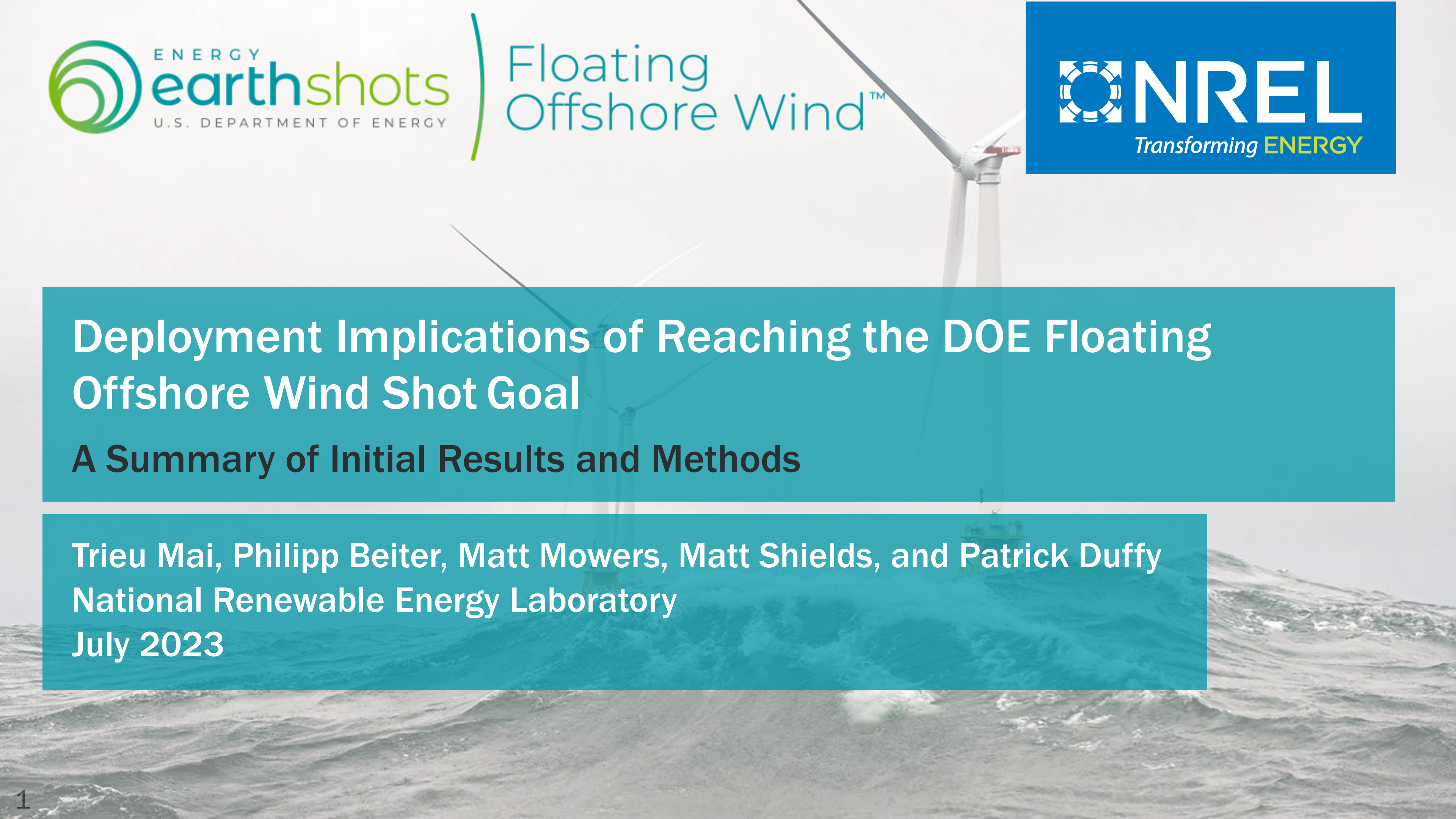


ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Floating Offshore Wind™

NREL Transforming ENERGY

Deployment Implications of Reaching the DOE Floating Offshore Wind Shot Goal

A Summary of Initial Results and Methods

Trieu Mai, Philipp Beiter, Matt Mowers, Matt Shields, and Patrick Duffy
National Renewable Energy Laboratory
July 2023

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Floating Offshore Wind™

The *Floating Offshore Wind Shot* will drive U.S. leadership in floating offshore wind design, manufacturing, and deployment to decarbonize our economy and revitalize our coastal economies.

Reduce the cost of floating offshore wind electricity by >70% in deep waters by 2035[1]

>70% Reduction

2035

The Bureau of Ocean Energy Management (BOEM) also announced an associated deployment goal of 15 gigawatts (GW) floating offshore wind by 2035.

---

[1] 70% cost reduction to $45 per megawatt hour (MWh) (in $2021).

1. The Floating Offshore Wind Shot Goal of $45/MWh

Method for Deriving $45/MWh by 2035

NREL analyzed a DOE Floating Offshore Wind Shot cost goal of $45 per megawatt-hour (MWh)[2] by 2035 (from the 2023 levels of $150/MWh) that can be attained through dedicated research and development.

Steps

1. Calculated a learning rate of 11.5% from global fixed-bottom offshore wind project cost data (Shields et al. 2022)
2. Estimated floating offshore wind LCOE as of 2023 through bottom-up cost modeling for multi-turbine-scale reference site
3. Derived assumptions about future global floating offshore wind deployment through 2035 (see Appendix)
4. Starting with the LCOE as of 2023 (Step 2), calculated annual cost reductions by combining the learning rate (Step 1) with the assumed global floating deployment (Step 3) to derive an LCOE for years 2023–2035.

