Offshore Wind Energy Resource Assessment for Alaska

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National Renewable Energy Laboratory

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Executive Summary

This report quantifies Alaska's offshore wind resource capacity while focusing on its unique nature. It is a supplement to the existing U.S. Offshore Wind Resource Assessment, which evaluated the offshore wind resource for all other U.S. states (Musial et al. 2016). Together, these reports provide the foundation for the nation's offshore wind value proposition. Both studies were developed by the National Renewable Energy Laboratory (NREL). The analysis presented herein represents the first quantitative evidence of the offshore wind energy potential of Alaska.

The technical offshore wind resource area in Alaska is larger than the technical offshore resource area of all other coastal U.S. states combined. Despite the abundant wind resource available, significant challenges inhibit large-scale offshore wind deployment in Alaska, such as the remoteness of the resource, its distance from load centers, and the wealth of land available for onshore wind development. Throughout this report, the energy landscape of Alaska is reviewed and a resource assessment analysis is performed in terms of gross and technical offshore capacity and energy potential.

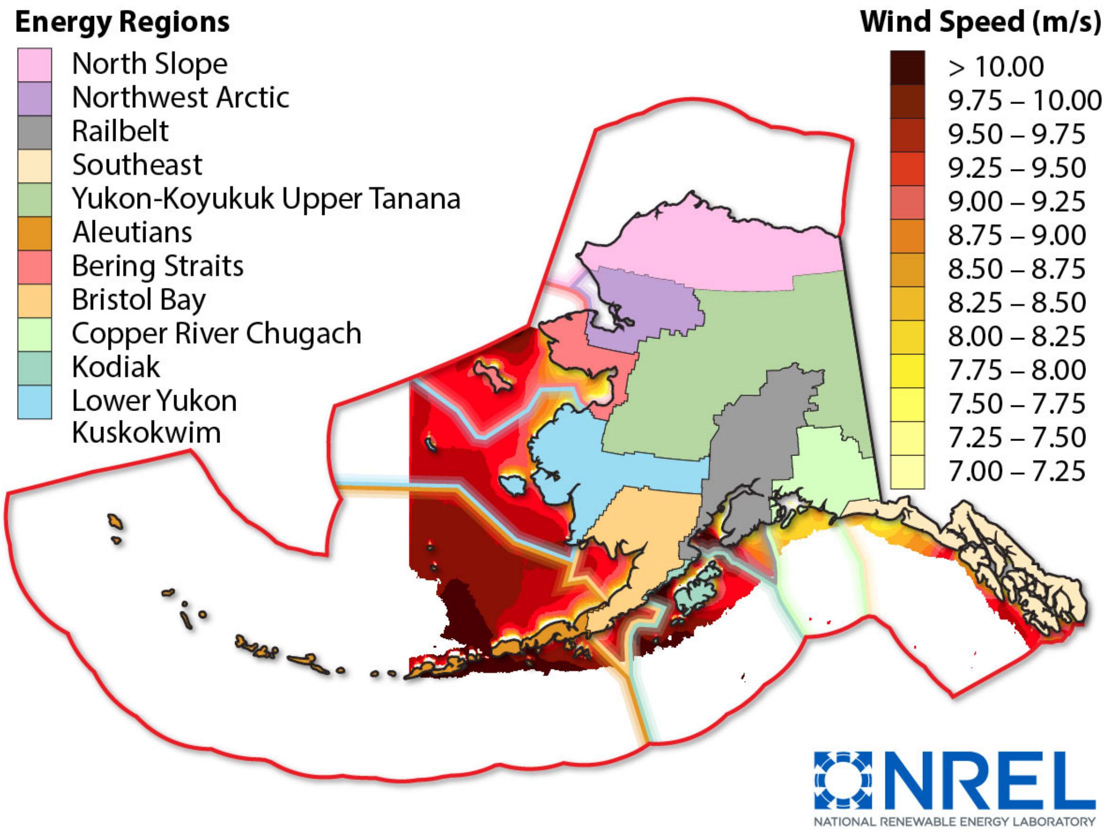

Figure ES-1. Wind speed (m s^{-1}) 100 m above ground temporally averaged over the entire simulation period for grid cells within the technical offshore wind resource area. Note that the data extent is limited due to the model simulation domain, which did not include part of the Aleutians Arc, as will be discussed in the report.

Some of the significant highlights featured in this report include:

- **Offshore wind energy potential in Alaska:** The net energy potential for Alaska is estimated to be 12,087 TWh/year for Alaska, which is substantially higher than the statewide electricity consumption of approximately 6 TWh/year and higher than the total U.S. consumption of 3,711 TWh/year (U.S. EIA 2017c).
- **Offshore energy regions:** Offshore wind energy regions are defined based on the onshore energy regions of the Alaska Energy Authority. The definition of these regions is valuable when determining how much offshore wind energy potential can be allocated to different population centers, which is extremely relevant given the sparse distribution of Alaska's population and the sparsely distributed structure of its electrical grid. We find

that while the largest resource values are seen for the Aleutians offshore region (net technical energy of 3,585 TWh/year due to its large size and high wind speed values), a small area of high wind speed and capacity factor is also found in the Railbelt region (net technical energy of 423 TWh/year), closer to the main interconnected grid in the state.

- **Technology exclusions:** The gross offshore wind potential is reduced to an estimate of the technical offshore wind potential based on bathymetry, average wind speed at 100 m, and climatological sea ice concentration. Only areas with water depth lower than 1,000 m are considered in the analysis. This cutoff value was chosen after consultation with global floating offshore wind technology developers, and is an expansion to the previously used value of 700 m to accommodate recent trends in floating technology and deployment in deeper waters. Areas with average wind speed lower than 7 $m\ s^{-1}$ are also removed from the analysis, thereby setting a lower bound for average wind speed where studies do not show any economic potential for large, utility-scale offshore wind development in the United States, according to Philipp Beiter et al. (2016). In terms of ice concentration, the cutoff latitude of 65.5° N was selected based on a climatological sea ice atlas to avoid latitudes in which sea ice concentration is 90%-100% across the entire longitudinal extent of the offshore region considered. The impact of each exclusion on the final resource is quantified, revealing that bathymetry restrictions reduce the gross energy by 39%, wind speed restrictions by 1%, and latitude restrictions by 20%.
- **Capacity factor:** Linear and quadratic relationships between mean wind speed at 100 m and gross and net capacity factor are proposed. These relationships are based on previous Openwind studies conducted for the U.S. West Coast offshore region and greatly simplify the estimation of offshore wind capacity and energy over the area of interest. For the majority of the Alaska technical region considered in this report, capacity factors vary between 40% and 55%, which is higher than what was found for the U.S. West Coast offshore region in Musial et al. 2016 (i.e., 30%-45% on the majority of the technical area).
- **Comparison with other U.S. states:** The estimated Alaska resource is compared to values for other U.S. states. Alaska has a net offshore wind energy potential that is 68% higher than that of all other states combined and 11 times that of Massachusetts, which after Alaska is the state with the highest offshore resource in the United States (Musial et al. 2016).

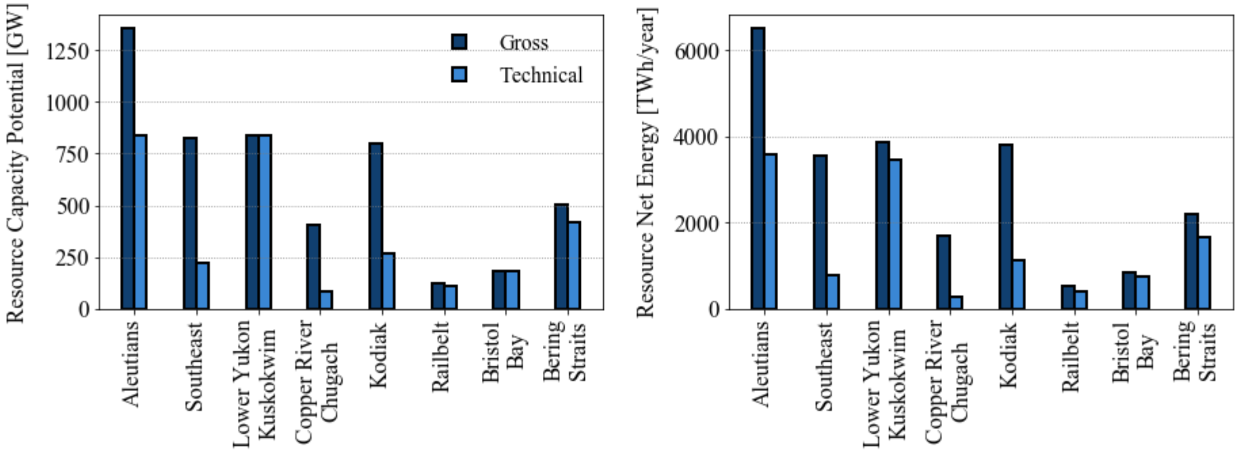

Figure ES-2. Offshore wind resource capacity (left) and net energy (right) from gross (dark blue) and final net technical (light blue) resource estimates for the eight offshore energy regions of Alaska south of 65.5° N

The analysis progression followed for this report is similar to that in Musial et al. (2016) and is shown in Figure ES-3 along with the resource totals at each analysis step. Through application of these analysis steps, the gross resource potential area is reduced by approximately 54% (from 2,166,601 to 991,409 km^2) to arrive at the technical resource potential area. The final technical potential eliminates approximately 58% (from 28,954 to 12,087 TWh/year) of the original gross energy supply. While in general the wind speed resource increases with distance from shore, a small area of high wind and low bathymetry can be identified close to the coast and to the Railbelt interconnected grid (Figure ES-1).

Regional assessments were carried out for the offshore wind energy regions of Alaska with coastlines below the

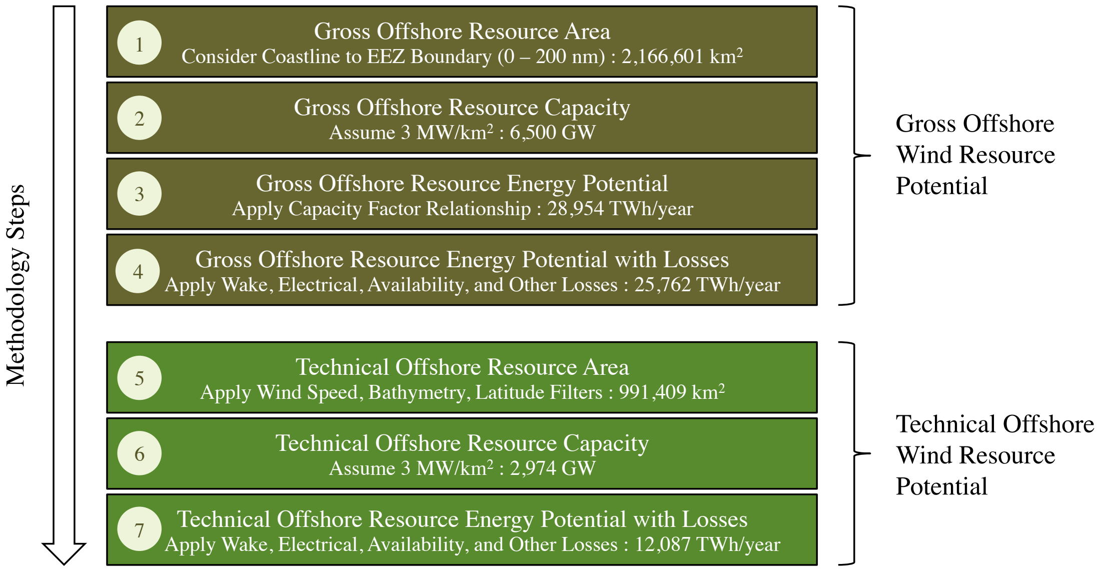

Figure ES-3. Progression of analysis for the 2017 Offshore Wind Energy Resource Assessment for Alaska

latitude cutoff filter. An example of this analysis is given in Figure ES-2 showing the comparison between gross and net estimates for both resource capacity and energy potential at each offshore region considered. In addition to the Alaska regional analysis, the results are compared to the offshore U.S. regions defined in the Wind Vision study scenario and to individual states, indicating that Alaska boasts substantially higher gross and net technical resource than any other U.S. region or state.

