Capacity Density Considerations for Floating Offshore Wind Farms in Ultradeep Waters

NREL/PR-5000-90811

Presentation for AFloat Technical Summit 2024 Conference

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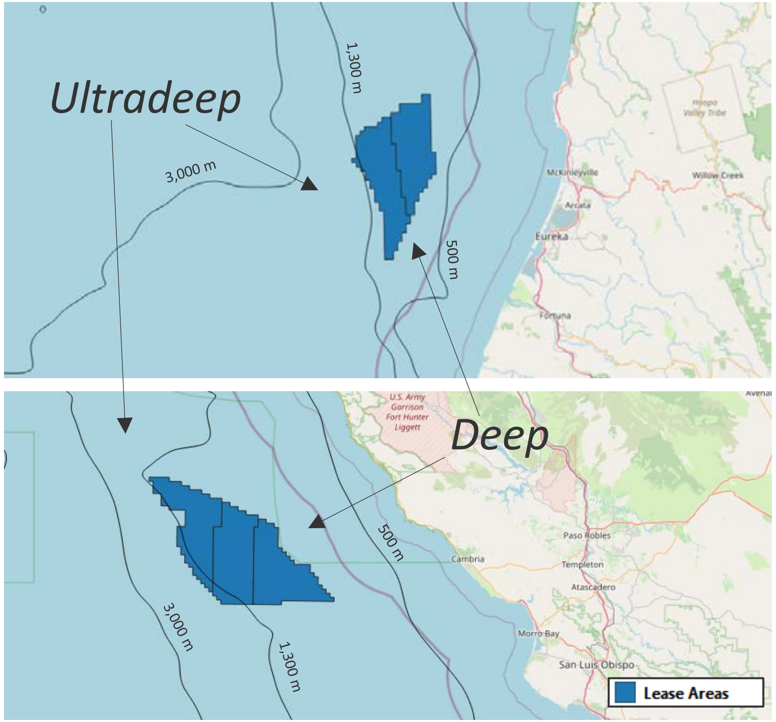
What Is Capacity Density? Why Does It Matter?

$$\text{Capacity Density} = \frac{\text{Project Capacity}}{\text{Area}} \quad \left[\frac{\text{megawatts}}{\text{kilometers}^2}\right]$$

- **Capacity density is crucial for:**
  - Resource potential analysis (calculating the U.S. Offshore Wind Pipeline)
  - Strategic planning
    - Supply chain
    - Port infrastructure needs
    - Workforce
    - Emissions
  - Managing expectations to avoid risks.

What Is Considered “Ultradeep”?

- Various sources define ultradeep water at different depths ranging from 1,500 meters (m) to 3,000 m (Caudle and McLeroy n.d.; DNV 2016; U.S. Energy Information Administration [EIA] 2016).
- We classify
  - existing California lease areas between 500 m and 1,300 m as deep
  - water depths between 1,300 m and 3,000 m as ultradeep.

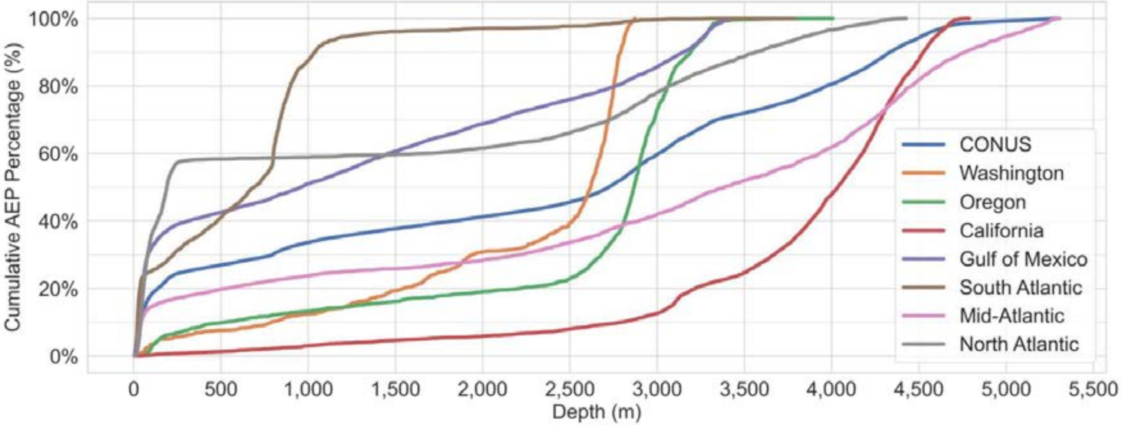


Map with California lease areas as of August 2024 and 500-, 1,300-, and 3,000-m water depth contours.

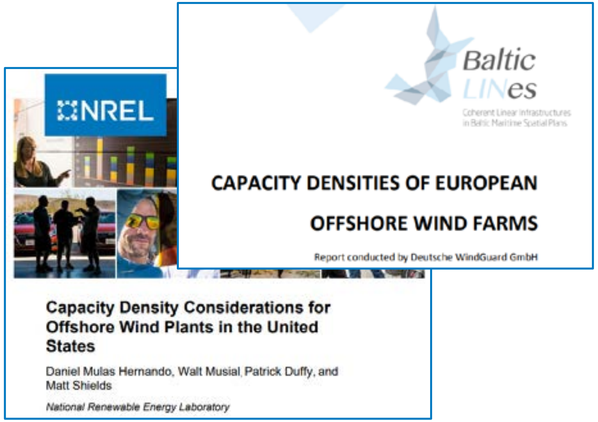
Why Look at Capacity Density of Floating Offshore Wind Farms at Ultradeep Waters?