Learning rate

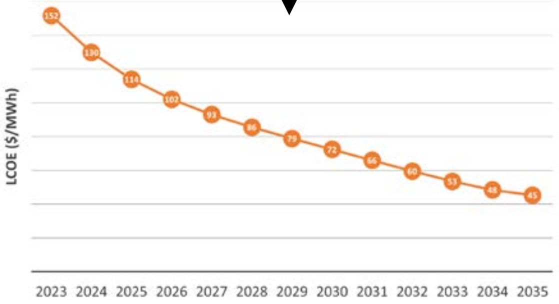
↓

$150/MWh in 2023

↓

31 GW floating by 2035

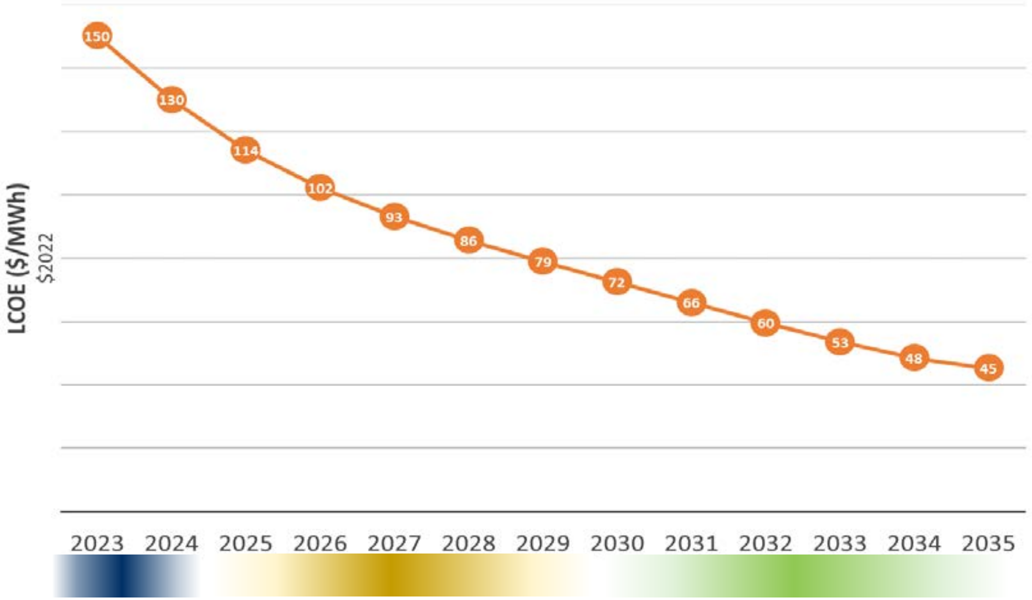
↓



---

[2] Denoted in 2021 dollars

The Floating Offshore Wind Shot Goal of $45/MWh by 2035



Multi-turbine demonstrations

Domestic supply chain formation
Transmission system expansion

Gigawatt-scale clusters
Serial manufacturing

LCOE = levelized cost of energy

Key Assumptions

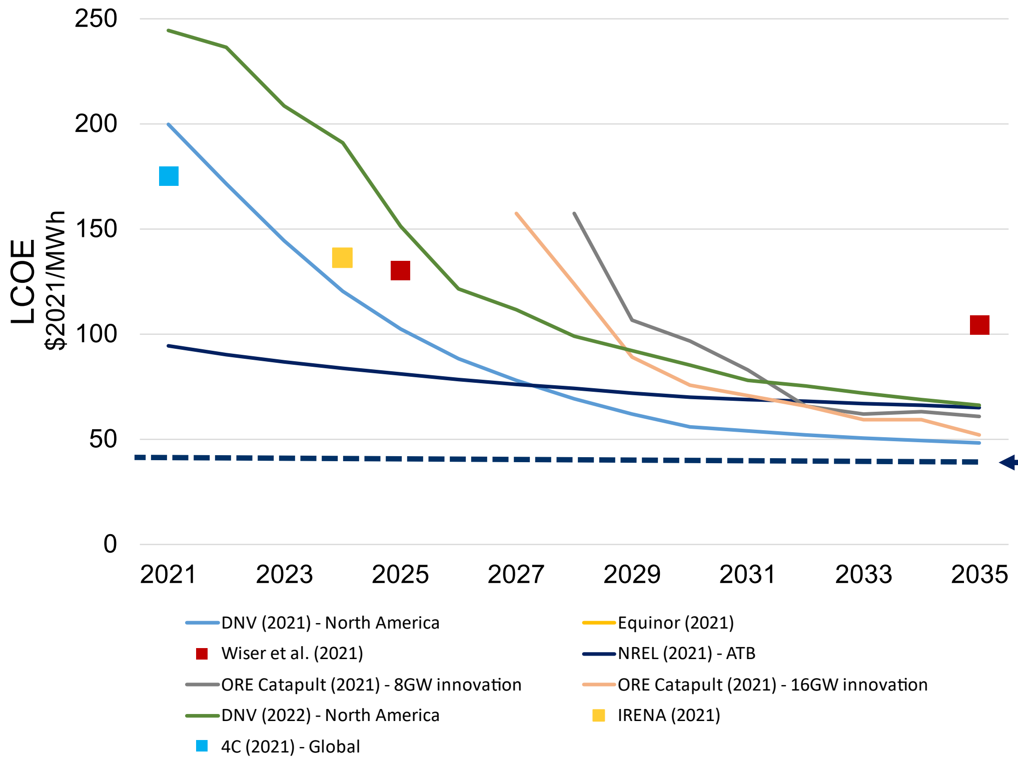
- **Generic reference site**
  - 1,000 meters (m) water depth[3]
  - 125 kilometers (km) from interconnection[4]
  - Net capacity factor of 46% in 2023.
- **The cost goal of $45/MWh is denoted in 2021 dollars (i.e., in constant dollar terms)**
- **Costs as of 2023 represent multi-turbine demonstrator project scale**
- **Cost trajectory assumes >30 GW of global floating offshore wind deployment by 2035**
- **Achieving target depends on full supply chain and transmission development**
- **Learning and technology transfer from fixed-bottom offshore wind sector.**

---

[3] Note that the reference site is defined for 1,000 m water depth; the resource assessment (Lopez et al. 2022) used for the Floating Offshore Wind Shot Regional Energy Deployment System (ReEDS™) analysis extends to a water depth of 1,300 m.

[4] The goal of $45/MWh includes expenditures for an export system cable from the site to the point of interconnection, an offshore converter station, and onshore substation upgrades.

