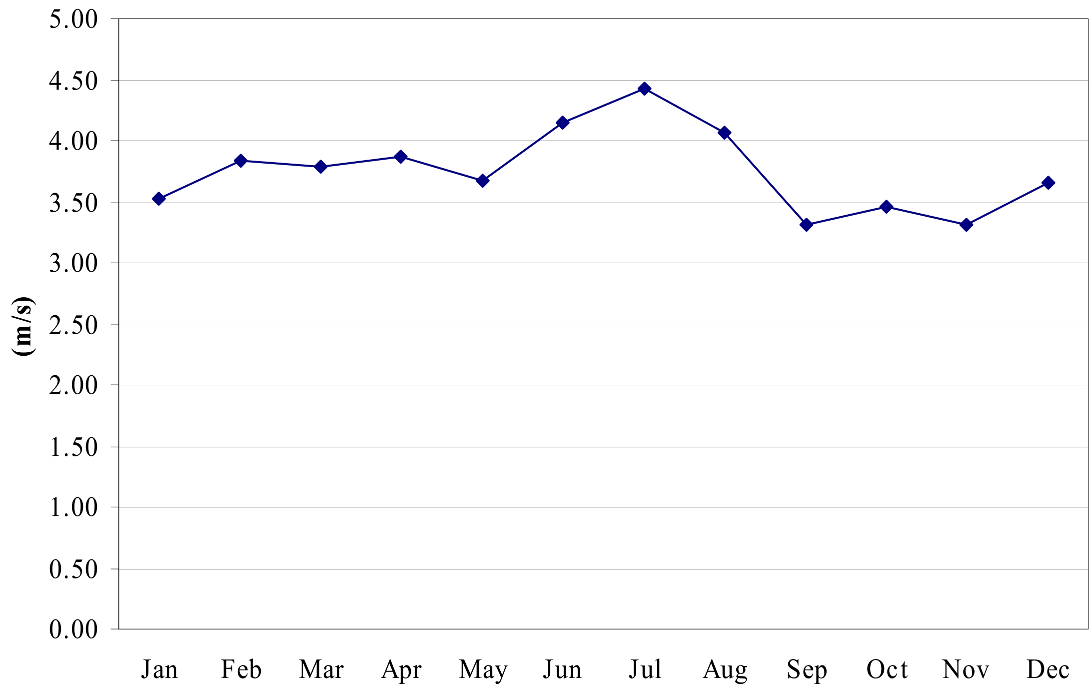


Figure 2-6 Puerto Rico Average Monthly Wind Speed

2.9.2 Diurnal Wind Effects in Puerto Rico

The diurnal effect is the change in wind speed from the night to the day. Puerto Rico presents this effect very clearly in inland areas. Figure 2-7 shows the average diurnal wind speed change. The graph shows that as the sun heats the ground in the morning hours the wind speed increases. At sunset the wind returns to the speed it had during the morning hours. Figure 2-8 presents the diurnal effect at different sites in Puerto Rico.

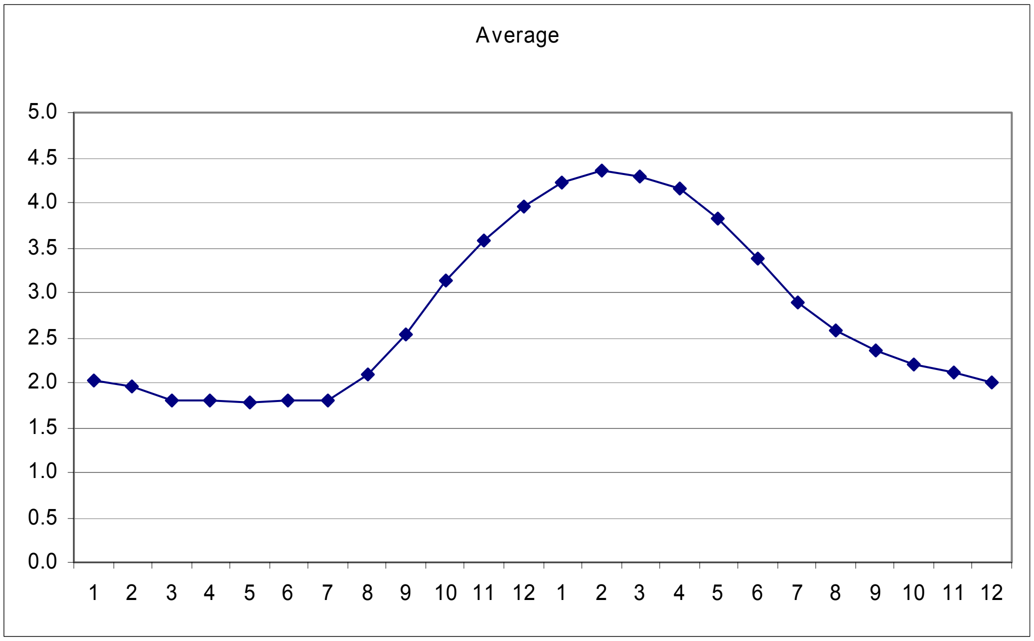


Figure 2-7 Puerto Rico Average Diurnal Wind Speed Effect

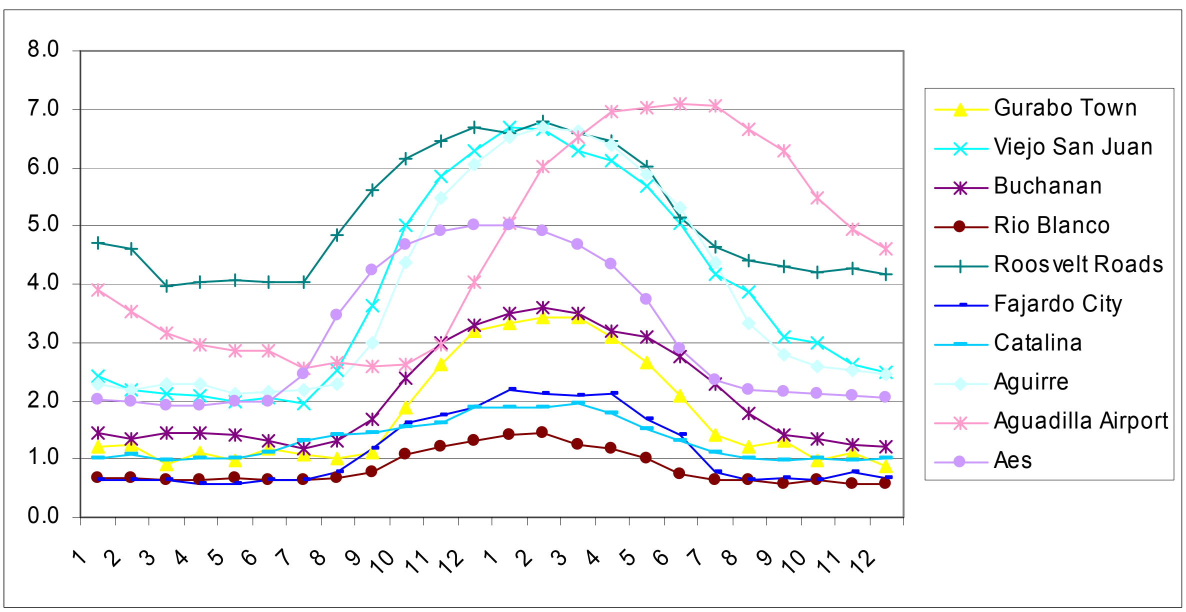


Figure 2-8 Hourly Average Wind Speed in Places with Diurnal Wind Effect Change

But not all places present this effect. For example places in Puerto Rico like Fajardo "Cape San Juan" and the Peak of Yunque Mountain that has no obtrusion to the northeast trade winds, do not present a significant diurnal change. The northeast trade winds have average speed around 6.5 m/s. Figure 2-9 presents the hourly average wind speed in places where there is no diurnal change effects.

