Capacity Density Considerations for Offshore Wind Plants in the United States

Daniel Mulas Hernando, Walt Musial, Patrick Duffy, and Matt Shields

National Renewable Energy Laboratory

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List of Acronyms

BOEM	Bureau of Ocean Energy Management
COD	commercial operation date
COP	construction and operation plan
CVOW-C	Coastal Virginia Offshore Wind Commercial Plant
DEIS	draft environmental impact statement
GW	gigawatt
km	kilometer
m	meter
MW	megawatt
nm	nautical mile
NREL	National Renewable Energy Laboratory
OCS	Outer Continental Shelf
OREC	offshore renewable energy certificate
PPA	power purchase agreement
SAP	site assessment plan
USCG	United States Coast Guard
WEA	wind energy area

Executive Summary

The United States is a rapidly emerging market for offshore wind energy, with a project pipeline estimated at more than 52 gigawatts as of May 31, 2023 (Musial et al. 2023). The capacity density, measured in megawatts per square kilometer (MW/km^2), is a crucial parameter for estimating the magnitude of the development pipeline and the nameplate potential of existing lease areas. The offshore wind energy industry comprises diverse participants, including developers, governmental bodies, investors, environmental advocacy groups, and researchers. These stakeholders use capacity density in different ways as a key metric for evaluating the potential of individual offshore wind lease areas or even a section of ocean space. This report presents our assessment of capacity density values in the current pipeline of emerging U.S. offshore wind farms and a detailed description of the main factors that influence capacity density. This understanding is critical for planning future lease areas, for estimating the technical resource potential of offshore wind on the U.S. Outer Continental Shelf, and for estimating ocean space requirements needed for meeting state and national goals for a carbon-neutral energy transition.

There is substantial variability in developers' planned capacity density, ranging from 2 to 9 MW/km^2 across the 17 fixed-bottom projects in the U.S. offshore wind energy pipeline that had publicly available array layout information. This variability makes it difficult to assign a single capacity density number for technical resource estimating purposes, but estimates of future offshore wind deployment potential can be improved using the weighted average from this study. Thus, the annual offshore wind market report published by the U.S. Department of Energy has historically adopted a capacity density metric of 3 MW/km^2, but this study conducted by the National Renewable Energy Laboratory's found that the overall weighted-average capacity density for the 17 studied U.S. projects is 4.4 MW/km^2. This average is consistent with data from European offshore wind projects, which range from 4.9 to 5.9 MW/km^2 (Borrmann et al. 2018; Müller et al. 2017; Hundleby and Freeman 2017). Based on these findings, the assumed capacity density used to assess the U.S. offshore wind pipeline in the *Offshore Wind Market Report: 2023 Edition* was raised to 4 MW/km^2 (Musial et al. 2023). Although this is 10% less than the U.S. weighted average, it affords a more realistic forecast of the future leased offshore wind development potential in the United States.

As this study shows, higher capacity densities in offshore wind projects may be planned by developers for better return on their lease sale investments. This financial benefit for developers also reduces offshore wind's required Outer Continental Shelf space to meet federal and state deployment goals and potential conflict with other ocean uses such as shipping and commercial fishing. However, higher capacity densities come with technical challenges, such as increased wake losses, higher structural loads, and greater potential for conflicts within the lease area involving stakeholders such as fisheries or environmental advocacy groups.

This report also addresses the capacity density implications of the U.S. Coast Guard (USCG) turbine spacing recommendation of 1 nautical mile (nm) in a rectilinear grid for all projects under development in the Massachusetts and Rhode Island wind energy areas. The USCG recommendation yields a noticeable decrease in the weighted-average capacity density for these states, as shown in Figure ES-1.

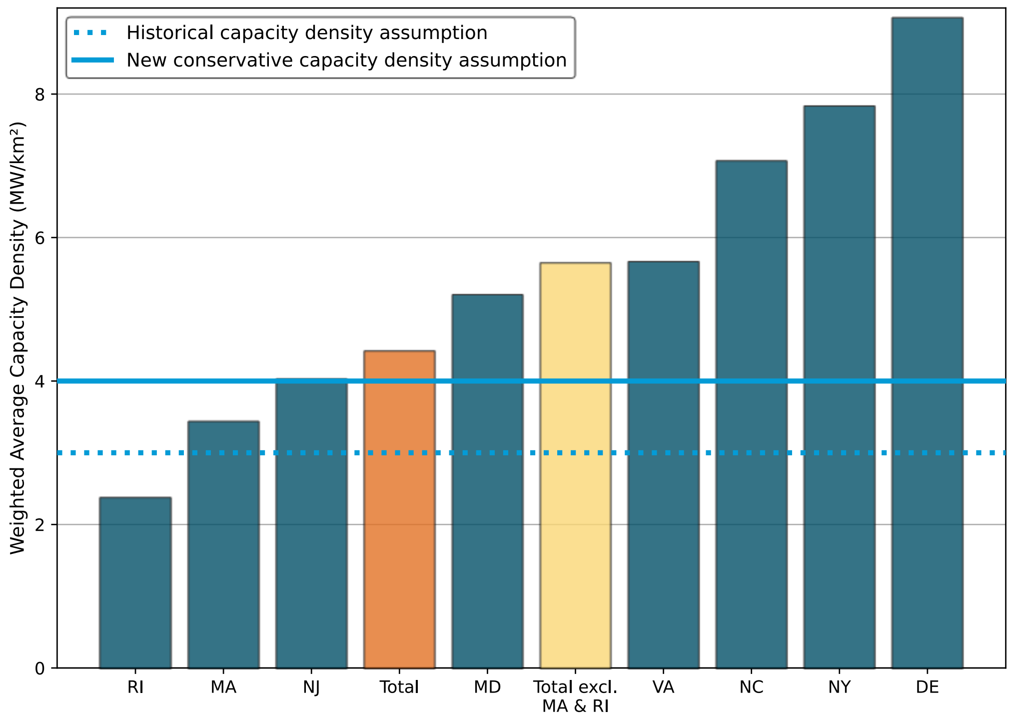

Figure ES-1. Weighted average capacity density by state.

RI = Rhode Island; MA = Massachusetts; NJ = New Jersey; MD = Maryland; VA = Virginia; NC = North Carolina; NY = New York; DE = Delaware

This report describes the uncertainties and variability associated with offshore wind plant capacity density planning by project developers. While precise predictions are challenging, this report provides valuable insights into the factors influencing capacity density, as shown in Table ES-1.

Table ES-1. Main Factors That Influence Capacity Density

Influencing Factor Category	Influencing Factors
Physical project design drivers	• Turbine spacing • Turbine generator rating • Adjacent wind farms
Area utilization	• Unfeasible turbine positions • Area lost from anchor placement in floating systems • Lease area geometry • Stakeholder considerations
Economic and policy factors	• Offtake agreements • Prescribed turbine spacing • Lease area prices • State renewable energy policy

Continued research, such as updating project databases as additional fixed-bottom projects undergo environmental review, and a deeper investigation of influencing factors for floating projects will further improve the ability of states and the nation to realistically assess offshore wind's potential to meet clean energy targets and to refine the supply chain needed to deliver the U.S. offshore wind pipeline.

Table of Contents

List of Figures

List of Tables

1 Introduction

The United States is one of the fastest growing markets for offshore wind energy. While operating offshore wind capacity in the United States totals only 42 megawatts (MW) of the more than 50 gigawatts (GW) deployed globally, the National Renewable Energy Laboratory (NREL) estimates the U.S. project pipeline at more than 52 GW as of May 31, 2023 (Musial et al. 2023). This offshore wind project pipeline is categorized by seven stages of development, including planning, site control, permitting, approval, financial close, under construction, and operation. The capacity density is an important parameter in calculating the magnitude of the development pipeline; it measures the concentration of wind energy generation within a given lease area, specified in terms of megawatts per square kilometer (MW/km^2). For wind energy areas (WEAs) and lease areas under site control earlier in the development process, NREL and the Bureau of Ocean Energy Management (BOEM) have historically estimated lease area capacity potential before project details are known based on the developable area using an assumed capacity density of 3 MW/km^2 (Musial et al. 2013; 2016; 2022). However, empirical data show capacity densities for operating European offshore wind projects range from 2 to 19 MW/km^2 with 90% of the projects expecting to range between 4.9 and 5.9 MW/km^2 (Borrmann et al. 2018; Müller et al. 2017; Hundleby and Freeman 2017). Our research reexamined the turbine spacing layouts of actual emerging projects in the United States to evaluate if 3 MW/km^2 might be overly cautious as a metric for offshore wind deployment estimation.

Higher capacity densities can have advantages and disadvantages with respect to project cost and energy production. Higher capacity densities can more efficiently utilize the available oceanic space. Furthermore, the concentration of turbines within a smaller area may result in a reduced footprint, that could potentially mitigate some cumulative impacts on marine ecosystems with fewer disruptions to marine traffic. On the other hand, higher capacity density may introduce technical complexities such as higher turbine wake effects and higher structural loads. Denser turbine arrangements may also amplify navigational hazards within the wind farm, and cause heightened concerns related to visual impacts and fisheries. In general, the implications of higher capacity densities in offshore wind projects contain a spectrum of impacts encompassing economic, technical, environmental, and social considerations. Each project must evaluate and balance these factors in its planning and execution.

The more precise we can be in estimating the capacity density of the current and future U.S. offshore wind pipeline, the more accurate we can be in estimating future ocean space requirements, and the potential for offshore wind energy to contribute to the future energy supply. This understanding is crucial for the estimation of the potential offshore wind energy requirements, but is also critical in determining project feasibility and estimating total renewable energy resource requirements. A better understanding of capacity density can also help estimate the needs for supply chain, port infrastructure, and workforce, which can help lower project development risk.

In this report, we explore capacity density values in the emerging U.S. offshore wind farms to better understand the project pipeline in the context of the national offshore wind target of deploying 30 GW by 2030. This report provides information on the variability and average capacity density values in the emerging U.S. offshore wind projects, which are affected by multiple key factors. As such, the current research shows that capacity density cannot be easily predicted for a given project and that no clear trend exists that would enable the capacity density of future individual wind projects to be estimated more accurately. Therefore, the primary objective of this report is to provide insights into the numerous factors that influence capacity density.

2 Methodology and Data Collection

The capacity density of an offshore wind farm is defined as the ratio of the project capacity in megawatts (MW) to its area in square kilometers (km^2), as shown in Eq. 1. The typical capacity density values are expressed in MW/km^2.

$$\text{Capacity Density} = \frac{\text{Project Capacity}}{\text{Area}} \tag{1}$$

To improve our quantitative estimates of the project pipeline, we calculate the capacity density values for all the proposed U.S. offshore wind farms with the available data. We collected the project capacities and the areas of each of the emerging U.S. offshore wind projects from published draft environmental impact statements (DEISs), construction and operation plans (COPs), site assessment plans (SAPs), and press releases. Some of the DEISs, COPs, and SAPs published by BOEM specify the wind development area, which is the specific space in the lease area in which the deployment takes place. When that is the case, we use the wind development area instead of the lease area to better assess nameplate capacity in megawatts that are planned for a specific area. We do not include pilot projects (e.g., the two Coastal Virginia Offshore Wind research turbines and the Block Island Wind Farm) in this assessment, as their capacity density is not representative of a full-sized commercial array. The projects are sorted based on BOEM's state leasing activities to identify any administrative or physical factors associated with a particular state or region that affect capacity density.