Cost Goal Falls Below LCOE Typically Estimated for Floating Offshore Wind

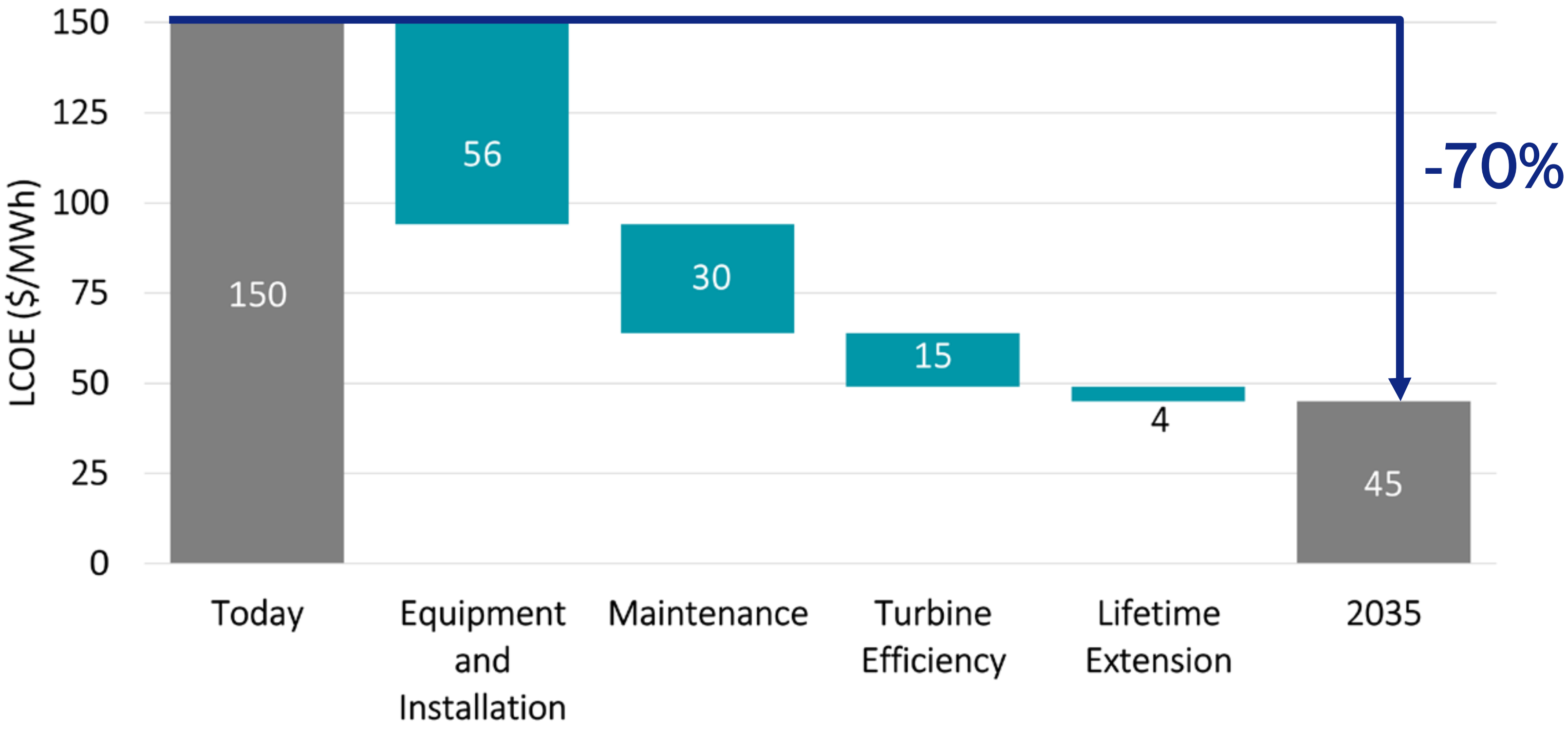


Floating Offshore Wind Shot target of $45/MWh

- The depicted cost estimates assume less challenging site conditions than the Floating Offshore Wind Shot reference site, which means that the goal is even more ambitious than this LCOE comparison suggests.

Figure Source: Musial et al. (2022). OWDB = Offshore Wind Database; GWEC = Global Wind Energy Council; BNEF = Bloomberg New Energy Finance; IRENA = International Renewable Energy Agency

Key Technical Cost Drivers To Attain $45/MWh



Key Technical Cost Drivers To Attain $45/MWh

- Enable use of increasingly more efficient and larger wind turbines through integrated turbine and floating platform system designs, components, and controls
- Develop serial manufacturing practices in domestic manufacturing facilities
- Advance systems engineering and controls co-design to reduce weight, increase efficiency, and reduce costs
- Support the development of new mooring, anchoring, dynamic cables, and floating substation concepts for deepwater deployment
- Develop operations and maintenance strategies and increase wind turbine reliability to reduce periods of nonoperation and reduce labor at sea through remote system health monitoring, inspection, and maintenance capabilities.

Source: DOE (2023)

2. Deployment Impacts of Attaining the Floating Offshore Wind Shot Goal

Objectives of Impacts Analysis

Across all major U.S. coastal areas, estimate the economic potential and deployment implications of achieving the Floating Offshore Wind Shot goal.

We seek to answer the following analysis questions:

1. How would achieving the Floating Offshore Wind Shot goal change the costs of floating offshore wind energy across all possible sites in the contiguous United States?
2. What is the economic potential of floating offshore wind energy in the mid-2030s and in 2050 if the Floating Offshore Wind Shot goal were achieved?
3. What estimated future deployment levels in the United States are consistent with achieving the Floating Offshore Wind Shot goal?
4. How would floating offshore wind energy deployment change when using cost assumptions based on the Floating Offshore Wind Shot goal?

Key Limitations and Caveats

- Estimates of economic potential reflect static snapshots of power market prices and project revenues; ultimately, the market potential (i.e., what might get deployed) will be less than the economic potential.
- The analysis relies on a single future scenario; different scenario assumptions would yield different outcomes.
- General limitations of capacity expansion modeling are applicable (see Ho et al. 2021; Beiter et al. forthcoming).
- Focus of the Regional Energy Deployment System (ReEDS™) study is on the electricity sector with limited representation of other energy sectors.

1. How would achieving the Floating Offshore Wind Shot goal change the costs of floating offshore wind energy across all possible sites in the contiguous United States?