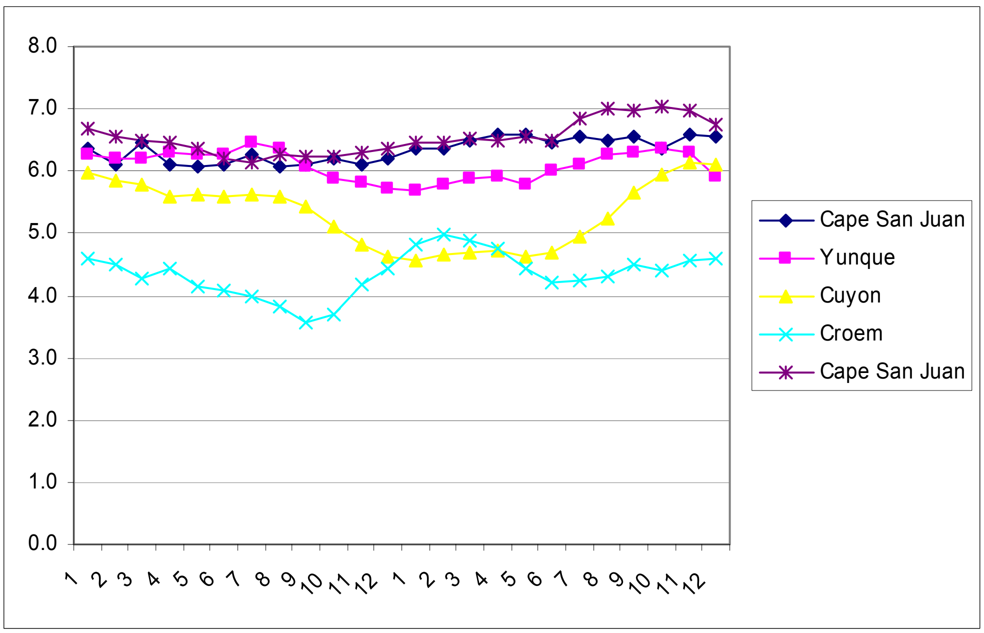


Figure 2-9 Hourly average wind speed with no diurnal change

2.10 Estimated Inland Required Surface or "Foot Print", for Wind Turbines

2.10.1 Estimated Inland Surface Area

The island of Puerto Rico has an area of approximately 160 km x 56 km = 8,960 km², or approximately 2.24 million cuerdas.[1] From wind maps we identify the best wind to be in a 3 km wide band along the north, east, and south coast, as shown in Figure 2-10. This 3 km band also has the best access to infrastructure; wide roads, proximity to the electric grid, ports etc. We estimate this 3 km wide band along the north, east, and south coast to has an area of approximately 960 km² (240,000 cuerdas). This is 10.7% of Puerto Rico's total area.

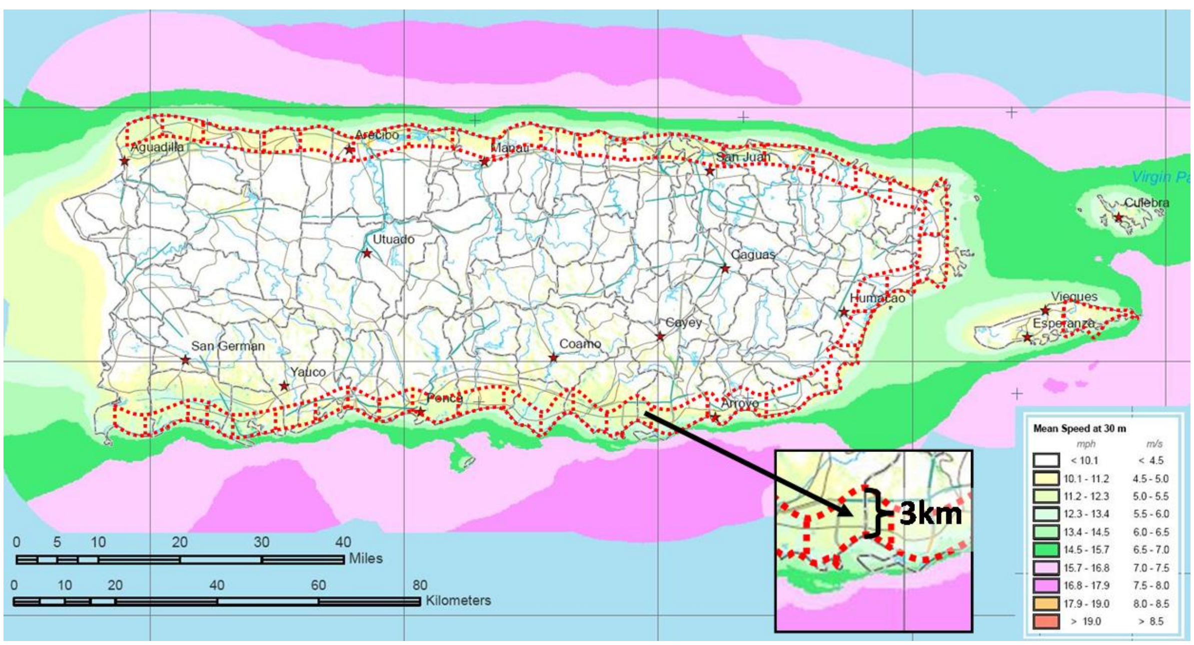


Figure 2-10 Selected Area with High Wind Speed Resources [Background map from AWS Truewind]

[1] One cuerda is an unit of area equal to approximately 4,000 m^2. 1 km equals 1,000 m, 1 km^2 = 1,000,000 m^2, thus 1 km^2 is approximately 250 cuerdas.

Not all of this land is available since a portion of it is being used. Thus, an assessment is needed to identify fallow and used land. Since determining if land is being used can become a philosophical debate we simplify the analysis dividing the area into populated areas, where structures are built, and unpopulated areas. We use satellite photography (using Google Earth) to perform this task and the results are shown in **Figure 2-11**. Areas marked with red dots represent unpopulated areas and areas marked with lines represent populated areas.

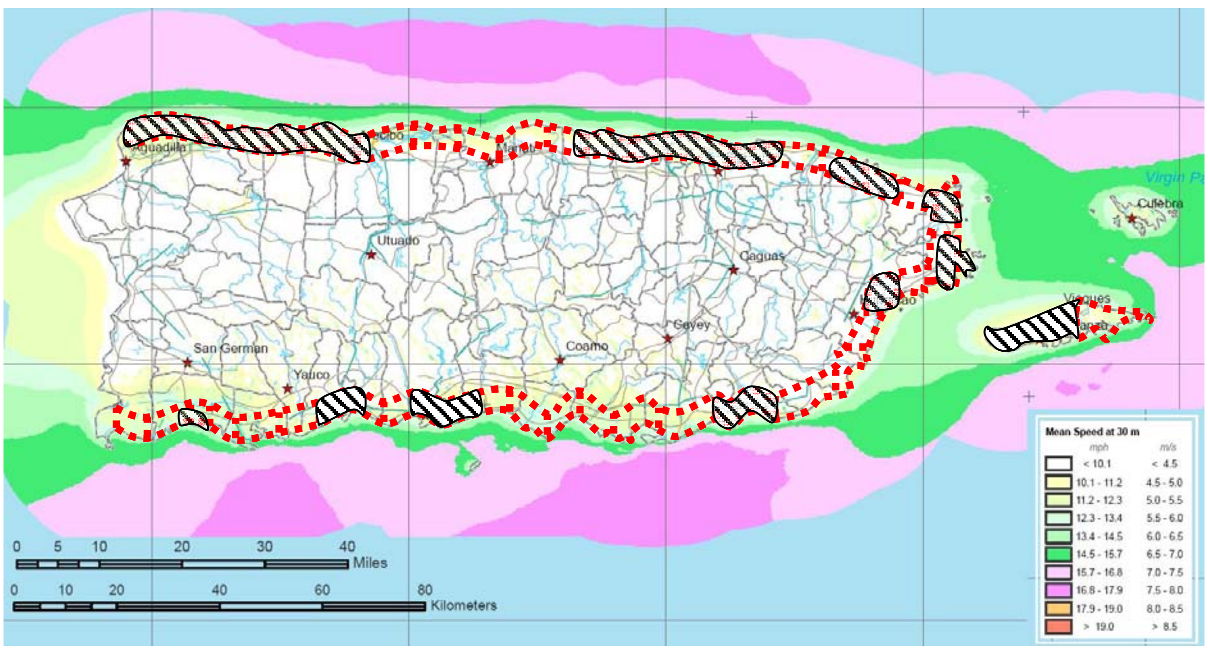


Figure 2-11 Populated Area and Unpopulated Area in Puerto Rico [Background map from AWS Truewind]

Further geometric analysis, using the map and a ruler, shows that approximately 50% of the total area in the 3 km band corresponds to populated areas, 480 km² or 120,000 cuerdas. We assume that populated areas may not be used to develop wind farms using large wind turbines but it can be used to install small wind turbines, residential and commercial type turbines. The remaining 50% of the 3 km wide band along the north, east, and south coast is not heavily populated and we assume it can be used to develop wind farms using large wind turbines.

2.10.2 Large Wind Turbine Spacing

A wind turbine is designed to extract energy from the wind as it passes thru its blades. Since the wind mass is the same before and after the turbine but the wind has less energy the wind speed decreases. If we wish to install a second wind turbine behind the first one we must separate the turbines enough for the wind to recover its original speed thus allowing the second wind turbine to produce as much electricity as the first one.

Optimum separation will vary with type of terrain, wind speed, wind turbines being used and other factors. In this work we use as general rule, assuming flat land, that large turbines will be placed apart a distance of 6 to 10 rotor diameters in the direction of prevailing wind and half of that separation, 3 to 5 rotor diameters, in the direction perpendicular to the prevailing winds, see Figure 2-12. Note that this separation is a function of the wind turbine rotor diameter, thus turbines with larger rotor will be placed farther apart than turbines with smaller rotor.

Thus assuming a desired separation factor, k, the area required by each turbine as a function of its rotor diameter can be easily calculated as shown in Figure 2-13.

