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United States offshore wind energy atlas: availability, potential, and economic insights based on wind speeds at different altitudes and thresholds and policy-informed exclusions

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ABSTRACT

This study presents the first comprehensive offshore United States wind energy atlas at multiple hub heights above 100 m that accounts for technical, climate, environmental, and social exclusions. The study uses Geographic Information System (GIS) mapping and open-source marine planning data. The atlas accounts for wind speed thresholds, bathymetry, ocean conditions, restrictions (including shipping lanes and military zones that can impede wind projects), regulations (including distance requirements from energy infrastructure, safety hazards, and marine protected areas), and modern wind turbine information (including size, spacing, and energy output). The results indicate that 64% of total (61.5% of contiguous) U.S. coastal area is available for offshore wind development, translating to a maximum possible nameplate capacity of 26,800 GW (7,150 GW for the contiguous U.S.). This far exceeds the U.S. 30 GW by 2030 target and projected capacity needs to power all energy sectors in 2050. The regions with the largest available areas at 150 m hub height and a 7 m/s wind speed threshold include Alaska (~1,784,300 km^2), Hawaii (~718,600 km^2), and the Northern California Coast (~127,000 km^2). The U.S. East and Gulf Coasts have ~363,200 km^2 and ~137,800 km^2 available, respectively. This atlas will enable site selection that maximizes energy generation while minimizing interference with other stakeholders, costs, required port infrastructure investments, and new transmission interconnection distances.

Introduction

The United States is undertaking a renewable energy transition in which offshore wind has a significant role to play [1–5]. Since 2014, advancements in wind technology have lowered the levelized cost of energy (LCOE) by more than 50%, moving floating offshore wind towards cost parity with fixed bottom turbine substructures and enabling global deployment of 260 GW by 2030 [6–8]. Given this trend, robust state-level procurement targets, strong federal support, ambitious new initiatives [9], and record-setting lease prices and pipeline expansions, the industry is poised for growth.

Several states, including New York [10,11], New Jersey, Massachusetts [12], and California [13,14], have set ambitious targets for offshore wind development and have taken steps to build the necessary infrastructure and supply chains [15–17]. In the coming years, national leasing plans call for offshore wind energy auctions in the Gulf of Mexico, South Atlantic, Pacific, and the Gulf of Maine. The federal government also plans to address the climate crisis, build new American infrastructure, and transition to a clean energy economy by setting a goal of deploying 30 GW of offshore wind capacity by 2030 [18]. This target is notable because it represents a substantial increase in the pace of offshore wind development in the U.S., establishing the pathway to deploy 110 GW or more by 2050 [18]. If achieved, this target would create tens of thousands of jobs, reduce greenhouse gas emissions, and provide an immense source of clean energy [18–20].

Reaching the 30 GW target will require considerable capital investments in new infrastructure, including wind turbines, transmission lines, and port facilities [21–25]. It will also necessitate coordination across multiple levels of government and the private sector to overcome technical, financial, environmental, and regulatory challenges. Among these, siting can be one of the most complex and time-consuming. However, if these obstacles are overcome with the help of a streamlined siting process that reduces development costs and uncertainty, the U.S. can emerge as a global leader in offshore wind.

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The U.S. offshore wind industry is still in its nascency, with only 42 MW currently deployed between the Block Island Wind Farm and the Coastal Virginia Offshore Wind pilot project [26]. As of 2022, though, the wind energy development pipeline has over 40 GW of potential generating capacity, driven by the Bureau of Ocean Energy Management (BOEM)'s auctions of new lease areas in the Atlantic and California coasts [7,27]. The next step is to determine the optimal placement of wind farms, for which there are several important factors to consider. The first and most consequential is the wind resource, as the wind speeds and wind patterns will determine the energy production of a wind farm. Second, the water depth and ocean floor characteristics must be suitable [28]. Shallow water is often preferred to minimize installation and maintenance costs. The distance from shore also affects the cost of transmission to the electrical grid. Wind farms must be located near existing or planned electrical transmission infrastructure to reduce the cost and technical challenges of connecting to the grid. Furthermore, offshore wind farms should be sited away from shipping lanes, fishing grounds, and protected marine areas. Public acceptance is an important factor [29–32], as local communities can have concerns about the visual impact, noise, and potential impact on fishing, local tourism, recreation, and other activities.

There have been previous efforts to map the offshore wind energy potential and spatial availability across the U.S., taking into account one or more of the factors discussed above. One resulted in an estimated cumulative wind potential of 2,472 GW of fixed-bottom and 2,787 GW of floating capacity [33], and another in 1,500 GW of fixed-bottom and 2,800 GW of floating capacity for the continental U.S. [5]. Despite considering meteorology and bathymetry at very high resolutions, these studies examine exclusions more simplistically than here and neither consider results at multiple hub heights nor cover the entire U.S. Furthermore, in contrast with this study, other studies prescribe strict distance, depth, and wind speed limitations. For instance, some reports use a technically feasible distance of 30 km [34], or 7 m/s wind speed and 50 m (fixed-bottom) and 50–1,000 m (floating) depth cutoff [1,33,35]. Others include areas further from shore (e.g., 200 km [33]), but limit the study area in other artificial ways, or consider outdated turbine hub heights or capacities [1,36,37]. Other groups of studies omit infrastructural and ocean use restrictions altogether [38–43], do not focus on the United States [28,37,44], or focus on only one state or region [40,45–52]. Some reports and guides define best-practices, recommend strategies, list important siting parameters, or analyze trends, but do not necessarily implement this information to elucidate geographically-specific insights or recommendations [3,53–62], or again, focus outside the U.S. [63,64] (although many of these guides helped to inform the choice of relevant exclusions and setback distances, as described in the Methods). Some private software exists that can assist with site assessment, including EMD WindPRO, which generates high-quality mesoscale time series data to plan projects [65], UL Windographer, which is designed for analyzing and visualizing wind resource data [66], UL Openwind, which optimizes wind farm layouts and maximizes LCOE [67], and UL Windnavigator, which is for wind energy site prospecting [68]. However, these consider only wind resources (Windographer, Windnavigator) without other restrictions, rely on user expertise, are not widely accessible, and do not provide insights over larger geographies (i.e., for an entire state or region), as is done here. Certain openly-available software do not include the U.S. [69], or lack offshore wind analysis data [70].

In comparison, this study considers an extensive set of relevant infrastructural, environmental, ocean use, and metocean parameters that inform siting decisions, while presenting an array of different wind energy scenarios that represent rapidly evolving turbine technologies. Importantly, this study includes wind speeds for modern offshore wind turbines up to 250 m above surface level (ASL), in contrast with previous studies that focused on altitudes around or below 100–150 m [1,36–39,48–50]. Offshore wind turbine heights have increased markedly in recent years as technology has improved. Starting from 35 m hub heights in the early 1990s [71], the largest contemporary offshore wind turbines now have hub heights over 150 m and rotor diameters of over 230 m, accompanied by larger nameplate capacities [72–77]. Taller turbines and longer blades capture more energy, as wind velocity increases with altitude and more wind energy is captured with a larger swept area, which improves the overall capacity factor of the wind turbine [78]. The increase in height has also allowed for the development of offshore wind farms further from shore in deeper waters, where wind resources are typically stronger and more consistent [79]. Furthermore, as turbine tip heights reach beyond 200 m and blades become longer, it is increasingly important to account for the vertical profile of atmospheric conditions, instead of focusing on wind speeds at the hub height as a representative estimate [80]. This study uses a 15 MW turbine which will soon come to dominate the market, rather than lower turbine ratings in other studies, such as 6 MW or 10 MW [1,34].

Additionally, the appropriate turbine substructures are examined based on bathymetry and soil characteristics [35,81], similar to the methodology presented in Lopez et al. [82]. However, this study includes more nuanced and varied substructure types in favor of assigning regions with either a fixed-bottom or floating designation. The substructure outputs in this study include monopile, gravity-based, jacket, tripod, semi-submersible, tension-leg buoy, spar, and different combinations thereof in areas where more than one substructure would be suitable, for water depths up to 1,000 m.

Beyond spatially specific resource estimations, the available areas are examined with an economic lens to highlight low-cost locations based on variables that impact the LCOE of offshore wind. Some of the main drivers of LCOE include water depth, wind speed, proximity to onshore grid interconnection, the capacity of transmission infrastructure, the complexity of the wind farm array cabling, and shore-based construction port facilities [34,37,83]. Many of these parameters are weighted and considered in a set of economic heatmaps.