Translating the Floating Offshore Wind Shot Goal From the Reference Site to All Potential Floating Sites

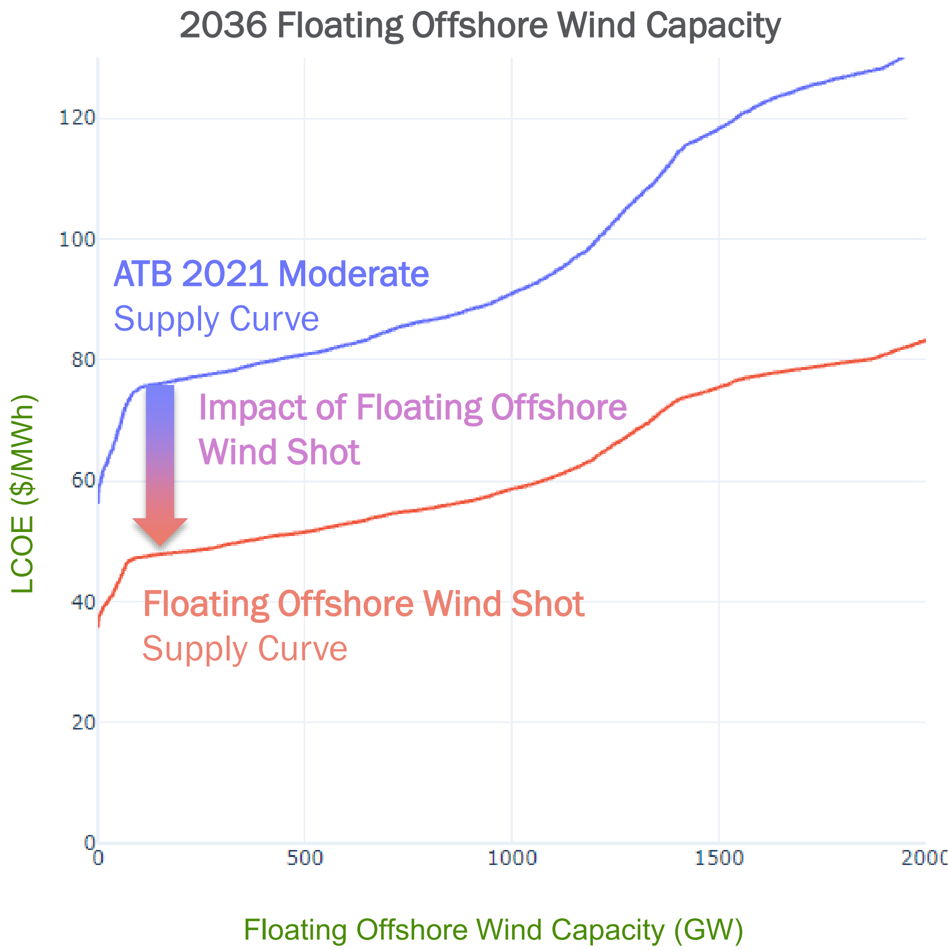
- The $45/MWh by 2035 Floating Offshore Wind Shot cost target is for a reference site (1,000 m water depth, 125 m from shore, 46% capacity factor).
- We identified sites from the Renewable Energy Potential (reV) supply curve that correspond to the spatial parameters of the reference site (i.e., water depth, distance to shore, wind speed).
- Comparing the Floating Offshore Wind Shot costs with the projected costs for 2035 (from Annual Technology Baseline [ATB] 2021 Moderate [NREL 2021]) for all potential floating sites yields an understanding of the incremental impact of the DOE Floating Offshore Wind Shot.

Achieving the Floating Offshore Wind Shot goal is roughly equivalent to plant and grid connection ***capital cost reductions of 33% and capacity factor improvements of 25%*** in 2035 beyond improvements that might otherwise occur (i.e., those already represented in ATB 2021 Moderate).

We assume no impact on operations and maintenance costs for this analysis to simplify the representation of floating costs in ReEDS. Note that other LCOE reduction pathways are also possible. Economic potential and deployment estimates are not expected to be substantially impacted by different pathways.

Floating Offshore Wind Shot Lowers Costs for All Floating Sites (2036)

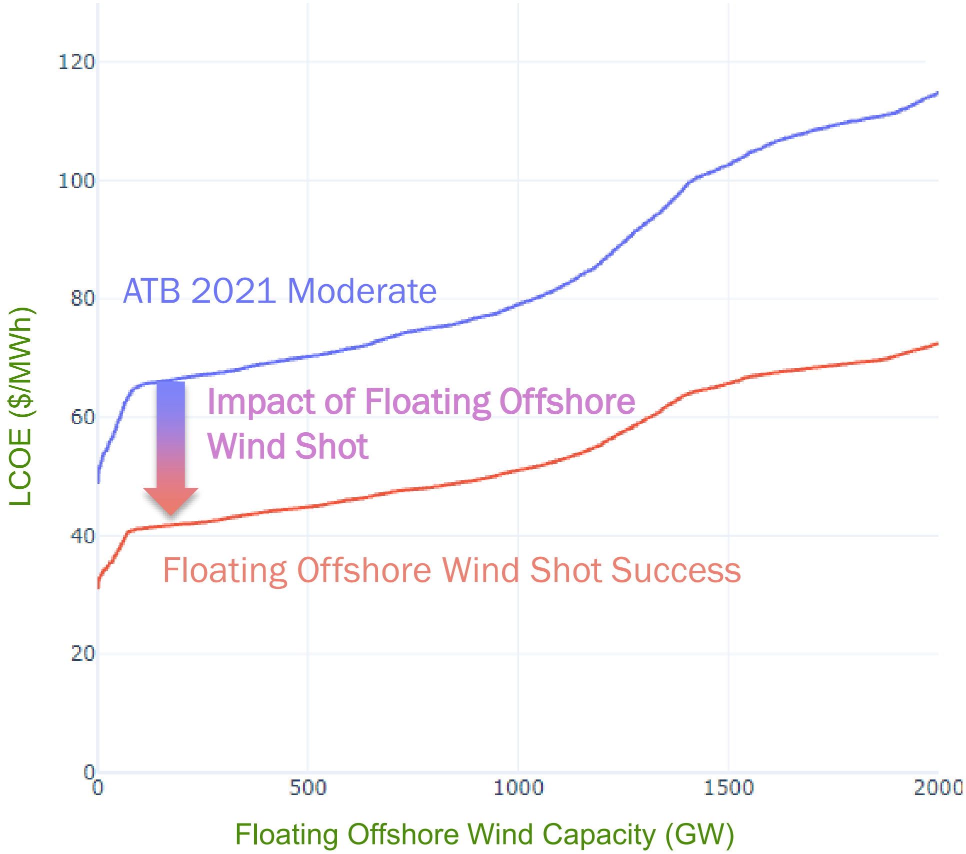
- A supply curve as depicted here ranks sites from lowest to highest LCOE in a given year.
- Without the Floating Offshore Wind Shot, LCOE in the mid-2030s is expected to remain above $70/MWh in all non-Pacific regions, and only a few Pacific sites would have LCOE slightly below $60/MWh (see Appendix for details).
- Applying the incremental capital cost reductions (−33%) and capacity factor improvements (+25%) to all sites shifts the floating offshore wind supply curve down and slightly flattens the curve.
- Achieving the Floating Offshore Wind Shot goal would yield 60 GW of estimated floating offshore wind with LCOE ≤ $45/MWh.