Table 2-12 shows an estimate of required area per turbine and installed capacity per unit area, as a function of wind turbines separation, for several wind turbines.

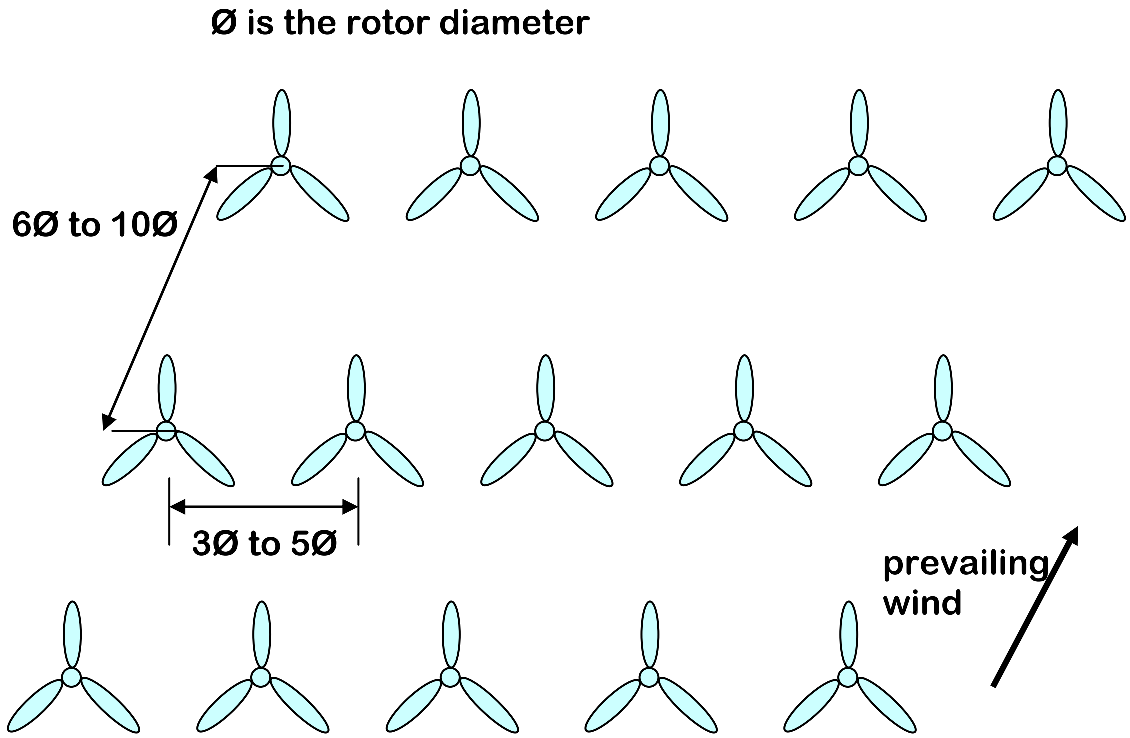


Figure 2-12 Large wind turbine spacing

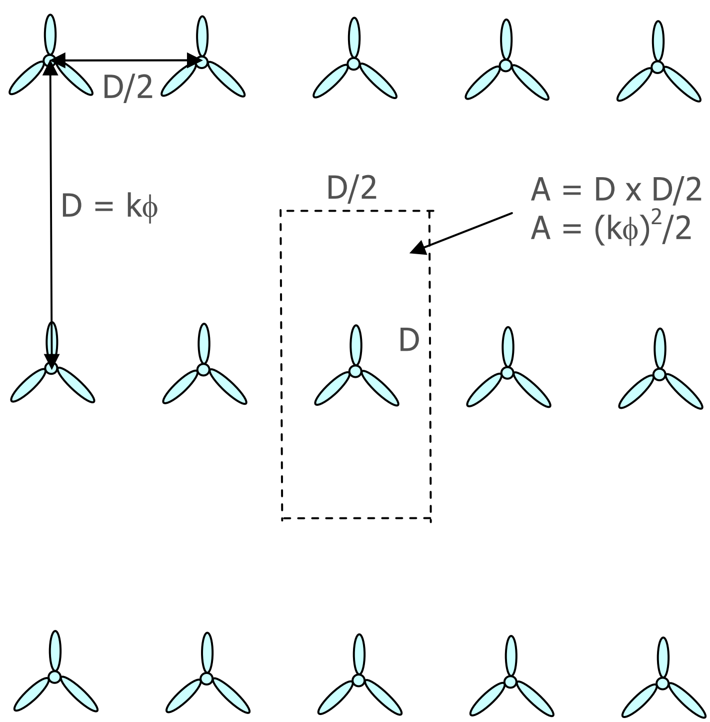


Figure 2-13 Area required by each large wind turbine

Table 2-12 Required area per turbine and installed capacity per unit area as a function of wind turbines separation for several wind turbines.

Turbine	Power capacity [MW]	Rotor diameter [m]	k=10	k=8	k=6	k=10	k=8	k=6
			Area per turbine [km^2]			Installed capacity per unit area [MW/km^2]		
Enercon E53	0.81	53	0.140	0.090	0.051	5.8	9.0	16.0
Vestas V52	0.85	52	0.135	0.087	0.049	6.3	9.8	17.5
Gamesa G58	0.85	58	0.168	0.108	0.061	**5.1**	7.9	14.0
AAER A1000	1.00	58	0.168	0.108	0.061	5.9	9.3	16.5
Enercon E 70	2.30	70	0.245	0.157	0.088	9.4	14.7	26.1
GE 2.5xl	2.50	100	0.500	0.320	0.180	**5.0**	7.8	13.9

Note that a commonly used "power density" of 5 MW/km^2 corresponds to a conservative separation of 10 rotor diameters in the direction of prevailing wind for these large turbines, k = 10.

2.10.3 Estimate number of large wind turbines and installed capacity

An estimate of the number of large wind turbines, per square kilometer, that could be installed in the unpopulated half of the 3 km wide band along the north, east, and south coast of Puerto Rico is shown in Table 2-13. If we were to use all available land, 480 km^2, and turbines with rotor diameter of 52 m, such as the Vestas V52, with a spacing factor k=8 then 5,547 turbines could be installed. In the other hand, if we were to use only 10% of the available land, 48 km^2, and larger turbines with rotor diameter of 100 m, such as the GE 2.5xl, with a spacing factor k=10 then only 96 turbines could be installed.

Table 2-13 Estimate of large wind turbines that could be installed

Turbine	Power capacity [MW]	Rotor diameter [m]	k=10	k=8	k=10	k=8	k=10	k=8
			Turbines in 480 km^2		Turbines in 240 km^2		Turbines in 48 km^2	
Enercon E53	0.81	53	3418	5340	1709	2670	342	534
Vestas V52	0.85	52	3550	5547	1775	2774	355	555
Gamesa G58	0.85	58	2854	4459	1427	2229	285	446
AAER A1000	1.00	58	2854	4459	1427	2229	285	446
Enercon E70	2.30	70	1959	3061	980	1531	196	306
GE 2.5xl	2.50	100	960	1500	480	750	96	150

Finally, an estimate of installed capacity in MW is shown in Table 2-14. If we were to use all available land, 480 km^2, and turbines with rotor diameter of 52 m, such as the Vestas V52, with a spacing factor k=8 then 4,715 MW could be installed. In the other hand, if we were to use only 10% of the available land, 48 km^2, and larger turbines with rotor diameter of 100 m, such as the GE 2.5xl, with a spacing factor k=10 then only 375 MW could be installed.

Table 2-14 Estimate of installed capacity in MW

Turbine	Power capacity [MW]	Rotor diameter [m]	k=10	k=8	k=10	k=8	k=10	k=8
			MW in 480 km^2		MW in 240 km^2		MW in 48 km^2	
Enercon E53	0.81	53	2768	4325	1384	2163	277	433
Vestas V52	0.85	52	3018	4715	1509	2358	302	472
Gamesa G58	0.85	58	2426	3790	1213	1895	243	379
AAER A1000	1.00	58	2854	4459	1427	2229	285	446
Enercon E70	2.30	70	4506	7041	2253	3520	451	704
GE 2.5xl	2.50	100	2400	3750	1200	1875	240	375

Is it better to install less very large turbines or smaller turbines? Wind turbines are not power producers, they are energy producers. The answer is install turbines that produce the most amount of energy, turbines that match the wind regime.

2.10.4 Estimate energy production using large wind turbines

To estimate the energy production per turbine we use the turbine power curve, as provided by the manufacturer, and the wind distribution. We offer an example for wind turbines that can be installed at similar height, 50 m in this case. Power curves for the wind turbines with rotor diameter of approximately 50 m; Enercon E53, Vestas V52, Gamesa G58, AAER A1000 and Suzlon Series 600 are shown in Figure 2-14.