- Capacity density known for fixed-bottom wind, unknown for floating wind.
- Lease areas and BOEM*-identified call areas extend into ultradeep waters.
- Additional resource possible if depths greater than 1,300 m become feasible.

** BOEM = U.S. Bureau of Ocean Energy Management.*



Cumulative annual energy production (AEP) percentage as function of depth for the contiguous United States (CONUS) and all regions under the Open Access, Conservative technology scenario from Zuckerman et al. 2023.



Baltic LINes
Coherent Linear Infrastructures in Baltic Maritime Spatial Plans

CAPACITY DENSITIES OF EUROPEAN OFFSHORE WIND FARMS

Report conducted by Deutsche WindGuard GmbH

NREL

Capacity Density Considerations for Offshore Wind Plants in the United States

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

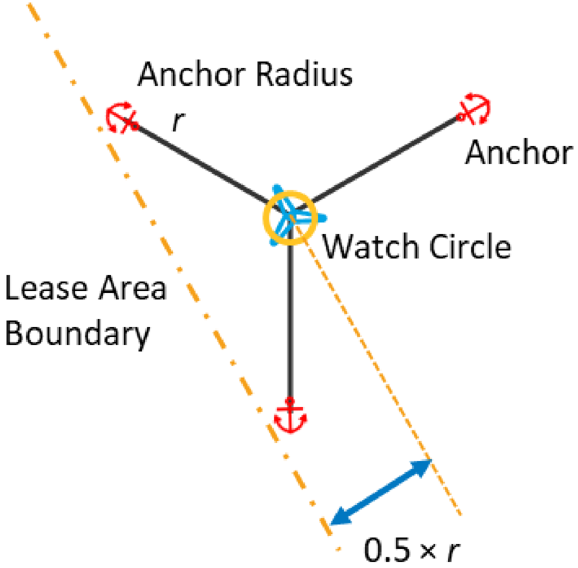
National Renewable Energy Laboratory

Publications that analyze capacity densities of fixed-bottom offshore wind projects (Borrman et al. 2018; Mulas Hernando et al. 2023)

How Does Capacity Density Differ Between Floating and Fixed-Bottom Systems?

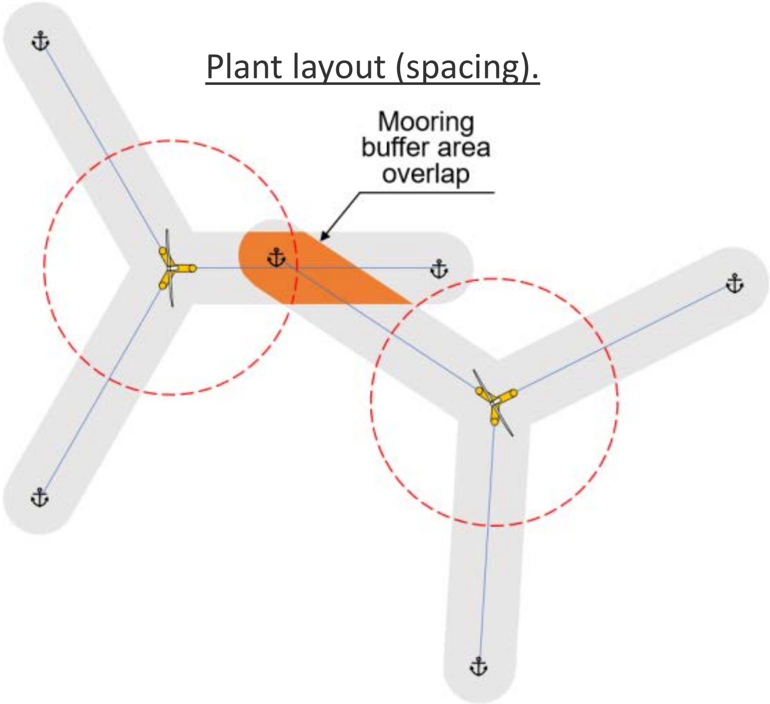
Mooring system placement may affect:

Boundary setbacks.



Depiction of setback from lease area boundary from Cooperman et al. (2024).

Plant layout (spacing).