Floating Offshore Wind Shot Lowers Costs for All Floating Sites (2050)

- Applying the same Floating Offshore Wind Shot incremental percentage improvements to future (post-2036) years would further expand the amount of low-cost floating offshore wind energy resource.
- Floating Offshore Wind Shot is estimated to result in more than 500 GW of floating offshore wind energy with LCOE ≤ $45/MWh by 2050.
- Caveat: Relative improvements (on a percentage basis) could decline over time if some innovations through the DOE Floating Offshore Wind Shot act as an accelerant to technology advancements.

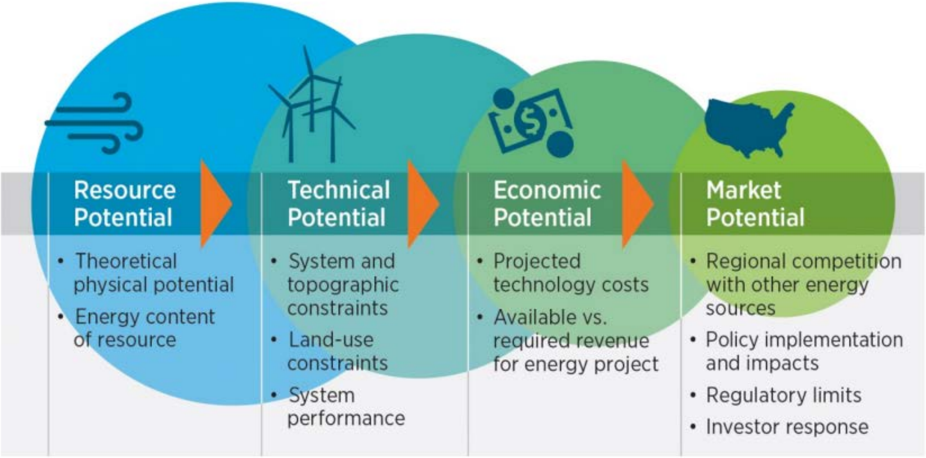
2050 Floating Offshore Wind Capacity



2. What is the economic potential of floating offshore wind energy in the mid-2030s and in 2050 if the Floating Offshore Wind Shot goal were achieved?

Economic Potential Is a Subset of a Resource’s Technical Potential With Costs Below a Specified Revenue Threshold

- **Economic potential < technical potential**
  - Floating offshore wind technical potential = 2.8 TW in U.S. waters (Lopez et al. 2022).
- **Market potential < economic potential**
  - Deployment affects market prices and project revenue
  - Demand can limit market potential
  - Only grid value considered; other factors (e.g., local economic development) can impact market potential.
- **“Reduced costs” from modeled scenarios inform the threshold for economic potential**
  - Reduced cost = the amount a resource cost needs to be lowered for economic viability; the cost premium is referred to as “reduced cost”
  - Offshore wind cost premium in scenarios inform the economic potential enabled by the Floating Offshore Wind Shot target
  - Reduced costs vary by site, year, and scenario and the characteristics of the technology (e.g., generation profile).



Resource Potential
- Theoretical physical potential
- Energy content of resource

Technical Potential
- System and topographic constraints
- Land-use constraints
- System performance

Economic Potential
- Projected technology costs
- Available vs. required revenue for energy project

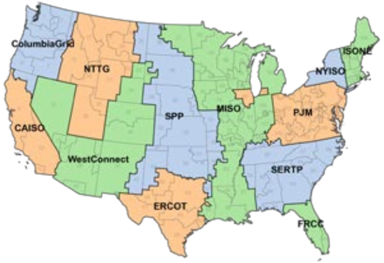
Market Potential
- Regional competition with other energy sources
- Policy implementation and impacts
- Regulatory limits
- Investor response

Brown et al. (2016)

Analysis Is Based on a Single "Reference" Condition; Results Are Sensitive to Alternative Scenario Choices

Reference conditions:

- **Tech costs:** ATB 2021 Moderate projections for all technologies, 30% offshore Investment Tax Credit (ITC) through 2035[5]
- **National carbon emissions constraint:** 80% reduction by 2035 (from 2005 levels) and 95% by 2050
- **Demand:** High load growth assumption from the "Electrification Futures Study" (EFS) High scenario (Mai et al. 2018)
- **Renewable energy siting:** Assumes considerable siting constraints for renewables – "Limited access" land-based wind and utility photovoltaics (PV) (Lopez et al. 2021)
- **Transmission:** New transmission allowed within each of 12 regions only (see map)
- **Tech availability:** No carbon capture and storage or nuclear small-modular reactors
- **State offshore targets:** Does not include aspirational offshore targets for California and Oregon.
- **Wind resource representation:** Site-specific and hourly capacity factor for more than 8,000 locations (10.6-km resolution)



Nonstandard assumptions for ReEDS (Cole et al. 2021)