This study aggregates a diversity of policy-informed exclusions and industry-informed siting characteristics. Major output of this study includes maximum available offshore area, nameplate capacity (GW), energy output (TWh), output power density (MW/km^2), and output energy density (TWh/km^2) for fifteen coastal regions over all U.S. coastal waters, with thirteen wind speed thresholds at four hub heights, and with three wake loss scenarios. Some of these metrics are compared with 2050 clean energy targets and 2021 national energy consumption data. The objective of this atlas is to streamline and accelerate the process of wind farm development by creating the first high resolution, country-wide offshore U.S. wind atlas to inform siting decisions.

Methods

All U.S. coastal areas are included in this study, as seen in Fig. 1. These are divided into the following regions: East Coast (Northern East Coast, Mid-Atlantic Coast, North Carolina Coast, Southern East Coast), Gulf Coast (Eastern Gulf Coast, Central Gulf Coast, Western Gulf Coast), West Coast (Washington Coast, Oregon Coast, Northern California Coast, Southern California Coast), Great Lakes, Alaska, Hawaii, and Puerto Rico, for a total of 15 study areas. U.S. federal waters extend to 200 nautical miles (nm) from shore, an area called the Exclusive Economic Zone (EEZ). Wherever possible, the study area extends to the outer boundary of the EEZ, otherwise the outer edge is defined by the outer limit of available wind speed data [84]. An overview of the methodology is provided in Table 1.

Using Geographic Information System (GIS) mapping, regions with other ocean uses or ecological significance, including airports, existing energy infrastructure, aquaculture, disposal areas, highly protected marine and bird areas, military areas, navigation and shipping lanes, reefs, kelp forests, submarine cables, and wrecks [57,64,85], were excluded (see Table S1). Rather than prescribing a minimum or maximum distance from shore to account for social (e.g., visibility) and economic (e.g., costs of installation and maintenance) concerns, this

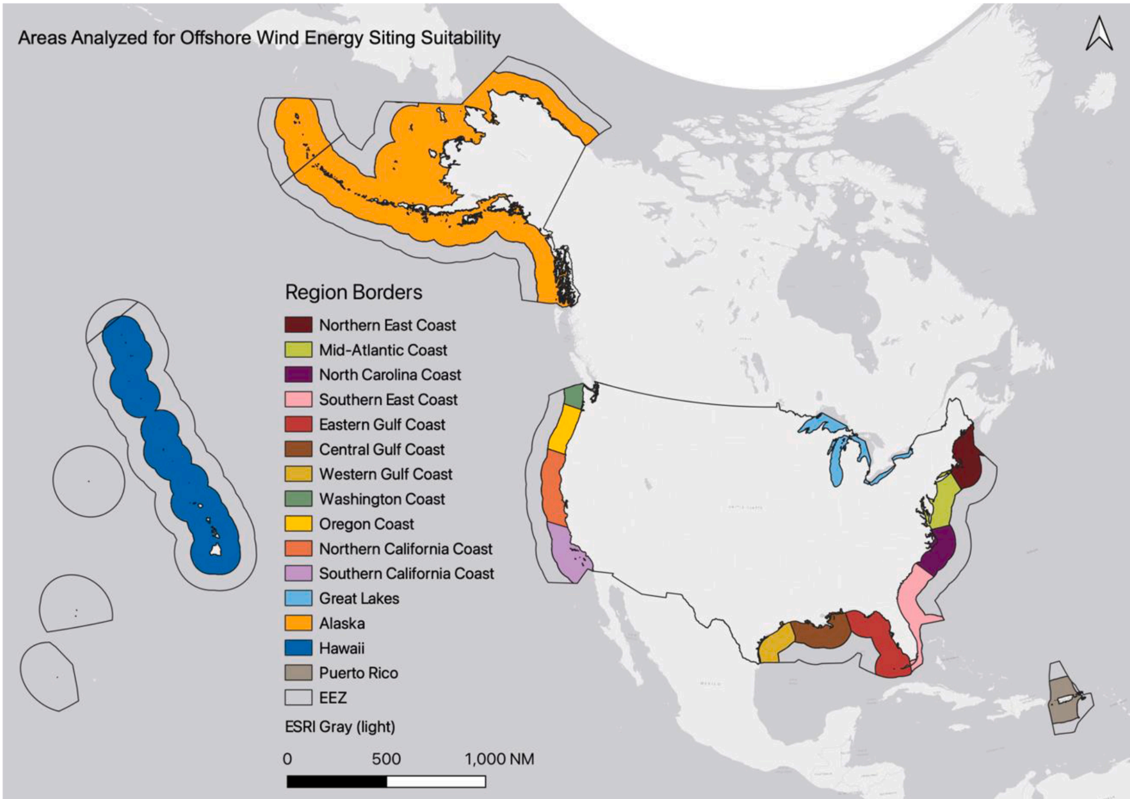

Fig. 1. Areas Analyzed for Offshore Wind Energy Siting Suitability. Map shows all areas included in the study; namely, all U.S. coastal waters, divided into regions.

atlas includes the full possible area and subsequently uses technical, social, environmental, and economic exclusions to restrict available areas to those most feasible for development. Further, no water depth maximum is imposed, as offshore floating technology in the U.S. is still rapidly evolving. However, the depth and seabed conditions are important components in the choice of the turbine foundation [2,26,86–89]. These restriction layers were buffered according to the policy-informed setback values in Table S1. Each layer was then rasterized to facilitate the calculation, following a similar methodology as Enevoldsen et al. [90], which was later refined in von Krauland et al [91].

To calculate the power generation in each study region, wind speed raster layers were obtained from the Global Wind Atlas at three different heights (100 m, 150 m, and 200 m) [84]. The Global Wind Atlas uses downscaled ERA5 multi-year average wind data from 2008 to 2017 to model local climates using WAsP on a 250 m grid [84]. The data was then aligned to the study resolution, 100 m. Since turbine hub height and blade length have increased rapidly in the past decades [75,76], wind speeds at 250 m were derived based on power-curve extrapolation, as seen in Equation S1. This data was validated with hourly-averaged annual data from the Vestas Climate Library, which consists of modeled data validated with in-situ measurements between 2000 and 2022. To analyze the wind power distribution and visualize the results, 13 binary wind speed threshold layers were generated in a range relevant for industry use (6 – 12 m/s with an interval of 0.5 m/s). These layers indicate whether the wind speed in each pixel exceeds the corresponding threshold.

The remaining area was calculated by subtracting each restriction layer and wind speed scenario from the border layer. The amount of available area (Fig. 2, Tables S3 and S4), maximum number of turbines (Table S5), and the average wind speed (Fig. 5, Figs. S5.1-S5.4, Table S8) were computed in all regions for each height and wind speed threshold. These statistics led to the computation of the maximum possible nameplate capacity (GW) (Figure S1.1, Equations S2-3, Tables S6 and S7), output power density (MW/km^2) (Fig. 5, Table S10), output energy and energy density under different wake loss scenarios (TWh/km^2) (Figs. S2.1-S2.2, Tables S11 – S14), and other useful metrics for site selection.

Furthermore, a reference layer was made to inform the appropriate turbine substructure choice throughout each region (Figs. 7-8, Figs. S7.1-S7.7). Following the foundation classification in Vazquez et. al. [81] the most suitable foundation type was evaluated based on bathymetry [92] and sediment data [93]. With this information, it was possible to determine which of the seven foundation types, or twelve total combinations of suitable foundations, would be the optimal choice at each location, which is relevant to port infrastructure requirements, capital expenditure (CapEx), and environmental impact.

To estimate the spatial cost variation for offshore wind projects, an economic parameter was designed that considers the relative costs of the turbine foundation, transmission interconnection, port proximity, and labor. Each of these parameters can have a significant impact on the CapEx of a wind project [94–96]. The proximity to a suitable port influences the transportation and installation costs. The cost of interconnecting the wind farm to the electrical grid depends on the distance to the nearest substation. Labor costs, including the cost of technicians and engineers, vary depending on the location of the wind farm and prevailing wages in the area. The cost of the turbine foundation depends on the water depth, sediment conditions, and foundation characteristics.

The economic parameter was computed from four independent equations for each of the CapEx variables (Equations S5-8), to create one unified equation (Equation S9) that can be used to draw conclusions about economic viability across all regions (Fig. 9, Figs. S8.1-S8.30). The turbine foundation cost was derived as a step function between water depth and foundation cost based on the turbine foundation type with the lowest cost in Bosch et. al. [87]. For substations and ports, the costs of the export cables and transportation, respectively, were similarly

Table 1
Summary of Methodology Component Descriptions and Impact. Each step of the methodology is described and the relevance to providing realistic wind power potential is elucidated. The supplemental information describes each component of the methodology in more detail.