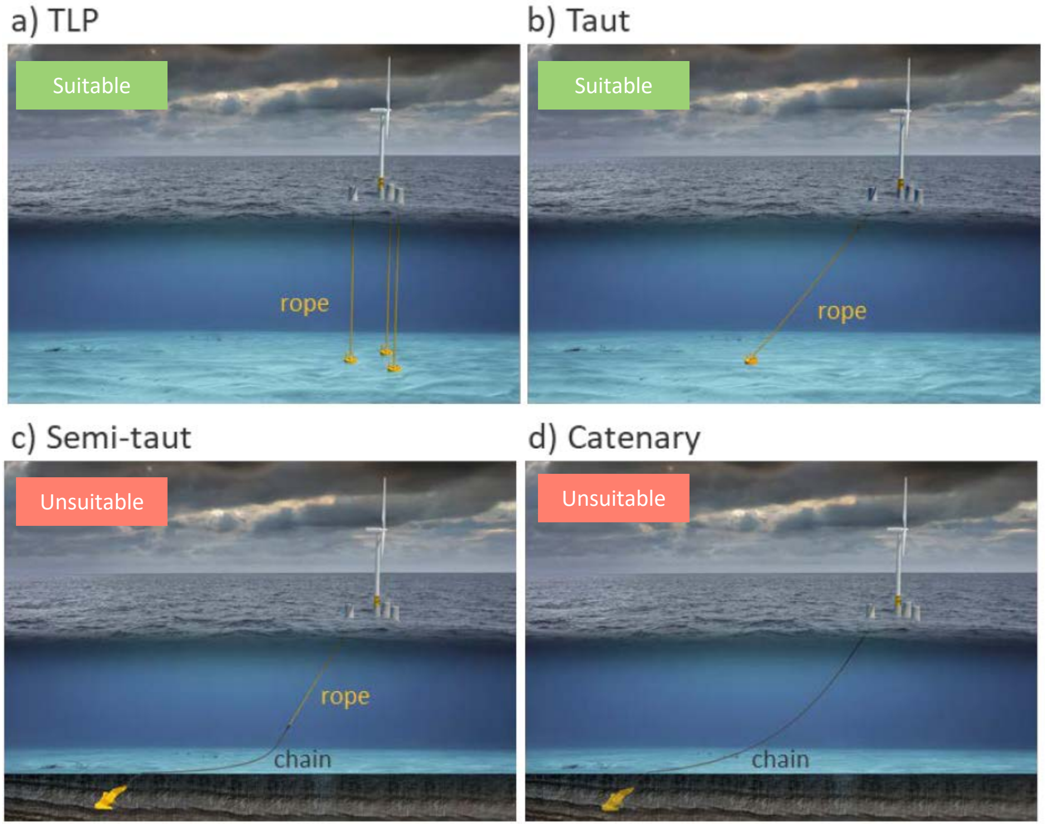


Overlap between buffer areas of adjacent moorings from Hall et al. (2024).

Analysis Approach

1. Identify mooring system types suitable for ultradeep waters.
2. Define the assumptions regarding anchor radius.
3. Establish spacing and boundary setback assumptions based on three layout configurations.
4. Provide a comprehensive definition of a generic floating wind plant.
5. Present results:
    a. Capacity density estimates for generic floating wind plants
    b. Area utilization estimates.

Tension Leg Platform (TLP) and Taut Mooring Systems Are Suitable for Ultradeep Waters



Four common mooring line configurations.
Illustration by Joshua Bauer, NREL

We Focus on Taut Systems Because TLP Systems Do Not Constrain Capacity Density

- **TLP anchor radius**
  - Has no technical limitations to achieve capacity densities comparable to fixed-bottom projects.
- **Taut anchor radius**
  - May pose challenges for achieving similar capacity densities as fixed-bottom projects, especially as water depths increase

- Two Taut designs considered to highlight cost trade-offs:
  - A minimum cost option with larger anchor radius
  - An option with greater anchoring angle (55˚)
- Lower anchor radius options result in marginally increased mooring system costs ($80/kW max. difference comparing 55˚ incline and min. cost designs).

Calculated mooring system anchor radii (r) as functions of water depth

Taut 55˚ incline (Cooperman et al. 2022)	Taut minimum cost (Cooperman et al. 2024)
r = 0.7 * depth	r = 0.91 * depth + 974

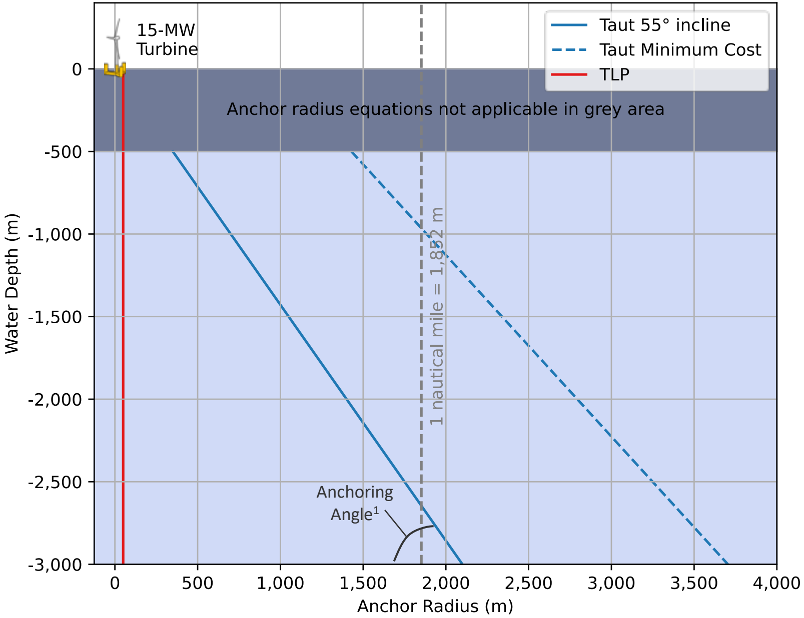


Illustration of anchor radii for TLP and taut mooring configurations from Cooperman et al. (2024); MW = megawatts.

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[1] the angle formed between the seabed and a straight line connecting the turbine to the anchor

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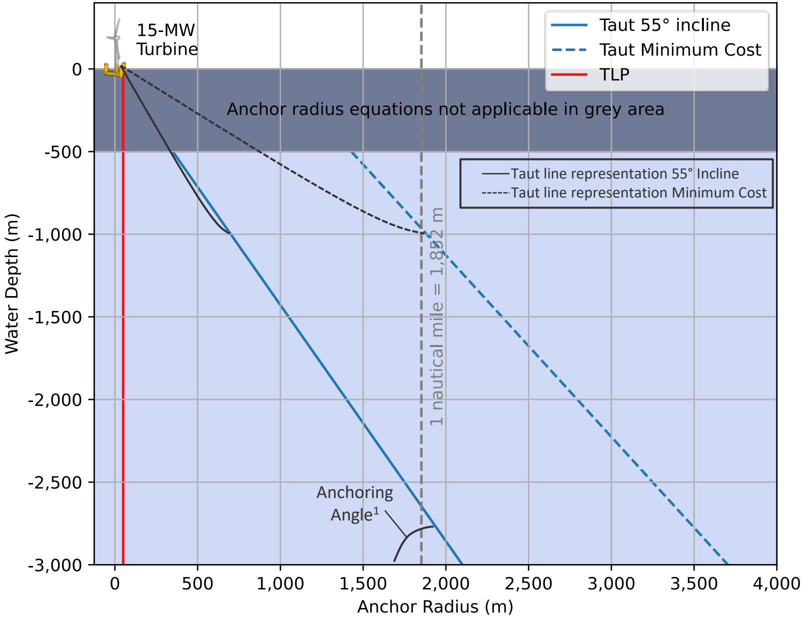


Illustration of anchor radii for TLP and taut mooring configurations from Cooperman et al. (2024); MW = megawatts.