Table of Contents

1 Introduction . . . **1**
- 1.1 The Energy Landscape of Alaska . . . 1
- 1.2 The Shifting Grid . . . 2
- 1.3 Offshore Wind in Alaska . . . 3

2 Uses and Limitations of This Report . . . **6**

3 Terminology . . . **7**

4 Methodology . . . **8**
- 4.1 Gross Resource Potential . . . 8
- 4.2 Technical Resource Potential . . . 8
- 4.3 Energy Regions of Alaska . . . 9

5 Data . . . **11**
- 5.1 Wind Speed Data . . . 11
- 5.2 Bathymetry Data . . . 11

6 Gross Offshore Wind Resource . . . **15**
- 6.1 Gross Offshore Wind Resource Area . . . 15
  - 6.1.1 Distance Zones . . . 15
  - 6.1.2 Depth Zones . . . 15
- 6.2 Gross Offshore Wind Resource Capacity . . . 16
- 6.3 Gross Offshore Wind Resource Energy . . . 16
- 6.4 Gross Offshore Wind Resource Energy with Losses . . . 17

7 Technical Offshore Wind Resource . . . **19**
- 7.1 Technology Exclusions . . . 19
  - 7.1.1 Water Depth Exclusions . . . 19
  - 7.1.2 Wind Speed Exclusions . . . 19
  - 7.1.3 Latitude Exclusions . . . 19
- 7.2 Technical Offshore Wind Resource Area . . . 20
- 7.3 Technical Offshore Wind Resource Capacity . . . 20
- 7.4 Technical Offshore Wind Resource Energy with Losses . . . 20
- 7.5 Relative Impact of Each Exclusion . . . 21

8 Regional Discussion . . . **23**
- 8.1 Offshore Energy Regions of Alaska . . . 23
- 8.2 Alaska and Offshore Regions of the Continental United States . . . 24
- 8.3 State-by-State Comparisons . . . 24

9 Summary and Key Findings . . . **27**

List of Figures

Figure ES-1. Wind speed (m s^{-1}) 100 m above ground temporally averaged over the entire simulation period for grid cells within the technical offshore wind resource area. Note that the data extent is limited due to the model simulation domain, which did not include part of the Aleutians Arc, as will be discussed in the report. v

Figure ES-2. Offshore wind resource capacity (left) and net energy (right) from gross (dark blue) and final net technical (light blue) resource estimates for the eight offshore energy regions of Alaska south of 65.5° N . vi

Figure ES-3. Progression of analysis for the 2017 Offshore Wind Energy Resource Assessment for Alaska . . . vii

Figure 1. Total Alaska population between 1945 and 2016 (line) and population divided by region for 2011-2016. Numbers given in thousands. Source: Parnell and Blumer (2014) and State of Alaska (2017). 1

Figure 2. Alaska Grid (AKGD) and Miscellaneous (AKMS) making up the two interconnection regions served by the Alaska Systems Coordinating Council [Source: U.S. EPA (2017)], and power lines as of 2010 [Source: Alaska Energy Inventory (2010)]. 2

Figure 3. Power plants in Alaska (as of March 2017) by primary energy source. Note that wind plants producing less than another (primary) energy source are not shown. Data source: U.S. EIA (2017d). . . . 3

Figure 4. Cumulative installed capacity of utility-scale wind turbines in Alaska, from 1997 to 2015. Data source: U.S. EIA 2015. 4

Figure 5. Wind power class 50 m above ground, according to previous work that considered an offshore extent of 12 nmi from shore 5

Figure 6. Offshore wind energy resource classification framework. Source: Beiter and Musial (2016). . . . 7

Figure 7. Progression of analysis for the 2017 Offshore Wind Energy Resource Assessment for Alaska . . . 8

Figure 8. Onshore energy regions of Alaska, as defined by Alaska Energy Authority (Fay, Meléndez, and Converse 2011), extended to cover the EEZ. The 170° W line marks the westernmost longitude at which simulation data are available for Alaska from north to south. The 65.5° N line marks the latitude cutoff used for technical exclusions. 10

Figure 9. Simulation domain used in WRF simulations 12

Figure 10. Wind speed (m s^{-1}) 100 m above ground temporally averaged over the entire simulation period . 13

Figure 11. Bathymetry (m) of Alaska extending out to EEZ and showing excluded areas with values > 1,000 m 14

Figure 12. Gross offshore area map highlighting distance-to-shore zones 16

Figure 13. Gross (left) and net (right) capacity factor as a function of wind speed as derived from Openwind data for the Pacific region. Markers represent individual Openwind simulations and lines show linear and quadratic fits for the two defined regimes: below and above 7 m s^{-1}. 17

Figure 14. Wind speed (m s^{-1}) 100 m above ground temporally averaged over the entire simulation period for grid cells within the technical offshore wind resource area 21

Figure 15. Offshore wind resource capacity (left) and net energy (right) from gross (dark blue) and final net technical (light blue) resource estimates for the eight offshore energy regions of Alaska south of 65.5° N . 23

Figure 16. Net capacity factor for technical resource area and outline of the 10 Alaska offshore energy regions 24

Figure 17. Net energy potential per region (TWh/year) by water depth category 25

Figure 18. Offshore wind resource capacity (left) and net energy (right) from gross (dark blue) and final net technical (light blue) resource estimates for five U.S. offshore wind resource regions and Alaska 25

Figure 19. Offshore wind net technical energy potential for U.S. states not including Alaska [7,203 TWh/year, refer to Musial et al. (2016)] given as a percentage of the net technical energy potential for Alaska. Given separately for water depths of less than 60 m (blue) and greater than 60 m (red). 26

List of Tables

Table 1. Average Price (U.S. cents/kWh) of Electricity (in July 2017) to Ultimate Consumers By End-Use Sector. Data Source: Table 5.6.A in U.S. EIA (2017b). 2

Table 2. Offshore Wind Resource Reductions by Exclusion Category Relative to Gross Resource Values of 6,500 GW for Capacity and 28,954 TWh/year for Energy Potential 22

Table 3. Technical Area, Resource Capacity, and Energy Potential for Each Offshore Region South of 65.5° N and for Areas Within the Simulation Domain 25

1 Introduction

This report quantifies Alaska's offshore wind resource capacity and focuses on the unique nature of Alaska's offshore wind resource. It is a supplement to the existing U.S. Offshore Wind Resource Assessment, which evaluated the offshore wind resource for all other U.S. states (Musial et al. 2016). Together, these reports provide the foundation for the nation's offshore wind value proposition.

1.1 The Energy Landscape of Alaska

The energy landscape of Alaska differs significantly from that of the contiguous United States because of its size and remote geographical location, sparse population, and extreme climate. The land in Alaska covers a vast geographical area (1,718,000 km^2) that is approximately 21% of the contiguous U.S. area. The state also possesses a long coastline (54,563 km) that is approximately 57% of the total coastline for the lower 48 (NOAA Office for Coastal Management 2017).

The marine environment is an integral part of Alaska's culture. A large fraction of the state's cities, towns, and villages are located along Alaska's massive coastline, where the small [∼ 0.2% of the national total in 2015 (U.S. EIA 2017a)] but increasing population is mostly concentrated (Figure 1). As a result, some marine infrastructure and capability is already established, which might facilitate future offshore wind development in the state.

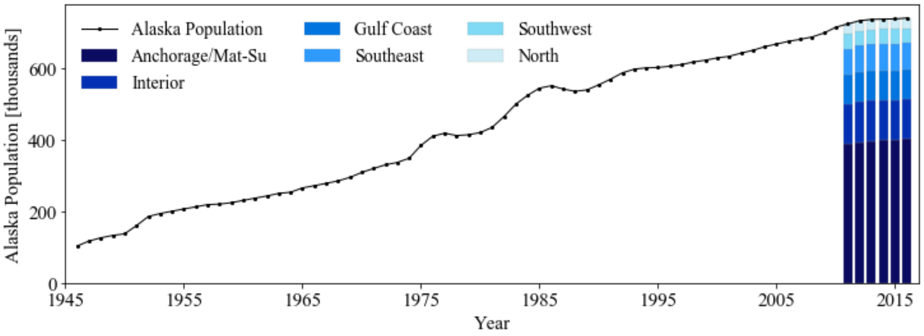

Figure 1. Total Alaska population between 1945 and 2016 (line) and population divided by region for 2011-2016. Numbers given in thousands. Source: Parnell and Blumer (2014) and State of Alaska (2017).

Other large differences between Alaska and other U.S. states pertain to the structure of the electrical grid. In contrast to the large interconnected grid of the contiguous United States, Alaska's transmission infrastructure is composed of hundreds of independent electrical grids (Alaska Energy Inventory 2010). The largest interconnection region is the Alaska Grid (AKGD; often referred to as "the Railbelt" transmission grid), which delivers power to the majority of Alaska's population, including Anchorage, Fairbanks, and the Kenai Peninsula, but covers only a fraction (∼14%) of the state's geographical area (Figure 2). The remaining area is serviced by smaller, local transmission networks powered predominantly by conventional hydro and diesel (Figure 3).

As a result of this unstructured grid, Alaska's electricity costs are among the highest in the nation. Most of the rural electrical grids throughout the state are powered by diesel generators. The fuel for these systems is delivered intermittently by truck (where roads exist, and when they are passable), by barge for coastal and river communities (when ice does not prevent this), and in steel drums aboard small aircrafts when other options are unavailable. In these communities, electricity costs are often greater than \$0.50/kWh [e.g., \$0.70/kWh in Atka, Alaska (Electricity Local 2017)]. On the state's largest power grid, economies of scale enable relative competitiveness, and electricity rates are comparable to costs in the contiguous United States [e.g., \$0.13/kWh in Anchorage, Alaska (Electricity Local 2017)]. However, the state-averaged values are still significantly higher than the national average considering all other states, especially for the industrial sector (Table 1). In terms of electricity consumption, values for Alaska (6.1 TWh in 2016) are ∼ 0.2% of the total U.S. demand (3,710.8 TWh in 2016), according to U.S. EIA (2017c). The net summer capacity of the electric power industry is ∼ 0.3% of the total United States, and was estimated to be ∼ 2,829 MW in March 2017 (U.S. EIA 2017a).

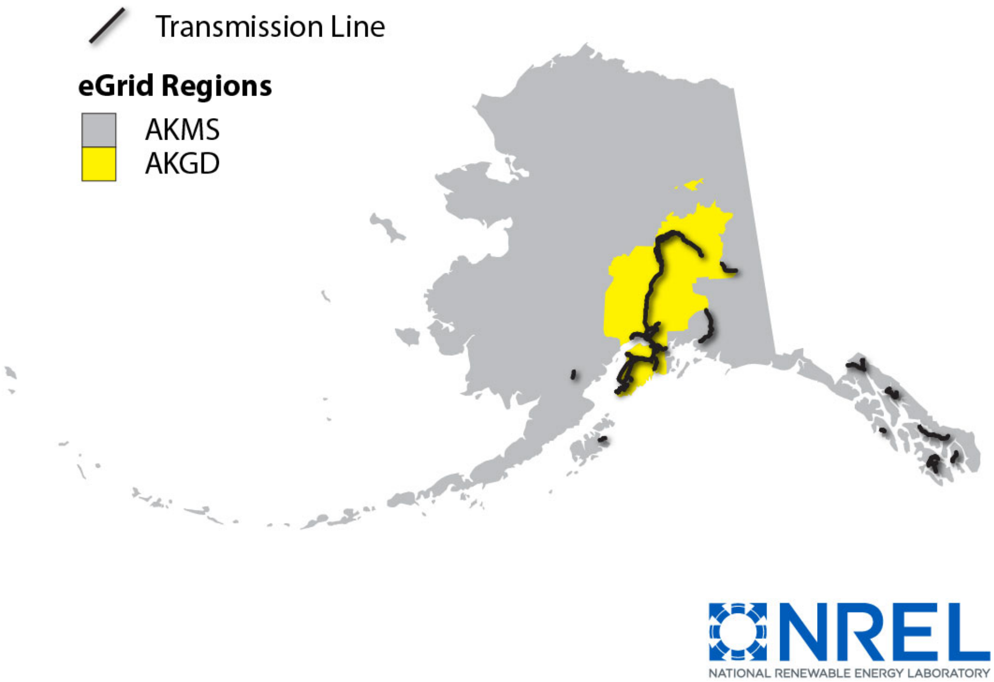

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Table 1. Average Price (U.S. cents/kWh) of Electricity (in July 2017) to Ultimate Consumers By End-Use Sector. Data Source: Table 5.6.A in U.S. EIA (2017b).

	Residential	Commercial	Industrial	All Sectors
Alaska	22.30	19.51	16.94	19.72
U.S. Average Without Alaska	13.62	11.11	8.18	11.33

1.2 The Shifting Grid

Alaska ranks second (to Hawaii) in per-capita generation of electric power from petroleum liquids. This can be explained by the reliance of isolated, rural communities on diesel for electricity. Despite the state's abundance of fossil fuel resources, the majority of oil extractions are shipped out of state for processing and refining. At the time of writing, Petro Star is the only Alaska-owned refining and fuel marketing operation in the state. In addition to petroleum liquids, the state produces a large amount of natural gas. The majority of this production takes place in northern Alaska, where it exceeds local demand. Some of the natural gas produced in the North Slope is used locally to support the large industrial operations established there, but a large portion is simply burned because no means are available to transport it southward. Natural gas is also extracted from Cook Inlet in the south, providing power generation for consumer use in south-central Alaska. In terms of coal, the only operational mine is Usibelli. Approximately half of its production is used to fire six power plants in the interior of Alaska, and the remainder is exported.