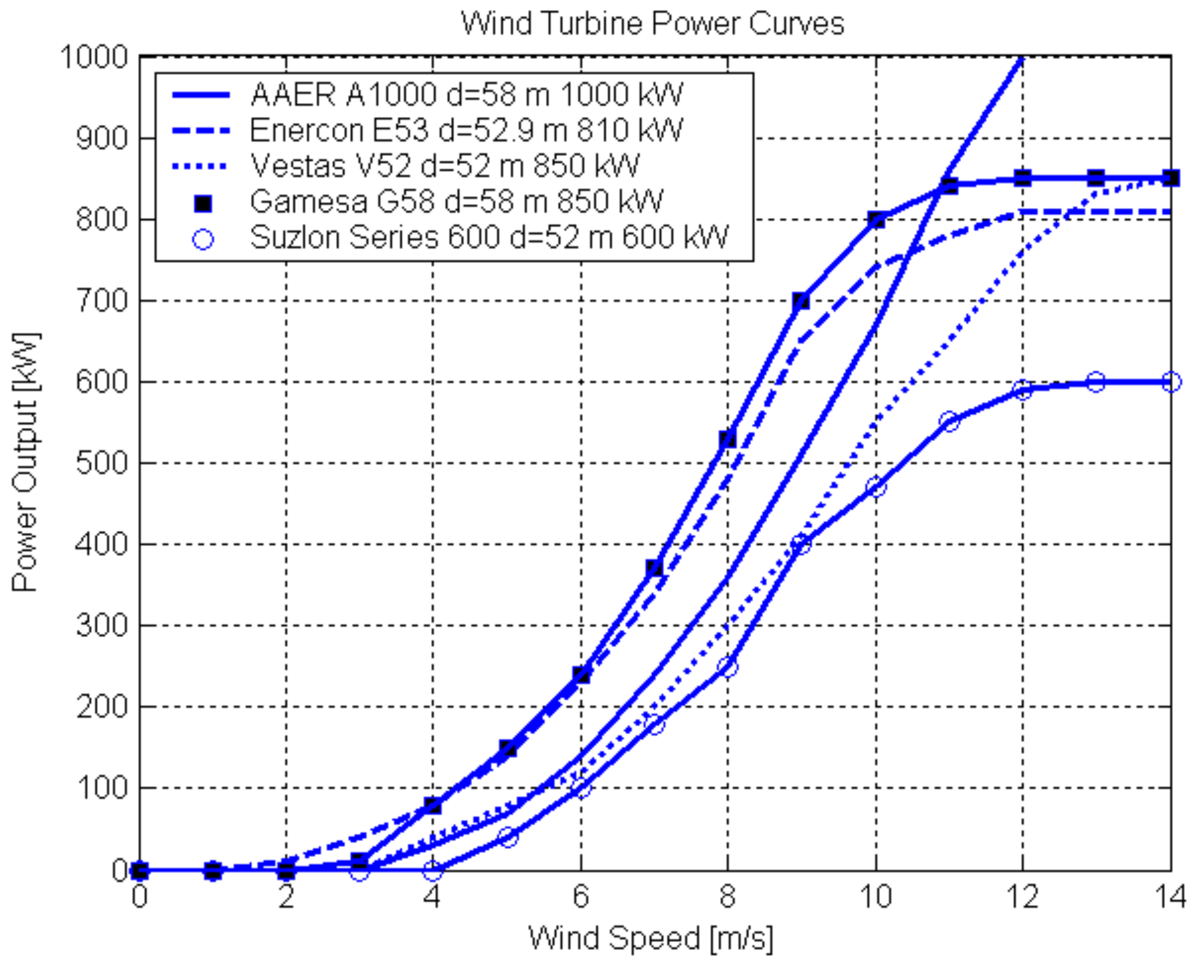


Figure 2-14 Power curves for turbines than can be installed at 50 m height; Enercon E53, Vestas V52, Gamesa G58 and AAER A1000.

Note that even thought they are rated at the same power, 850 kW, the Gamesa G58 generates greater or equal power than the Vestas V52 at all wind speeds. This is so because the Gamesa G58 has a larger rotor and will produce more energy than the Vestas V52.

Also note that even though the AAER A1000 is rated at 1,000 kW and has a rotor diameter of 58 m, equal to the Gamesa G58 rotor diameter, the Gamesa G58 will produce more energy because it generates greater or equal power than the AAER A1000 at wind speeds under 11 m/s.

Wind speed varies with wind site and, at most sites in Puerto Rico, the wind speed is less than 11 m/s during most of the hours of the year as shown in Figure 2-15.

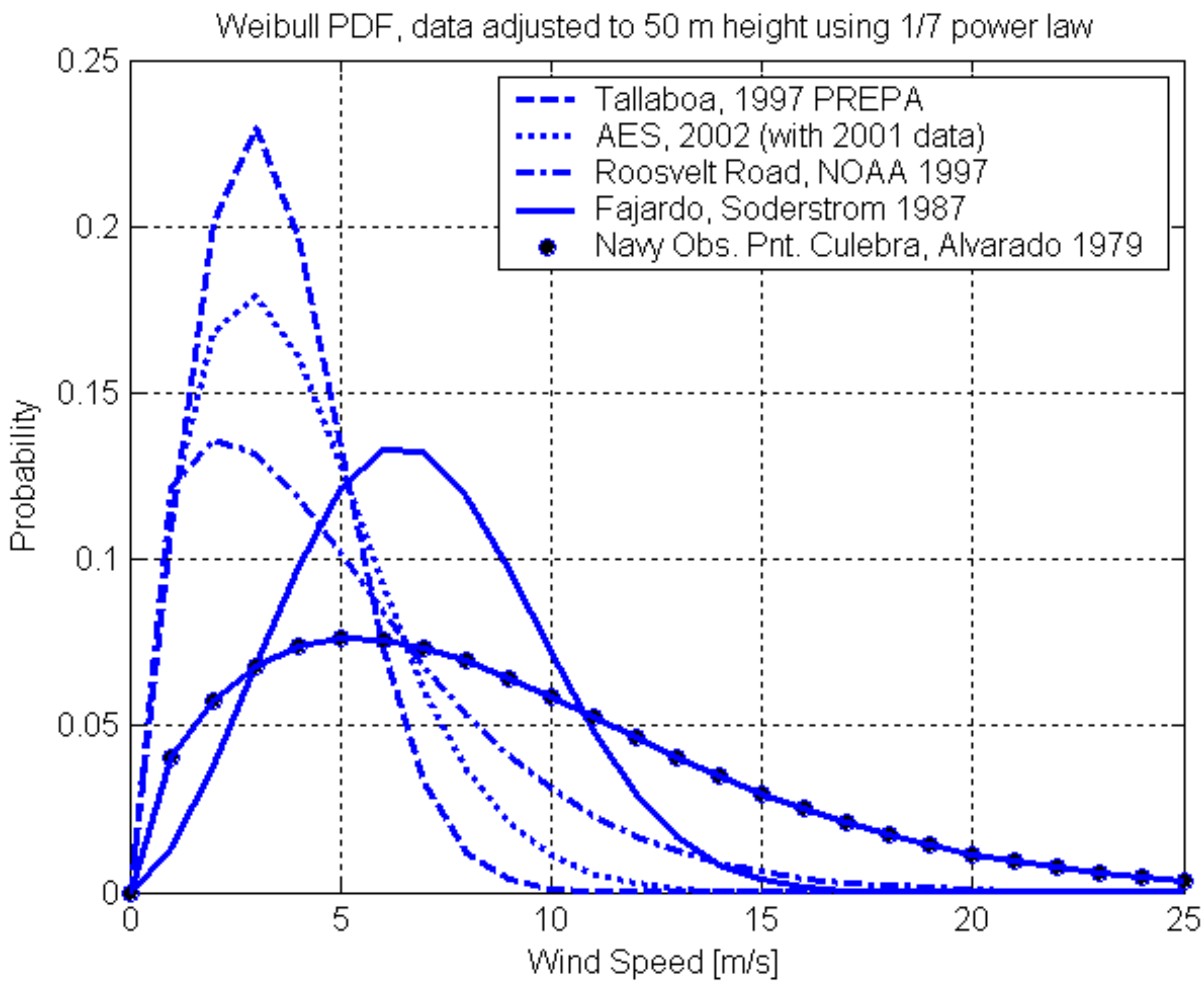


Figure 2-15 Weibull probability density functions at five sites in Puerto Rico.

A probability density function (pdf), in this case a Weibul pdf, summarizes the probability of the wind blowing at a given speed. The probability axis, the vertical axis, can be easily converted to hours in a year by simply multiplying it by the number of hours in a standard year, 8760 hours. Then the plot will indicate the number of hours the wind was blowing at a given speed.

Figure 2-16 shows the location of the sites with wind speed (Weibull) pdf shown in Figure 2-15**.** Note how the probability of higher wind speeds increases as we move from west to east and from south east to north east.