The data used for the analysis is extracted from the most updated version (as of May 2023) of the NREL database used for the *Offshore Wind Market Report: 2023 Edition* (Musial et al. 2023). All the COPs follow a project design envelope approach, where a wide range of turbine ratings, turbine positions, and rotor diameters may be considered for the final wind farm design. This approach gives some flexibility to developers to provide different alternative actions (wind farm designs) depending on the different types of stakeholder concerns they may encounter. The project capacity may vary depending on the selected alternative action, which means that the capacity density values shown in this report are subject to change as projects get closer to the construction stage. We can anticipate that the project capacities considered for this assessment may have to be adjusted over time as the respective National Environmental Policy Act processes and BOEM reviews progress to final stages. The data used for the capacity density analysis carried out in this report are shown in Table 1. The table is accompanied by a series of explanatory footnotes.

Throughout this report, we calculate area-weighted average capacity density values for different subgroups of the data collected (like state, developer, and commercial operation date [COD] year). The area-weighted average value for a particular subgroup is computed by adding together the capacities of all the projects within that subgroup and then dividing the sum by the total lease area covered by the same subgroup.

Table 1. U.S. Large-Scale Offshore Wind Energy Projects Data

Project	Lease Area Name	State	Area (km^2)	Project Capacity (MW)	Capacity Density (MW/km^2)	Project(s) Name(s)	Commercial Operation Date (COD)	Main Developers	Lease Area Price (2022$ MM)
Revolution Wind	OCS-A 0486	MA/RI	335	704	2.10	Revolution Wind	2026	Ørsted & Eversource	1.63
South Fork Wind	OCS-A 0517	MA/RI	55	132	2.40	South Fork Wind	2024	Ørsted & Eversource	0.27
Sunrise Wind 1	OCS-A 0487	MA/RI	351	924	2.63	Sunrise Wind 1	2026	Ørsted & Eversource	1.90
Bay State Wind	OCS-A 0500	MA	759	2,000	2.64	Bay State Wind	to be determined (TBD)	Ørsted	0.34
Vineyard Wind 1	OCS-A 0501	MA	264	800	3.03	Vineyard Wind 1	2024	Avangrid	0.07
Ocean Wind 2	OCS-A 0532	NJ	344	1,148	3.34	Ocean Wind 2	2028	Ørsted	0.56
Ocean Wind 1	OCS-A 0498	NJ	306	1,100	3.59	Ocean Wind 1	2025	Ørsted	0.50
SouthCoast Wind	OCS-A 0521	MA	516	2,004	3.88	SouthCoast Wind 1, SouthCoast Wind 2, Residual	2028, 2029, TBD	Shell	154.56
Beacon Wind	OCS-A 0520	MA	521	2,430	4.66	Beacon Wind 1, Residual	2029, TBD	Equinor Wind US & BP	154.56
New England	OCS-A 0534	MA	411	2,036	4.95	Park City Wind, Commonwealth Wind	2027	Avangrid	0.11
US Wind	OCS-A 0490	MD	323	1,678	5.20	MarWin, Momentum Wind, Future Development	2025, 2028, TBD	US Wind	10.55
Atlantic Shores South 1	OCS-A 0499	NJ	284	1,510	5.32	Atlantic Shores South 1	2027	Shell	1.21
Coastal Virginia Offshore Wind Commercial Plant (CVOW-C)	OCS-A 0483	VA	456	2,587	5.67	CVOW-C	2026	Dominion Energy	1.97
Kitty Hawk	OCS-A 0508	NC	495	3,500	7.07	Kitty Hawk North 1, Kitty Hawk North 2, Kitty Hawk North 3	TBD	Avangrid	10.59
Empire Wind 1	OCS-A 0512	NY	110	816	7.42	Empire Wind 1	2026	Equinor Wind US & BP	20.12
Empire Wind 2	OCS-A 0512	NY	155	1,260	8.13	Empire Wind 2	2027	Equinor Wind US & BP	28.49
Skipjack	OCS-A 0519	DE	107	966	9.03	Skipjack 1, Skipjack 2	2026, 2027	Ørsted	-

Notes: Pilot projects are not included in this assessment. We select the wind development area stated in the COP/DEIS/SAP for Sunrise Wind 1, Empire Wind 1, and Empire Wind 2. Under a conservative approach, we select the project 1 area plus the project 1 and 2 overlap area available for use for Atlantic Shores South 1. For the lease areas that were partitioned into separated lease areas after being auctioned, we distribute the original lease area price proportionally to the area (km^2) of each of the new partitioned areas.
MA = Massachusetts; RI = Rhode Island; NJ = New Jersey; MD = Maryland; VA = Virginia; NC = North Carolina; NY = New York; DE = Delaware

3 Results of U.S. Capacity Density Assessment

Multiple offshore wind projects on the East Coast are set to be constructed in the next decade (Musial et al. 2023). In the next figures, we show the relationships between distinguishing project parameters (area, project capacity, and lease price) and the capacity density value of the emerging U.S. offshore wind projects. The relationship between the project area and its capacity density by state and by developer is shown in Figure 1 and Figure 2, respectively.

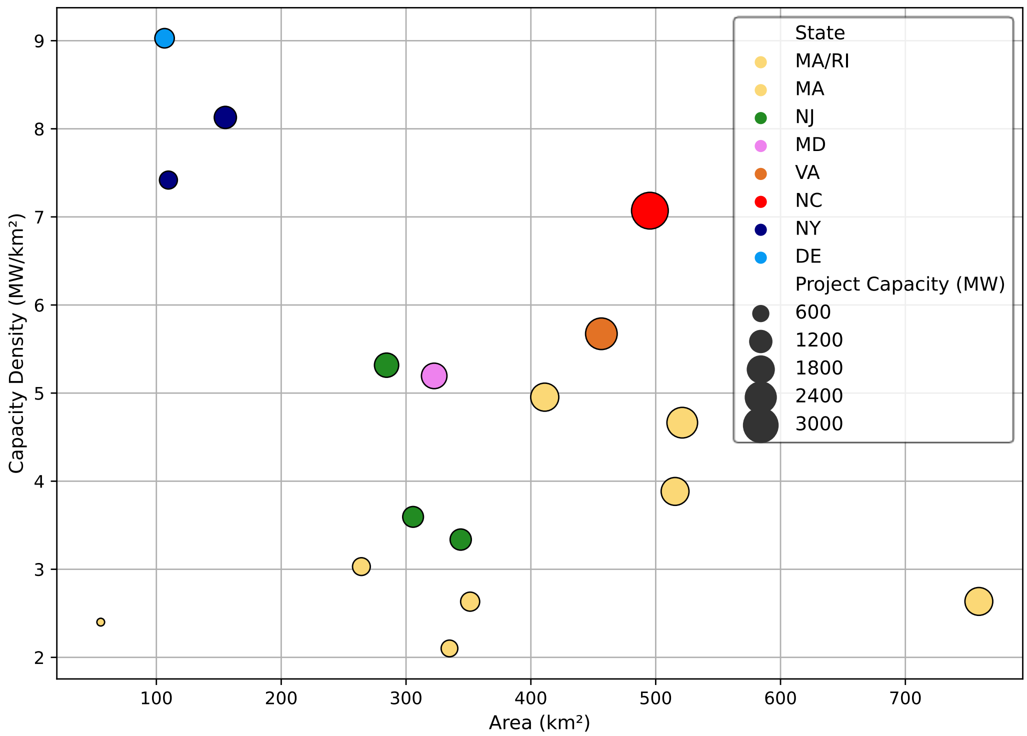

Figure 1. U.S. offshore wind energy project areas and capacity density values by state

Only 4 out of the 17 project phases shown in Figure 1 and Figure 2 are below the legacy 3 MW/km^2 capacity density metric. These four projects are located in the Massachusetts and Rhode Island WEAs. In these WEAs, the USCG recommended a uniform 1 × 1-nautical-mile (nm) grid pattern for navigation safety reasons, which was agreed to by the states and lease holders (USCG, DHS 2020). Three out of those four projects—Revolution Wind, South Fork Wind, and Sunrise Wind 1—have a turbine supply agreement for 11-MW turbine models (Marine Cadastre 2023; Revolution Wind 2023). Under the interpretation of having one turbine per 1 nm^2 and using an 11-MW turbine, the capacity density would be 3.2 MW/km^2. This means that projects with capacity densities less than 3 MW/km^2 may have other capacity density influencing factors driving down the capacity density. Capacity density drivers are described in detail in Section 3.2.

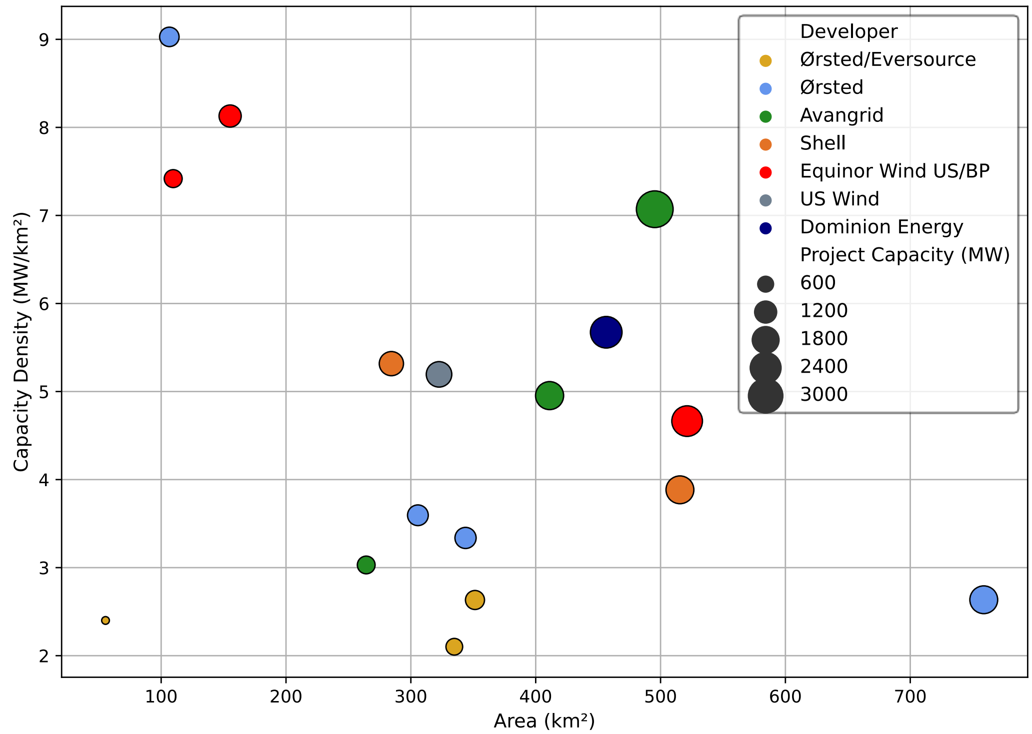

Figure 2. U.S. offshore wind energy project areas and capacity density values by developer

Many projects under development in other states have chosen grid patterns in their proposed layouts that position the turbines closer to each other, as shown in Table 2. Table 2 shows the grid pattern of those U.S. projects that have a published DEIS, COP, or SAP indicating their turbine spacing.