Method Component	Description and Impact
Select Data and Setback Distances	Review of literature and best practices, including hundreds of academic papers and industry reports, review of over 150 databases, and interviews with dozens of experts; More comprehensive exclusion consideration than any U.S. offshore wind atlas
Organize Datasets by Study Region	First atlas to include all U.S. coastal areas (East Coast, Gulf Coast, West Coast, Great Lakes, Alaska, Hawaii, and Puerto Rico); Combine complementary datasets for unique level of detail and high resolution
Buffer Restrictions	Apply policy-informed setbacks to represent realistic siting parameters (more detail in Table S1)
Reproject Layers	North America Albers Equal Area Conic and Hawaii Albers Equal Area Conic reference systems minimize distortions over large study regions, equal area preserves area dimensions
Rasterize Restrictions and Resample	Create uniform 100 m resolution files for all layers with matching extent; Assign value of 1 to all restricted pixels to facilitate subsequent calculation with multiple restriction layers
Sort Wind Speed Data; Convert to Binary Format; Extrapolate to 250 m	Compute wind speed thresholds from 6 to 12 m/s with an interval of 0.5 m/s to determine technical and economic viability of potential sites; Convert to binary format; Extrapolate wind speed data to 250 m to account for climate dynamics affecting modern wind turbines with higher hub heights and longer blades (study encompasses 100 m, 150 m, 200 m, and 250 m altitudes)
Subtract from Border Layers	Merge restriction and wind speed raster layers for all combinations into one layer by subtracting from study boundary rasters
Convert to Binary; Calculate Available Areas	Convert to binary format to distinguish available from unavailable grid cells; Quantify available cells from single layer and mean wind speeds in each region
Calculate Key Metrics	Within available areas, compute maximum possible nameplate capacity (GW) with representative modern offshore wind turbine (V236-15) and realistic spacing density, potential energy output (TWh) with different wake loss scenarios (0%, 5%, 10%, 20%) and unique capacity factor for every region with each altitude and wind threshold, output power density (MW/km^2), and output energy density (TWh/km^2)
Create Turbine Foundation Map	Create map with appropriate turbine foundation type(s) for each available location based on bathymetry and sediment analysis
Create CapEx Heatmap	Economic analysis based on weighted summation of bathymetry, distance to ports and substations, and coastal state relative wage rates to produce heatmap with important CapEx parameters scaled relative to representative reference project

obtained as functions of various distance ranges. These distance layers were generated based on the presence of onshore substations that are less than 5 km from the coast and staging ports with a channel depth over 7.9 m and a shelter parameter of excellent, good, or fair categorization in the World Port Index [88,97]. The overhead limit was also considered as a port parameter, but due to inadequate labelling of the data, this parameter is used only for visualization (Fig. 9). As for the wage parameter, average hourly wages of the coastal states bordering the study region were considered for jobs directly pertinent to offshore wind development and installation (Table S2). The maximum state wage was compared to the average to determine a ratio that describes cost variation. All of these components were normalized based the reference project with a water depth of 34 m, a transmission and port distance of 50 km [98], and an average wage of all coastal states. They were then paired with a corresponding weighting factor [98,99] and summed to determine the relative cost.

Results

Fig. 2 shows an overview of the remaining area in all U.S. offshore regions, with restrictions and low wind speeds below 7 m/s at 150 m height excluded from the available areas. It is apparent that available area ranges from 7.9% off the Eastern Gulf Coast to 88.7% off the coast of Puerto Rico. Overall, 3,556,957.01 km^2, or 63.97% of areas, are available with this wind speed threshold, which translates to an enormous maximum possible nameplate capacity and energy output.

Although all regions have some restricted areas, certain areas are especially restricted due to conflicting ocean uses, protected areas, or low wind speeds. For instance, the coastal areas surrounding many of the smaller northwestern Hawaiian Islands are completely excluded due to their protected status as national wildlife sanctuaries, conservation areas, and other sensitive habitat designations. Similarly, large portions of the West Coast and some segments of the East Coast and Great Lakes are blocked for marine wildlife protection. The Aleutian Islands of Alaska are largely restricted due to shipping regulations that delineate areas to be avoided "to reduce the risk of a marine casualty and resulting pollution and damage to the environment" [100].

The U.S. military accounts for another portion of restricted areas, with presence in nearly all study regions. In the Western and Central Gulf Coast, oil and gas infrastructure, such as pipelines, wells, and platforms, account for most restricted areas. However, most of the restricted areas in the Eastern Gulf Coast and Southern East Coast are dominated by low wind speeds below the 7 m/s threshold. In contrast to the 17,918 km^2 available in this scenario, approximately 135,285 km^2 are available with no wind speed restriction in the Eastern Gulf Coast (see Table S4). Similarly, rather than 73,227 km^2 available for development above 7 m/s mean wind speeds, 113,774 km^2 would be available without considering wind in the Southern East Coast. Because areas with low wind speeds are unlikely to be economical, the more realistic 7 m/s wind speed threshold scenario is shown in Fig. 2 and in Figs. 4-8.

With a higher wind speed threshold, the amount of available area decreases, as shown in Fig. 3, particularly in the southeastern U.S. coastal regions, where wind speeds are not as strong. For instance, at 150 m and with a 9 m/s wind threshold, the average available area is only 29.9%. In this scenario, the Central and Eastern Gulf Coast, Puerto Rico, and the Southern East Coast have no available area for offshore wind, given the low mean wind speeds in these regions. At 150 m and 11 m/s, the average available area diminishes further to 1.71%. With a high wind speed threshold, most regions with the exception of Alaska, Hawaii, Northern California, and the Oregon Coast, which have particularly strong wind resources, will have no unrestricted area.

Fig. 4 reveals how available area is impacted by increasing hub height, ranging from 100 m to 250 m. At higher hub height (200 m) and with a 7 m/s wind speed threshold, the overall area (3,599,648.41 km^2) and percentage (65.32%) available are higher than those at 150 m, respectively, due to stronger average wind speeds at higher altitudes. At 250 m, with a 7 m/s wind threshold, these values are slightly higher still (3,631,052.6 km^2 and 66.3%). Correspondingly, at a lower hub height of 100 m and with a 7 m/s wind threshold, the available area (3,499,531.07 km^2 and 62.13%) is lower. The amount of available area is generally more sensitive to the wind speed threshold rather than the hub height, which is evidenced by the relatively constant (yet slightly increasing) bar heights in Fig. 4, particularly when compared to the sharper changes between threshold values in Fig. 3. However, in some regions, it is clear that there is a significant change in the available area with increasing hub height. Ultimately, the appropriate choice of