1: the angle formed between the seabed and a straight line connecting the turbine to the anchor

Spacing and Boundary Setback Assumptions

- Mooring lines do not cross; i.e., they do not intersect when viewed from above.
- Mooring lines that do not share an anchor should be separated by a minimum distance (buffer [b]).
- Mooring lines can intersect at a shared anchor.

Under these assumptions, the minimum spacing between watch circle centers for a taut mooring configuration is an anchor radius (r)

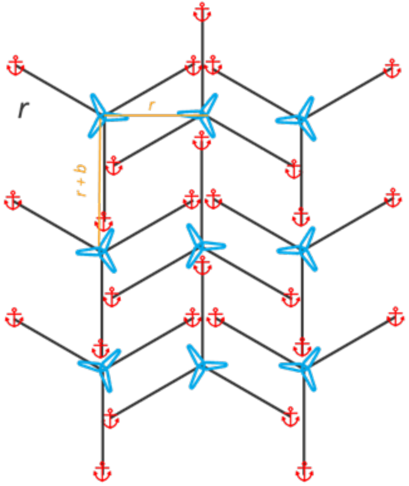
Spacing and turbine-to-boundary equations for a taut system

Metric	Depth Range (m)	Mooring System Type	
		Taut 55° Incline	Taut Minimum Cost
Boundary setback	500–3,000	0.35 × depth	0.46 × depth + 487
Minimum spacing	500–3,000	0.7 × depth	0.91 × depth + 974
Source	-	Cooperman et al. (2022)	Cooperman et al. (2024)

Buffer (b) refers to the radius around the anchors and mooring lines in the mooring buffer area, set to 50 m as per Hall et al. (2024).

Layout Types Analyzed and Main Assumptions

Nonshared
Minimum Spacing Layout
1 line per anchor
(r + b) by r spacing grid



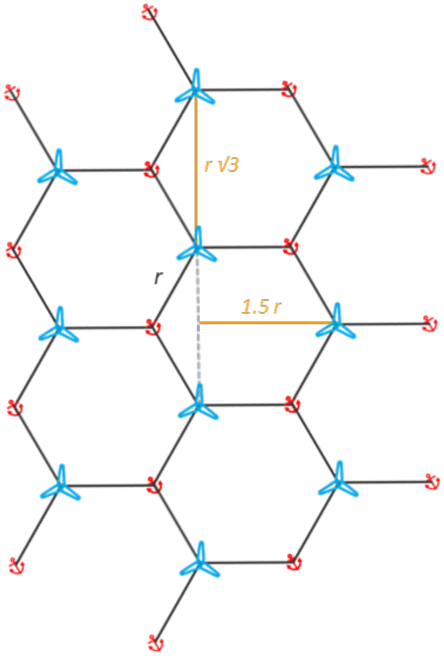
technically, the horizontal spacing here is at least

$r\sqrt{3}/2 + b$

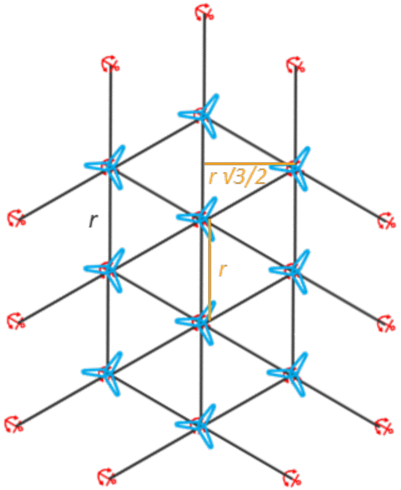
which can be less than r if

$$b < \left(1 - \frac{\sqrt{3}}{2}\right) r \approx 0.13r$$

Shared Anchor
Hexagonal Layout
Up to 3 lines per shared anchor
r √3 by 1.5 r spacing grid