Despite the apparent abundance of fossil-fuel-powered plants, the state is beginning to shift toward renewable energy sources for electricity. This shift is driven by the State of Alaska Legislature, which in 2010 adopted the goal of supplying 50% of Alaska's energy needs from renewable energy sources by the year 2025 (Alaska Energy Authority 2017). This initiative seeks to diversify the state's energy portfolio, providing a pathway toward renewable energy

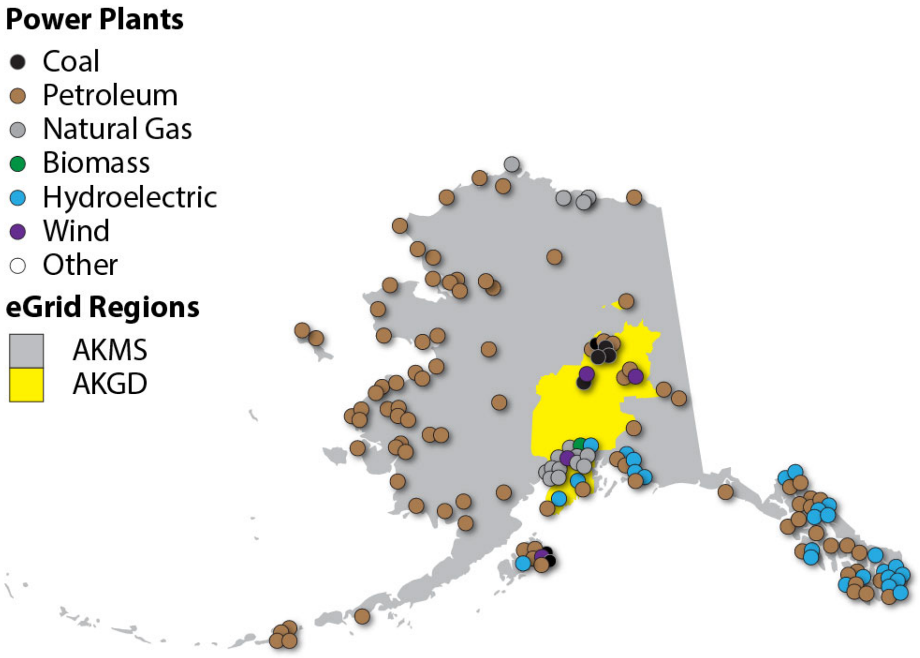

Figure 3. Power plants in Alaska (as of March 2017) by primary energy source. Note that wind plants producing less than another (primary) energy source are not shown. Data source: U.S. EIA (2017d).

integration with projects that include geothermal, biomass, solar, and wind as renewable energy sources. In March 2017, 46.3% of electricity generation was from renewables, 25.4% from natural-gas-fired power plants, and 19.6% from petroleum-fired plants (U.S. EIA 2017a).

In terms of wind, all of the developments and projects so far have been on the Alaska mainland [e.g., Eva Creek Wind Farm (Golden Valley Electric Association 2017)] or on islands [e.g., Fire Island Wind Farm (Cook Inlet Region, Inc. 2017) and Kodiak Island project (Tetra Tech 2017)]. The first wind turbines in the state date back to 1997 (Figure 4) and were kilowatt-scale machines installed in Kotzebue, Alaska. In contrast, the largest project to date is the Eva Creek wind farm, with a total installed capacity of 24.6 MW. Eva Creek was commissioned in 2012 and marks the start of significant growth in total installed wind capacity in the state, which was 60.6 MW in 2015 (Figure 4). In addition to the more recent utility-scale plants, there is a large number of smaller wind projects in Alaska, which are part of wind-diesel systems. These systems are intended to leverage the volatility of diesel prices and therefore the electricity cost in rural and island communities that rely heavily on oil as an energy source (Fay, Keith, and Schwörer 2010; Fay, Meléndez, and Converse 2011).

1.3 Offshore Wind in Alaska

While onshore wind development has been taking place for the last 20 years, Alaska has seen no offshore development yet. The largest obstacle that needs to be overcome before offshore wind can be heavily incorporated into the national grid pertains to its economical feasibility, which can be accomplished through innovation and economies of scale (U.S. DOE 2015). For the continental United States, these challenges are expected to be overcome in future scenarios such as the Wind Vision study, in which 35% of the national electricity demand could be provided from wind by the year 2050 (Musial et al. 2016). In Alaska, offshore wind faces additional challenges: extreme cold and icing (Diamond 2012); the discontinuous nature of the electrical grid; the wealth of land for developing onshore wind; and the abundance of

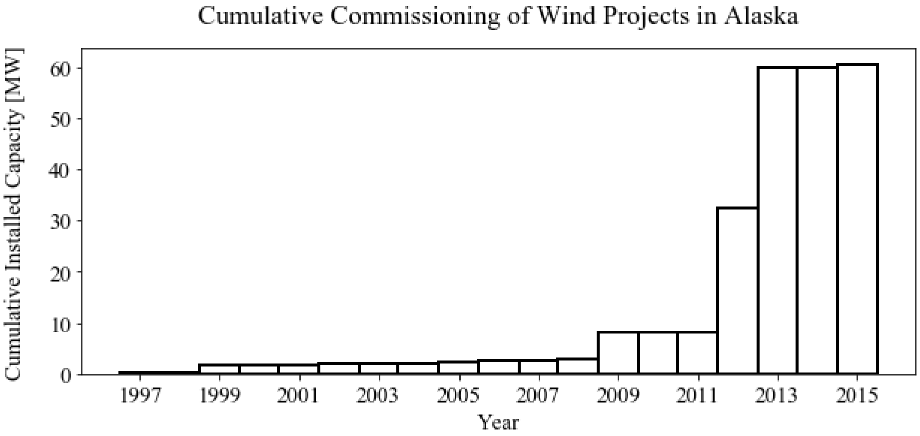

Figure 4. Cumulative installed capacity of utility-scale wind turbines in Alaska, from 1997 to 2015. Data source: U.S. EIA 2015.

hydrological resources facilitating the development of conventional hydropower.

Given the abundant wind resource that is known to be available in Alaska (Johnson et al. 2012) and the desirable shift toward energy security (National Renewable Energy Laboratory 2012) it is important to have an up-to-date accounting of Alaska's offshore wind resource for the purpose of understanding opportunities at the highest levels and to serve as a basis for more detailed site-specific studies.

With that in mind, the analysis presented herein is a critical addition to the offshore wind resource assessment report for the contiguous United States and Hawaii (Musial et al. 2016). The results presented in Musial et al. (2016) are updated, expanded, and more detailed than the previous report on U.S. offshore wind resource assessment (Schwartz et al. 2010). Alaska was not included in either of the previous reports because of the complexity of its landscape and coastline and because of the spatial sparseness of in situ measurements available, which complicate the task of model validation. Up until now, the only existing wind data set for Alaska that includes offshore regions was that produced by AWS Truepower and validated by the National Renewable Energy Laboratory (NREL) as shown in Figure 5 (National Renewable Energy Laboratory 2009). It extends only 12 nmi from the coastline and was not produced with the intent of assessing the offshore wind resource. In contrast, the current report is based on high-resolution simulations of atmospheric conditions in Alaska and covers the entire Exclusive Economic Zone (EEZ) out to approximately 170° W. The simulations were conducted by the National Center for Atmospheric Research (NCAR) and the simulated wind data (described in Section 5) were carefully validated against a large observational network (Lee et al. 2018).

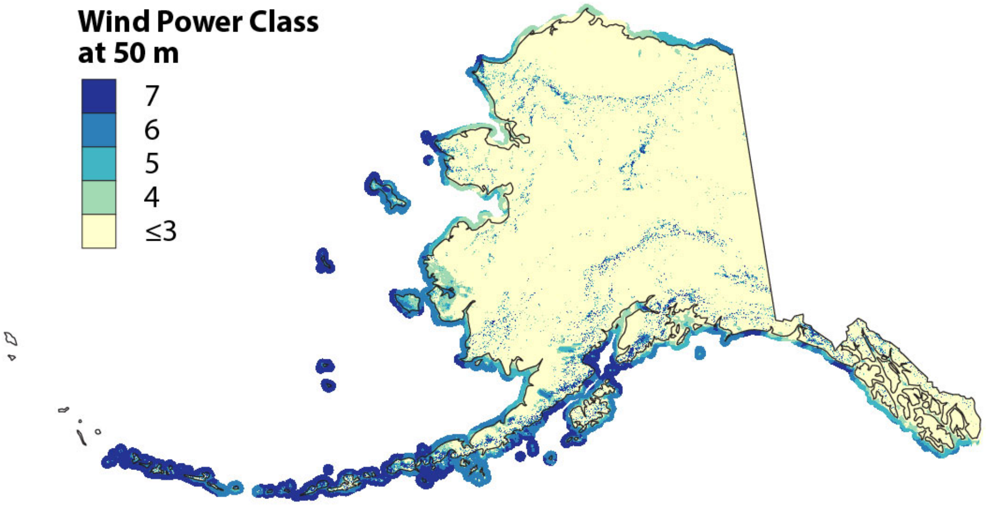

Figure 5. Wind power class 50 m above ground, according to previous work that considered an offshore extent of 12 nmi from shore

2 Uses and Limitations of This Report

The objective of the current report is to quantify the offshore wind resource of Alaska using validated numerical model simulations at high spatial resolution (4 km) so that the state's complex coastline and terrain are appropriately taken into account when describing Alaska's wind resource. Additionally, we examine other data relevant to offshore wind development and provide the download locations for open-source data sets so that users can extend the analysis to their specific needs. The two main limitations of the work presented herein are (1) the data extent, which does not include part of the Aleutians Arc for which simulation data were not available; and (2) the lack of exclusions due to conflicting use and environmental restrictions, which were not included in the original Black & Veatch (2010) study. An analysis of conflicting use and environmental restrictions for Alaska is forthcoming, but the analysis was not complete at the time that the current report was written.

While the spatial resolution of the wind data used for this work is high in the context of numerical models and the large area that is being considered, the current analysis should be limited to preliminary assessments such as the initial identification of potential areas for wind development. Given the uncertainty associated with these data and the relative absence of explicit uncertainty quantification efforts, it will also be desirable to collect future site-specific empirical data before advancing to a particular project or capital investment decision. Site-specific empirical data collection is common practice in the current wind energy industry. Future research efforts focusing on uncertainty quantification of modeled simulation results may one day reduce the need for empirical data collection efforts to be completed before more advanced development or planning is executed. We also suggest that additional feasibility and design-level studies be based on a more rigorous marine spatial planning study, which in turn can be informed by and based on the current report.

Finally, although the results presented herein show resource areas that have been reduced to account for technology limits, these reductions were applied with broad criteria. It is important to keep in mind that these limits will vary widely depending on the technology being considered and that this study should not be used as a substitute for more rigorous engineering analyses.

3 Terminology

The terminology used hereinafter is based on the definitions proposed by Beiter and Musial (2016), in which the wind energy resource language is redefined to correspond as closely as possible to the language that has traditionally been used in the oil and gas industry. This homogenization effort was prompted by the fact that licensing and permitting of offshore wind projects are carried out by the same bureau that regulates oil and gas projects in the outer continental shelf− namely, the Bureau of Ocean Energy Management (BOEM). Therefore, having a comparable terminology structure facilitates the understanding of resources and development across energy sources.

A summary of the terminology used is given by the schematic in Figure 6. The **total resource potential** is represented by the largest ellipse and decreases as constraints are added to the wind resource characterization process. The total resource considers recoverable and unrecoverable wind in the upper atmosphere and in high seas (i.e., further than 200 nmi from shore; distance representing the limit of the EEZ). The first subset ellipse refers to the **gross resource potential**, which is theoretically recoverable without regard for technological considerations. The technological constraints are added in the next subset ellipse, which gives the **technical resource potential**. Next, economical viability is considered to yield the **economic potential**. Finally, only a portion of this potential will actually be realized in the smallest subset ellipse that represents the **Deployment**.