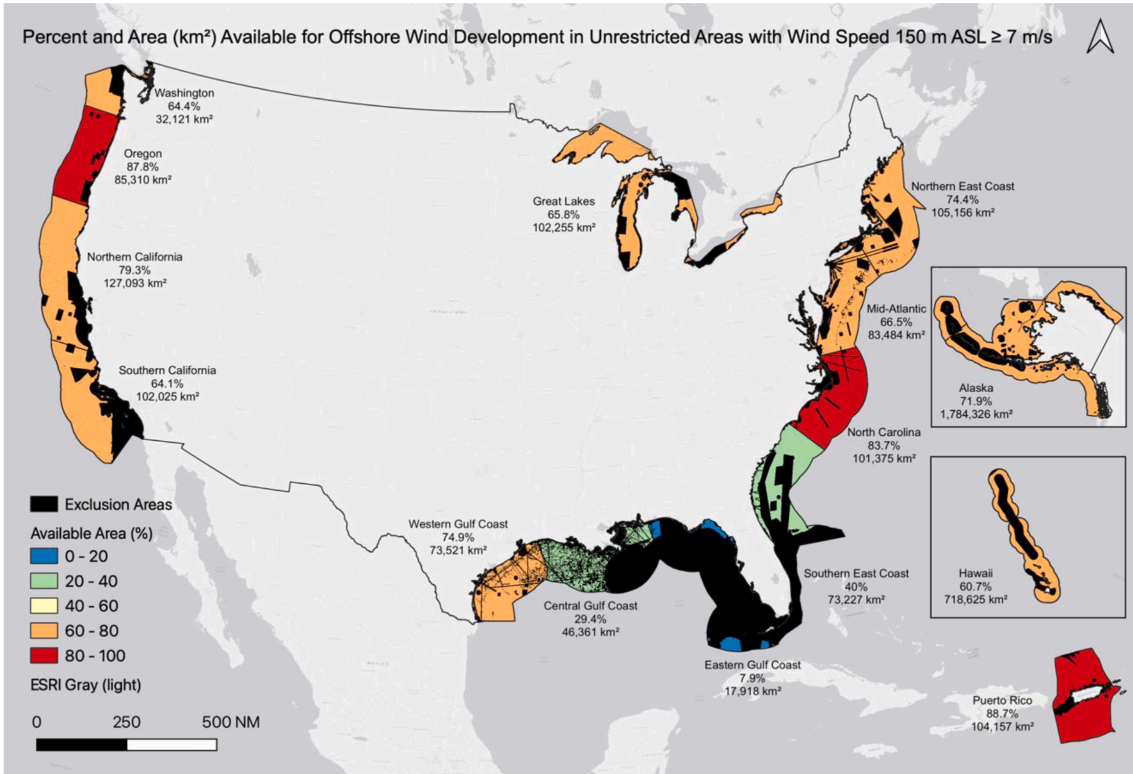

Fig. 2. Percent and Area (km^2) Available for Offshore Wind Development. Map shows the percentage and offshore area available for wind farms after excluding all restrictions in Table S1 and wind speeds below 7 m/s at 150 m ASL. Colors indicate the percentage of available area in each of the fifteen study regions. See Tables S3-4 for all hub height and wind speed threshold combinations.

turned height and location will depend on highly site-specific energy production and subsequent economic tradeoffs, which depends on other criteria explored below.

The potential output power densities in Fig. 5 were calculated by multiplying maximum possible nameplate capacities by the capacity factor in each corresponding region, divided by the remaining area after

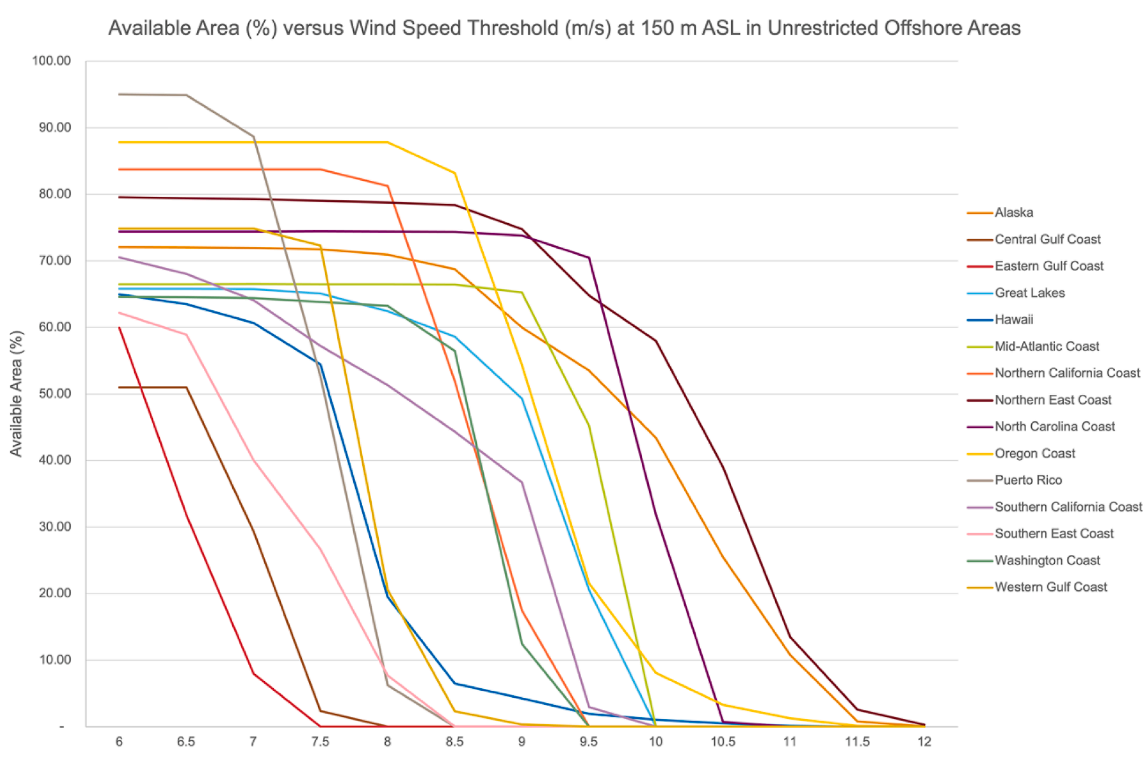

Fig. 3. Available Area (%) versus Wind Speed Threshold (m/s). Graph shows percentage of available area in each region after taking into account all restrictions in Table S1 for each wind speed threshold, from 6 m/s to 12 m/s at 150 m ASL. See Tables S3-4 for all hub height and wind speed threshold combinations.

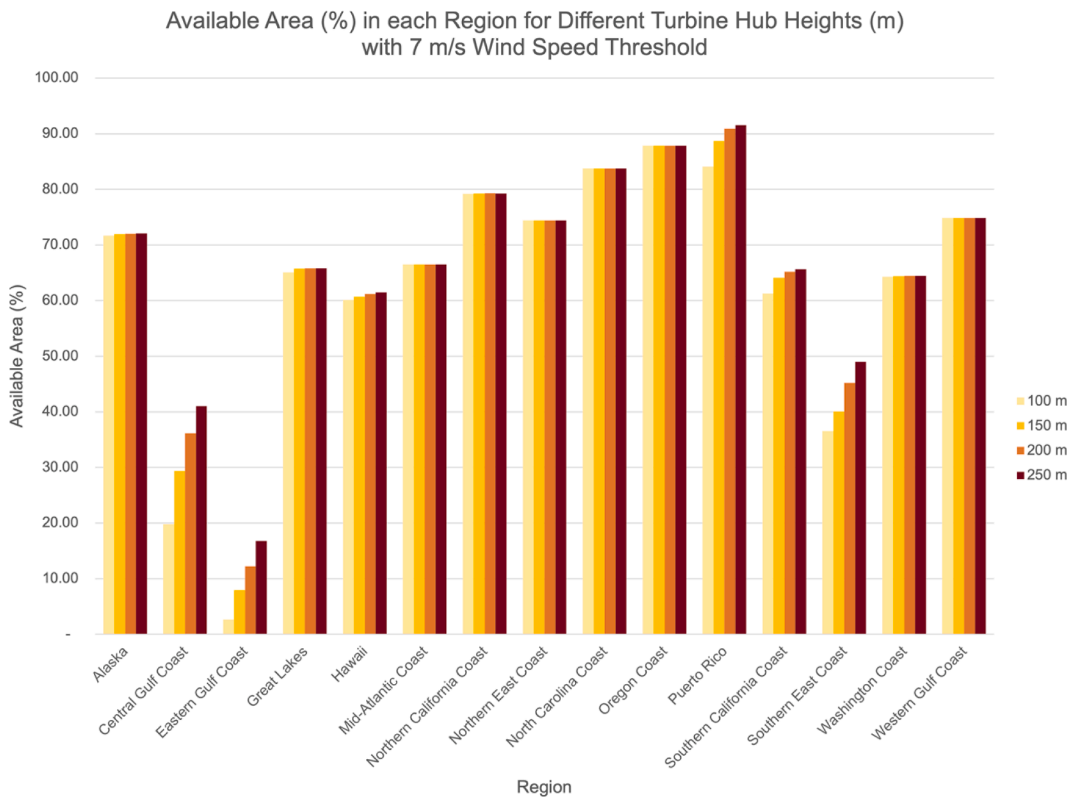

Fig. 4. Available Area (%) in each Region for Different Turbine Hub Heights (m). Height of each bar corresponds to available area (%) in each region at four different altitudes (100 m, 150 m, 200 m, and 250 m ASL), represented with different colors. Values are after accounting for all restrictions in Table S1 with 7 m/s wind speed threshold. See Tables S3-4 for all hub height and wind speed threshold combinations.

accounting for each wind speed threshold. Rather than relying on a uniform capacity factor, the capacity factor for each region (Table S9) was calculated as a function of mean Rayleigh-distributed wind speed, the rated power of the turbine, and the turbine blade diameter [101], as seen in Equation S4.