Table 2. Identified Turbine Spacing of the Emerging U.S. Offshore Wind Projects

Project	Lease Area	State	Turbine spacing (nm)
New England	OCS-A 0534	MA	1 x 1
Bay State Wind	OCS-A 0500	MA	1 x 1
SouthCoast Wind	OCS-A 0521	MA	1 x 1
Vineyard Wind 1	OCS-A 0501	MA	1 x 1
Beacon Wind	OCS-A 0520	MA	1 x 1
South Fork Wind	OCS-A 0517	RI/MA	1 x 1
Sunrise Wind 1	OCS-A 0487	RI/MA	1 x 1
Revolution Wind	OCS-A 0486	RI/MA	1 x 1
US Wind	OCS-A 0490	MD	0.77 x 1.02
Kitty Hawk	OCS-A 0508	NC	0.76 x 1.19
Atlantic Shores South	OCS-A 0499	NJ	1 x 0.6
Ocean Wind 1	OCS-A 0498	NJ	1 x 0.8
Empire Wind 1	OCS-A 0512	NY	0.71 x 0.71
Empire Wind 2	OCS-A 0512	NY	0.71 x 0.71
CVOW-C	OCS-A 0483	VA	0.75 x 0.93

In Figure 3 and Figure 4, we plot the capacity density as a function of the lease area price by state and by developer, respectively. Skipjack does not have a public lease area price in our database, so it is not included in the following figures. Note that the y-axis of these figures is in a logarithmic scale to enable us to illustrate the cost escalation that occurred from 2015 to the present day. By inspection, when we exclude the projects conforming to the USCG recommendations for 1 × 1-nm turbine layouts—specifically, the yellow symbols in Figure 3 representing the Massachusetts and Rhode Island lease areas—it becomes evident that the capacity density generally rises as the lease price increases. However, it may be worth noting that the MA and MA/RI lease areas also exhibit an upward trend in capacity density as lease prices increase, although to a lesser extent, due to their adoption of the 1 × 1-nm spacing recommendations.

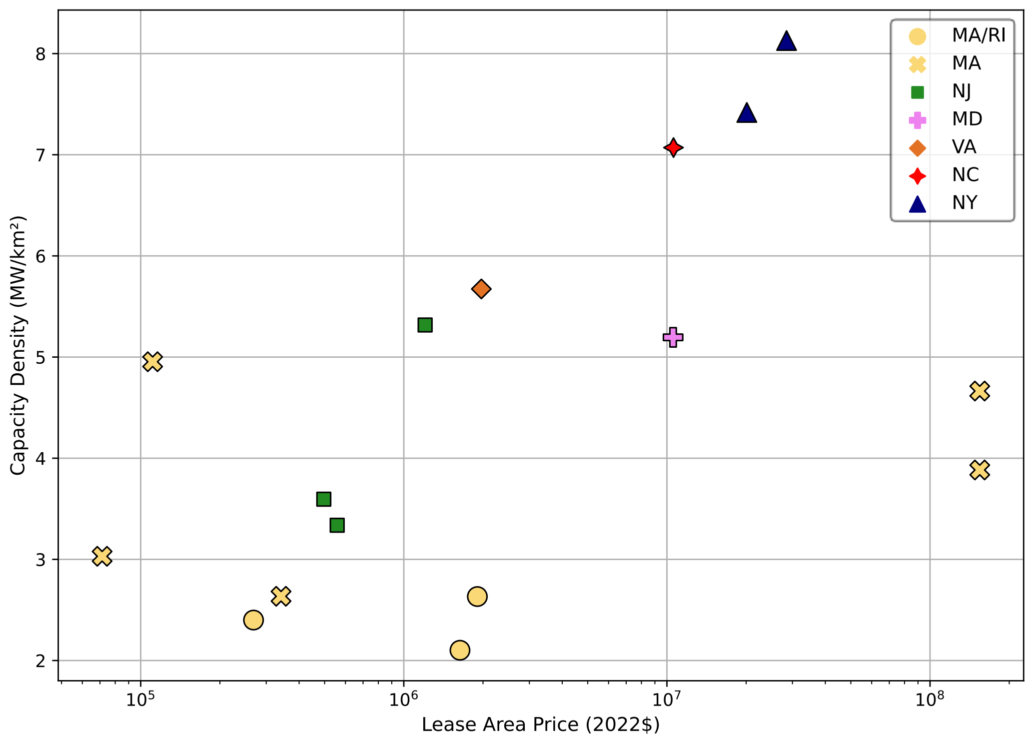

Figure 3. U.S. offshore wind project lease prices and capacity density values by state

In Figure 4, we plot the capacity density versus lease area prices identifying the projects by developer rather than the state. While there is no clear pattern, capacity density range appears to be narrower when limited to individual developers. For example, Ørsted projects are in a tighter group on the lower side of the total range.

We show the capacity density as a function of the lease area price per square kilometer by state and by developer in Figure 5 and Figure 6, respectively. These figures also illustrate that capacity density tends to increase with lease price per square kilometer. This potential correlation of higher capacity density with higher lease area prices (absolute or per square kilometer) is logical to some degree because developers who pay higher prices may be motivated to increase the wind farm's nameplate capacity to recover some of the lease area investment.

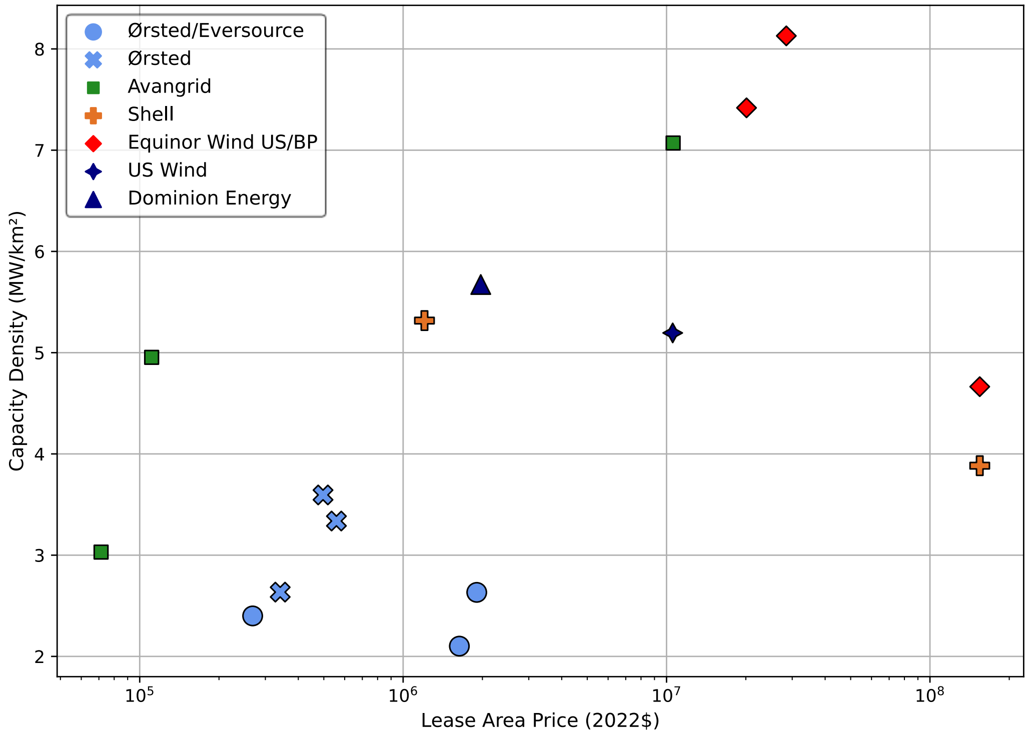

Figure 4. U.S. offshore wind project lease prices and capacity density values by developer

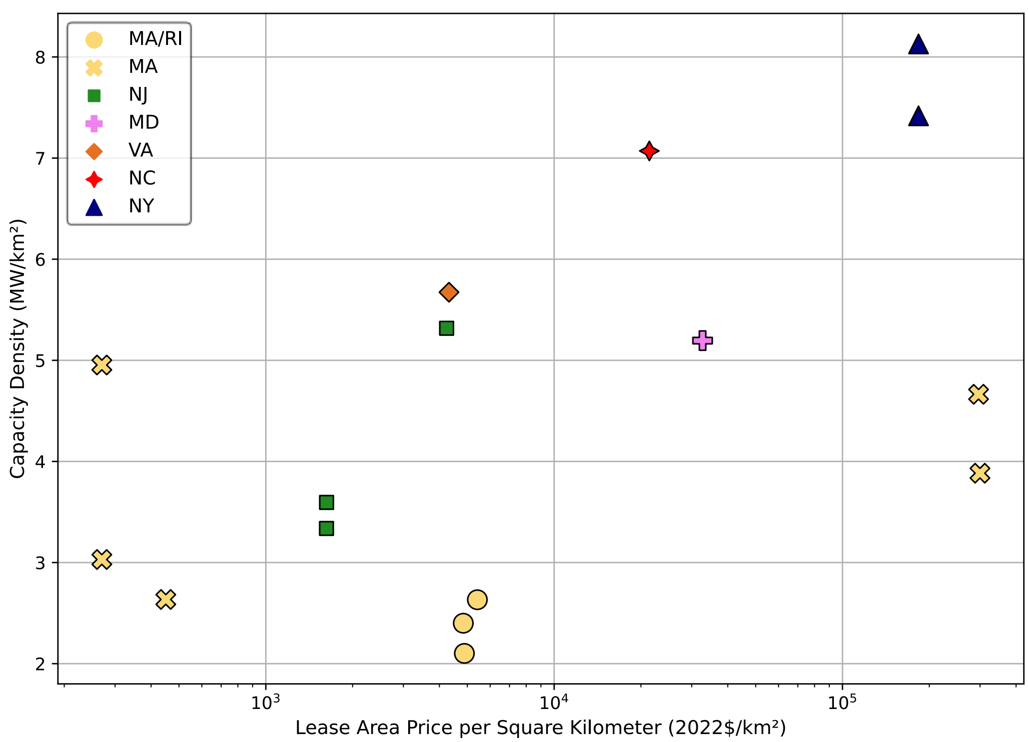

Figure 5. U.S. offshore wind project lease prices per square kilometer and capacity density values by state