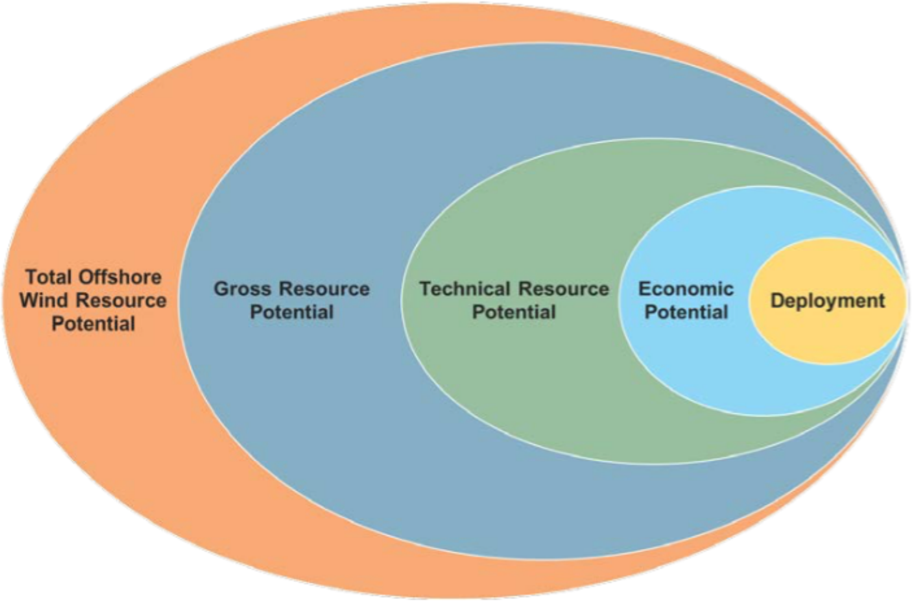

Figure 6. Offshore wind energy resource classification framework. Source: Beiter and Musial (2016).

As mentioned in Musial et al. (2016), some of the offshore wind resource in Alaska may be technically unrecoverable even if it is within the EEZ limits because of the remoteness of electricity load centers. In addition to the gross offshore wind resource, this report seeks to provide data on the electrical grid logistics and on marine quantities of interest in order to quantify the technical resource potential in Alaska. However, the scope of this report is limited to the gross and technical resource potential, and no economic considerations are made.

4 Methodology

The methodology employed in this report is consistent with that used to quantify the gross and technical offshore wind resource potential of the contiguous United States and Hawaii (Musial et al. 2016), with the exception of the criteria considered in the technical exclusions and of the methodology used to estimate capacity factor, as is described below.

4.1 Gross Resource Potential

The following steps briefly outline the methodology used to quantify the gross resource potential, as also summarized by steps 1-4 in Figure 7. Detailed results of this analysis are given in Section 6.

1. **Define the gross offshore wind resource area**: The total offshore resource domain is defined, and its area (km^2) is calculated using geographic information system (GIS) tools.
2. **Calculate the gross offshore wind resource capacity**: The gross offshore resource capacity (GW) is calculated by multiplying the gross domain area by the array power density, which is assumed to be 3 MW/km^2. This value is based on developer input for likely array spacing in U.S. projects (Musial et al. 2013) and is consistent with the resource assessment performed for the other U.S. states (Musial et al. 2016) and with the DOE Wind Vision study (U.S. DOE 2015).
3. **Calculate the gross offshore wind resource energy potential**: The gross capacity factor at each offshore point is estimated using a relationship between mean wind speed and gross capacity factor derived from an analysis of the U.S. West Coast offshore wind resource (Musial et al. 2016) using the Openwind analysis program (AWS Truepower 2014b). The total gross energy potential (TWh/year) is then computed as gross capacity times gross capacity factor integrated over the entire area and multiplied by 8,760 hours.
4. **Calculate and apply losses**: Geospatial criteria accounting for site conditions are applied to the gross offshore wind resource energy potential to include an estimate of typical losses (i.e., wakes, electrical, availability, and others) and to obtain the gross offshore wind resource energy potential with losses (TWh/year).

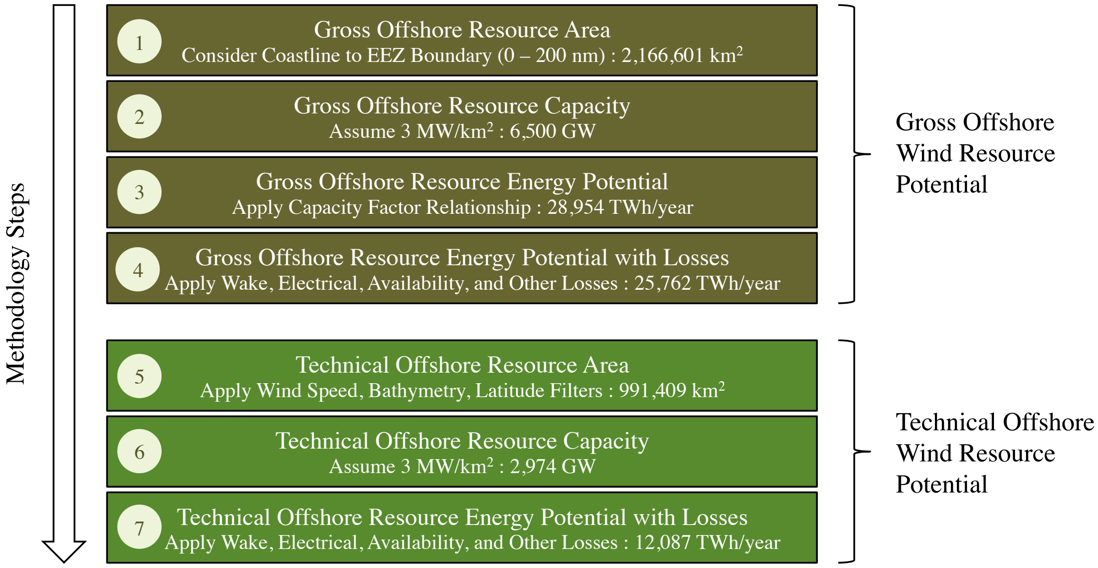

Figure 7. Progression of analysis for the 2017 Offshore Wind Energy Resource Assessment for Alaska

4.2 Technical Resource Potential

The methodology used to quantify the technical resource potential is briefly described below and in steps 5-7 of Figure 7. Note that the final estimates consider wake, electrical, availability, and other miscellaneous losses but do not consider exclusions for industry use and environmental conflicts because exclusion data, as were used in Musial et al. (2016), are presently unavailable for Alaska.

5. **Define the technical offshore wind resource area:** The exclusions applied in this step are meant to restrict the resource to geographic locations suitable for the technology based on industry experience to date. These exclusions do not limit development or restrict innovation. In fact, it is expected that the boundaries used for technical potential in this report will change as new technology is developed and more experience is gained. With that in mind, the gross resource area is reduced to the technical resource area (km^2) by applying technology exclusion filters: a minimum average wind speed of 7 m s^{-1} at 100 m, a maximum water depth of 1,000 m, and a maximum latitude of 65.5° N.

   The minimum wind speed value of 7 m s^{-1} was selected to remove from the analysis areas that do not show any economic potential for large, utility-scale offshore wind development in the United States.

   The bathymetry cutoff of 1,000 m was selected after consultation with global floating offshore wind technology developers, but it does not represent a hard limit on water depth at which the technology can be deployed. This value is low enough that it avoids eliminating critical resource areas while remaining consistent with past studies.

   The latitude cutoff value is chosen based on sea ice climatological data (University of Alaska Fairbanks 2017) and is applied to remove from the analysis offshore areas in which the mean sea ice concentration is between 90% and 100% continuously across the state waters in the longitudinal direction, acknowledging that floating substructures cannot handle sea ice under present technology. These high concentration values start close to 64.5° N and extend northward. As a conservative measure, we identify the Bering Strait as a useful northerly reference latitude and select the narrowest point at the Bering Strait at $\sim$65.5° N as the geographical cutoff location.

   The resource potential is also evaluated after each exclusion is individually applied, and the effect of each of these exclusions on the resource is discussed in Section 7.5.

6. **Calculate the technical offshore wind resource capacity**: The technical offshore resource capacity (GW) is calculated by multiplying the technical domain area by the array power density, which is assumed to be 3 MW/km^2, as explained in Section 4.1.

7. **Calculate the technical offshore wind resource energy potential with losses**: The gross offshore wind resource energy potential (TWh/year) with losses is considered and further reduced to account for technical exclusions. This step accounts for the effect of wind turbine wakes and electrical and other miscellaneous losses.

4.3 Energy Regions of Alaska

There is no accepted definition of Alaska regions for the purpose of offshore wind characterization. The Alaska Energy Authority defines 11 onshore regions that are used in planning and energy diagnostics (Fay, Meléndez, and Converse 2011), as shown by the shaded, continental areas in Figure 8. For the purposes of the offshore wind resource assessment carried out in this report, these regions are extended beyond the coastline to the EEZ limit by assigning each offshore grid point to the region that it is closest to. The objective in defining these offshore energy regions is to help distinguish how different continental regions of Alaska can benefit from offshore wind development, as will be further discussed in Section 8.

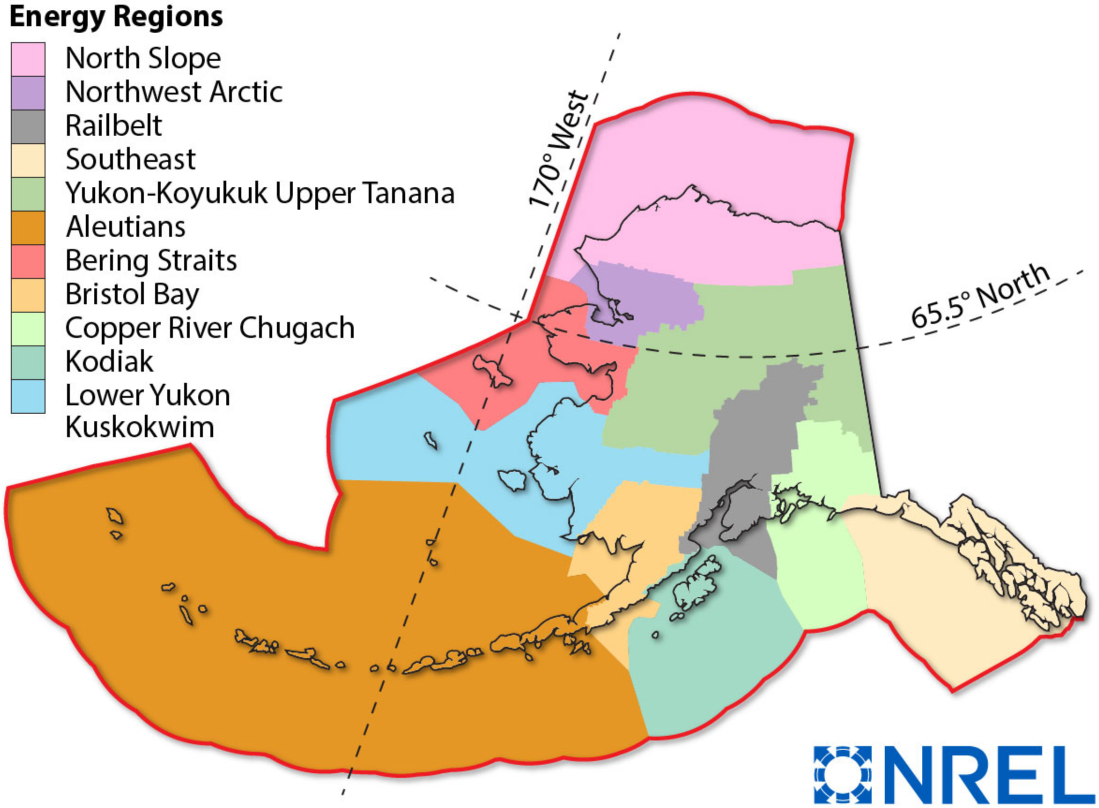

Figure 8. Onshore energy regions of Alaska, as defined by Alaska Energy Authority (Fay, Meléndez, and Converse 2011), extended to cover the EEZ. The 170° W line marks the westernmost longitude at which simulation data are available for Alaska from north to south. The 65.5° N line marks the latitude cutoff used for technical exclusions.

5 Data

This section describes all the data sets used to conduct the assessment of net offshore wind resource potential for Alaska.

5.1 Wind Speed Data

The wind speed data used to conduct the analyses presented in this report were generated with the Weather Research and Forecasting (WRF) model and span a 14-year period between 2002 and 2016. This period is assumed to be long enough to include inter-annual variability in the wind data but is not necessarily sufficient for a climatologically representative assessment, which should consider decades of data so as to include wind variations on large time scales that are brought on by phenomena such as the El Nino Southern Oscillation or the Pacific Decadal Oscillation.

The horizontal resolution of the model grid is 4 km, and wind fields were saved every 6 hours. The lateral boundary conditions were prescribed from ERA-Interim (at a spatial resolution of $\sim$ 80 km globally), and lower boundary conditions include NASA MUR sea surface temperatures and sea ice concentration (at a spatial resolution of $\sim$ 1 km). Figure 9 shows the model domain used. Note that the data extent is limited to longitudes west of 170° W, excluding a portion of the Aleutians Arc from the present study. These simulations were validated against an extensive network of observations. More details on the configuration of the WRF simulations and on the validation procedure can be found in Lee et al. (2018). The mean wind speed over the entire simulation period is shown in Figure 10 and was used to conduct the wind resource assessment presented in Sections 6 and 7.