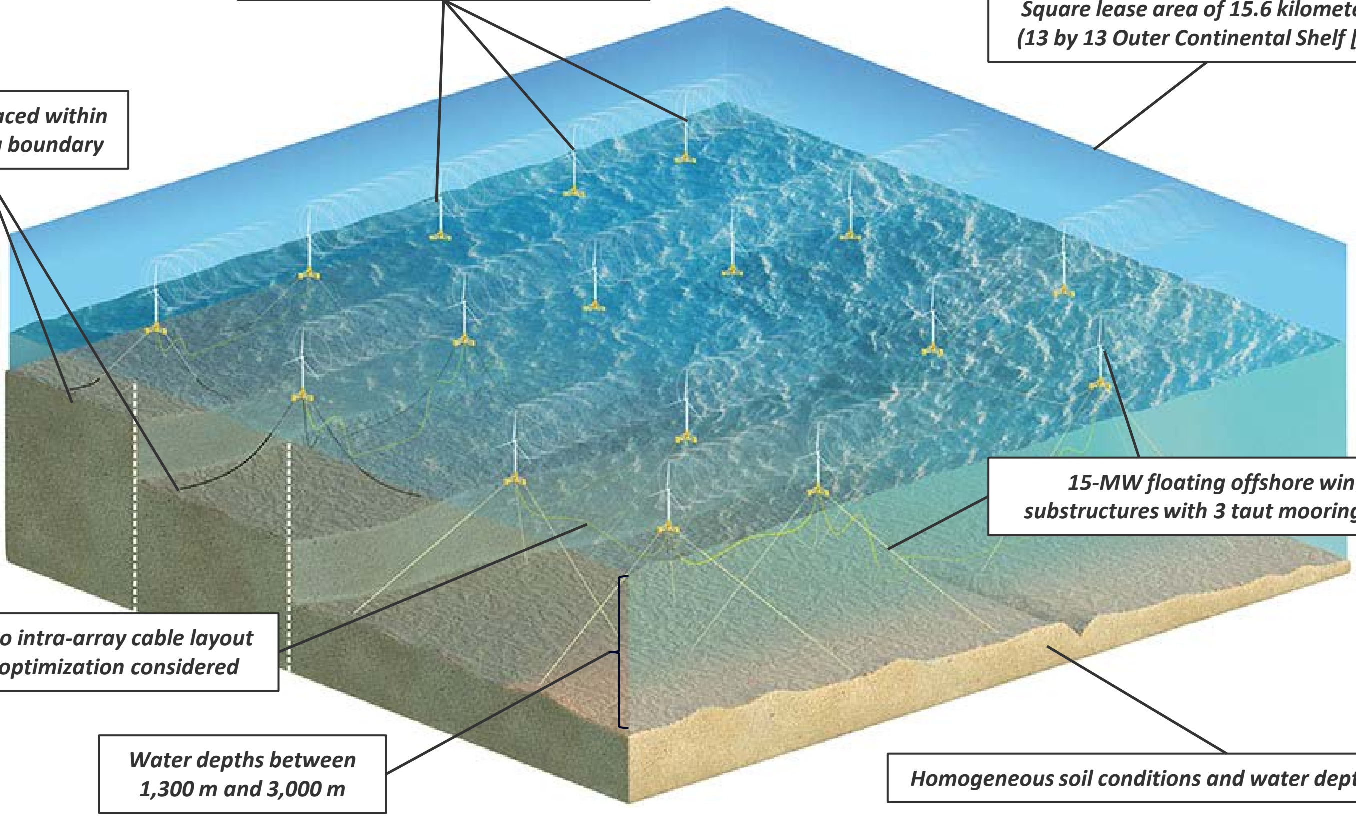
Shared Anchor
Double-Hexagonal Layout
Up to 6 lines per shared anchor
r by r √3 /2 spacing grid



(anchors allowed to be placed below turbines from a top-down perspective)

Buffer (b) refers to the radius around the anchors and mooring lines in the mooring buffer area, set to 50 m as per Hall et al. (2024).
Radius (r) refers to the distance between the center of the watch circle and the anchor of the floating turbine from a top-down perspective.

Our Definition of Generic Floating Wind Plants



Assume all the positions are feasible

Square lease area of 15.6 kilometers (km) x 15.6 km (13 by 13 Outer Continental Shelf [OCS] lease blocks)

All anchors placed within the lease area boundary

15-MW floating offshore wind turbines on substructures with 3 taut mooring lines per turbine

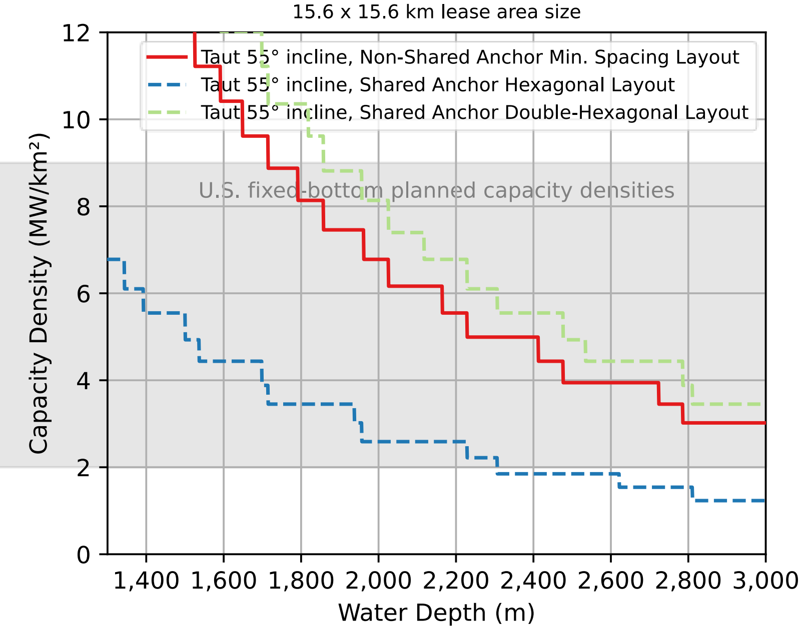
No intra-array cable layout optimization considered

Water depths between 1,300 m and 3,000 m

Homogeneous soil conditions and water depth (constant depth)