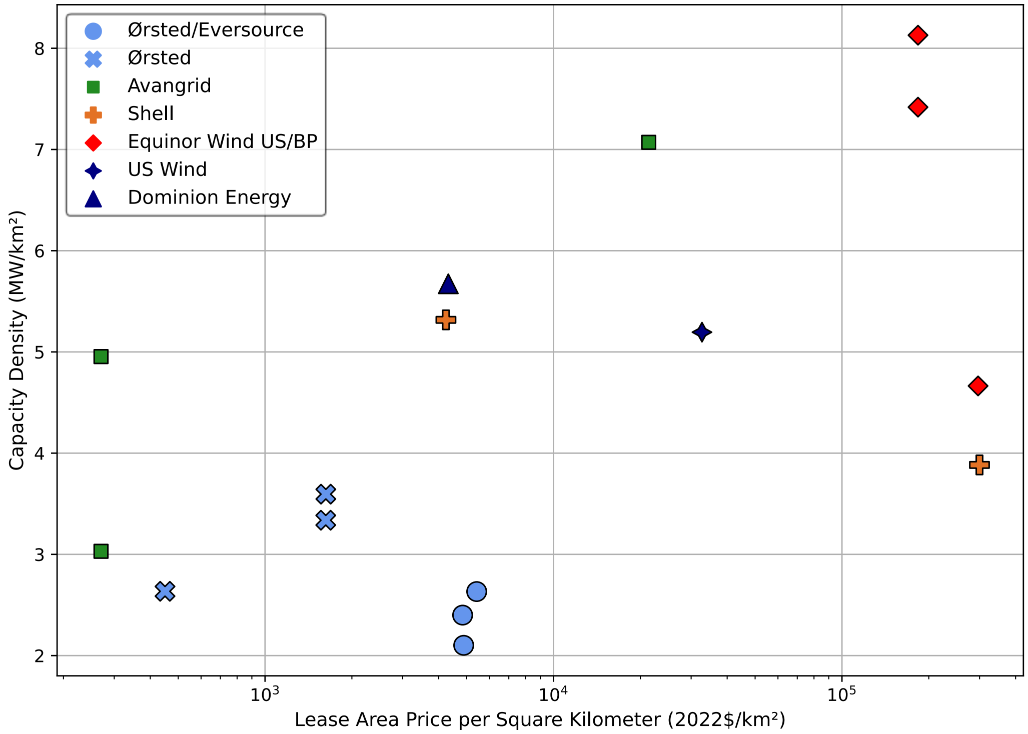

Figure 6. U.S. offshore wind project lease prices per square kilometer and capacity density values by developer

The New York Bight lease areas, which were auctioned in early 2022, yielded record sale prices ranging from $600 million to $1,100 million, but the construction and operating plans for these areas have not been submitted at the time of this publication, and their planned capacity density is not yet known. Those capacity density values will be included in subsequent analysis to observe if the trend identified in this report remains consistent. As we describe later, lease area price is only one of many factors that might influence capacity density.

In general, larger wind turbines are not necessary to increase capacity density because smaller turbines can be spaced closer together to get the same total output. However, larger turbines are desired by some developers to reduce the number of turbine positions to reduce installation and operation costs. As larger 15-MW-scale turbines become available during this decade, developers with fixed spacing constraints (and therefore a fixed number of turbine positions) such as the Massachusetts and Rhode Island sites will be able to increase project capacities. Chinese manufacturers have made turbine upsizing announcements in the past year (Buljan 2022; Durakovic 2023), and General Electric announced plans to develop an upscaled version of the Haliade-X model with a turbine rating in the range of 17 to 18 MW (Lewis 2023; Buljan 2023). Musial et al. (2023) shows a turbine upsizing trend in the past two decades. Although it is not certain that further turbine scaling beyond the 15-MW turbines will continue, to some developers, procuring the turbine with the highest rating is a valid strategy to maximize the output of certain lease areas.

In Figure 7 and Figure 8, we present the capacity density values of the emerging U.S. projects and the weighted capacity density by the developer's announced COD year. Only the projects in

Table 1 with a single COD year or with phases that are expected to be operational one year apart from the other (like Skipjack 1 and Skipjack 2) are included in these figures.

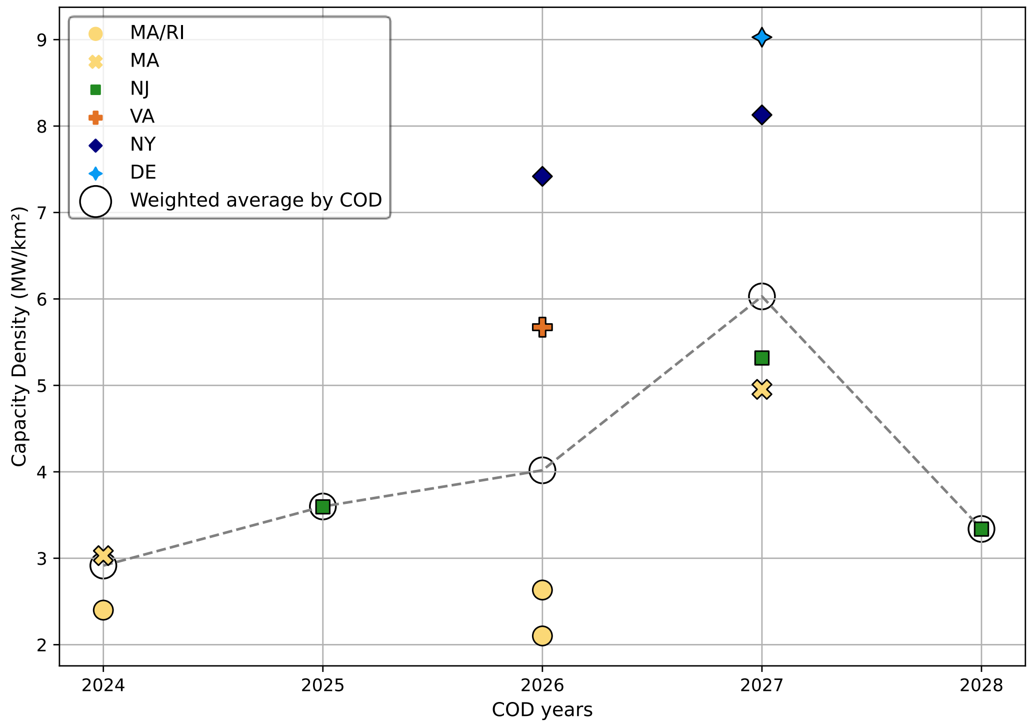

Figure 7. U.S. offshore wind project capacity densities by COD year and state

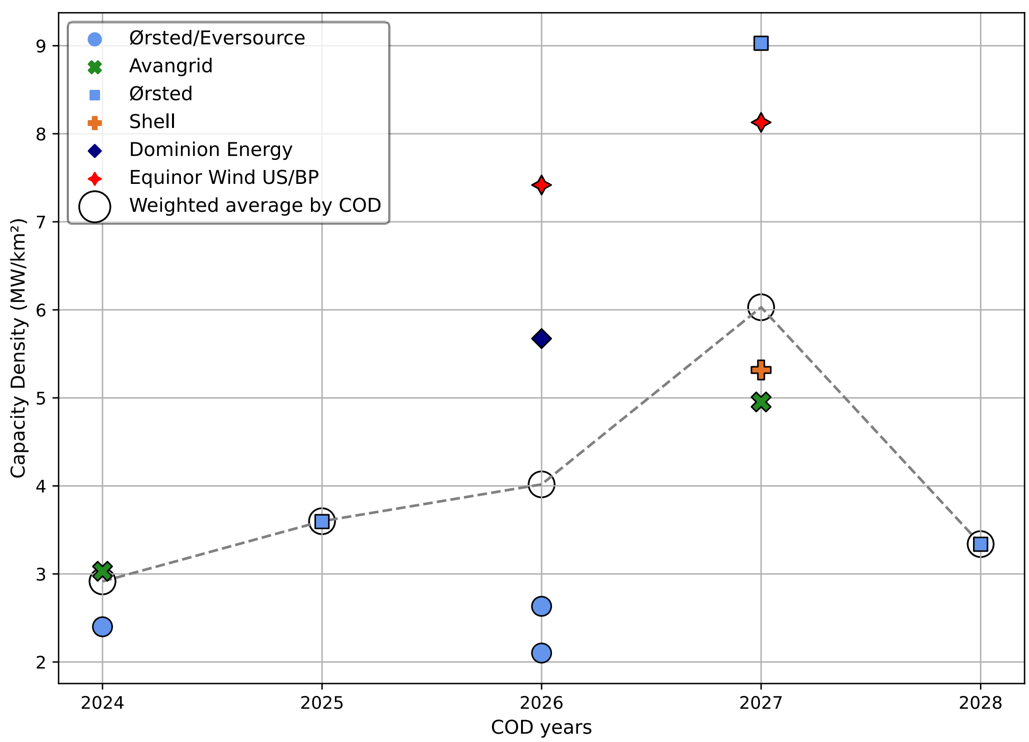

Figure 8. U.S. offshore wind project capacity densities and COD years by developer

There is an upward trend in weighted capacity density over time from 2024 to 2027, but the reader is cautioned that this trend may not reflect a valid correlation because the data are limited and are potentially influenced by developer preferences, constrained turbine spacing, and lease prices, among other things. The single data point with expected COD of 2028 (Ocean Wind 2) takes the weighted average capacity density back into the range between 3 and 4 MW/km2 after 2027. Ocean Wind 2 is a project without a published COP yet. It will be insightful to observe how this trend evolves in the future as new project data for the recently auctioned lease areas become available. When comparing the capacity density of projects developed by Ørsted (blue in Figure 8), we identify that the Ørsted projects under development in Massachusetts or Rhode Island (yellow in Figure 7) have lower capacity density values than projects for other states like New Jersey or Delaware.

To capture the capacity density differences between different regions in the United States, we calculated the weighted average capacity density by state, as shown in Figure 9. As we predicted by tracking the turbine spacing of the emerging U.S. projects in Table 2, the projects under development in Massachusetts or Rhode Island are the projects that tend to have the lowest capacity density values because of their 1 × 1-nm turbine spacing requirements. We also illustrate the weighted capacity density values by developer in Figure 10.