5.2 Bathymetry Data

The bathymetry data used in this study were obtained from the National Oceanic and Atmospheric Administration ETOPO1 Global Relief Model (Amante and Eakins 2009) at a spatial resolution of 1 arc-minute, which for Alaska corresponds to $\sim$ 2 km in the latitudinal direction and $\sim$ 1 km in the longitudinal direction. Figure 11 shows the area considered when computing the gross resource potential in Alaska. It is bounded by the 200-nmi EEZ and includes areas with water depths greater than 1,000 m and latitudes north of 65.5° N.

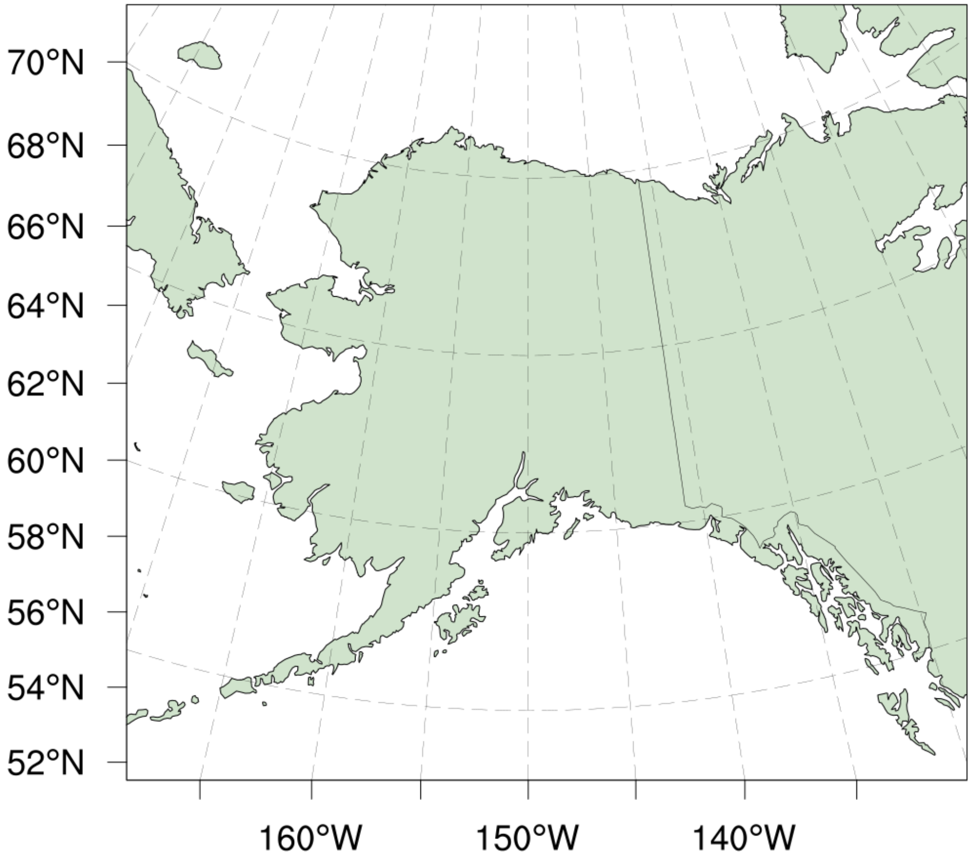

Figure 9. Simulation domain used in WRF simulations

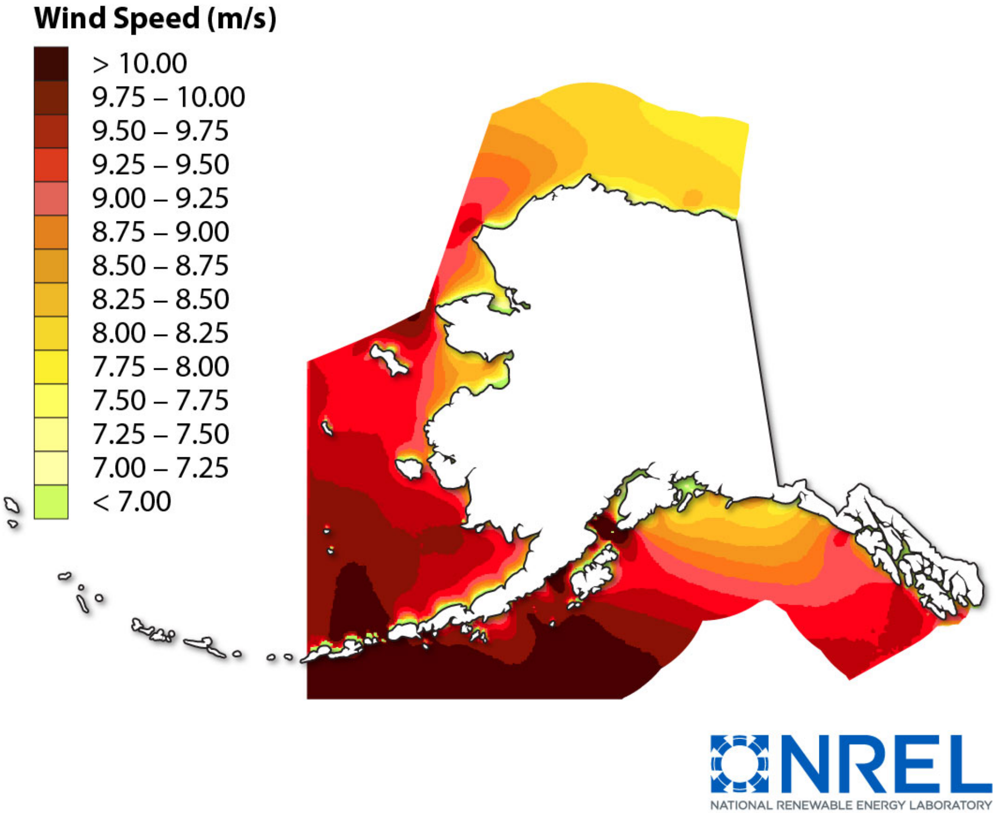

Figure 10. Wind speed (m s^{-1}) 100 m above ground temporally averaged over the entire simulation period

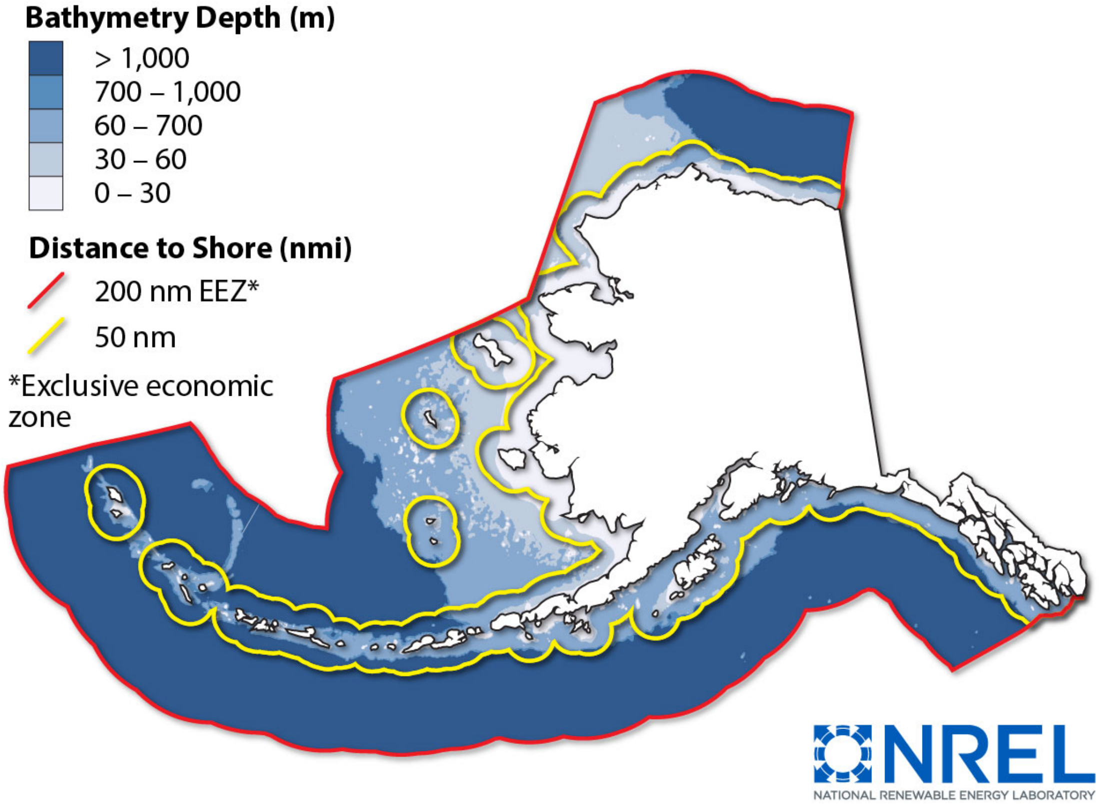

Figure 11. Bathymetry (m) of Alaska extending out to EEZ and showing excluded areas with values > 1,000 m

6 Gross Offshore Wind Resource

The gross resource in this study considers all coastal waters in Alaska that have federal and state jurisdiction. The calculation of gross resource does not discriminate on the basis of possible technology or use conflicts, or environmental impacts. Therefore, it intentionally includes areas that might not be economical to develop or could be unsuitable for various reasons that normal site screening might eliminate using today's knowledge base. However, the assessment does take into consideration the experience and trends of the offshore wind industry over the past few decades to establish physical parameters for array power density and turbine height that are needed to limit power capacity and energy production. The gross potential resource presented herein provides an upper bound on the maximum offshore wind potential but should not be used as a proxy for long-term deployment estimates. The assumptions made when applying exclusions are consistent with those applied in Musial et al. (2016), enabling a direct comparison between the Alaska values and those presented for the continental United States and Hawaii in the previous report. Results obtained while carrying out the methodology steps 1-4 (described in Section 4.1) are presented in Sections 6.1 to 6.4.

6.1 Gross Offshore Wind Resource Area

The updated wind resource assessment of Musial et al. (2016) considered a distance from shore of 200 nmi, extending farther than the original offshore resource assessment study of Schwartz et al. (2010), which only extended out to 50 nmi. This expansion in the offshore area considered is driven by a consistent trend in offshore wind projects to be planned at large distances from shore in more mature markets. An example is the Dogger Bank development consisting of four wind projects that are planned as far as 195 km (105 nmi) from the coast in the North Sea (Statoil 2017). For consistency, the gross resource area outlined in this report includes all offshore water area from the shoreline to the 200-nmi EEZ (as long as it is included in the simulation domain; see Section 5) and was calculated to be 2,166,601 km^2, which is $\sim$ 60% of the U.S. gross resource area of the other 29 coastal states, excluding Alaska.

6.1.1 Distance Zones

The economic zones considered within the total gross resource area domain are defined by their distance from shore and shown in Figure 12.

- **The 0-to-3-nmi zone**: This zone is generally the area that contains state waters but is outside BOEM's jurisdiction (Musial and Ram 2010).
- **The 3-to-12-nmi zone**: This zone extends to the territorial waters boundary at 12 nmi. In this zone, conflicting-use impacts may be higher than in areas farther out. Some studies have found that opposition to offshore wind projects on the basis of view shed or aesthetics begin to decline rapidly beyond 12 nmi (Lilley, Firestone, and Kempton 2010).
- **The 12-to-50-nmi zone**: The 50-nmi boundary was originally selected to focus the effort of offshore wind resource evaluation on the near-shore area where access to grid and shore-based support services was more feasible (Schwartz et al. 2010). Subsequent assessments show that project feasibility is not necessarily limited to 50 nmi but this distance is kept here to facilitate comparison with other studies.
- **The 50-to-200-nmi zone**: This additional distance from shore was added to the gross resource area in Musial et al. (2016) to provide the possibility of development beyond 50 nmi, thus minimizing conflict areas and maximizing developable areas in terms of bathymetry. For this study, the 200-nmi delineation is retained to accompany trends of developments at large distances from shore and to provide consistency with previous studies.

6.1.2 Depth Zones

The domain area was also classified separately in five water depth bands: 0-30 m, 30-60 m, 60-700 m, 700-1,000 m and greater than 1,000 m, as shown in Figure 11. These depth-band classifications are the same as those in Musial et al. (2016) and are based on fixed-bottom technology (limited to 30-60 m) and on expected depth limits for floating technology (700-1,000 m).