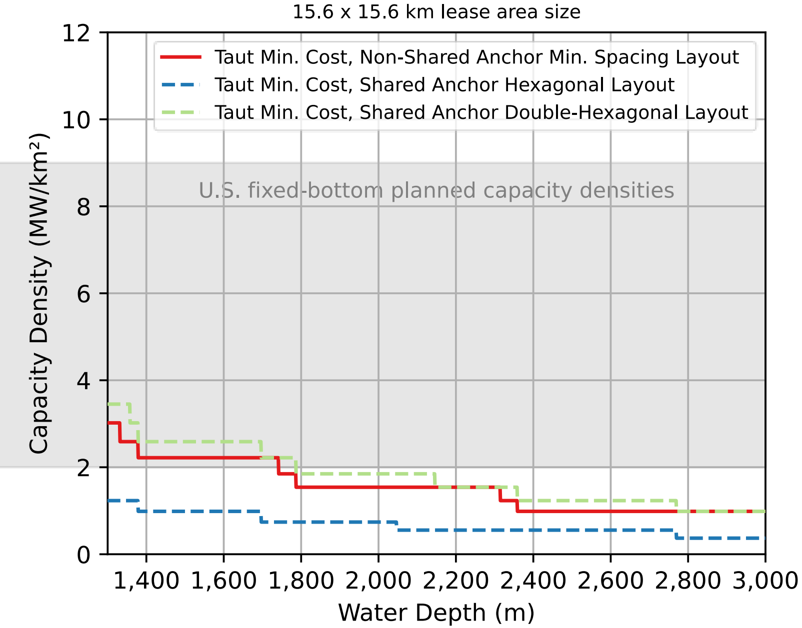
For Taut Mooring Configurations, Achieving Capacity Densities on Par With Fixed-Bottom Requires Balancing Trade-Offs Between Anchoring Angles and Costs

Taut mooring systems with a 55° incline can largely achieve capacity densities on par with U.S. fixed-bottom projects.



Taut 55˚ Incline Capacity Density from Cooperman et al. (2024).

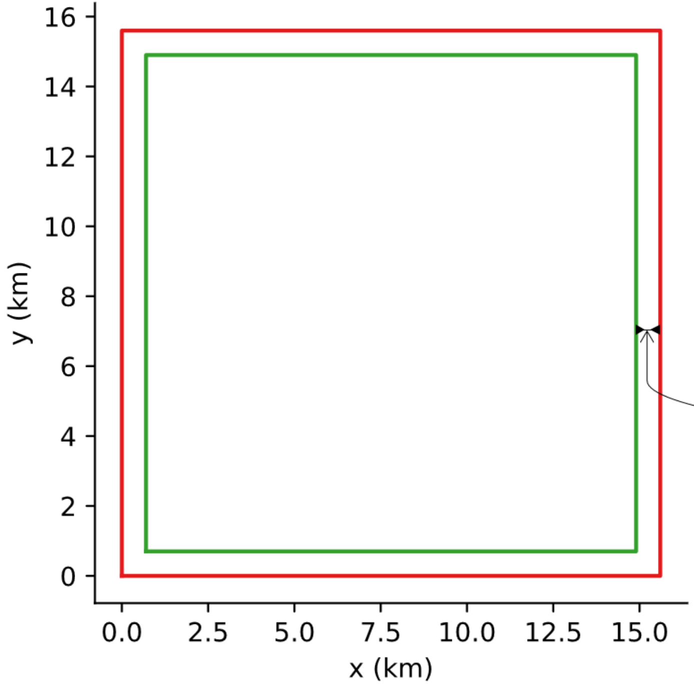
The minimum cost taut mooring configuration is more limiting, with capacity densities mostly below 3 MW/km^2.



Taut Minimum Cost Capacity Density from Cooperman et al. (2024).

We Also Research Which Lease Area Characteristics Increase the Useful Area for Turbine Siting

We characterize area utilization with the following formula:



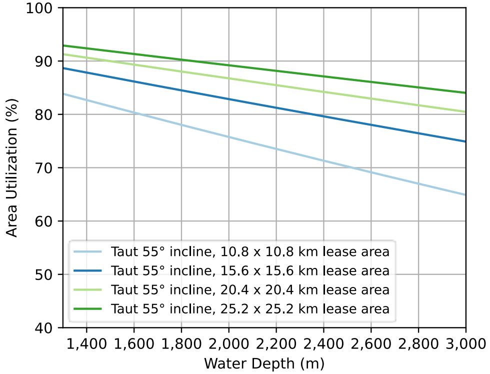
$$\text{Area Utilization (\%)} = \frac{100 \times \text{Useful Area}}{\text{Total Lease Area}}$$

Minimum Boundary Setback

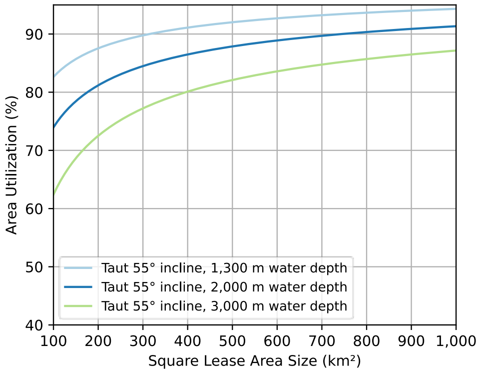
Depth, Lease Size, and Lease Shape Drive Area Utilization

Taut 55° Incline

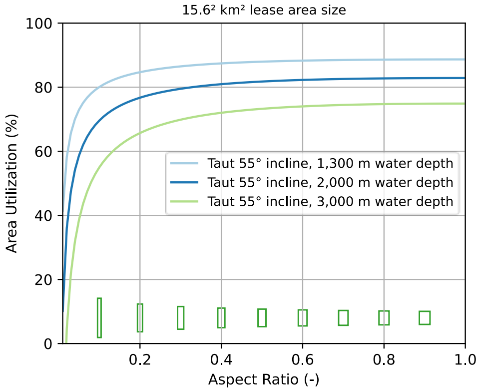
Area utilization decreases with water depth



Area utilization increases with lease area size



Square leases yield higher area utilization than narrow, rectangular leases

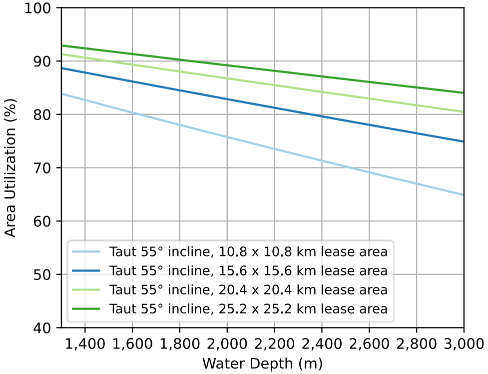


Area Utilization Figures from Cooperman et al. (2024).