Regions with the largest mean wind speeds include Northern California and Alaska, followed by the Northern East Coast, the Mid-Atlantic Coast, Oregon Coast, and the Great Lakes. This can be seen in the areas shaded red and dark orange in the map, which have average wind speeds of 10–13 m/s. Portions of Northern California and Oregon relatively close to shore would be of particular interest for wind farm siting, and indeed these areas were among the first to be explored by BOEM for leasing. The lowest wind speeds can be found off the Eastern and Central Gulf Coast and Southern East Coast. Wind speed exclusions block large sections of these regions, as the wind speed falls below the threshold.

Following a similar pattern after normalizing by available area, the highest output power densities can be found off the coast of the Northeast, Northern California, and Alaska, which all have output power densities above 4.5 MW/km^2 in Fig. 5. Compared with the U.S.-wide average output power density of 3.6 MW/km^2 for wind speeds above 7 m/s at 150 m ASL, portions of the West Coast, Northeast, Great Lakes, and Alaska have higher than average power densities. The range of average output power densities across all regions from 100 m to 250 m hub height is 3.5–3.8 MW/km^2. When considering all wind speed thresholds and hub heights, the average output power density is 4.1 MW/km^2.

Also computed is the installed power density, which is found to be 7.5 MW/km^2 across all regions, wind speed thresholds, and hub height scenarios. Those in Europe were found from data to be 7.2 (3.3–20.2) MW/km^2 [102].

Fig. 6 shows the relationship between mean wind speed and increasing hub height across all regions. A similar pattern of mean wind speeds can be detected in each region to varying degrees as the turbine hub height increases due to reduced impact from surface frictional forces. The steepest increase in mean wind speed can be found off the coast of Northern California, followed by Alaska. This aligns with the regions in Fig. 5 that have areas of extremely high wind speeds, and correspondingly high output power densities (MW/km^2). A higher mean wind speed can generally be expected to translate to overall higher power output, which is indeed the case, as seen in Figs. S1.1. However, as wind speed thresholds increase, the amount of available area sharply declines, as discovered in Fig. 3, which actually results in a lower aggregated possible nameplate capacity (GW) for each incrementally increasing wind threshold, ranging from 28,700 GW across all regions in the 6 m/s threshold scenario, to below 1,000 GW in the highest wind speed threshold scenarios, which can be seen in Figure S1.2.

Fig. 7 shows how the choice of turbine foundation is highly dependent on bathymetry and substrate composition, resulting in bands of differently colored regions. The largest portion of available areas has a water depth of greater than 1,000 m, necessitating floating platforms. The next most common designation calls for either semi-submersible or spar technology, which are appropriate for water depths beyond 200 m. Closer to the coast, there is an array of acceptable foundation types, dominated by gravity-based platforms, but also including areas where jacket, tension-leg buoy, and spar platforms would be suitable. Within inland channels, there are almost exclusively monopile and some gravity-based platforms, due to the shallow water depth in these areas. As floating technology develops, technical potential will expand, enabling economic deployment in moderate-quality and deeper water sites [82].

It is apparent where the BOEM lease areas are in relation to available areas and turbine foundation types. The lease areas are close to shore, ranging from approximately 15–100 km off the coast, and in mostly shallow water, which explains why monopile and gravity-based

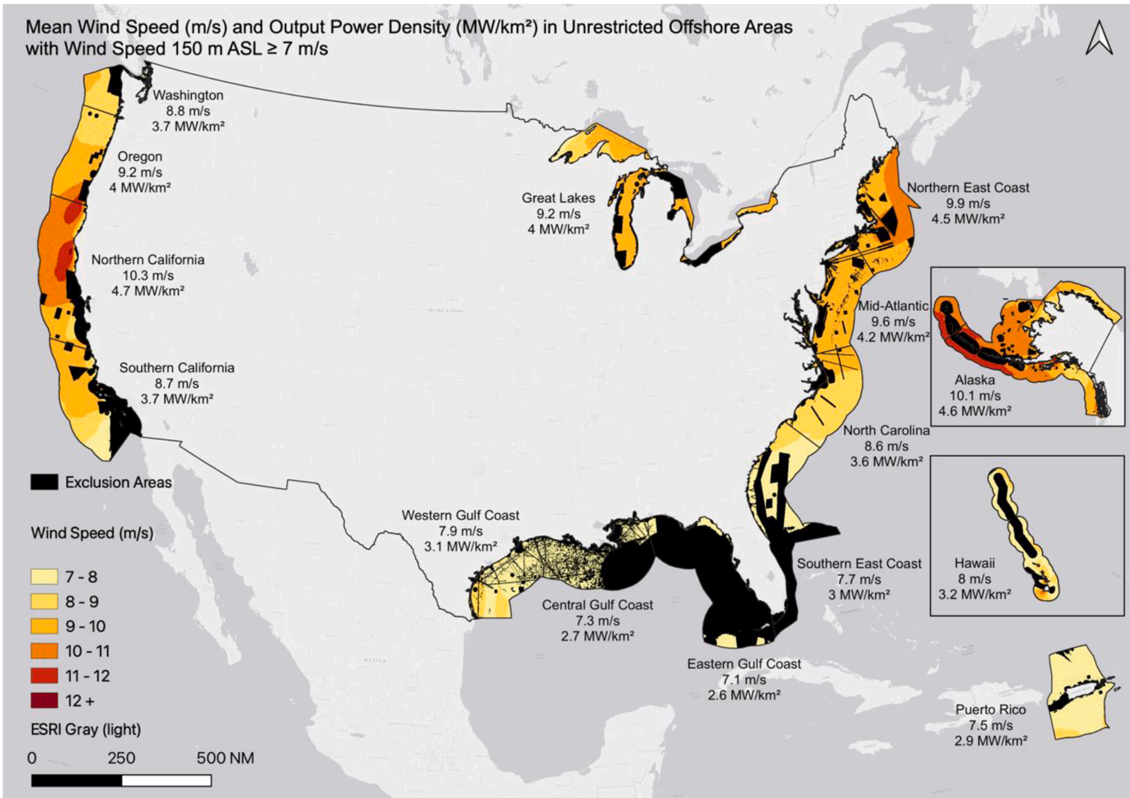

Fig. 5. Mean Wind Speed (m/s) and Output Power Density (MW/km^2). The mean wind speed in each region is shown alongside the output power density (MW/km^2) in all unrestricted offshore areas with wind speed at 150 m ASL $\geq$ 7 m/s. The color scale represents the full range of wind speed values (m/s) in each grid cell. See Figs. S5.1–5.4 and Table S8 for all hub height and wind speed threshold combinations.

substructures will likely be predominant in these areas. With a 7 m/s wind speed threshold, one can observe that BOEM lease boundaries occur outside of exclusion areas, especially for the northeastern projects. The conflict off the coast of New Jersey and Delaware is due to a military-designated area that overlaps partially with the BOEM lease areas, which may be due to a change in military use areas that is yet to be

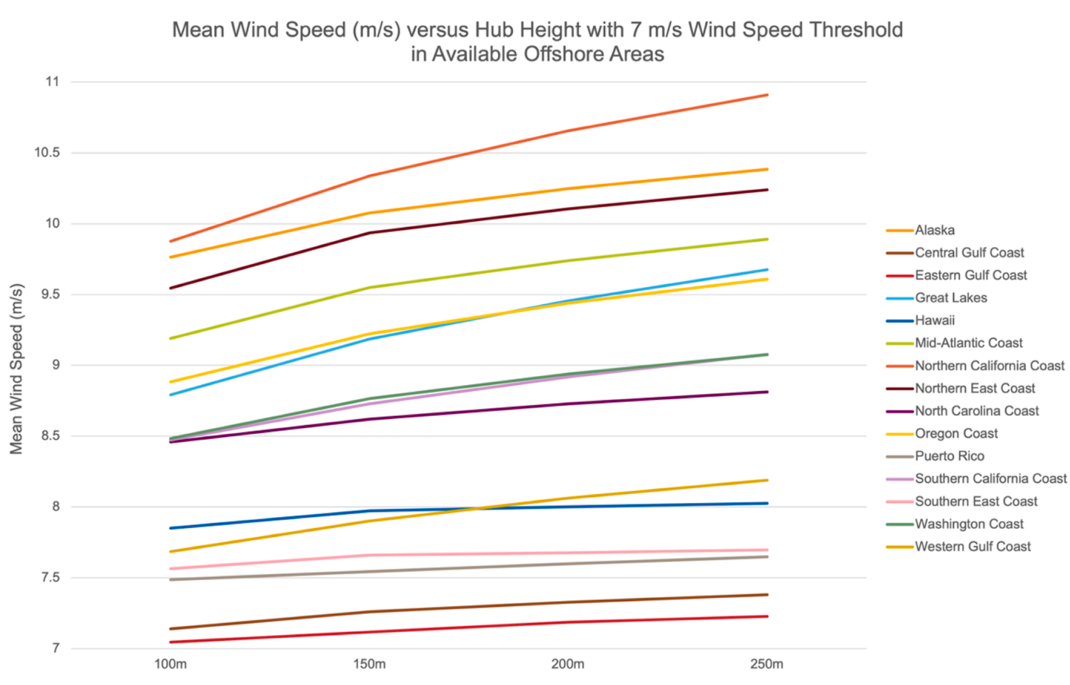

Fig. 6. Mean Wind Speed (m/s) versus Hub Height. Colored lines correspond to mean wind speed (m/s) in available areas with 7 m/s wind speed threshold for each region at four different altitudes (100 m, 150 m, 200 m, and 250 m ASL). See Table S8 for all hub height and wind speed threshold combinations.