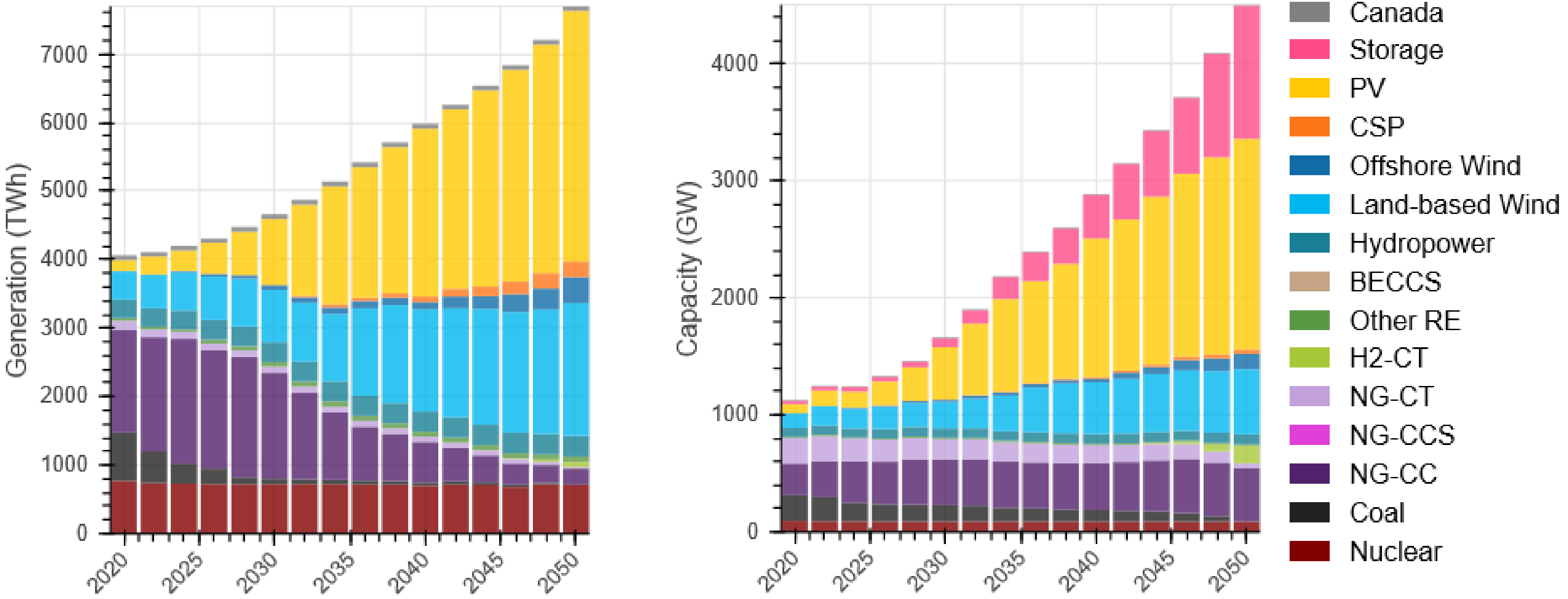
Changing these assumptions would change the economic case for offshore wind. For example, relaxing onshore siting and transmission constraints could adversely affect offshore wind's economic viability. Conversely, more stringent conditions (e.g., 100% carbon-free electricity) could expand economically viable floating offshore capacity. These scenarios also do not include H_2 demand for transportation and industry.

---

[5] This analysis was conducted before the passage of the Inflation Reduction Act of 2022

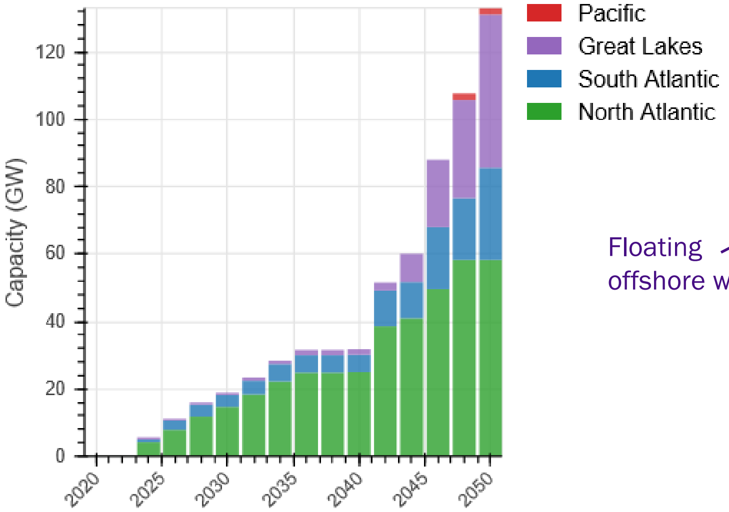
Limited Floating Offshore Wind of 2 GW Projected in the Absence of the Floating Offshore Wind Shot

In the scenario shown, floating offshore wind costs represent a “business as usual” scenario and fall above the DOE Floating Offshore Wind Shot cost target.