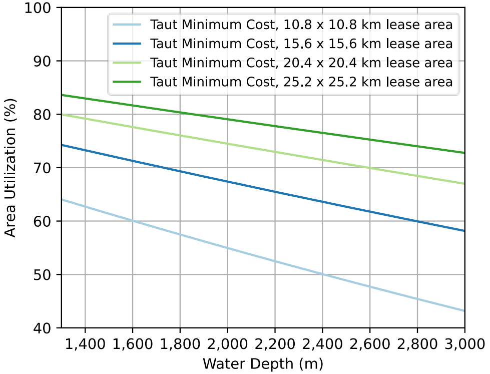
Area Utilization Is Lower With Systems With Greater Anchor Radii

Area utilization decreases with water depth

Taut 55° Incline



Taut Minimum Cost



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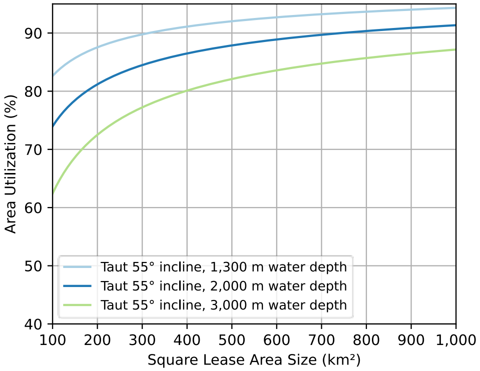

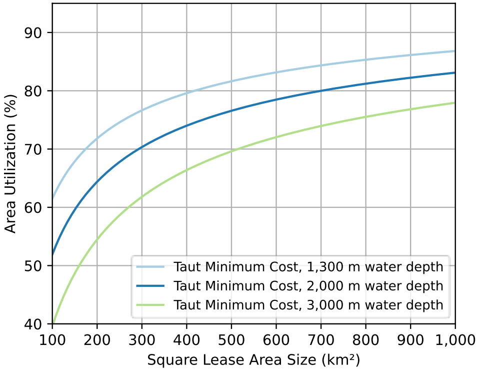

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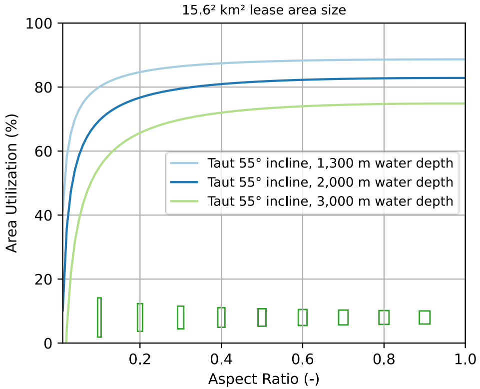

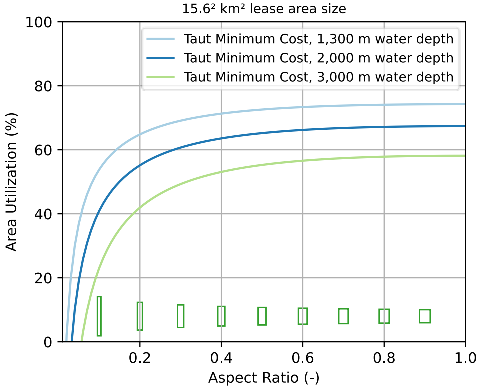

Area Utilization Figures from Cooperman et al. (2024).

Conclusions

- **TLP and taut are the least sensitive to the challenges of ultradeep water.**
- **Capacity density**
  - **TLP mooring system placement does not limit capacity densities.**
  - **For taut systems:**
    - Capacity densities become constrained as depth increases (assuming mooring lines cannot cross).
    - Layouts with a 55° incline can achieve capacity densities similar to U.S. fixed-bottom projects.
      - Minimum cost configurations are more limiting, with densities mostly below 3 MW/km^2 in ultradeep waters.
      - Greater anchoring angles that allow higher densities may result in increased mooring system costs.
    - Shared anchor double-hexagonal layouts* > layouts without shared anchors and minimum spacing.
    - Shared anchor hexagonal layouts << layouts without shared anchors and minimum spacing.
- **Area utilization**
  - Decreases with increasing water depth
  - Increases with larger lease area size
  - Depends on lease area shape; square leases yield more usable areas than narrow rectangular leases
  - Increases with anchoring angle, but greater anchoring angles may increase mooring system costs.

** That layout configuration may pose maintenance challenges.*

Thank You!

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References

Borrman, R., R. Knud, A.-K. Wallasch, and S. Lüers. 2018. *Capacity Densities of European Offshore Wind Farms* (Technical Report SP18004A1; Interreg Baltic Sea Region – Project Baltic LINes). Deutsche WindGuard GmbH. https://vasab.org/wp-content/uploads/2018/06/BalticLINes_CapacityDensityStudy_June2018-1.pdf.