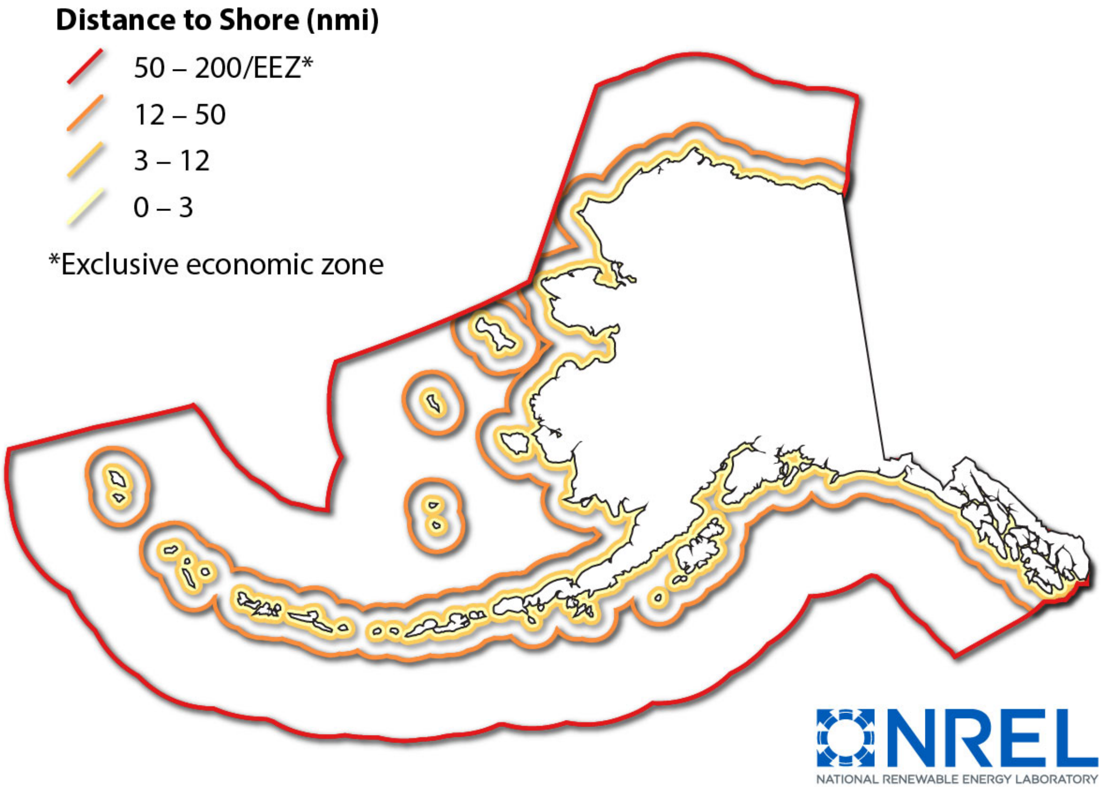

Figure 12. Gross offshore area map highlighting distance-to-shore zones

6.2 Gross Offshore Wind Resource Capacity

The gross resource capacity was calculated by multiplying the gross resource area by the assumed nominal array power density of 3 MW/km^2, which results in a gross capacity of 6,500 GW for the entire state. This number represents $\sim$ 60% of the gross resource capacity estimated for the remainder of the United States and is the theoretical recoverable resource that would be possible if wind turbines were installed everywhere on the outer continental shelf without regard to technology and use limits or power delivery constraints, at a density of 3 MW/km^2. While optimum spacing will vary with atmospheric conditions, the assumed array power density selected for this study is lower than that of Schwartz et al. (2010) in order to account for normal turbine spacing with increasingly large rotors while also considering internal wind plant buffers. Additionally, it is consistent with the density used for assessing the offshore resource of the contiguous United States and Hawaii (Musial et al. 2016) and with the value proposed in the Wind Vision study (U.S. DOE 2015). Note that this assumption constitutes a previously established methodology for estimating wind resource potential and does not suggest that realistic deployment scenarios would necessarily adopt the power density assumed herein.

6.3 Gross Offshore Wind Resource Energy

The gross offshore wind resource energy potential was calculated over the entire gross resource area of 2,166,601 km^2 described in Section 6.1. Gross resource energy potential is calculated for each grid cell in the simulation domain as

$$\begin{aligned}\text{Gross Energy} &= \text{Grid Cell Area} \times \text{Array Power Density} \times \text{Gross Capacity Factor} \times \text{Hours in a Year} \qquad (6.1)\\ &= \sim 16\ \text{km}^2 \times 3\ \text{MW km}^{-2} \times \text{Gross Capacity Factor} \times 8,760\ \text{hours} \qquad (6.2)\end{aligned}$$

and then integrated over the entire domain. Note that the data are not on a rectilinear grid. As a result, the grid cell area varies between $\sim$ 14 and 17 km^2 throughout the simulation domain and $\sim$ 16 km^2 is given here as an approximate mean grid cell area. The final value of the gross energy is reported in terawatt hours per year (TWh/year). The gross capacity factor is estimated at each grid point using a relationship between mean wind speed and gross capacity factor. This relationship was derived based on Openwind simulations for an offshore zone between 0 and 50 nmi on the Pacific coast of the United States assuming a 10×10 array comprised of 6-MW turbines. More detail on these simulations can be found in Musial et al. (2016). The derived relationship for capacity factor is shown in Figure 13 where each marker represents one Openwind simulation conducted for a 600-MW wind plant in the Pacific, and the lines give the derived relationship between both variables. We identify two regimes:

$$\text{Gross Capacity Factor} = 0.07953U - 0.19246 \tag{6.3}$$

which is a linear regime applied for $U < 7$ m s^{-1} and

$$\text{Gross Capacity Factor} = -0.00993U^2 + 0.23294U - 0.78366 \tag{6.4}$$

following a quadratic relation for $U > 7$ m s^{-1}. With no assumed technology, conflicting use, or environmental exclusions, and no performance losses (i.e., wakes, electrical), the gross Alaska offshore resource area can theoretically produce 28,954 TWh of energy each year, representing ∼ 65% of the value reported for the remainder of the United States in Musial et al. (2016).

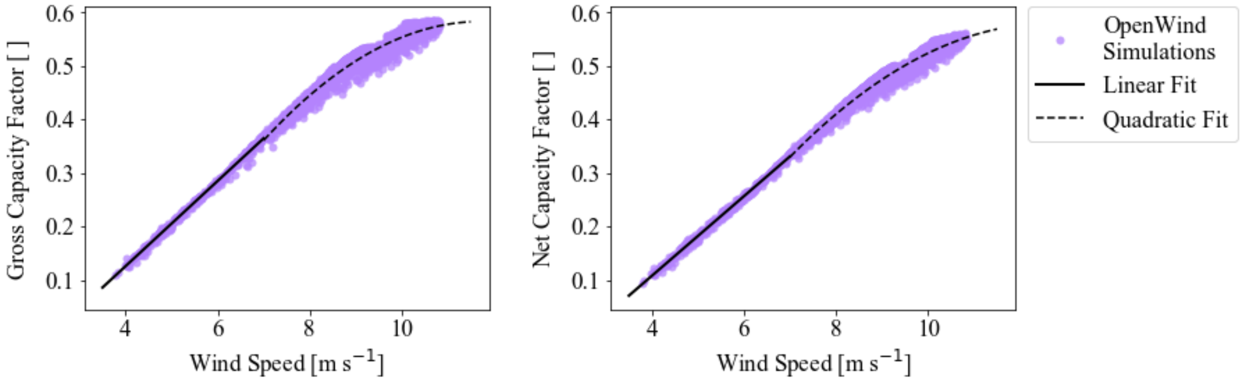

Figure 13. Gross (left) and net (right) capacity factor as a function of wind speed as derived from Openwind data for the Pacific region. Markers represent individual Openwind simulations and lines show linear and quadratic fits for the two defined regimes: below and above 7 m s^{-1}.

6.4 Gross Offshore Wind Resource Energy with Losses

In this section, the potentially available gross energy is reduced to actual net available gross energy by accounting for real-world losses: wind turbine wakes, electrical losses, and other miscellaneous losses. The losses considered in this study are only intended to reduce the gross capacity factor to nominal net energy levels and to approximate geographic biases as a result of wind speed and electrical transmission losses. This study does not provide a comprehensive assessment of losses on a site-specific basis and should not be used as a siting tool to determine net annual energy production. To perform these more rigorous analyses, refer to DNV KEMA (2013) and AWS Truepower (2014a). We compute the net gross energy potential with losses as

$$\text{Gross Energy with Losses} = (1-0.05)\,(\text{Grid Cell Area} \times \text{Array Power Density} \times \text{Net Capacity Factor} \times \text{Hours in a Year}) \tag{6.5}$$

$$= (1-0.05)\left(\sim 16\text{ km}^2 \times 3\text{ MW km}^{-2} \times \text{Net Capacity Factor} \times 8,760\text{ hours}\right) \tag{6.6}$$

where the net capacity factor is computed similarly to what was done in Section 6.3 to compute the gross capacity factor. We assume a relationship between net capacity factor and wind speed as obtained from Openwind simulations for the Pacific Ocean (i.e., the U.S. West Coast offshore region), as shown in Figure 13 and as described by

$$\text{Net Capacity Factor} = 0.07425U - 0.18917 \tag{6.7}$$

for $U < 7$ m s^{-1} and

$$\text{Net Capacity Factor} = -0.00767U^2 + 0.19496U - 0.65940 \tag{6.8}$$

for $U > 7$ m s^{-1}. This net capacity factor already includes wake losses as estimated by Openwind for the 10×10 wind turbine array considered in each simulation. The 5% energy loss factor in Equation 6.6 includes electrical and other losses. Electrical losses are assumed to be 3% in accordance with previous work (Philipp Beiter et al. 2016) that predicted 1%-5% electrical losses using a geospatial relationship to account for export cable length based on distance to shore and water depth. Other losses are assumed to be 2% based on internal NREL fixed and floating analyses also discussed in Philipp Beiter et al. (2016). Note that large distances to shore and long transmission lines might result in larger electrical losses. Specific deployment scenarios warrant a more detailed quantification of these losses, which is beyond the scope of the current report. Within the assumptions presented herein, the final value obtained for the gross offshore wind resource energy with losses is 25,762 TWh/year.

7 Technical Offshore Wind Resource

The technical offshore wind resource potential represents the subset of gross offshore wind resource potential that can be considered recoverable using available technology within reasonable limits. This estimate often includes technical limits of offshore wind, such as system performance and loss criteria, conflicting use and environmental constraints, and technology limits. The exclusions considered in this report are described in Section 7.1, and results obtained while carrying out the methodology steps 5-7 (described in Section 4.2) are presented in Sections 7.2 to 7.4.

7.1 Technology Exclusions

Technology filters are generally applied as a function of precise geographical location to the gross resource area and thereby reflect in calculations for the resource capacity and energy potential. Based on the exclusions, the resource is restricted to geographic locations suitable for the technology based on industry experience to date. These technology exclusions are not intended to limit development or restrict innovation. In fact, it is expected that the boundaries used for technical potential in this report will change as new technology is developed and more experience is gained. Three technology filters were used to reduce the gross resource area for offshore wind to new boundaries defined for technical offshore wind resource potential. The technical resource area limits water depth to less than 1,000 m and wind speed to areas with a multi-year average that is greater than 7 m s^{-1} at 100 m above sea level and considers only latitudes below 65.5° N.

7.1.1 Water Depth Exclusions

Areas where the water depth is greater than 1,000 m were excluded from the technical potential assessment. This cutoff value results from consultation with global floating offshore wind technology developers based on current technology and industry experience. Note that no hard limits can be identified at this point to deploying the technology in deeper waters and that this limit may change along with advances in offshore wind technology. In fact, the cutoff depth limit used herein is higher than the previous cutoff of 700 m used in the Wind Vision study scenario (U.S. DOE 2015). For consistency with previous work, we maintain the 700-m delineation to allow for a quantification of the resource at different depths and for a comparison with previous studies.

The excluded area due to this imposed cutoff of 1,000 m is marked in the bathymetry map in Figure 11. In most of the Aleutians Arc and the Gulf of Alaska, the depth limit is reached before the 200-nmi EEZ limit, which makes the 1,000-m isobath the exterior boundary of the technical resource area, effectively reducing the average distance between the technical area boundary and the shore.

7.1.2 Wind Speed Exclusions

Areas where the temporally averaged wind speed is less than 7 m s^{-1} at 100 m were also eliminated from the technical potential assessment. This cutoff value corresponds to the linear regime of the two relationships discussed in Sections 6.3 and 6.4 and used to estimate the gross and net capacity factors. This wind speed cutoff value removes areas with gross capacity factor lower than 36% and with net capacity factor lower than 33%. This wind speed cutoff value is consistent with exclusions that were used by Schwartz et al. (2010) and Musial et al. (2016) and sets a lower bound for average wind speed where studies do not show any economic potential for large, utility-scale offshore wind development in the United States (Philipp Beiter et al. 2016). Note that this low-wind technical resource exclusion does not preclude development in areas with low winds and where high energy prices may warrant consideration of less energetic sites (e.g., isolated rural and island communities) or deployment of smaller wind systems.