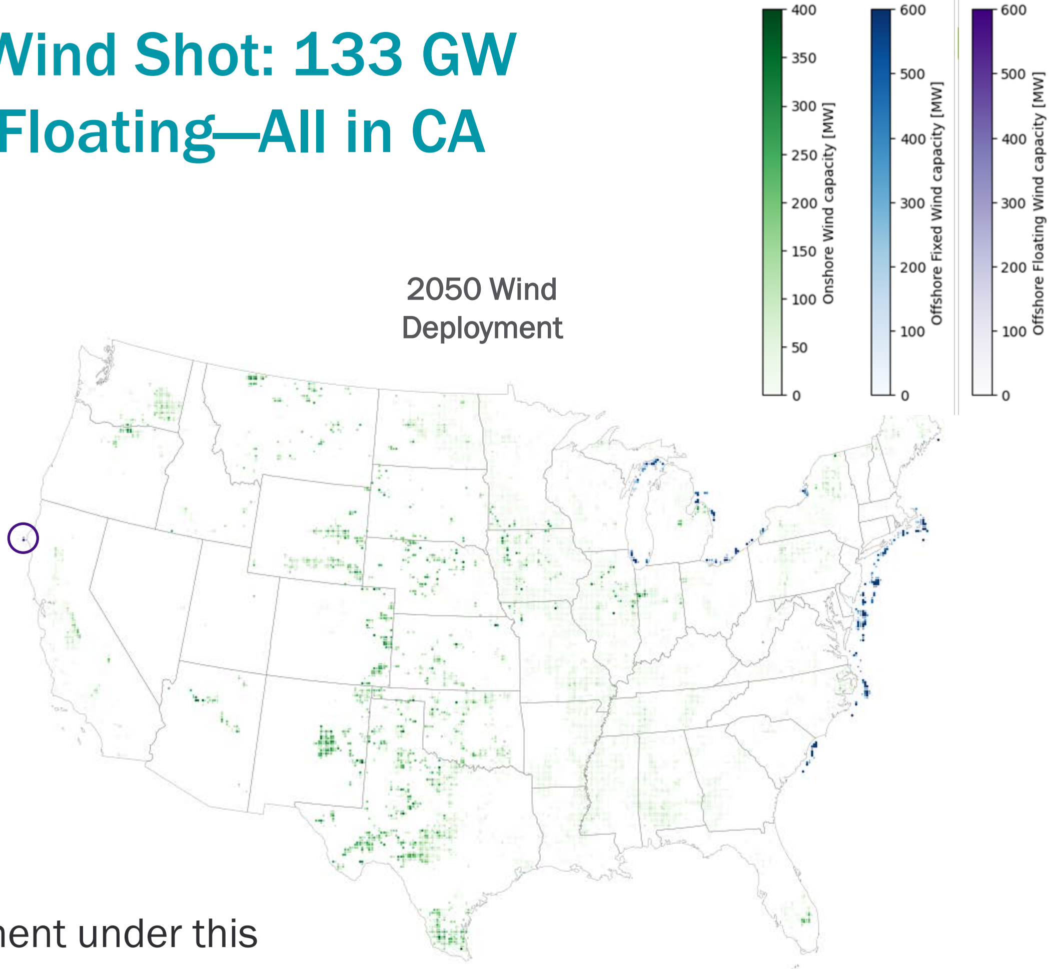


PV = photovoltaics; CSP = concentrating solar power; BECCS = bioenergy with carbon capture and sequestrations; H2 = hydrogen; NG = natural gas; CT = combustion turbine; CC = combined cycle; CCS = carbon capture and sequestration

Without Floating Offshore Wind Shot: 133 GW Total Offshore Wind, 2 GW Floating—All in CA



Floating offshore wind


2050 Wind Deployment

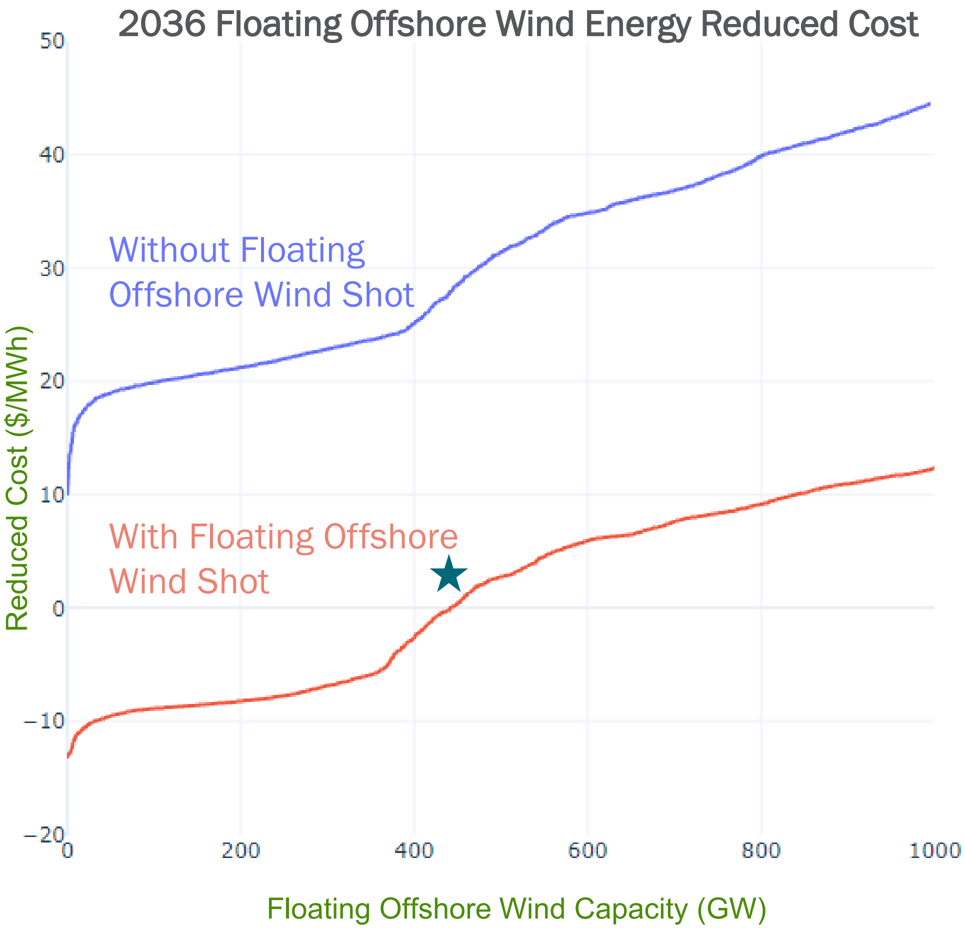
- The limited floating offshore wind deployment under this scenario does not represent the aspirational offshore targets set by California and Oregon (see Slide 19).

Economic Potential: 2036

- Lowering costs of floating offshore wind energy by ~$10/MWh would enable additional capacity beyond the 2 GW (estimated in the scenario without the Floating Offshore Wind Shot) to become economically viable during the mid-2030s in the modeled scenario.

- Floating Offshore Wind Shot cost and performance advancements would lower the reduced cost[6] to <$0/MWh for over 400 GW.

Achieving Floating Offshore Wind Shot would expand the floating offshore wind economic potential to 400+ GW in the mid-2030s.