Caudle, B. H., and P.G. McLeroy. (n.d.). Petroleum Production—Deepwater, Ultradeepwater, Drilling. Britannica. Accessed July 12, 2024. https://www.britannica.com/technology/petroleum-production/Deep-and-ultradeep-water.

Cooperman, A., P. Duffy, M. Hall, E. Lozon, M. Shields, and W. Musial. 2022. *Assessment of Offshore Wind Energy Leasing Areas for Humboldt and Morro Bay Wind Energy Areas, California*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-82341. https://www.nrel.gov/docs/fy22osti/82341.pdf.

Cooperman, A., M. Hall, S. Housner, C. Hein, P. Duffy, D. Mulas Hernando, and W. Musial. 2024. *Investigation of Challenges of Offshore Wind in Ultradeep Water*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-XXXX. https://www.nrel.gov/docs/fy22osti/XXXX.pdf (forthcoming).

DNV. 2016. Modelling Different Upstream Oil and Gas Operations. August 11, 2016. Accessed August 6, 2024. https://www.dnv.com/article/modelling-different-upstream-oil-and-gas-operations-207958/.

Hall, M., M. Biglu, S. Housner, K. Coughlan, M. Y. Mahfouz, and E. Lozon. 2024. Floating Wind Farm Layout Optimization Considering Moorings and Seabed Variations: Article No. 062038*. Journal of Physics: Conference Series* 2767(6). https://doi.org/10.1088/1742-6596/2767/6/062038.

Mulas Hernando, D., W. Musial, P. Duffy, and M. Shields. 2023. *Capacity Density Considerations for Offshore Wind Plants in the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-86933. https://www.nrel.gov/docs/fy24osti/86933.pdf.

U.S. Energy Information Administration (EIA). 2016. Offshore Oil Production in Deepwater and Ultra-deepwater Is Increasing. October 28, 2016. Accessed August 6, 2024. https://www.eia.gov/todayinenergy/detail.php?id=28552.

Zuckerman, G., A. Lopez, T. Williams, R. Green, and G. Buster. 2023. *Impacts of Siting Considerations on Offshore Wind Technical Potential in the United States*. U.S. Department of Energy Office of Scientific and Technical Information. https://doi.org/10.2172/1989233.

Supplemental Slides

Mooring System Types Suitable for Ultradeep Waters (Detailed text from Cooperman et al. 2024)

Type	Suitable?	Rationale
TLP	Yes	Tension-leg mooring configurations typically have a vertical or near-vertical inclination and are typically made with very stiff materials to restrain the platform from any appreciable motion along the taut-leg's axial direction. TLPs used in the offshore oil and gas industry have typically used steel pipe tendons for their high stiffness, although their significant weight and installation complexity means that other materials like strong synthetic ropes may be preferable for floating wind applications. The main challenge for tension-leg moorings in ultradeep water (analyzed in Section 6.1) is achieving sufficient stiffness over the water depth with cost-effective materials. Tension-leg moorings have unique advantages in that their vertical orientation avoids the space challenge of other configurations and has a smaller footprint within the water column.
Taut	Yes	Taut mooring systems consist primarily of synthetic fiber rope and rely on the rope's elasticity to provide the desired compliance and restoring stiffness on the platform. Taut polyester rope mooring systems are used in the oil and gas industry in ultradeep water depths. Common rope materials for floating wind applications are polyester and high-modulus polyethylene (HMPE), though other materials such as nylon and liquid-crystal polymers could also be considered. In contrast to the steel chain or wire used in catenary systems, synthetic fiber ropes are close to neutrally buoyant (they have approximately the same density as seawater), avoiding issues with weight. Taut mooring systems typically only have seabed contact near the anchor where the padeye can be below the mudline. A short section of chain is often used for any portions that touch the seabed to prevent abrasion that could occur if the rope made connect with the seabed. Steeper angles between the mooring line and the seabed allow for relatively short anchor radii, which are advantageous in deeper waters.
Semi-Taut	No	Semi-taut mooring configurations combine aspects of catenary and taut configurations. They typically consist of a fiber rope section that spans most of the water column and a chain section that connects to the anchor and lays some length along the seabed. The platform restoring stiffness is provided by a combination of the weight of the chain and the elasticity of the rope. Their anchor radii are typically somewhere between the anchor radius of a catenary and a taut mooring configuration. Semi-taut mooring configurations share many similarities with taut configurations for ultradeep water because the taut rope portion will be sized in accordance with the water depth, while the chain portion would generally not change in size. The main differences in a semi-taut configuration are that the chain will require a moderately larger anchor radius than the taut mooring and provide some additional compliance (or stiffness reduction) to the mooring system. In shallower areas semi-taut configurations can use low-cost drag embedment anchors, but in ultradeep water these anchors would require more time to install and result in less precise positioning. As a result, semi-taut configurations, while feasible, **appear more challenging than taut configurations.**
Catenary	No	Catenary mooring configurations typically consist of steel chain—potentially with added sections of steel wire rope—and provide stability to a floating platform based on their weight and curved profile. They require some amount of chain to remain on the seabed to avoid extreme anchor loads, and therefore require a relatively large anchor radius (the horizontal distance from platform center to the anchor). At ultradeep depths, the weight of catenary mooring configurations is problematic in terms of both line tensions and burden on the floating platform. Previous NREL analyses have indicated excessive weight at 1000 m depth, meaning greater depths are even less suitable. With the additional challenges of fatigue life, high cost, and limited production capacity for large amounts of steel components, catenary mooring configurations can be **considered inapplicable to ultradeep waters**.