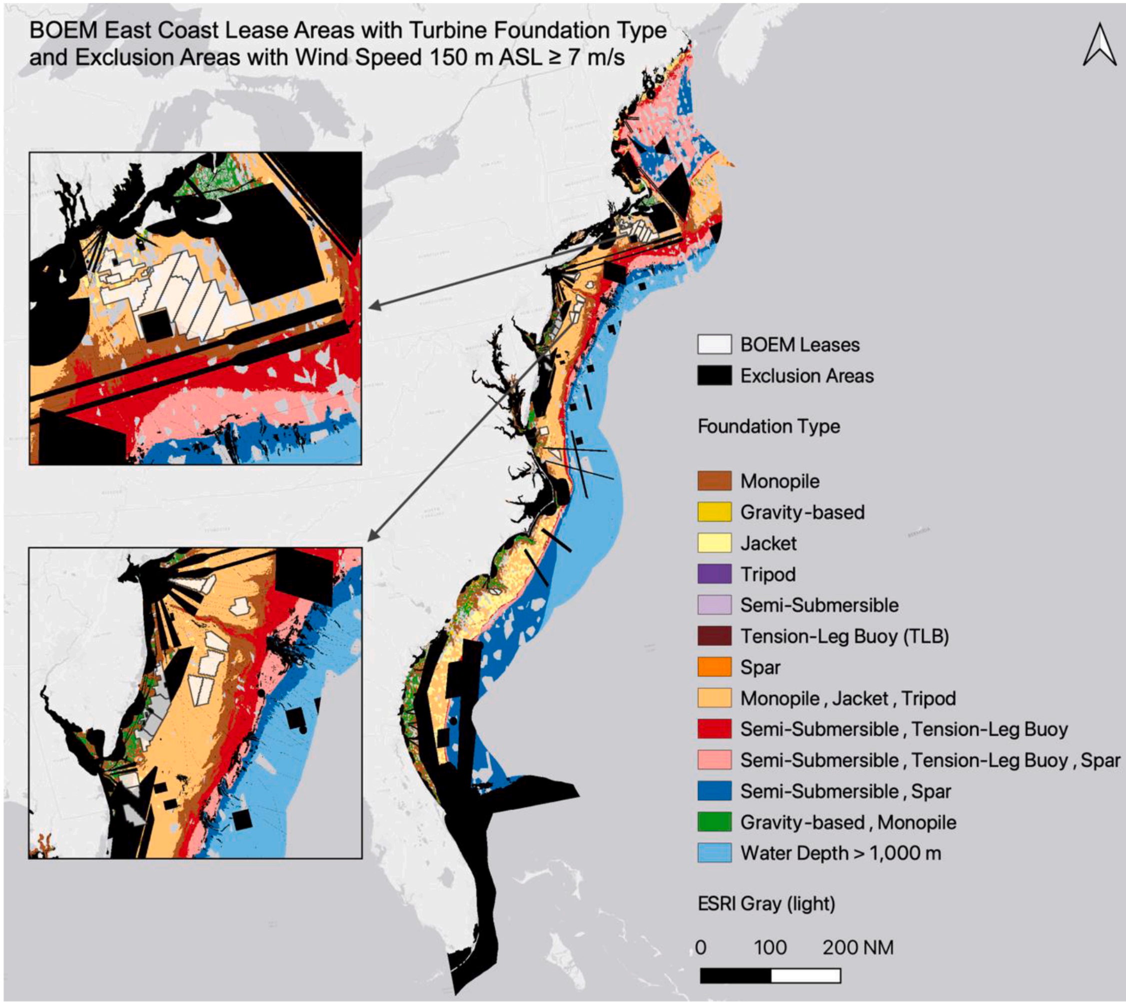

Fig. 7. BOEM East Coast Lease Areas with Turbine Foundation Type and Exclusion Areas. Boundaries of offshore wind energy lease areas [103] (white) in relation to exclusion areas (black) are shown. The remaining area is colored according to the appropriate turbine foundation, determined based on water depth and seabed composition, as detailed in the supplemental information. See Figs. S7.1–7.7 for other regions.

reflected in the latest iteration of publicly available data.

In contrast to the East Coast, Fig. 8 shows how the deeper bathymetry of the West Coast will result in strikingly different substructure technology requirements. Relatively close to shore, in some cases less than 10 km from the coast, it will be difficult to find water depths shallower than 1,000 m.

The BOEM lease areas off the west coast are located the same distance from shore, approximately 30–60 km away. However, the entire lease boundary falls within areas requiring semi-submersible, spar, or other floating platform types, where much of the region is deeper than 1,000 m. One can again see relatively good alignment between areas identified by BOEM and exclusion areas, with an exception in California's central coast where the southeastern portion of the lease area overlaps with part of the Piedras Blancas State Marine protected area offshore of San Luis Obispo County.

Over time, the choice of substructure may change as other factors, such as component costs, installations and maintenance logistics, seafloor geologic conditions, stakeholder ocean use, and permitting evolve with technology and policy [5]. However, these maps provide a reasonable estimation of foundation choice given contemporary conditions and can assist in the selection of the wind farm configuration, which has major implications for wind farm cost, as discussed below.

Fig. 9 provides an overview of the relative cost values in unrestricted areas across the entire United States, along with the locations of ports that could potentially support offshore wind projects. The cost values are based on four important parameters that influence capital expenditure (CapEx): turbine substructure (20%), transmission interconnection (10%), relative wages of coastal states (2.45%), and port to project roundtrip transit distance (0.63%).

The maximum cost value in any region is 9.82 in Alaska, which has a high portion of cost-prohibitive areas. However, given Alaska's small energy demand, this is unlikely to be a barrier in developing sufficient offshore wind capacity to fulfill a substation portion of power demand. Other high-cost regions include Hawaii, Puerto Rico, much of the West Coast, and some parts of the East Coast, due primarily to water depth.

In contrast, the lowest cost values can be found in the Great Lakes, which has a maximum cost value of only 1.41. In fact, the bulk of pixels are below 0.5 in this region, making it the region with the highest frequency of low-cost locations. The East Coast also has large low-cost areas, and indeed, this is where the most new projects are being