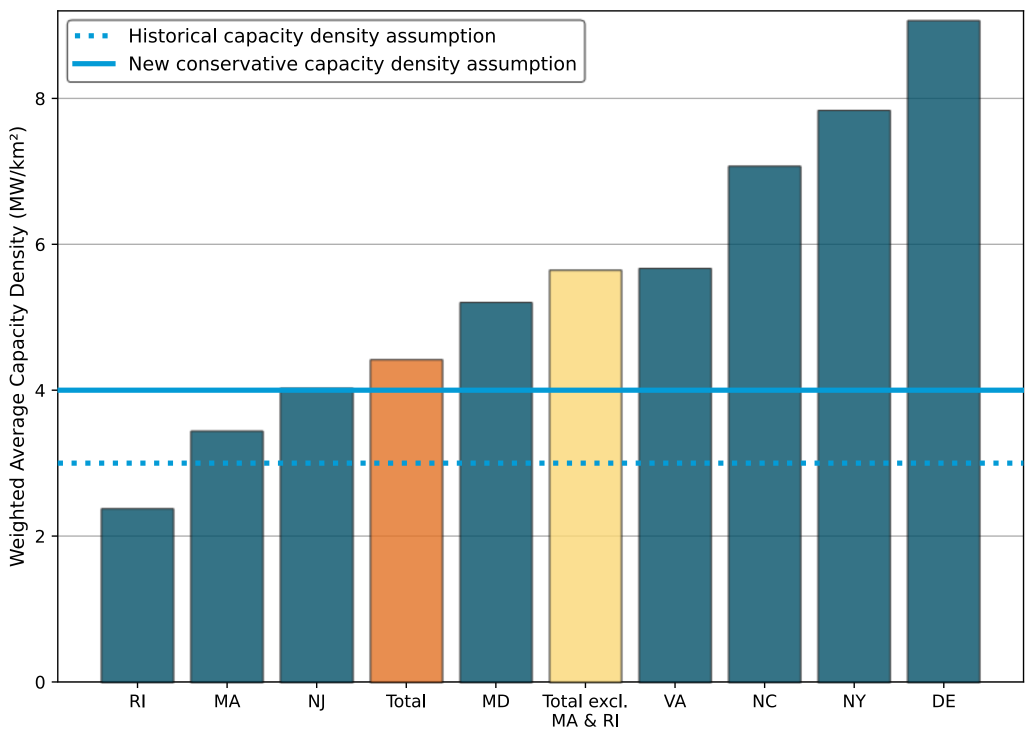

Figure 9. Weighted average capacity density by state

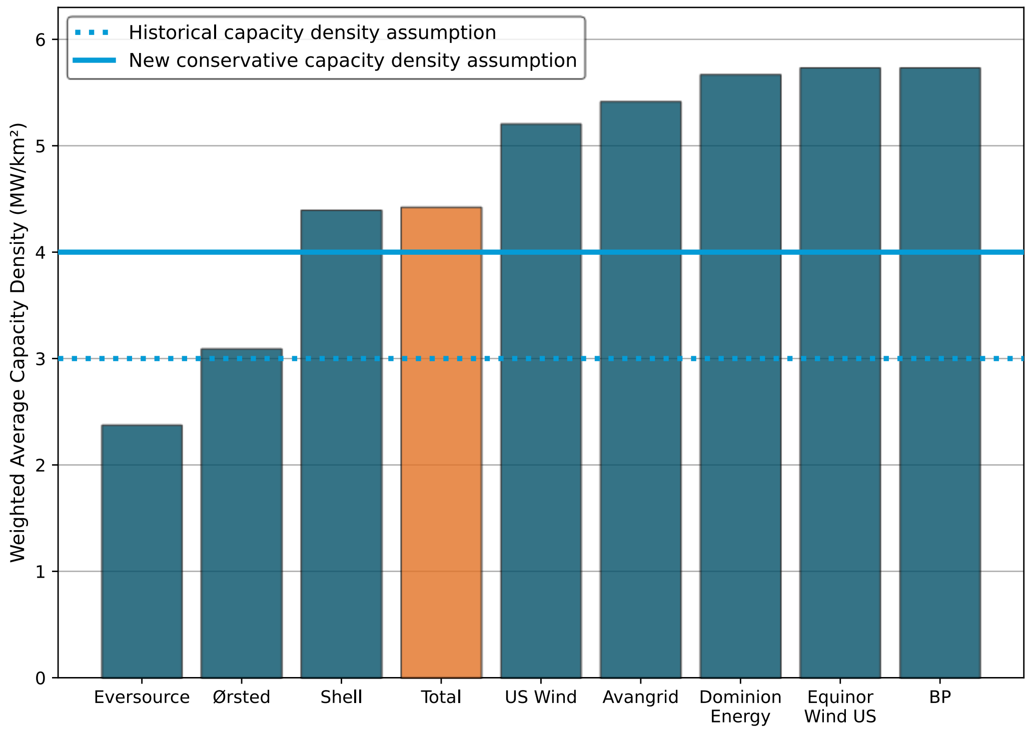

Figure 10. Weighted average capacity density by developer

The total weighted average capacity density for U.S. projects is 4.42 MW/km^2 (orange bar in Figure 9). If the projects that are limited to wide turbine spacing in Massachusetts and Rhode Island are excluded, the weighted average capacity increases to 5.64 MW/km^2 (yellow bar in Figure 9) for early projects in the United States. Based on this information, NREL revised its standard metric upwards to 4-MW/km^2 metric in the *Offshore Wind Market Report: 2023 Edition* for calculating offshore wind energy capacity in lease areas where developers have not yet specified their project capacity and layout (Musial et al. 2023). This metric is still conservative relative to the data shown in Figures 9 and 10 but is more realistic than the previous metric of 3 MW/km^2. Ørsted and Eversource are among the developers/sponsors with the highest percentage of projects under the development efforts of Massachusetts or Rhode Island in their offshore wind energy portfolio. As shown in Figure 10, the weighted average capacity densities for both companies are lower than the industry norm. The weighted average values of the rest of the developers fall in the range of 4 to 6 MW/km^2, which is comparable to 90% of the European projects falling within a range of 4.9 to 5.9 MW/km^2 (Borrmann et al. 2018; Müller et al. 2017; Hundleby and Freeman 2017), and which helps validate the 4 MW/km^2 metric.

For the data examined here, the most significant factor influencing the capacity density was the prescribed turbine spacing of 1 × 1 nm that was adopted on the lease areas in Massachusetts and Rhode Island. Other possible factors that were examined included the lease prices, developer preference, commercial operations date, and the state the project is located in. While there were possible correlations with the capacity density data no predictive methods were identified, likely because multiple variables influence developers' decisions. In addition, our sample size is relatively small, and a significant amount of variability is present, further hindering the ability to derive conclusions or identify clear trends. The next section provides a qualitative discussion of those variables.

4 Factors That Influence Capacity Density

In Sections 2 and 3 we analyzed the announced projects in the U.S. offshore wind industry pipeline to assess the likely capacity density of the upcoming offshore wind projects. We have shown that for the 17 projects examined, the capacity density ranges from 2.1 MW/km^2 to 9.03 MW/km^2. This wide range of capacity density values results from multiple factors that can influence the final array configuration.

In this section we examine the factors that influence the capacity density of a lease area and group them within the following three categories:

1. **Physical project design drivers:** Factors that the developer generally controls as part of the design process.
2. **Area utilization:** Factors that generally limit the full development of the lease area and usually result in lower capacity density.
3. **Economic and policy factors**: Administrative or regulatory factors that a developer may comply with that can change the capacity density.

4.1 Physical Project Design Drivers for Capacity Density

4.1.1 Turbine Spacing

The criteria for turbine spacing significantly impact capacity density. Widely spaced turbines allow the wind within the wind farm to regain sufficient kinetic energy, benefiting downstream turbines in the array. Conversely, closely spaced turbines may not generate enough energy to be economically viable, and the fatigue loading on turbines deep in the array tends to increase. Configurations with widely spaced turbines often involve fewer turbines, resulting in lower total energy production. The size of the turbine does not affect the amount of available kinetic energy in a given lease area. However, larger turbines, being taller, can achieve incremental energy capture advantages by reaching the higher layers of the inflow.

The key turbine spacing metric is the number of rotor diameters between towers, as illustrated in Figure 11. With larger turbines, the spacing increases, yet the capacity density remains relatively constant.

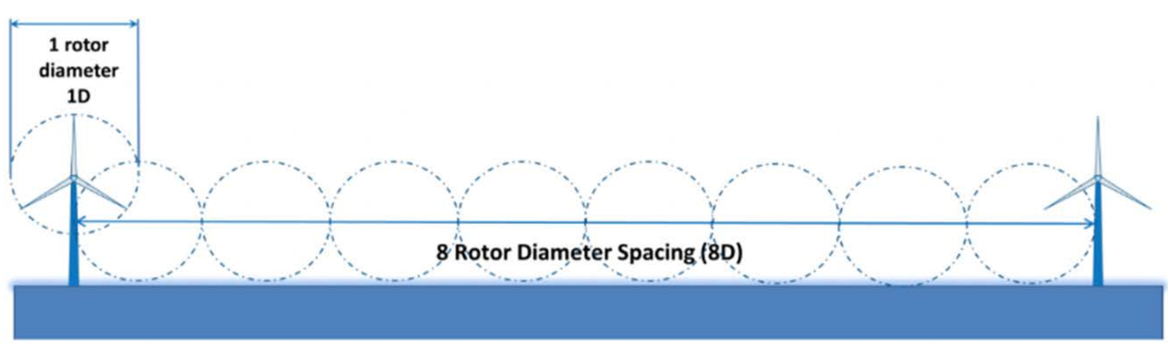

Figure 11. Example of wind turbine spacing based on 8 rotor diameters independent of turbine generator rating. ***Image by Walt Musial***

Another factor affecting turbine spacing is array cable cost. Array cable cost is an economic factor that can affect capacity density because fewer array cables are used for tighter spacing and may lower capital costs. However, NREL's economic models do not support array cable cost as a major consideration for turbine spacing. The projects examined in this study show array cable costs that are less than 10% of the total project capital expenditures, suggesting that developers may optimize energy production over energy losses and increased fatigue loading.

Wake losses[1] vary based on wind speed, wind direction, atmospheric stability, and turbine specific power.[2] Additionally, wake losses tend to be greater for sites with lower average wind speed and for turbines with higher specific power. Developers in low-wind WEAs may be compelled to increase turbine spacing and lower capacity density to mitigate energy losses from upstream turbine wakes. For example, Musial et al. (2013) calculated the total wake loss differences between two offshore wind farms with the same number of wind turbines and the same turbine model, but with different turbine spacing. The wind farm with wider turbine spacing—8 rotor diameters (D) × 12D—experienced 12% to 13% lost energy from wake losses, whereas the wind farm with closer turbine spacing—8D × 8D—experienced 16% to 17% lost energy from wake losses.

Tighter turbine spacing, for a given turbine rating, leads to higher wake losses and increased structural loading due to intra-array turbulence. However, this configuration also enhances the total nameplate capacity for a given lease area, consequently increasing capacity density.

4.1.2 Turbine Generator Rating

The turbine generator's nameplate rating does not directly impact capacity density, as turbine spacing is generally determined by a distance derived from the rotor diameter multiplied by a scaler, typically falling within the range of 4 to 10. As the turbine size increases, the spacing between turbines remains roughly proportional to the rotor diameter, maintaining approximately the same capacity density for a given area but with fewer turbine positions. However, in regions where turbine spacing is fixed by regulations, so are the number of turbine positions, and larger turbines may be wanted to achieve reasonable (higher) capacity densities. In the Massachusetts and Rhode Island lease areas where turbine spacing is fixed at 1 × 1 nm, a larger turbine rating is one of the only options to increase capacity density. Developers in these lease areas are more likely to push turbine manufacturers to provide larger turbine sizes to compensate for low capacity densities. Turbine generator rating has little effect on capacity density for new wind farm design; however, increasing turbine generator rating for predetermined array geometry (e.g., repowering) increases capacity density.