7.1.3 Latitude Exclusions

In Musial et al. (2016), several environment-siting constraints were considered based on competing use (e.g., shipping and towing lanes) and environmental exclusions (e.g., marine sanctuaries). The data used to define these constraints are from Black & Veatch (2010), a study which identified potential federal and state offshore wind resource exclusions but that did not include Alaska. Due to unavailability of these data in the Black & Veatch (2010) study for the regions of interest in this report and to the complexity of these exclusions in Alaska's unique environment, this report does not account for marine conflicting use. Instead, to enable a comparison of the resource estimates computed here to those previously obtained for the remainder of the United States, we apply a latitude cutoff that seeks to remove from the analysis areas in which offshore wind development is unlikely to occur in the near future due to the formation of sea ice. An analysis of conflicting use and environmental restrictions for Alaska is forthcoming, but the analysis was not complete at the time that the current report was written.

The cutoff latitude was selected based on the climatological sea ice atlas available from University of Alaska Fairbanks (2017). The atlas is based on a large array of observational data sets covering the period between 1954 and 2013. As a conservative cutoff value, we select the latitude of 65.5° N, which is a useful northerly reference latitude and approximates the latitude at which compact (90%-100%) ice is climatologically present across the entire offshore area of interest in the longitudinal direction. Future studies seeking to evaluate realistic build-out scenarios for Alaska should perform a more in-depth analysis of sea ice concentration at the location of interest, of the impact of sea ice formation and break-up on the wind turbine foundations and platforms, and on the predicted impact of ice and frost formation on a wind turbine's blades and tower.

7.2 Technical Offshore Wind Resource Area

The technical offshore wind resource area is determined by applying the technical exclusions described in Section 7.1 to the gross offshore resource area. When these exclusions are applied, the area is reduced from 2,166,601 km^2 to 991,409 km^2, a reduction of 54%. This level of reduction is substantially lower than what was found for the remainder of the United States [75%, see Musial et al. (2016)], thus highlighting the high wind speed values found in Alaska and the low bathymetry encountered in offshore areas outside of the Pacific, as shown in Figure 11. Figure 14 shows the wind speed map for Alaska considering the total technical offshore wind resource area, thus eliminating regions where depth is above 1,000 m, where mean wind speed is below 7 m s^{-1}, and where the latitude is higher than 65.5° N.

7.3 Technical Offshore Wind Resource Capacity

The technical offshore wind resource capacity was calculated by multiplying the technical resource area by the assumed nominal array power density of 3 MW/km^2, which results in a technical resource capacity of 2,974 GW. This value is 12% higher than was obtained for the continental United States and Hawaii (2,658 GW) after technical exclusions were applied, highlighting once again the large potential in Alaska and a much smaller reduction from gross to technical resource area than what was seen for the remainder of the United States. This value represents the technically recoverable resource, assuming installation of wind turbines everywhere inside the boundaries of the technical offshore resource area, without regard for conflicting use or environmental restrictions, and based on turbine nameplate capacity and array spacing that is possible with current technology.

7.4 Technical Offshore Wind Resource Energy with Losses

Technical offshore resource energy potential with losses was calculated by applying the technology exclusion area reductions to the gross offshore resource energy potential with losses. This assessment was done without applying conflicting use exclusions and resulted in a technical resource energy potential of 12,087 TWh/year. This value is 53% lower than what was obtained for the gross offshore wind resource energy potential with losses and 30% higher than the value of 9,284 TWh/year for all other states combined before competing use and environmental exclusions are deducted from the technical offshore wind resource (Musial et al. 2016).

This technical energy potential was calculated using the same loss assumptions described in Section 6.4. The resulting energy values are the net energy resource that wind turbines would be able to produce within the technical offshore resource area if turbines were installed at a density of 3 MW/km^2 everywhere inside the technical boundaries but without regard for conflicting use or environmental restrictions. Note that while a portion of the Aleutians Arc is not included in this analysis (for being outside the bounds of the simulation domain, see Section 5), this final estimate for the energy potential is still significantly larger than the one for the remainder of the United States [7,203 TWh/year as presented in Musial et al. (2016)] due to the large technical resource area available in Alaska and due to the lack of conflicting use and environmental exclusions in the present study. As aforementioned, an analysis of conflicting use

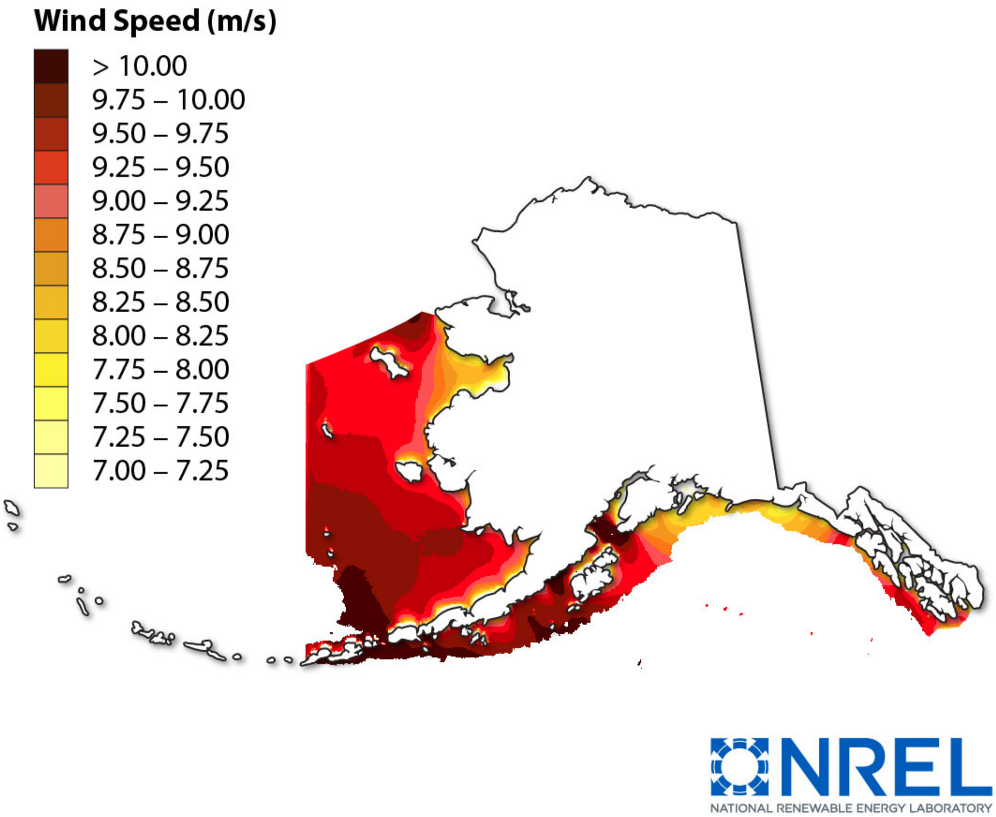

Figure 14. Wind speed (m s^{-1}) 100 m above ground temporally averaged over the entire simulation period for grid cells within the technical offshore wind resource area

and environmental restrictions for Alaska is underway. The analysis will complement that of Black & Veatch (2010) but was not complete at the time that the current report was written.

7.5 Relative Impact of Each Exclusion

The relative impacts of each individual exclusion and of all exclusions combined are summarized in Table 2 and given relative to the starting values for gross resource capacity and energy potential. We see that most of the difference between the original gross value and the final technical value for capacity and energy can be attributed to water depth constraints. The wind speed restriction is the one that least affects the energy potential assessment. Due to the high wind speed values expected in the portion of the Aleutians Arc that is not included in the analysis (Figure 5) and the high bathymetry values found at those locations (Figure 11) the contribution of these two constraints to the total exclusions would likely remain similar if data had been available for the entire Aleutians offshore region. The latitude cutoff reduces the total capacity and energy by $\sim 22\%$ by removing some high wind speed areas in the Northwest Arctic and North Slope regions from the analysis. Note that including environmental and conflict use exclusions would further reduce the estimated Alaska wind potential. For reference, these exclusions amounted to 23% for the remainder of the United States (Musial et al. 2016).

Table 2. Offshore Wind Resource Reductions by Exclusion Category Relative to Gross Resource Values of 6,500 GW for Capacity and 28,954 TWh/year for Energy Potential

Gross Resource	6,500 GW		28,954 TWh/year	
Exclusion Type	Capacity Reduction (GW)	(%)	Energy Reduction (TWh/year)	(%)
Wake, Electrical, and Other Losses	N/A	N/A	3,192	11
Water Depth Exclusions	2,509	39	11,329	39
Wind Speed Exclusions	106	2	286	1
Latitude Cutoff	1,459	22	5,925	20
All Above Exclusions	3,526	54	16,867	58

8 Regional Discussion

In Alaska, a total of 10 (out of 11) energy regions line the coast. After applying the latitude filter, 8 of these regions remain in the technical area considered. As previously discussed, the Alaska population is sparsely distributed [1.2 per mi^2 in 2010, U.S. Census Bureau (2016)] but concentrated in regions close to the coast [$\sim$ 84% of the population in 2008 was restricted to coastal counties according to Wilson and Fischetti (2010)]. To put the wind resource assessment analysis conducted in the context of each of these regions, and especially to isolate the most populated Railbelt area, this section presents a breakdown of the results by energy region as they were defined in Section 4.3, and updates the state-by-state comparison presented in Musial et al. (2016).

8.1 Offshore Energy Regions of Alaska

Figure 15 gives gross and technical capacity and energy potential integrated over the offshore regions previously defined, for latitudes below 65.5° N. The largest resource is seen for the Aleutians, despite this region not being considered in its entirety in the analysis due to the limited extent of the simulation domain (see Section 5). The total resource in the Railbelt region appears to be one of the lowest in the state, but that is due to its smaller size compared to the other offshore regions. In fact, while the net capacity factor generally increases with distance from shore, there is an isolated area in the Railbelt offshore region with values comparably large to those found further offshore (higher than 55%, see Figure 16).

Although not evident in Figure 15, all regions present similar energy potential density (technical energy potential divided by energy region technical area, see Table 3) with values between 10 and 13 $(\mathrm{GWh/year})/\mathrm{km}^2$. Even the smallest offshore regions (e.g., Railbelt, Bristol Bay) yield net annual energy potential estimates that exceed the total statewide electricity demand of approximately 6 TWh/year (U.S. EIA 2017c). It can also be seen from Figure 15 that the greatest resource losses in going from gross to technical estimates are found in the Aleutians, Southeast, Copper River Chugach, and Kodiak regions. Much smaller differences are seen for Lower Yukon Kuskokwim, Railbelt, Bristol Bay, and Bering Straits.

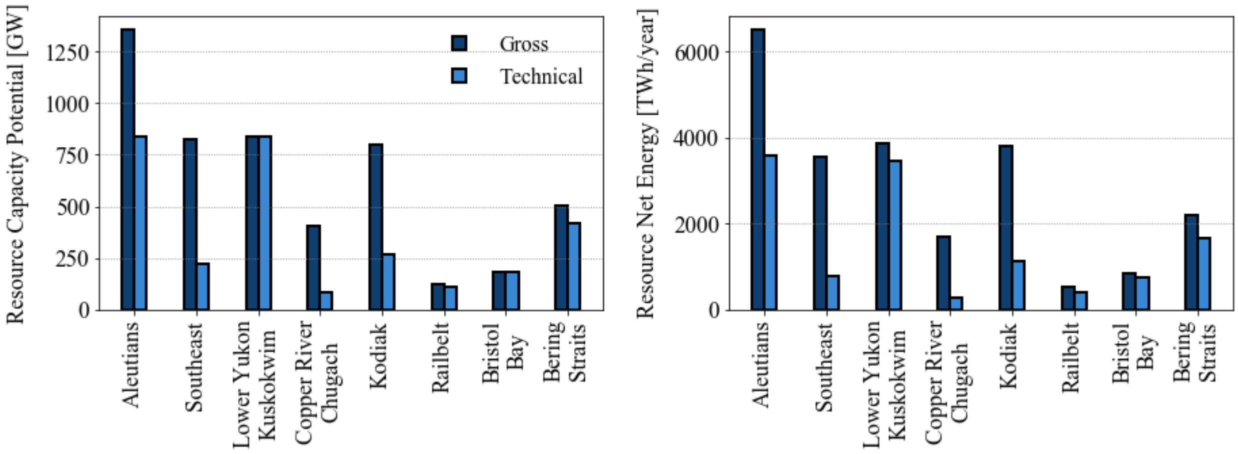

Figure 15. Offshore wind resource capacity (left) and net energy (right) from gross (dark blue) and final net technical (light blue) resource estimates for the eight offshore energy regions of Alaska south of 65.5° N

Figure 17 shows the total energy potential by region and water depth. It reveals that most of the resource potential in the Aleutians is in waters between 60 and 700 m, a depth category that also dominates the resource potential in the Southeast, Copper River Chugach, Kodiak, and Railbelt offshore regions. All regions except Southeast and Copper River Chugach present a considerable resource in shallower waters, with at least 100 TWh/year available in the 0-30 m category.