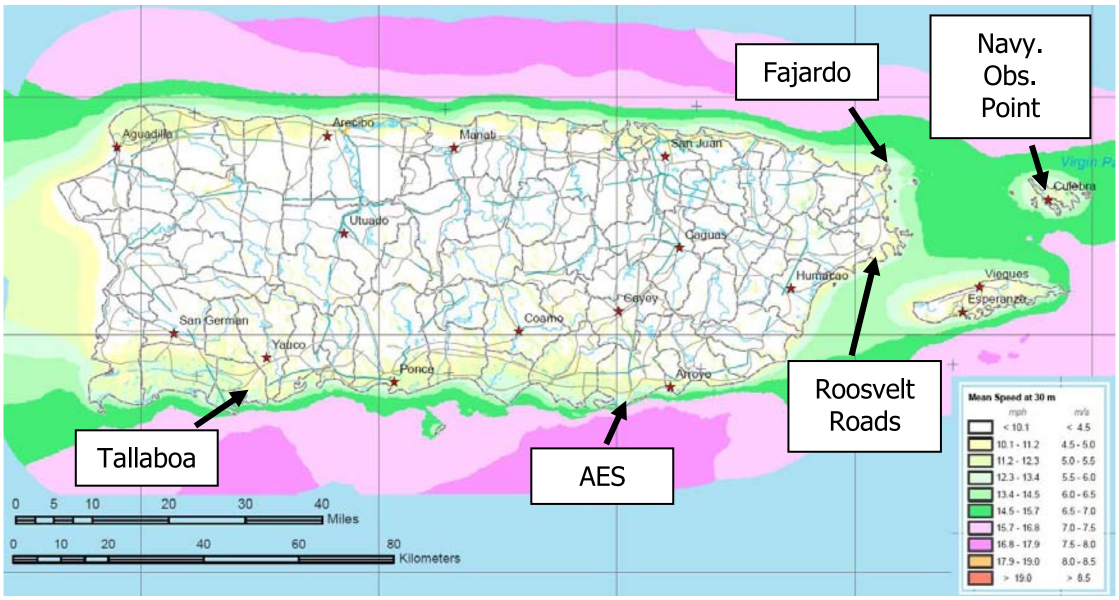


Figure 2-16 Sites with wind speed (Weibull) pdf shown in Figure 2-15 [Background map from AWS Truewind]

To obtain the energy production for a given wind turbine we combine its power curve and the probability density function of wind speed at a given site. Figure 2-17 shows the Weibull pdf (in hours/year) at AES and the Gamesa G58 power curve. The point by point product of hours per year and power produced at each wind speed produces the energy density function shown in Figure 2-18.

The area under the energy density function, or alternatively the sum of all products of hours per year and power produced at each wind speed, provide an estimate of the annual energy production of the wind turbine at the specific site.

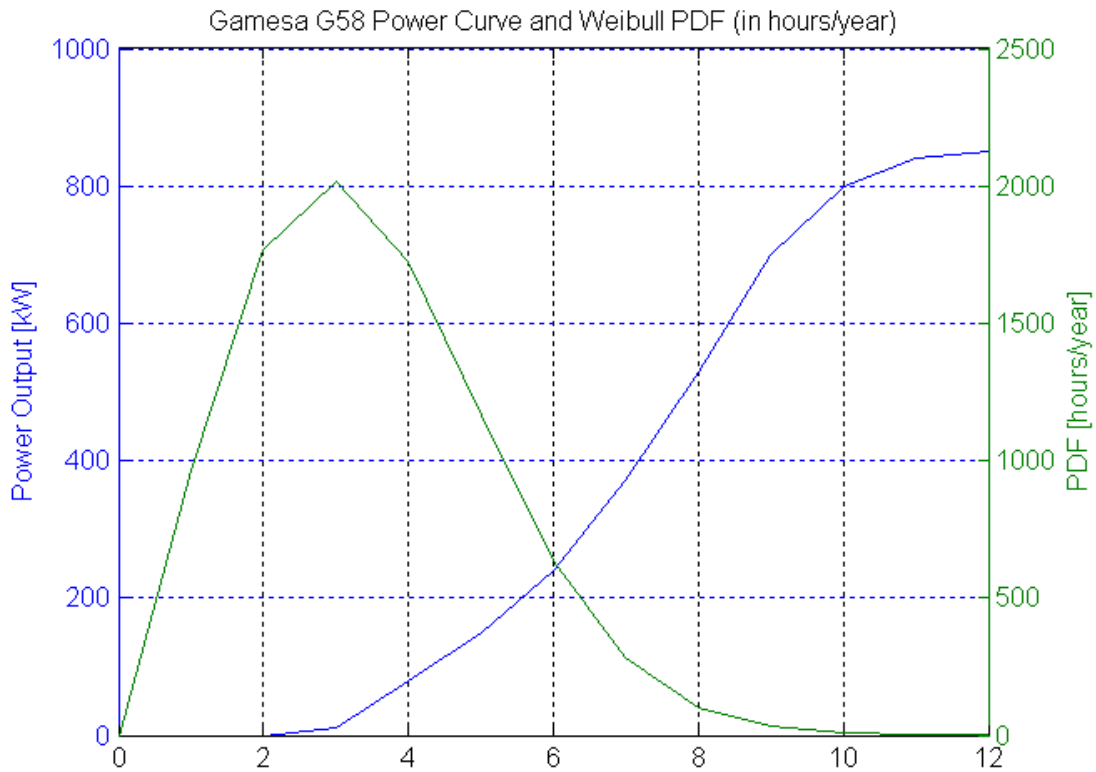


Figure 2-17 Wind speed Weibull pdf (in hours/year) at AES and Gamesa G58 power curve.

Table 2-15 shows the annual energy production, in MWh, per turbine @ 50 m height and different sites in Puerto Rico. Note that the Gamesa G58 produces more energy than the AAER A1000 at all sites. Also note that the Enercon E53 produces more energy than the Gamesa G58 in Tallaboa where the wind blows at lower speed.

Table 2-15 Annual energy production, in MWh, per turbine @ 50 m height

Turbine	Power capacity [MW]	Rotor diameter [m]	Tallaboa	AES	Roosvelt Roads	Fajardo
Enercon E53	0.81	53	**725**	**1127**	**1722**	**3142**
Vestas V52	0.85	52	**348**	**637**	**1154**	**2153**
Gamesa G58	**0.85**	58	**681**	**1136**	**1793**	**3355**
AAER A1000	**1.00**	58	**354**	**714**	**1378**	**2614**

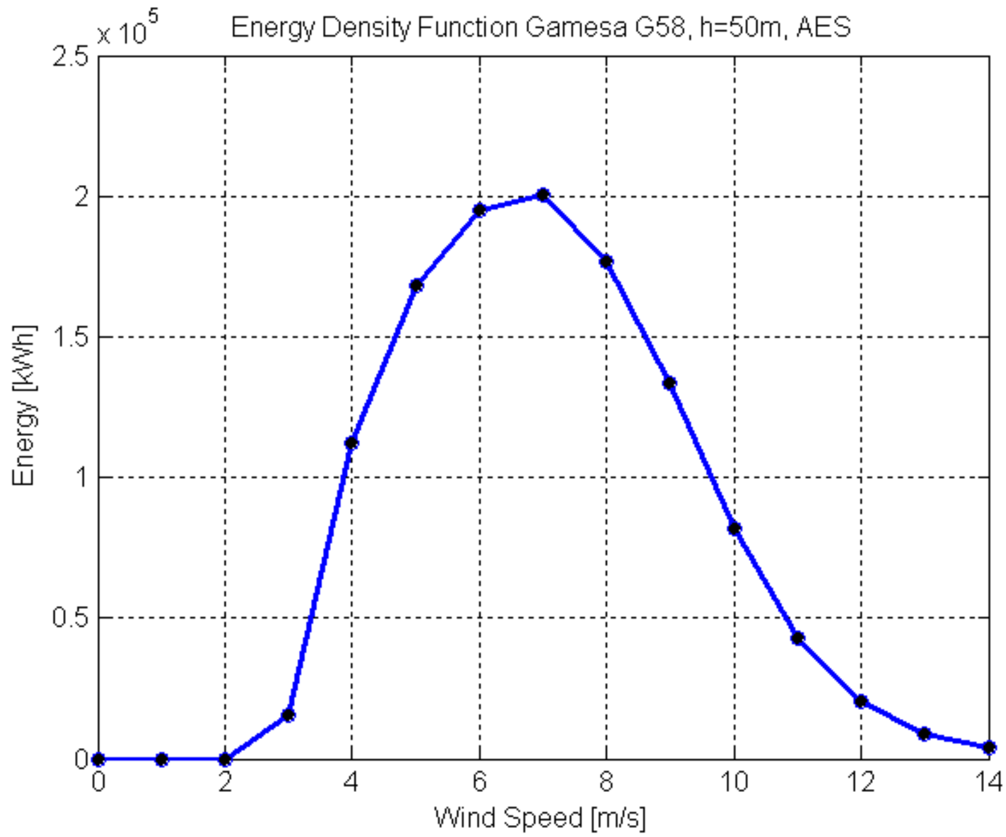


Figure 2-18 Estimate of the energy density function for a Gamesa G58 wind turbine installed at 50 m in the vicinity of AES, Guayama Puerto Rico.

Assuming we were to use only 10% of the available land, 48 km^2, and Gamesa G58 turbines with spacing factor k=10, then 285 turbines could be installed. Assuming an annual 1136 MWh per turbine the 285 turbines will generate approximately 323,760 MWh per year.