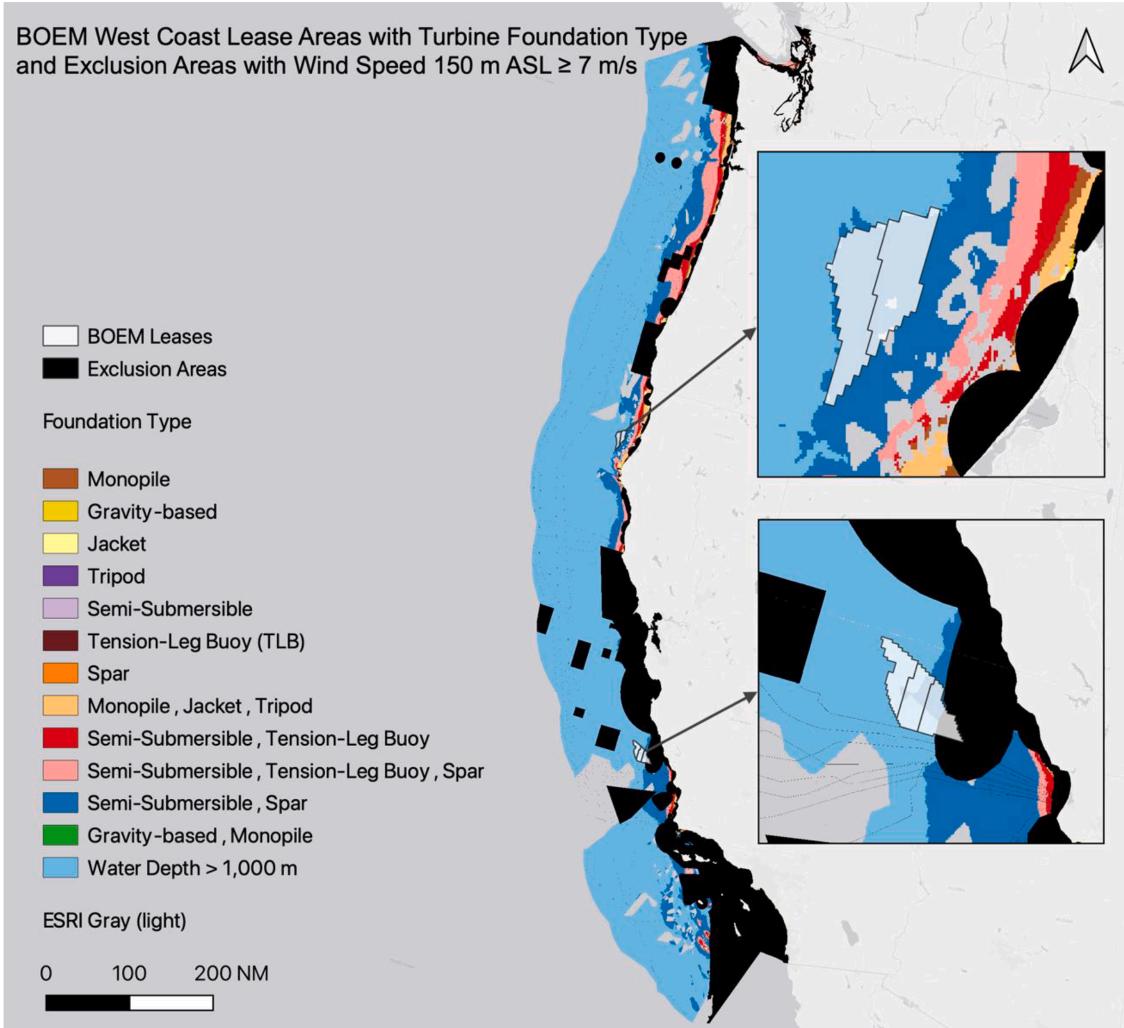

Fig. 8. BOEM West Coast Lease Areas with Turbine Foundation Type and Exclusion Areas. Boundaries of offshore wind energy lease areas [103] (white), in relation to exclusion areas (black) are shown. The remaining area is colored according to the appropriate turbine foundation, determined based on water depth and seabed composition, as detailed in the supplemental information. See Figs. S7.1–7.7 for other regions.

proposed.

Throughout the country, the mean cost value is 2.16. A histogram with all values shows a bimodal distribution where values peak at 1.3 and 3.8. When removing the Great Lakes from the analysis to exclude a high concentration of low-cost values, the mean increases to 2.36.

The availability of port infrastructure with the necessary conditions is a crucial component for offshore wind development, and currently millions of dollars are being invested to make necessary upgrades across all coasts [104–109]. Overlaid on the heatmap are locations of staging ports, which are used for the construction phase of wind projects (as opposed to operational ports post-installation). The channel depth and degree of shelter are two principal factors in targeting viable ports, although many other factors are also important [110,111]. The ports labelled with blue points in Fig. 9 have a channel depth of at least 7.9 m and shelter rating of either "fair," "good," or "excellent" [88]. Additionally, the ports shown in yellow have no overhead limit, which is a necessary characteristic to support semisubmersible technologies and other fully integrated substructures. Across the U.S., there are 227 ports that meet the first two conditions, and, of these, 30 ports that also meet the third. There are several ports scattered across all regions that could potentially meet the needs of offshore wind installation, which will enable the rapid construction of installed capacity.

This heatmap helps to determine where to prioritize siting efforts. Meeting the Biden Administration's target of 30 GW by 2030 would require 11,727 km^2 of coastal area. The lowest-cost available areas are concentrated in the Great Lakes, which alone could meet this target at a cost of less than half the reference project. Alternatively, for a more geographically dispersed approach, a thin stretch of areas along the East and Gulf Coasts could achieve this target at low cost, particularly the southern half of the East Coast and areas off the coast of Texas and the Gulf Coast of Florida. Either of these scenarios in Fig. S9.1-S9.2 would be sufficient to meet the 30 GW target. In addition to considering capital costs, it will also be necessary to account for grid integration challenges, state goals, energy demand, electricity markets, transmission systems, and other interrelated variables that impact the overall project cost.

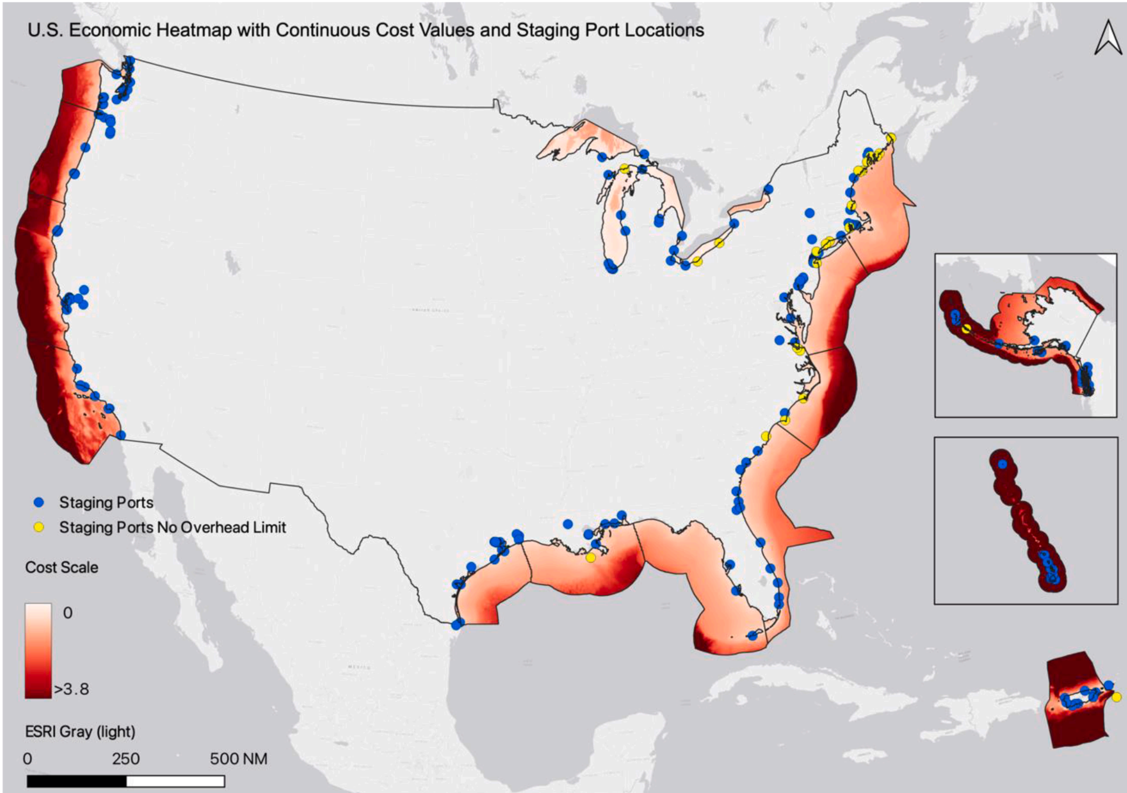

Fig. 9. U.S. Economic Heatmap with Continuous Cost Values and Staging Port Locations. U.S. economic heatmap with uniform continuous color ramp is shown. The unitless cost scale is the cost of a project relative to that of a reference project with a value of 1 (fixed-bottom 2018 baseline LCOE: $83/MWh, 2030 target LCOE: $51/MWh [98]). Staging port locations that have a channel depth of greater than 7.9 m and shelter rating of either "fair," "good," or "excellent" [88] (blue), and staging ports with an additional "no overhead limit" criteria (yellow) are shown. See Figs. S3.1–3.2, S8.1–8.30 for continuous and discrete economic heatmaps of all regions.

Discussion

The emerging offshore wind industry will require substantial planning efforts to meet state and federal deployment targets in a timely, cost-effective, environmentally sustainable, and socially responsible way. Commercial developers and government agencies, particularly BOEM, would benefit from a streamlined wind farm site selection process. Existing BOEM lease areas have already been examined in the context of study results, but this atlas can also be used to expedite the identification of the next set of lease areas.