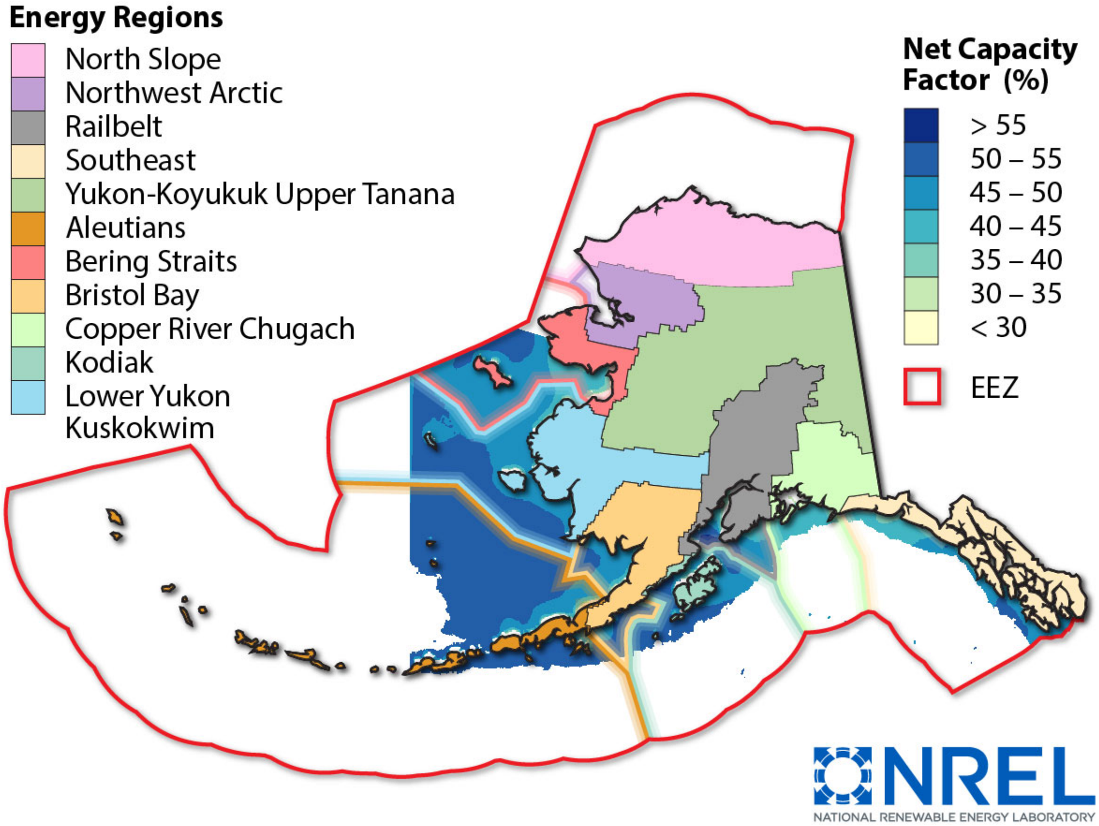

Figure 16. Net capacity factor for technical resource area and outline of the 10 Alaska offshore energy regions

8.2 Alaska and Offshore Regions of the Continental United States

Figure 18 shows offshore wind resource capacity and energy potential obtained with gross and technical estimates for each U.S. region defined in Musial et al. (2016) and for Alaska. Analogous to the analysis presented in Musial et al. (2016), the final values obtained for Alaska and shown in Figure 18 can be put in the context of the Wind Vision study scenario (U.S. DOE 2015), which requires a deployment of 86 GW of offshore wind by 2050. This deployment would require an area $\sim 29,000$ km^2, which represents $\sim 2.9\%$ of Alaska's technical resource area and $\sim 1.3\%$ of its gross resource area. Although each region shown in Figure 18 has the resource supply to contribute substantially to a viable offshore wind industry through deployment to serve its local and regional energy needs, these comparisons between the Alaska net resource and deployment scenarios are made simply to illustrate the magnitude of the estimated resource and do not speculate on actual deployment potential.

8.3 State-by-State Comparisons

With the inclusion of Alaska, the net technical energy resource potential of the United States is increased from 7,203 TWh/year to 19,290 TWh/year. The breakdown of this number per state was given in Musial et al. (2016) and is revisited here as a percentage of the Alaska net energy potential, as shown in Figure 19. Even the State of Massachusetts, which boasts a large offshore wind energy potential, is still substantially lower than the numbers for Alaska: about 6% of the Alaska total below 60 m and 11% for other considered water depths. This analysis further highlights the large amount of resource available in Alaska relative to other sites in the United States, even when only shallow waters are considered.

Table 3. Technical Area, Resource Capacity, and Energy Potential for Each Offshore Region South of 65.5° N and for Areas Within the Simulation Domain

Region	Area (km^2)	Capacity (GW)	Energy Potential (TWh/year)
Aleutians	280,380	841	3,585
Southeast	74,185	223	798
Lower Yukon Kuskokwim	280,548	842	3,466
Copper River Chugach	28,673	86	292
Kodiak	89,689	269	1,119
Railbelt	37,475	112	423
Bristol Bay	61,240	184	742
Bering Straits	139,219	418	1,663

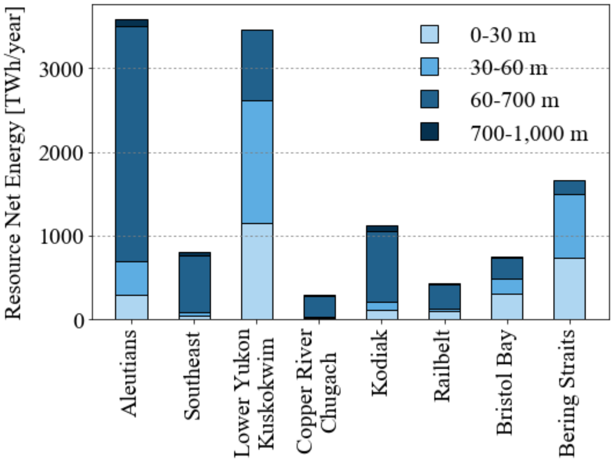

Figure 17. Net energy potential per region (TWh/year) by water depth category

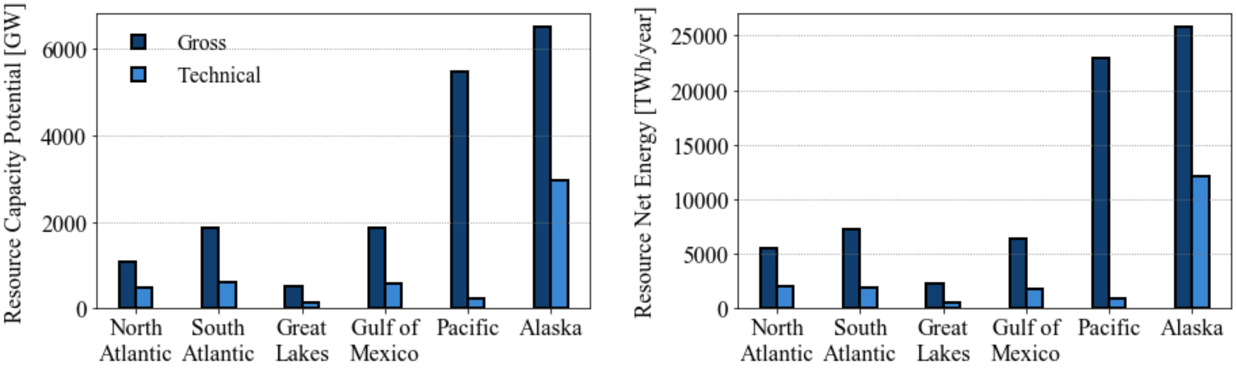

Figure 18. Offshore wind resource capacity (left) and net energy (right) from gross (dark blue) and final net technical (light blue) resource estimates for five U.S. offshore wind resource regions and Alaska

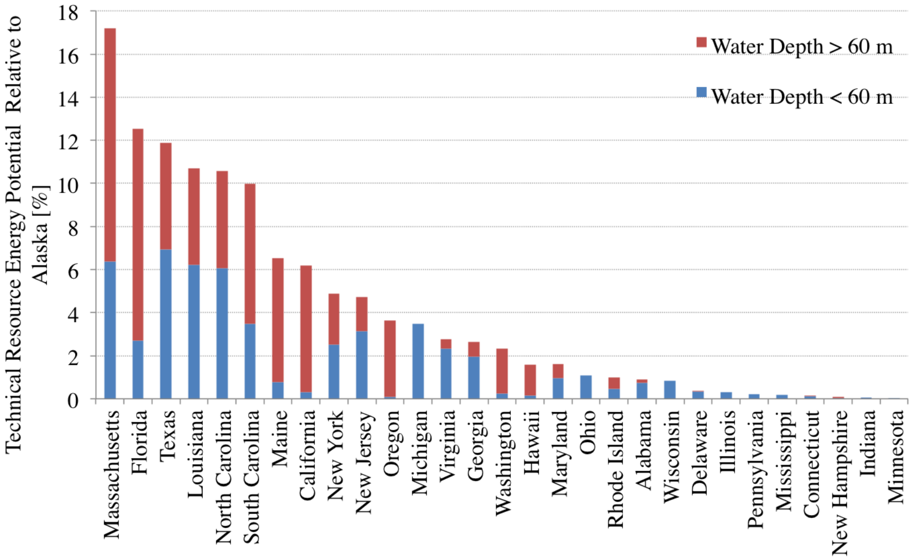

Figure 19. Offshore wind net technical energy potential for U.S. states not including Alaska [7,203 TWh/year, refer to Musial et al. (2016)] given as a percentage of the net technical energy potential for Alaska. Given separately for water depths of less than 60 m (blue) and greater than 60 m (red).

9 Summary and Key Findings

This report was sponsored by the U.S. Department of Energy (DOE) and complements the analysis presented in Musial et al. (2016) for all U.S. states other than Alaska. It marks the completion of the U.S. offshore wind resource assessment effort and is intended to support the joint DOE and Department of Interior offshore wind strategy. It is also intended to serve as supporting reference for any in-depth resource assessment studies for the nation. Moreover, this report constitutes the first offshore wind resource assessment for Alaska because this state was also not included in the original study of Schwartz et al. (2010). All of the methods presented herein are consistent with those employed for the other U.S. states in Musial et al. (2016) to enable a direct comparison between the results obtained for Alaska and those for the rest of the nation.

Throughout the analysis, the offshore wind capacity and energy potential are estimated considering the Alaska gross and technical area. Additionally, wake, electrical, and other miscellaneous energy losses are considered. While the gross analysis makes no reference to currently available technology, the technical analysis restricts the considered area based on mean wind speed at 100 m, bathymetry, and formation of sea ice, leading to technical capacity (technical net energy) values of 2,974 GW (12,087 TWh/year), which are 54% (58%) lower than the starting gross estimates of 6,500 GW (28,954 TWh) . Even after all these filters are applied, the final results indicate a net energy potential for Alaska that is 68% higher than the equivalent value for all other U.S. states combined. The final net energy potential of 12,087 TWh/year is substantially larger than the state's annual consumption of 6.1 TWh/year and three times the total U.S. consumption of approximately 3,711 TWh/year (U.S. EIA 2017c).

Despite identifying a high offshore wind energy potential for Alaska, this report makes no claims regarding the feasibility of offshore wind developments in the state. A brief discussion was presented regarding its energy landscape and electrical grid structure, along with recent trends in the development of traditional and renewable energy sources. While no offshore wind projects currently exist in Alaska, the present analysis has identified an area of high capacity factor with low bathymetry and high wind speed that is relatively close to shore in the Railbelt energy region. Although not as high in resource, future studies may also choose to focus on the south of the southeast region, where a region with relatively high energy potential is also within close proximity to a sizeable energy load (i.e., the "BC Hydro" grid that extends from British Columbia in Canada to southeast Alaska).

At present, near-term offshore development in Alaska might seem unlikely because of the abundant land available for onshore development. However, onshore wind in Alaska also faces challenges such as permafrost thawing and the transportation of heavy equipment to and within rural locations (Petrie et al. 2007; Dilley and Hulse 2007). Given these hurdles and the decreasing trend in offshore wind technology costs, future work should carry out detailed cost analyses to determine whether it is more viable to develop wind power on- or offshore in Alaska.

Finally, the main limitations of the analysis must be considered when interpreting the results presented. Namely, the lack of mean wind speed data for a portion of the Aleutians Arc and the lack of environmental exclusions and conflict use data. Addressing the first would likely increase the net offshore wind energy potential for the state by including low bathymetry, high wind speed zones in the Aleutians energy region. Addressing the second limitation would decrease the net estimates, similar to what was seen for the contiguous United States in Musial et al. (2016).

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