According to the Puerto Rico Electric Power Authority in Puerto Rico the average residential costumer demands 800 kWh per month or 9,600 kWh per year (9.6 MWh per year). These 285 turbines could produce the annual energy required by 33,725 residential customers. On the other hand, according to the "Banco de Desarrollo Económico de Puerto Rico" in 2006 Puerto Rico demanded 20,600,000 MWh, thus these 285 turbines could only produce 1.57% of the energy required in 2006. If we were to use 50% of the unpopulated land in the 3 km wide band along the north, east, and south coast to install this type of turbines we will be able to produce approximately 7.86% of the energy demanded in Puerto Rico in 2006.

2.10.5 Estimate number of small wind turbines

For small wind turbines we use a very conservative estimate that each wind turbine will occupy approximately 20,000 m^2, or 5 cuerdas. Even with this assumption the total number of small wind turbines that can be installed in the populated zones of the 3 km band is, $531000000m^2/20000m^2$ = 26,550 turbines. Half of these, or 13,275, will still be a significant market for small wind turbines.

2.10.6 Estimate energy production using small wind turbines

Analysis of TABLE 2-1 shows that the Bornay Inclin 3000 and Inclin 6000 are the small turbines with lowest installation cost per unit of capacity, 2.67 $/W for the Inclin 3000 and 2.01 $/W for the Inclin 6000. Further analysis of TABLE 2-4 shows that these two small turbines produce the most amount of energy for the wind regimen we find in Puerto Rico.

We assume that small wind turbines will be installed at a height of 25 m.
Figure 2-22 shows the Weibull pdf adjusted to 25 m height, for several sites in Puerto Rico.

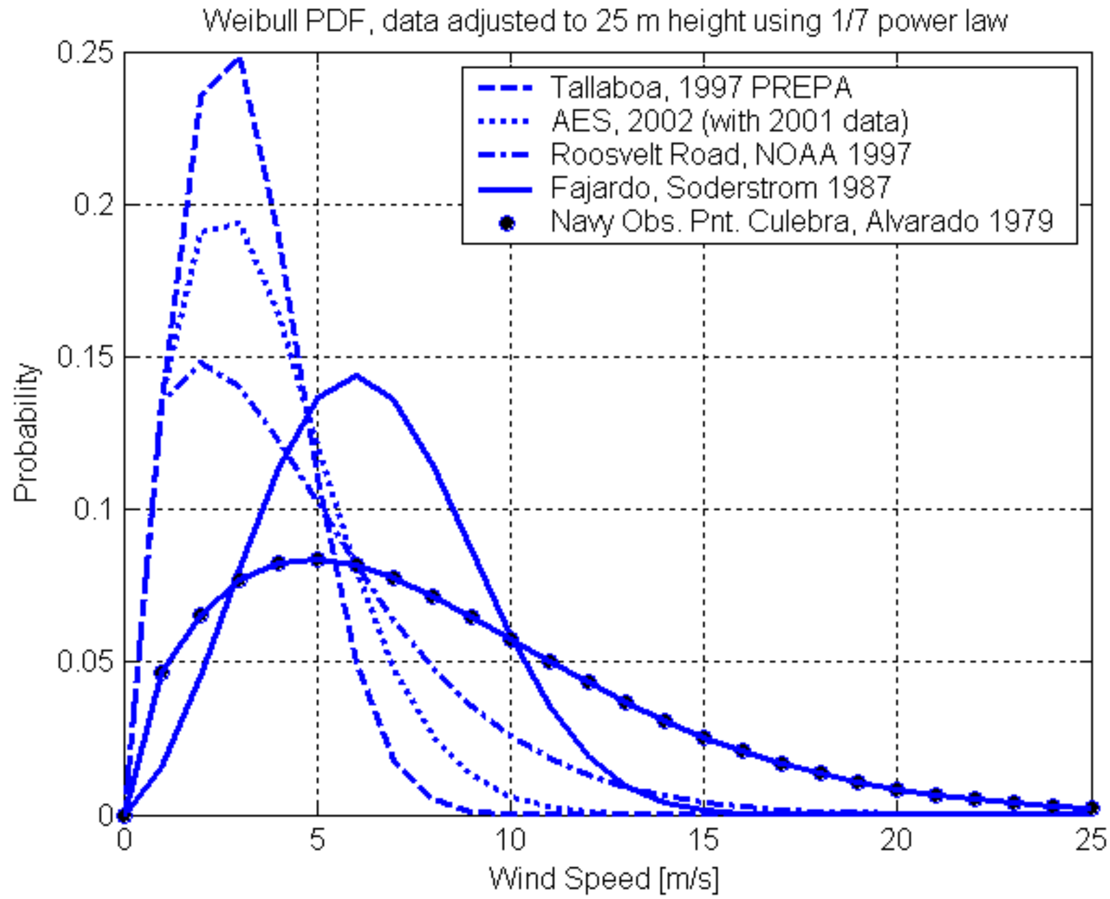


Figure 2-19 Weibull pdf, adjusted to 25 m height, for several sites in Puerto Rico.

Figure 2-20 shows the power curves for the Bornay Inclin 3000 and Inclin 6000 small turbines. Using these power curves and Weibull pdf we estimate the annual energy production, in kWh, per turbine at 25 m height. Figure 2-16 shows the estimated energy production.

Table 2-16 Annual energy production, in kWh, per turbine @ 25 m height

Turbine	Power capacity [kW]	Rotor diameter [m]	Tallaboa	AES	Roosvelt Roads	Fajardo
Bornay Inclin 3000	3	3.7	2870	4148	6334	11,104
Bornay Inclin 6000	6	3.7	6777	9298	13,505	23,200

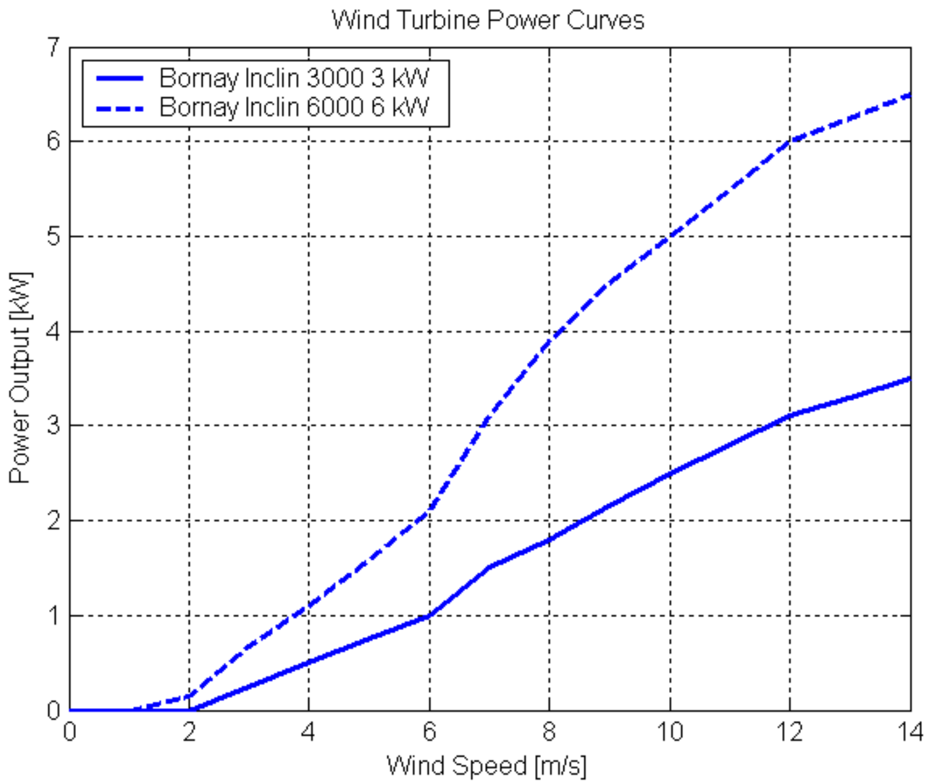


Figure 2-20 Power curves for Bornay Inclin 3000 and Inclin 6000.

Recall that the average residential costumer in Puerto Rico demands 800 kWh per month or 9,600 kWh per year (9.6 MWh per year). The Bornay Inclin 3000 exceeds the annual energy required a residential customer in Fajardo. The Bornay Inclin 6000 exceeds the annual energy required a residential customer in Roosvelt Roads and Fajardo and almost supply the energy demand at AES.

Is it worth to install a small wind turbine? Table 2-17 shows the annual dollar value of the energy produced by each small turbine, and at each site, assuming a residential rate of 27.5 ¢/kWh and net metering program that allows the residential customer to sale all excess energy at the residential rate of 27.5 ¢/kWh.