Beyond site identification, this atlas can answer important questions about the offshore wind capacity necessary to fulfill energy demand in a particular region or grid. For instance, 1,203 15-MW turbines off the coast of Hawaii could provide 9 GW of nameplate capacity, translating to 71.4 TWh, assuming a 7 m/s wind speed threshold at 150 m ASL and 10% wake loss. This is enough to meet 100% of Hawaii's 2021 total energy demand from offshore wind energy alone [112]. In fact, offshore wind can generate up to 252 times as much energy as needed in the state. Hawaii currently relies on imported petroleum for 60% of its electricity generation and has the highest electricity retail price of any state, nearly triple the U.S. average [113]. Strategic placement of offshore wind turbines could present an opportunity to capture high quality wind energy resources without compromising other ocean uses or protected areas, contributing to Hawaii's energy independence while reducing emissions and potentially energy costs. This is also true in other regions, where the enormous offshore wind energy potential can become a significant portion of grid capacity.

It is also possible to make initial estimations of cost feasibility using this atlas, and for the first time these can be made at higher altitudes, up to 250 m. One important question to consider when determining the appropriate turbine hub height is the tradeoff between increased component costs and power output with height. With every 50 m increment in altitude, the turbine tower cost increases 32.8%, on average, with larger cost increments between lower altitudes. However, considering that the tower is only about 1.9% of the total cost of an offshore wind project (including installation, maintenance, operations, and decommissioning) [99], the incremental impact on the project cost is only 0.62% between 50 m hub heights. On the other hand, the maximum possible nameplate capacity increases approximately 4.3% on average between incremental heights. As the annual energy production correlates with revenue, it is worth building taller turbines that capture more energy, which is indeed the trend seen in industry. This atlas can help predict energy output for future turbine scenarios, and enable studies that explore this tradeoff in more depth.

Although most studies conclude that the U.S. has vast offshore wind resources, this study tends to report higher technical potential estimates. This is in part due to the higher hub heights used in this study, as well more inclusive study areas. For instance, Musial et. al. [1] only includes areas less than 1,000 m in depth, arbitrarily limiting the study area. Compared to Lopez et. al. [82], this study uses more conservative setback distances in some instances (e.g., for shipping lanes and existing energy infrastructure), and less conservative distances in other cases, (e.g., submarine cables, excluding state waters, limiting depth to 1,300 m). The proper choice of setback distance is often ambiguous and in flux, particularly as policies may change to accommodate future offshore wind development [114]. Another distinction is the output power density, which is 3 MW/km^2 in most studies [1,82], or 3 MW/km^2 for wind speeds between 7 and 8 m/s and 4 MW/km^2 for wind speeds greater than 8 m/s [33]. Output power densities from European offshore wind farms average 2.9 (1.2–6.3) MW/km^2 [102]. This study uses an average output power density of 3.5–3.8 MW/km^2 with a 7 m/s wind speed threshold at 150 m ASL based on [115], which uses an average factor of 5.98 rotor diameters between turbines. However, with higher hub heights, the power density reaches a maximum of 6 MW/km^2. Installed and output power densities have been historically underestimated due to the inclusion of space outside of wind farm boundaries, space between clusters of turbines, and double counting [102], resulting in lower estimated power output. As a consequence, the results here point toward higher energy projections than previous studies.

In creating an atlas over a large geographical extent, necessary simplifications are made that homogenize the wind farm siting process. In reality, each project is unique and must be considered in the context of its local regulatory, environmental, and social climates. Where feasible, this study includes a range of possible values to represent realistic conditions that developers might face. For instance, wake loss depends on many factors, including wind conditions, turbine size and configuration, and site layout. Similarly, costs will vary based on specific site conditions, prevailing market conditions, and technology used, which may change over time as new practices are adopted and turbines evolve. This study encapsulates several important variables that affect CapEx, but does not capture others, such as the lease price or the turbine cost [98]. Further, the economic heatmap does not yet describe the full nuance and variability in projects costs, such as being able to model the entire range of turbine foundation technology cost functions. The data itself is in part the cause of incomplete modelling, as there is a high degree of uncertainty in some data layers. For example, a large portion of the ports layer has no indication of whether overhead limits are present. Other data, such as military zones, which might include sensitive or secure information, can be imprecise. Finally, policy guidelines are unclear or nonexistent in many cases. For example, it is difficult to ascertain precisely which marine protections apply to offshore wind development, as this was likely not a consideration when many policies were made. This study provides insights to expedite decision making for the first steps in the siting process, but is not meant to replace micro-siting. Using this atlas as a foundation, it would be beneficial to conduct a micro-siting analysis to narrow the selection of suitable areas to prioritize.

The U.S. has the rare opportunity to rethink its aging energy infrastructure and significantly curtail emissions with a new industry that promises to benefit both the economy and the environment. Major federal legislation has already been passed that paves the way for offshore wind development. The Inflation Reduction Act has multiple provisions for offshore wind leasing, transmission interconnections, and tax credits that facilitate planning and investment [116]. The Biden-Harris Action Plan for America's Ports and Waterways will launch programs to modernize ports and enhance supply chains, supporting the deployment of offshore wind turbines [117]. In the future, an expanded analysis with data that enables more detailed criteria for port infrastructure and transmission interconnection requirements can help guide strategic investment decisions.

The critical next step is to transform ambition into action. This study aims to integrate many of the complex components of the wind farm siting process to facilitate decision making for policymakers and developers. Through detailed analyses of exclusion areas, wind speed threshold and wake loss scenarios, and economic cost modelling, it is possible to reduce time in the initial site selection phase of a wind project. Having the capability to plan more strategically will ultimately lower the LCOE of projects, enhance the certainty around long-term target-setting, and accelerate the deployment of offshore wind energy.

Conclusions

In 2023, the United States is far short of meeting climate targets despite a rising penetration of renewable electricity on the grid and a rapidly mobilizing offshore wind industry. By transitioning to 100% clean, renewable energy, the United States has the opportunity to drastically reduce annual energy and social costs, prevent tens of thousands of premature air pollution deaths per year, and create long-term, full-time jobs, while keeping the grid stable [19]. Offshore wind energy is a key component of the transition, given the extensive wind resources along U.S. coastlines and the potential to provide large-scale, reliable, and emissions-free energy. With faster and more consistent winds available offshore, modern offshore wind turbines will be able to power millions of homes throughout the country. Technical feasibility combined with the U.S. target of building 30 GW of offshore wind capacity by 2030 mean that this goal should quickly become a reality. Because state and federal waters are being used for many purposes, such as for fishing and shipping, marine protection, and military activities, maps of available offshore area are needed to facilitate the siting and building of offshore wind farms.

This study aims to provide such maps in an atlas. The U.S. has ~3,557,000 km^2 of available space for offshore wind, equating to 64% of all coastal regions (~949,900 km^2, equivalent to 61.5% of contiguous U.S. regions) when using a 7 m/s wind speed threshold 150 m ASL. The regions with the largest available areas include Alaska (~1,784,300 km^2), Hawaii (~718,600 km^2), and the Northern California Coast (~127,000 km^2). The U.S. East, West, and Gulf Coasts have ~363,200 km^2, ~346,500 km^2, and ~137,800 km^2 available, respectively. In relation to region size, Puerto Rico (88.6%), the Oregon Coast (87.8%), and the North Carolina Coast (83.7%) have the most available area. The cumulative maximum possible nameplate capacity across the U.S. is 26,800 GW (7,150 GW for the contiguous U.S.) with 10% array losses, far exceeding the U.S. 30 GW by 2030 target and projected capacity requirements for all energy uses in 2050. This atlas is the first to present results for 13 wind speed thresholds at four different turbine hub heights. From this analysis, it is clear that technical potential is generally more sensitive to increasing wind speed than hub height, and that regions with low annual wind speeds, such as the Central and Eastern Gulf Coast, Puerto Rico, and the Southern East Coast, experience particularly acute diminishing area with higher wind speed thresholds. Evaluating available areas from an economic lens, this study finds which regions can deploy offshore wind turbines for the lowest capital cost. Prioritizing siting efforts in the Great Lakes, and the East and Gulf Coasts would be the most cost-effective way to deploy 30 GW by 2030 from a capital cost perspective. However, each region has substantial resources and most have opportunities to develop at relatively low costs. Results from this study will help catalyze the U.S. offshore wind industry, ultimately moving the U.S. toward a sustainable energy grid.

CRediT authorship contribution statement

Anna-Katharina von Krauland: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Qirui Long:** Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Peter Enevoldsen:** Conceptualization, Writing – review & editing. **Mark Z. Jacobson:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2023.100410.

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