4.1.3 Adjacent Wind Farms

As the leasing on the Outer Continental Shelf (OCS) continues, the cluster wakes that can extend long distances downstream from upstream wind farms may influence the turbine layout of new projects being placed near existing projects. These adjustments may affect the capacity density of

[1] Wake losses: When a wind turbine extracts kinetic energy from the wind, it creates a wake—a region of slower-moving air behind the turbine. Subsequent turbines located in this wake experience lower wind speeds, resulting in wake losses.
[2] Specific power: The specific power of a turbine is the ratio of its nameplate capacity rating to its rotor-swept area.

a project. Numerical modeling of inter-array wakes for hypothetical projects in the New York Bight by Pryor et al. (2021) and Stoelinga et al. (2022) suggest that wind farm wakes can extend downstream tens of kilometers. One key finding drawn by Pryor et al. (2021) is that the adoption of lower capacity densities, despite potentially diminishing revenue streams for individual developers, could yield advantages by mitigating systemwide power losses and alleviating wind turbine fatigue loading caused by wakes within and between wind farms. Therefore, the potential energy reduction resulting from the presence of a neighboring wind farm may motivate developers to strategically restructure layouts of adjacent projects, minimizing power losses within specific groups of adjacent lease areas. This layout restructuring could lead to lower capacity densities. In conclusion, the downstream winds from adjacent wind farms may drive developers to modify their turbine layouts and may drive the capacity density up or down in the lease area depending on the specific conditions.

4.2 Area Utilization Drivers

4.2.1 Unfeasible Turbine Positions

For as-built offshore wind arrays, the designed array layout may not always be possible in practice because the flexibility to reposition foundation or anchor locations can be very limited. Poor soil conditions or geohazards that might not be detected during initial geotechnical or geophysical surveys may render some turbine locations unfeasible for the selected substructure technology. For example, the drivability of monopiles may be critically impacted due to boulders, unexpected types of soils (e.g., glauconite), fault lines, or other geohazards that could eliminate some turbine positions (BOEM 2023). This may be especially significant in the nascent U.S. offshore wind market where a diversity of foundation options is not yet available in the domestic supply chain. In addition, some positions must be dedicated to the offshore substation(s). Losing turbine positions drives down the capacity density of the lease area.

4.2.2 Lease Area Geometry

Developers with narrow or irregular-shaped lease areas may find a nonuniform optimal spacing of turbines to achieve the required array density, rather than an even spacing pattern between turbines and rows. An example of a narrow-shaped lease area is shown in Figure 12. The degree of irregularity will depend on the specific lease area dimensions, the technology used (especially for floating wind turbines), and any additional regulatory constraints. For example, in narrow lease areas, one turbine spacing strategy could be to stretch or contract the rows as needed to place turbines so the turbines at the end of the rows are close to the lease area boundaries to maximize lease area utilization. In summary, an irregular-shaped lease area may drive developers to optimize capacity density by choosing nonuniform spacing patterns, which may drive the number of turbine positions up or down.

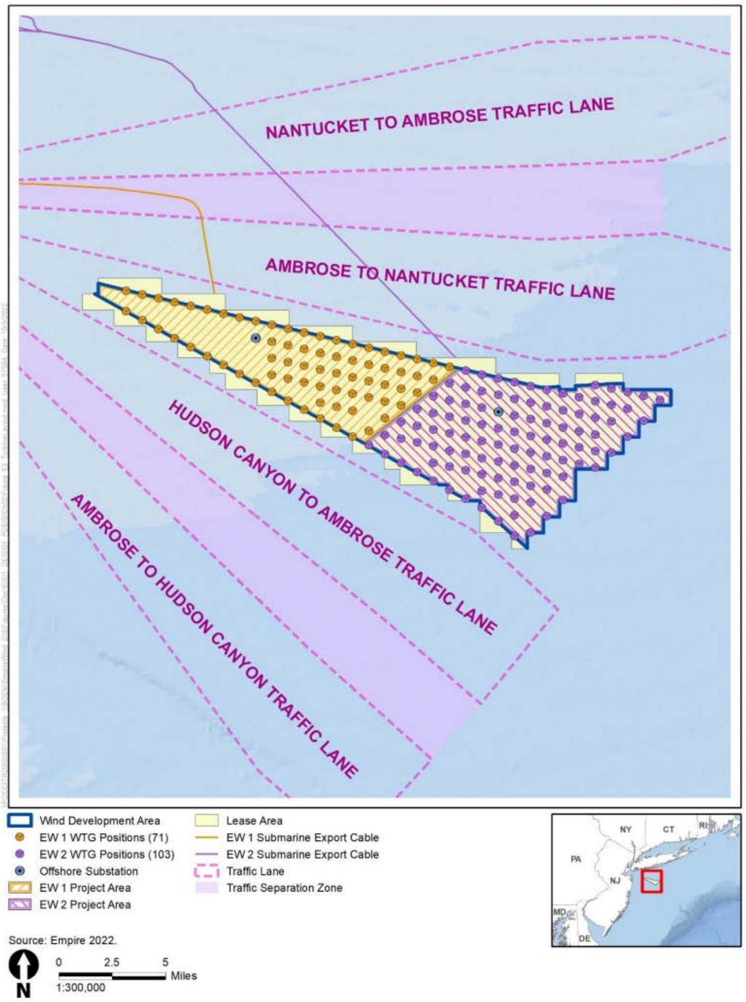

Figure 12. Empire Wind lease area. ***Figure from BOEM (2022a)***

4.2.3 Stakeholder Considerations

As we observe in the different proposed alternative wind farm designs in the DEISs of the emerging U.S. projects, compromises made with fishermen, U.S. Coast Guard, and local residents about spacing, transit corridors, and mitigating visual and wildlife habitat impacts usually drive projects toward lower capacity density. Fishermen and marine traffic generally want wider turbine spacing to allow boats to maneuver. Viewshed concerns from coastal communities also have the impact of eliminating turbine locations in the viewshed that are closer to shore. Larger turbines may exacerbate viewshed issues because larger turbines are taller and can be seen from larger distances.[3] Figure 13 show a layout alternative to mitigate visual impacts. Figure 14 illustrates the proposed transit lanes to facilitate navigation across OCS-A 0508. In general, stakeholder considerations typically reduce the number of turbine positions, which drives down the capacity density.

[3] The viewshed issue is very subjective because residents also say that they prefer fewer turbines in the viewshed, which larger turbines provide.

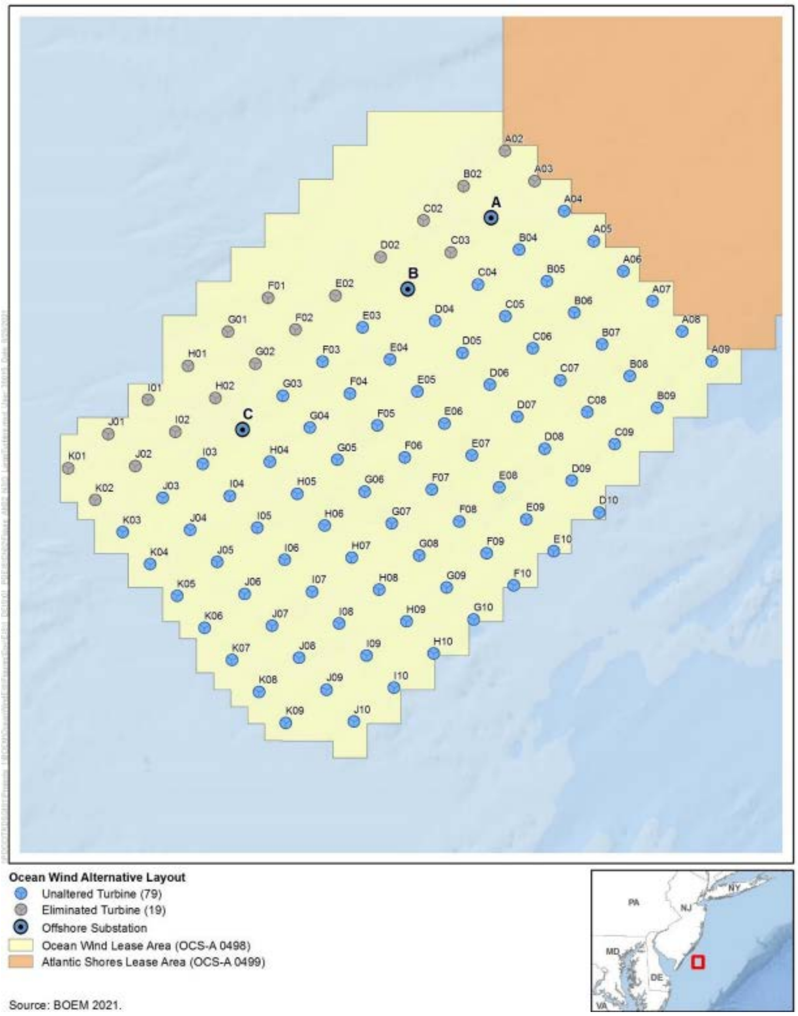

Figure 13. Example of the wind turbine positions that could be eliminated to mitigate visual impacts in Ocean Wind 1. ***Figure from BOEM (2022b)***

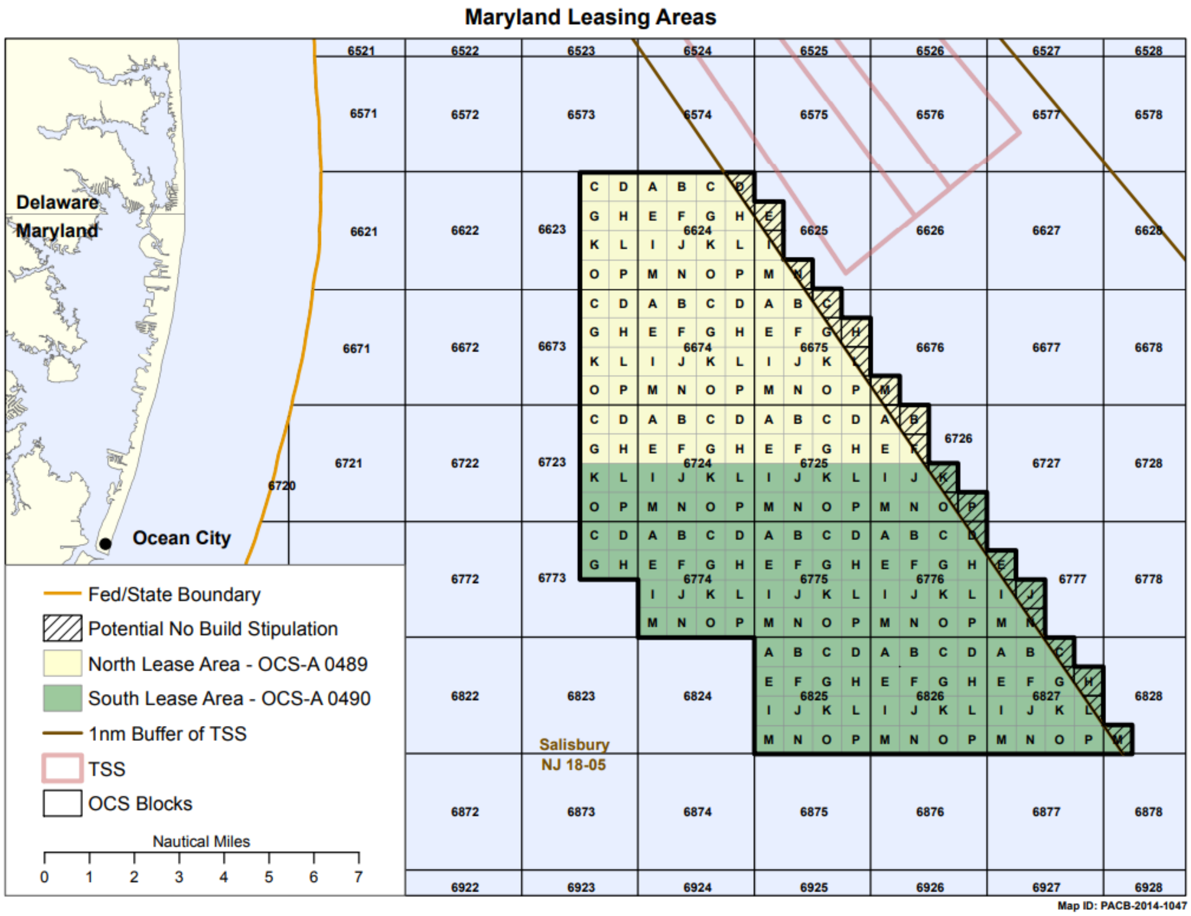

Figure 14. Maryland wind energy area showing no-build stipulation to accommodate transit lanes. ***Image from BOEM***