Table 2-17 Dollar value of annual energy production per turbine @ 25 m height

Turbine	$/kWh	Tallaboa	AES	Roosvelt Roads	Fajardo
Bornay Inclin 3000	0.275	$789	$1,141	$1,742	$3,054
Bornay Inclin 6000	0.275	$1,864	$2,557	$3,714	$6,380

Table 2-18 shows the present value of the energy produced by these small wind turbines assuming an annual interest rate of 2.5% (a conservative inflation adjustment for the cost of money), a fixed and unlikely electricity rate of 27.5 ¢/kWh and 20 years of operation.

Table 2-18 Present worth of the energy produced by small wind turbines

Turbine	Estimated cost of installed turbine	Tallaboa	AES	Roosvelt Roads	Fajardo
Bornay Inclin 3000	$12,000	$12,412	$17,939	$27,393	$48,021
Bornay Inclin 6000	$16,000	$29,308	$40,211	$58,405	$100,333

In all cases an investment in a small turbine returns a profit.

2.11 Offshore Wind Generation

2.11.1 Estimate of offshore area suitable for wind turbine installation

To estimate the area available for off shore wind turbines we use the map provided by NOAA [NOOA 2003] and shown in Figure 2-21. This map allows locating areas with ocean floor 0 to 30 m deep, the standard depth use to install offshore wind turbines.

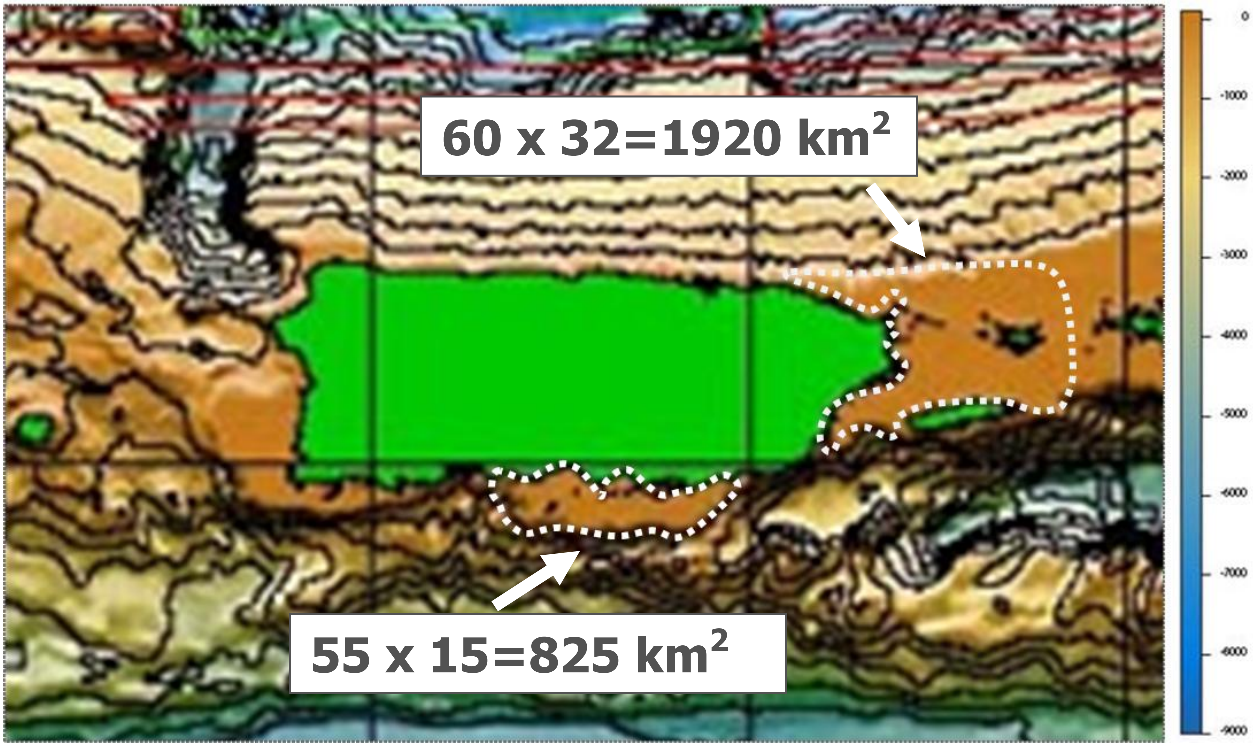


Figure 2-21 Areas of suitable depth for offshore wind turbines [NOOA, 2003]

From this analysis the total suitable are for off-shore wind turbines installation is approximately 2,745 km^2.

2.11.2 Estimate of offshore wind power capacity

Assuming a power density of 5 MW/km^2 the 2,745 km^2 can accommodate 13,725 MW of installed wind capacity. If only 10% is used we still have 1,372 MW.

2.11.3 Estimate of offshore wind energy production

We assume that off-shore wind turbines will be installed at a height of 100 m and that the off-shore wind regime has a Weibull pdf, adjusted to a height of 100 m, similar to wind regime in Roosvelt Roads or Fajardo.

Figure 2-22 shows the Weibull pdf adjusted to 100 m height, for Roosvelt Roads and Fajardo.

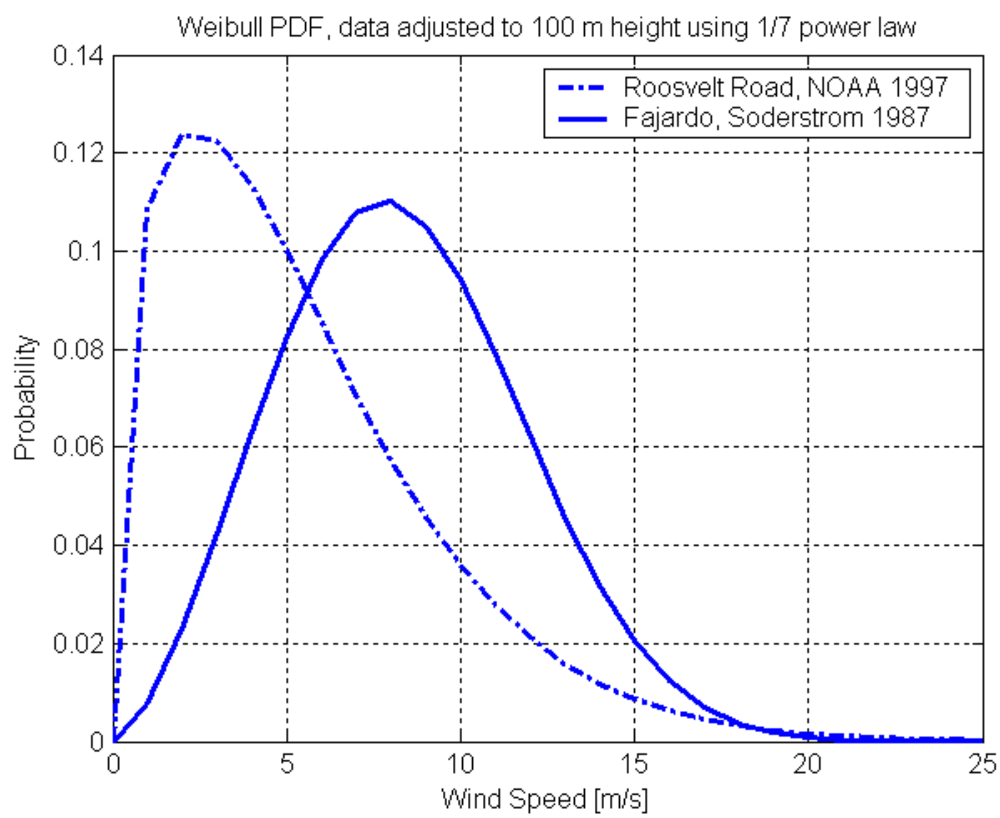


Figure 2-22 Weibull pdf, adjusted to 100 m height, for Roosvelt Roads and Fajardo.

In our analysis we consider four wind turbines that can be installed at 100 m height; Enercon E 70, GE 2.5xl, Vestas V90 and Fuhrlander FL 2500. Figure 2-23 shows the power curves for these large turbines.

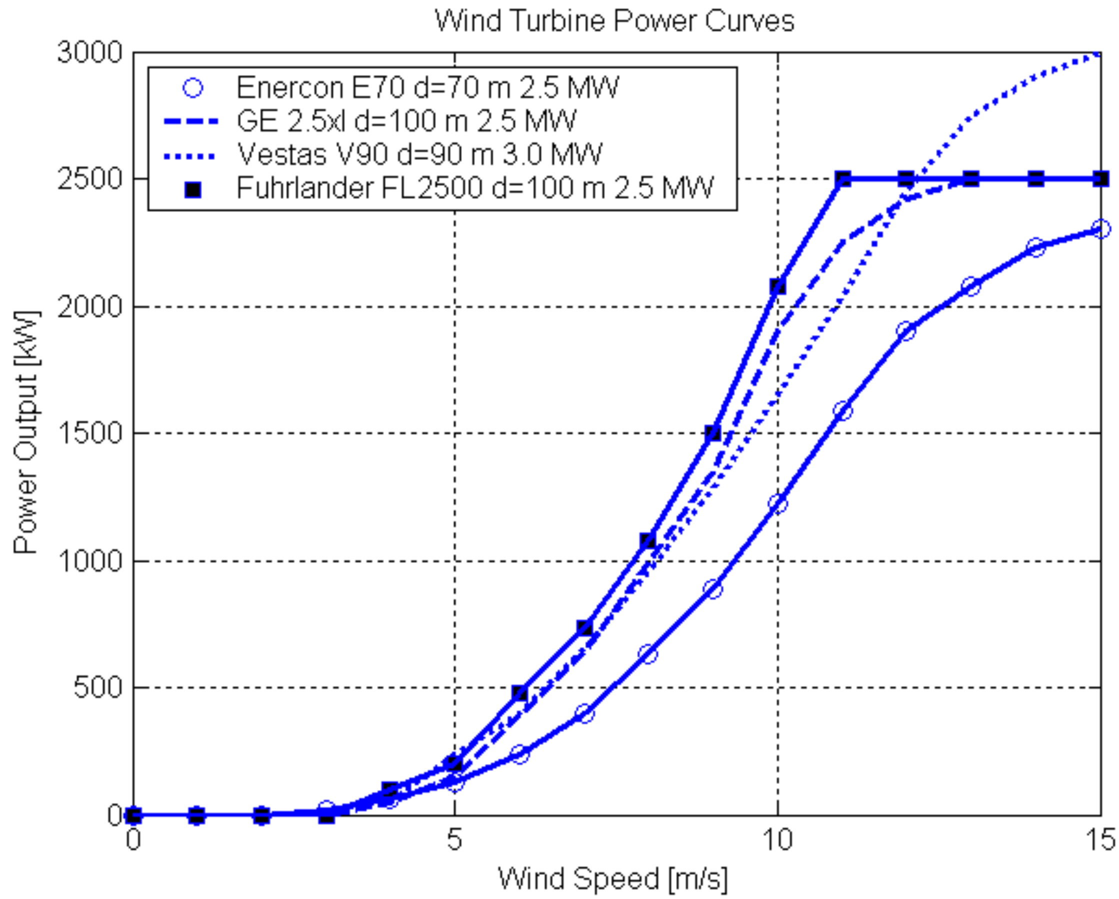


Figure 2-23 Power curves for large wind turbines to be installed at 100 m.

Using these power curves and Weibull pdf we estimate the annual energy production, in MWh, per turbine at 100 m height. Table 2-19 shows these values assuming an off-shore wind regime with a Weibull pdf similar to the specified site.

Table 2-19 Annual energy production, in MWh, per turbine @ 100 m height

Turbine	Power capacity [MW]	Rotor diameter [m]	Roosvelt Roads*	Fajardo*
Enercon E70	2.3	70	3118	7155
GE 2.5xl	2.5	100	4305	9864
Vestas V90	3.0	90	4339	9810
Fuhrlander FL2500	2.5	100	4759	10,680

* The off-shore wind regime is assumed to have a Weibull pdf, adjusted to 100 m height, and similar to the specified site.

Note that the Fuhrlander FL2500 produces more energy than any of the other wind turbines even though its rated capacity of 2.5 MW is less than the 3.0 MW rated capacity of the Vestas V90.

Assuming we were to use only 10% of the available off-shore area, 275 km^2, and Fuhrlander FL2500 turbines with spacing factor k=10, then 550 turbines could be installed. Assuming an annual 4759 MWh per turbine the 550 turbines will generate approximately 2,617,450 MWh per year.

Recall that the average residential costumer in Puerto Rico demands 800 kWh per month or 9,600 kWh per year (9.6 MWh per year). These 550 off-shore turbines could produce the annual energy required by 272,651 residential customers.

According to the "Banco de Desarrollo Económico de Puerto Rico" in 2006 Puerto Rico demanded 20,600,000 MWh, thus these 550 off-shore turbines could produce 12.7% of the energy required in 2006. If we were to use 50% of the available off-shore area to install this type of turbines we will be able to produce approximately 63.5% of the energy demanded in Puerto Rico in 2006. The latter case will require a new approach to the operation of the electric grid.

2.12 Interconnection Issues

High penetration of intermittent wind power (greater than 20% of generation meeting load) in the system faces fundamental technical and financial constraints with regards to the connection of wind farms to the electrical network. These challenges include power quality, active and reactive power flow, infrastructure, network stability, cost recovery and profitability. Technically, it affects the network in the following ways and has to be studied in detail [Zhenyu et al. 2006]:

1) Power flow - Ensure that the interconnecting transmission or distribution lines will not be over-loaded. This type of analysis is needed to ensure that the introduction of additional generation will not overload the thermal limit of the lines and other electrical equipment. Both active and reactive power requirements should be investigated. Reactive power should be generated not only at the interconnection point (PCC), but also throughout the network, and should be compensated locally.

2) Short circuit - Determine the impact of additional generation sources to the short circuit current ratings of existing electrical equipment on the network.

3) Transient stability - dynamic behavior of the system during contingencies, sudden load changes and disturbances. Voltage and angular stability during these system disturbances are important. In most cases, fast acting reactive-power compensation equipment, including SVCs and STATCOMs, should be included for improving the transient stability of the network.

4) Electromagnetic transients – Ensure these fast operational switching transients have a detailed representation of the connected equipment, wind turbines, their controls and protections, the converters, and DC links.

5) Protection – Investigate how unintentional islanding and reverse power flow may have a large impact on existing protection schemes, philosophy, and settings.

6) Power leveling and energy balancing - Due to the fluctuating and uncontrollable nature of wind power as well as the uncorrelated generation from wind and load, wind power generation has to be balanced with other fast controllable generation sources. These include gas, hydro, or renewable power generating sources, as well as short and long-term energy storage, to smooth out fluctuating power from wind generators and increase the overall reliability and efficiency of the system. The costs associated with capital, operations, maintenance and generator stop-start cycles have to be taken into account as well.

7) Power Quality - Fluctuations in the wind power and the associated power transport (AC or DC), have direct consequences to the power quality. As a result, large voltage fluctuations may result in voltage variations outside the regulation limits, as well as violations on flicker and other power quality standards.

2.13 References

[Archiba] VAWT Darrieus-windmill snapshot by A. Archiba

[AWS Truewind] AWS Truewind Wind Resource of the US Virgin Island and Puerto Rico UTM, Zone 19N, WGS84

[Burton et al. 2001] T. Burton, D. Sharpe, N. Jenkins, E. Bossanyi, Wind Energy Hanbook, Wiley, 2001.

[Creative Commons] Creative Commons Picture; CC-BY-SA-2.5.

[DWIA 2003] Danish Wind Industry Association. June 2003. Guided Tour on Wind Energy. http://www.windpower.org/en/tour/index.htm

[Gipe 2004] Paul Gipe, Wind Power for Home & Business, Chelsea Green Publishing Company,1993.

[González 1998] L.C. González, "A Procedure to Determine Wind Power Capacity Value and its Future Application to Puerto Rico's Electric Power System," M.S. dissertation, Dept. of Electrical Engineering, University of Puerto Rico, Mayagüez, P.R, 1998.

[Mathew 2006] S. Mathew, Wind Energy Fundamentals Resources Analysis and Economics, Springer, 2006.

[NOAA, 2003] Uri ten Brink, "Puerto Rico Trench 2003" Tracklines of the multibeam bathymetry cruises Summary and Results, U.S. Geological Survey, NOAA 2003. http://oceanexplorer.noaa.gov/explorations/03trench/welcome.html

[NREL] U.S. Department of Energy-National Renewable Energy Laboratory. Wind Energy Resource Atlas of the United States. [Online]. Available: http://rredc.nrel.gov/wind/pubs/atlas/maps.html

[Patel 2006] M. Patel, Wind and Solar Power Systems 2edt, Taylor & Francis Group, 2006

[Soderstrom] K. Soderstrom, "Wind Farm Assessment for Puerto Rico," Prepared for the Puerto Rico Office of Energy Office of the Governor and the Center for Energy and Environment Research University of Puerto Rico, May 1989.

[The wind indicator 2005] The wind indicator (2005) Wind energy facts and figures from windpower monthly. Windpower Monthly News Magazine, Denmark, USA

[USDA Forest Service] C.B. Briscoe, “Weather In The Luquillo Mountains of Puerto Rico,” Forest Service U.S. Department of Agriculture, Institute of Tropical Forestry Rio Piedras, Puerto Rico, 1966.

[USDE 2003] U.S. Department of Energy-National Renewable Energy Laboratory, "Wind Power Today," Prepared for the U.S. Department of Energy-Energy Efficiency and Renewable Energy, May 2003.

[Wiki] Wikipedia , “Wind Turbine” Wikimedia Foundation, Inc, May 2005, http://en.wikipedia.org/wiki/Wind_turbine

[World Wind Energy] World Wind Energy, Worldwide installed capacity and prediction 1997-2010, Source: http://www.wwindea.org

[Zhenyu et al. 2006] Zhenyu Fan and Johan H.R. Enslin, “Wind Power Interconnection Issues in the North America” KEMA T&D Consulting, 3801 Lake Boone Trail, Ste200, Raleigh, NC 27613 USA, 2006.