4.2.1 Area Lost From Anchor Placement in Floating Systems

4.2.1.1 Anchor Footprints

Floating projects may not have as many issues with geotechnical conditions as fixed-bottom projects; however, they may lose a percentage of the available lease area to accommodate the spread of the mooring and anchor system within the lease area. For catenary moorings, the anchors may need to be placed at a distance that is more than twice the water depth from the nominal turbine position. If we compare a fixed-bottom project and a floating project, the lease area utilization of the floating project may be lower than that of the fixed-bottom project for the same turbine spacing. This reduced area utilization will be mostly dependent on water depth, with deeper waters requiring greater margins for anchor placement. The advancement of mooring systems with smaller footprints is underway and promises to help reduce this problem (Green et al. 2023; West et al. 2021). Figure 15 conceptually illustrates the turbine-to-lease area boundary distance for a single floating wind turbine platform with three mooring lines. Figure 16 shows the area that could be lost because of the mooring system in the Humboldt lease areas for two different mooring technologies. More detail about the area utilization concept for different floating lease areas is shown in Appendix A. In general, anchor footprints of floating turbines will reduce the amount of developable area, which will lower the capacity density of the project.

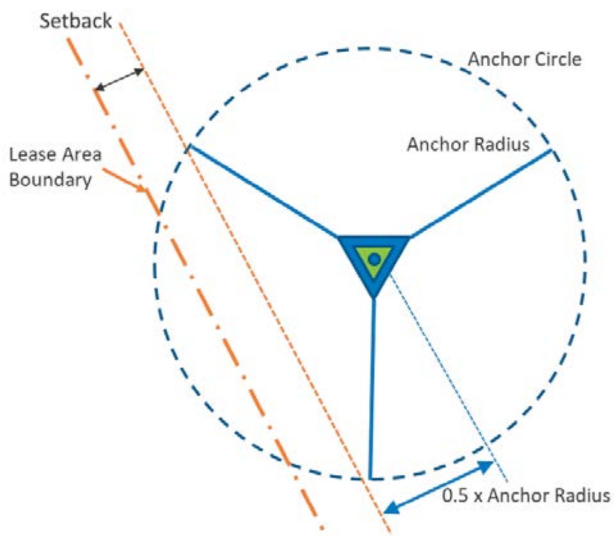

Figure 15. Conceptual diagram of anchor placement near lease area boundary. *Figure from Cooperman et al. (2022)*

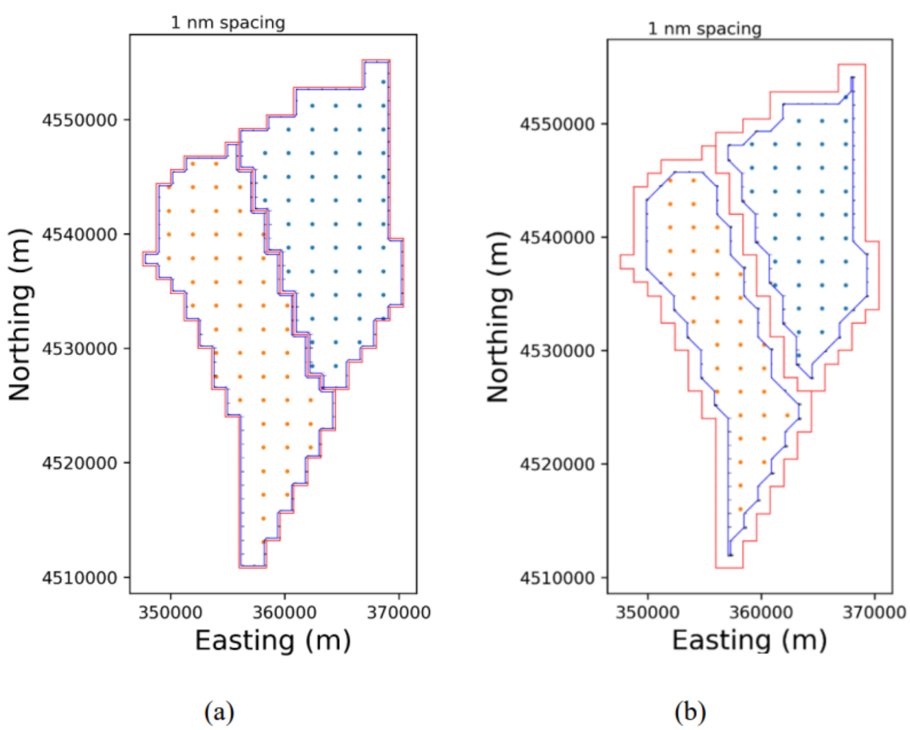

Figure 16. Examples of wind turbine space filling in the Humboldt, California, lease area: (a) 1-by-1-nm spacing using tension-leg platform technology (best case), (b) 1-by-1-nm spacing using catenary technology (worst case). The red lines are the lease area boundaries, and the blue inner lines indicate the required mooring setback. *Figure from Cooperman et al. (2022)*

4.2.1.2 Mooring System Technology Mitigation

Floating wind farms often have larger footprints on the seabed than fixed-bottom wind farms because additional area is needed to accommodate the breadth of their mooring systems, which can extend a large distance horizontally from the wind turbines. The type of mooring system that is used in the turbine system design can have a significant influence on the diameter of the anchor circle and the amount of lease area that is sacrificed for anchor spread. Several different mooring system types are shown in Figure 17.

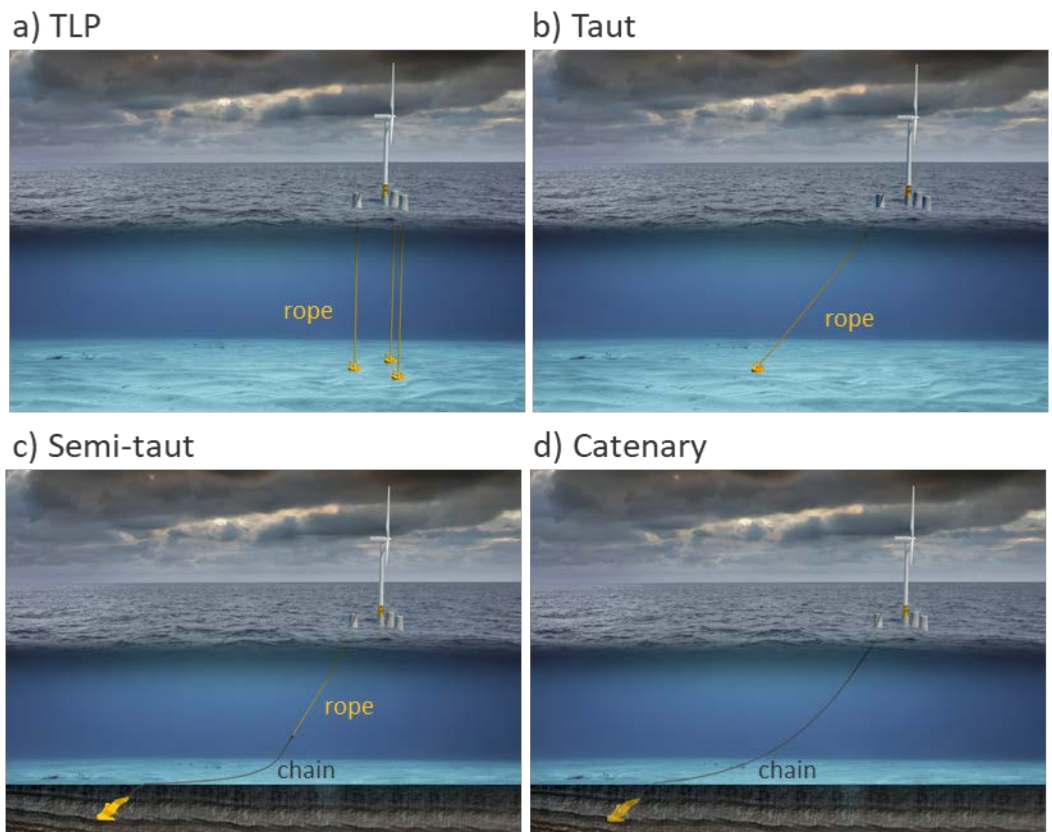

Figure 17. Four typical mooring line configurations: (a) tension-leg platform (TLP), (b) taut, (c) semitaut, and (d) catenary. ***Illustration by Joshua Bauer, NREL***

Vertical mooring lines are used in tension-leg platforms (Figure 17a). They require high-capacity vertical load anchors but have the smallest footprint for a floating wind turbine and therefore could potentially offer the highest capacity density. Their main drawback is that there has not yet been a full-scale demonstration of this technology in the wind industry. Taut mooring lines (Figure 17b) can provide an anchor circle diameter that is half the size of a catenary mooring system but require anchors with some vertical capacity such as suction piles. Semitaut mooring lines (Figure 17c) need a slightly larger anchor circle to function. Catenary mooring lines (Figure 17d) are the simplest and most conventional approach but have the largest anchor circle and therefore occupy the largest space on the seabed. Catenary mooring configurations will be more feasible in moderate water depths such as the Gulf of Maine, which is nominally around 200 meters (m) deep but may be less feasible in deeper waters such as those along the U.S. Pacific Coast where lease areas are up to 1,300 m deep. The use of technologies that lower the mooring system footprint generally increases the number of turbine positions available, which increases the capacity density of the project. Reducing the mooring system footprint may also increase options for co-existence with fishermen.

4.3 Economic and Policy Factors Affecting Capacity Density

4.3.1 Offtake Agreements

Power purchase agreements (PPAs) and offshore wind renewable energy certificates (ORECs) are negotiated before the wind farm is built. These obligations, combined with the regulatory COP, tend to lock the developer into a minimum capacity density requirement that is needed to deliver the contracted energy offtake. These agreements may include contingencies to account for the possibility that the wind farm's capacity might be modified during construction. In general, developers try to meet the PPA/OREC obligations. In some projects, an unanticipated reduction in the number of feasible turbine and offshore substation positions could force developers to push for larger turbines to meet the PPA/OREC obligations (BOEM 2022c). Larger turbine ratings drive up the capacity density of the area when turbine spacing has been set.

4.3.2 Prescribed Turbine Spacing

Regional offshore wind capacity density can sometimes be administratively constrained by conditional requirements that are set in negotiations to accommodate stakeholders for co-use of the ocean space. One example is in the Massachusetts and Rhode Island WEAs mentioned earlier where the USCG recommended a uniform 1 × 1-nm grid pattern for navigation safety reasons, which was agreed to by the states and leaseholders (USCG, DHS 2020). This agreement was made to increase safe transit through the wind farms in these lease areas, maintain navigational safety, and provide vessels with multiple straight-line options to pass through large wind farms. For these leases areas the capacity densities are demonstrably lower than the U.S. average. One of the only means to increase capacity density in these cases is to increase turbine size. The reduced capacity density resulting from fixed turbine spacing in the Massachusetts/Rhode Island WEAs may also have the unintended consequence of increasing the total long-term ocean area requirements needed to meet the New England states' decarbonization targets.

4.3.3 Lease Area Prices

In Section 3, we found there may be a correlation between lease prices and capacity density in the planned wind farms undergoing BOEM review in the Atlantic. This would make sense because a developer that paid a higher price for the lease area may be more motivated to install higher capacity on a given lease area to try to recover some of the up-front costs incurred from the initial investment. Therefore, unless there are constraints on turbine spacing, higher lease prices will likely add pressure to drive up capacity density. Although this trend is not strongly correlated because there are many other factors that influence capacity density that would make this relationship uncertain.

4.3.4 State Renewable Energy Policy

Many states have established ambitious offshore wind procurement mandates or set planning targets. With a fixed amount of ocean space designated for offshore wind, state energy goals may potentially be met more easily if developers build larger projects with denser arrays within the existing areas. If allowed, developers may choose tighter spacings (e.g., higher capacity densities) to help states meet their renewable energy goals.

The Coastal Virgina Offshore Wind Commercial (CVOW-C) project off the coast of Virginia is an example of a project whose capacity density has been increased to help meet Virginia renewable energy targets. The CVOW-C COP states the following to justify turbine spacing of less than 1 nm (Dominion Energy 2022):

> *The possibility of a layout with corridors of 1 nm in one or both directions in the layout grid was assessed; however, 1 nm spacing would preclude the Lease Area from attaining the goal in the Virginia Clean Economy Act to achieve a project capacity of between 2,500 MW and 3,000 MW of offshore wind power by 2028.*

As a result, the developer, Dominion Energy, is proposing turbine spacing of 0.75 × 0.93 nm using Siemens 14-MW wind turbines with a rotor diameter of 222 m, resulting in a capacity density of 5.67 MW/km^2, which is almost twice the capacity density of the lease area development in Massachusetts/Rhode Island.

5 Conclusions and Next Steps

This report highlights the importance of capacity density on the estimation of the offshore wind pipeline and analyzes the capacity density values of the U.S. offshore wind projects in the permitting pipeline. It also provides a qualitative summary of the main drivers of capacity density.

Our observations reveal the variability of capacity density, spanning from 2 to 9 MW/km^2 across 17 fixed-bottom projects in the United States. The overall weighted average capacity density for these projects is calculated to be 4.42 MW/km^2. As a result of the findings presented in this report, we adjusted the metric that we use to estimate capacity density in the *Offshore Wind Market Report: 2023 Edition* from a conservative 3 MW/km^2 metric to a value of 4 MW/km^2 for ocean resource areas that have not yet been specified by a developer (Musial et al. 2023). This updated assumption is still conservative compared to the majority of projects analyzed but offers a more realistic estimate for future offshore wind capacity leasing in the United States.

This report also highlights the impact of the constrained spacing characteristics observed in projects under the development efforts of Massachusetts and Rhode Island. The restricted spacing guidelines implemented in these particular lease areas along the East Coast show a notable decrease in the capacity density in those specific states.

Although we make no assertion of being able to predict the actual capacity density of a lease area, this report sheds light on the factors that affect capacity density, which may provide valuable insights for future marine spatial planning.

Moving forward, we recommend the following research to delve deeper into the analysis of capacity density:

1. Periodically update the NREL project database as new projects progress toward the final stages of their permitting process and incorporate these updates into our findings to ensure that our analysis remains up to date and reflective of the latest U.S. offshore wind developments.
2. Conduct a more detailed investigation of influencing factors in floating offshore wind projects to identify, analyze, and quantify the factors that impact capacity density in floating offshore wind projects.
3. Assess various deployment scenarios to identify gaps in lease area availability that may threaten federal and state targets to inform strategic planning efforts.

Through these initiatives, we seek to enhance our understanding of capacity density and provide valuable insights for the future development and planning of offshore wind projects in the United States.

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Appendix A. Other Floating Wind Considerations

All the projects analyzed in this report are fixed-bottom offshore wind projects, as there are no published construction and operation plans or similar records for U.S. floating offshore wind projects. Floating offshore wind projects may require additional space to ensure that the mooring systems and anchors are kept within the lease area. Further research is needed to understand how the mooring and array spacing design challenges of a large-scale floating offshore wind farm could affect capacity density (Cooperman et al. 2022).

The use of a floating substructure instead of a fixed-bottom foundation changes the array design strategy. Floating offshore wind turbine platforms must be placed a certain distance from the lease area boundary to keep the mooring system within the lease area. This causes a decrease in the percentage of area available and, consequently, a decrease in capacity density.

In an initial analysis, we chose taut mooring technology to illustrate the impacts of water depth on the area lost in the available Call Areas. Taut mooring configurations are expected to be the most cost-effective option for deep waters because they avoid the large mooring system weights and footprint sizes of mooring systems with catenary components in deep water. At water depths nearing 1,300 m such as those found in the California lease areas, polyester mooring lines, which are well established in the offshore oil and gas industry, provide restoring characteristics that are well suited to the stationkeeping needs of floating wind turbines. Estimates of the turbine-to-lease-area boundary distances as a function of water depth are provided in Cooperman et al. (2022). For taut mooring technology, the estimated minimum turbine-to-boundary distance is calculated using Eq. 2:

$$\text{minimum turbine to boundary distance} = 0.35 * \text{water depth} \tag{2}$$

To estimate the area lost from the spacing of the mooring system in the edge of the area, we calculate the average water depth along the perimeter using bathymetry data from General Bathymetric Chart of the Oceans (2022). We compute the average minimum turbine-to-boundary distance for each Call Area and the total potential area lost due to the mooring technology.

The results from the U.S. Call Areas for offshore wind development are shown in Table A-1. We show the area lost for the Call Areas that are appropriate for floating projects using a taut mooring configuration (water depths greater than 500 m).

Table A-1. Percentage of Area Available for the Deployment of Floating Offshore Wind Projects With Taut Mooring Systems in the Bureau of Ocean Energy Management Call Areas With Water Depths Greater Than 500 m

Area Name	Average Water Depth at the Edge (m)	Average Turbine-to-Boundary Distance (m)	Area Lost (km^2)	Area (km^2)	Percentage of Area Available (%)
Central Atlantic Call Area E	2,021	707	444	7,001	93.7
Central Atlantic Call Area F	2,037	713	237	3,317	92.8
Hawaii Call Area - Oahu North	1,081	378	42	621	93.3
Hawaii Call Area - Oahu South	1,023	358	65	1,341	95.1
Oregon Call Area – Brookings	914	320	66	1,159	94.3
Oregon Call Area - Coos Bay	764	267	81	3,533	97.7
California Call Area - Morro Bay	905	317	38	196	80.6
California Humboldt - OCS-P 0561	785	275	24	256	90.7
California Humboldt - OCS-P 0562	978	342	36	279	87.1
California Morro Bay - OCS-P 0563	1,136	398	45	324	86.3
California Morro Bay - OCS-P 0564	1,013	355	30	326	90.8
California Morro Bay - OCS-P 0565	1,020	357	34	326	89.5

Through the Bureau of Ocean Energy Management's established process, wind energy areas tend to be partitioned (or delineated) into lease areas. Assuming different developers own neighboring areas and that they do not allow each other to place anchors and mooring lines in their respective leases, the delineation process leads to additional area being lost. An exaggerated example in Figure A-1 of the area lost because of the delineation of a Call Area into two lease areas illustrates this concept.

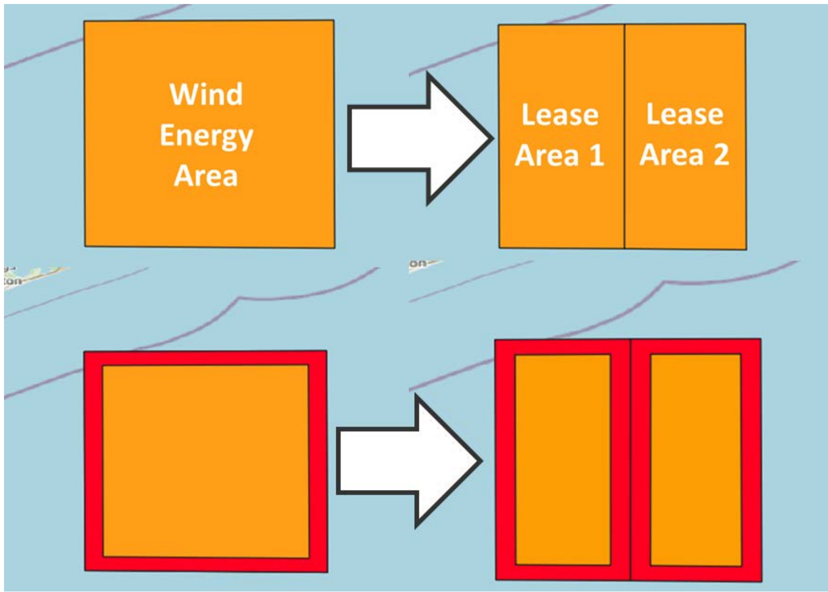

Figure A-1. Area lost (red) because of the mooring lines of floating projects for nonpartitioned and partitioned wind energy areas

For floating offshore wind projects, the depth, mooring technology design choices, and lease area size determine the available area for wind turbine placement within a lease. In general, the greater the water depths and the smaller the lease area size, the greater the percentage of area lost due to mooring lines and anchor placement. This may impact capacity densities for floating offshore wind farms but does not include design constraints arising from anchor placement within lease area interiors. It may be valuable for the Bureau of Ocean Energy Management to consider the potential impacts of mooring technologies and water depths on capacity densities when identifying and delineating future areas for possible floating offshore wind energy development.

Even though further research needs to be done to understand the array spacing challenges of designing a floating offshore wind farm given its site-specific conditions, this report provides a preliminary estimate of the range of percentage decreases of capacity density for floating offshore wind projects compared to fixed-bottom projects and the relation of those decreases to depth and total area.