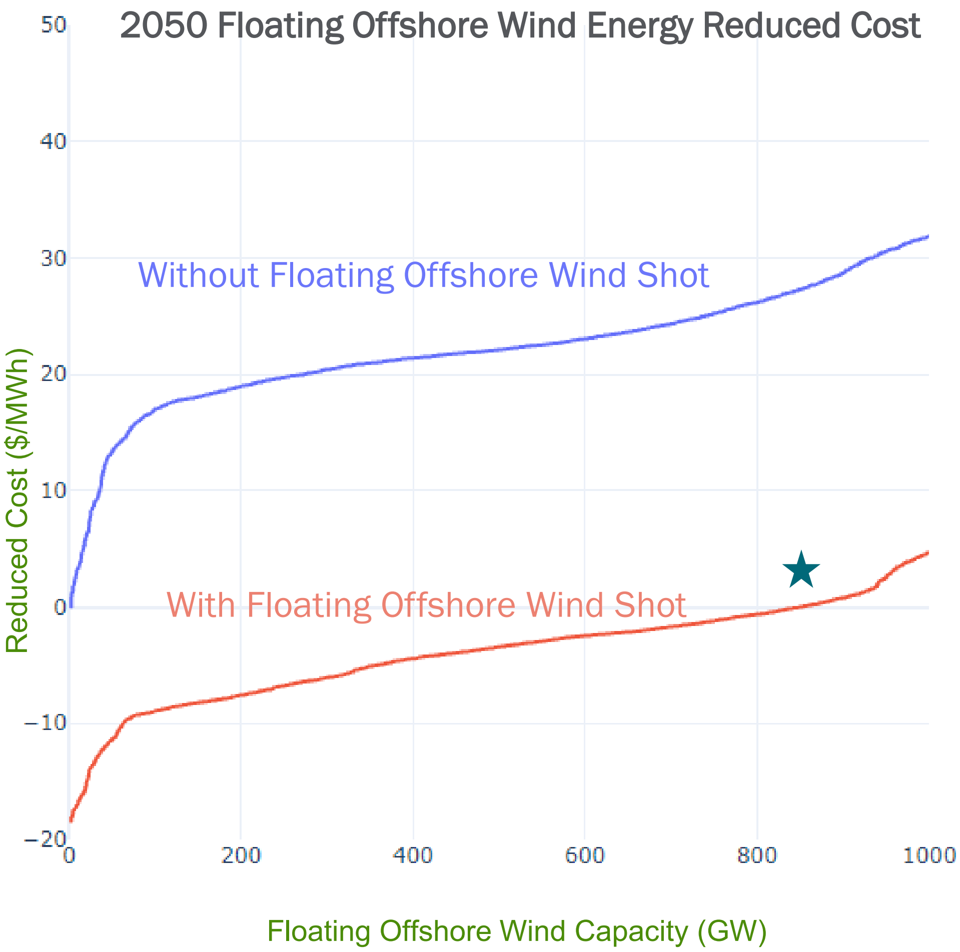
---

[6] The "reduced cost" in this context is that the offshore wind cost premium in scenarios inform the economic potential enabled by the Floating Offshore Wind Shot target

Economic Potential: 2050

- Without the Floating Offshore Wind Shot, economic deployment of floating offshore wind starts in 2050 but with limited overall deployment (2 GW in CA).
- Floating Offshore Wind Shot enables many more floating wind sites to become economically viable if we assume the same percentage reductions relative to the ATB 2021 baseline projections.

Achieving Floating Offshore Wind Shot would expand the floating offshore wind economic potential to 800+ GW by 2050.

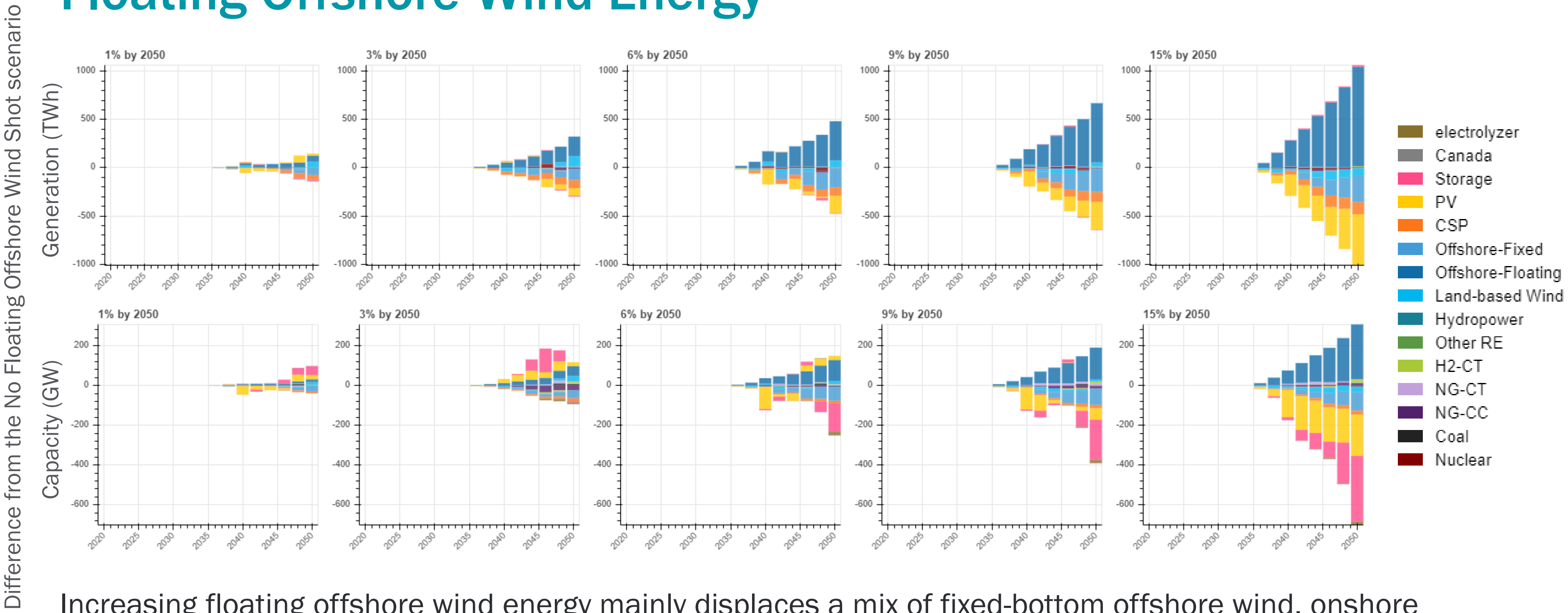


3. What estimated future deployment levels are consistent with achieving the Floating Offshore Wind Shot goal?

Approach

- In least-cost planning models, there exists an equilibrium between a technology's costs and its deployment level, e.g., lowering technology costs would yield greater estimated deployment.
- This equilibrium point can also be identified by prescribing a desired generation level and backing out the "required cost" that the technology needs to achieve that level of deployment. This method takes into account the location, variability, and all other characteristics of the technology (see Mai et al. [2019] for details on the method).
- Our approach applies this method using scenarios that force an increasing amount of floating offshore wind generation. Scenarios with 1%, 3%, 6%, 9%, and 15% of 2050 U.S. electricity generation from floating offshore technologies are modeled, and the required cost of floating offshore wind is identified.

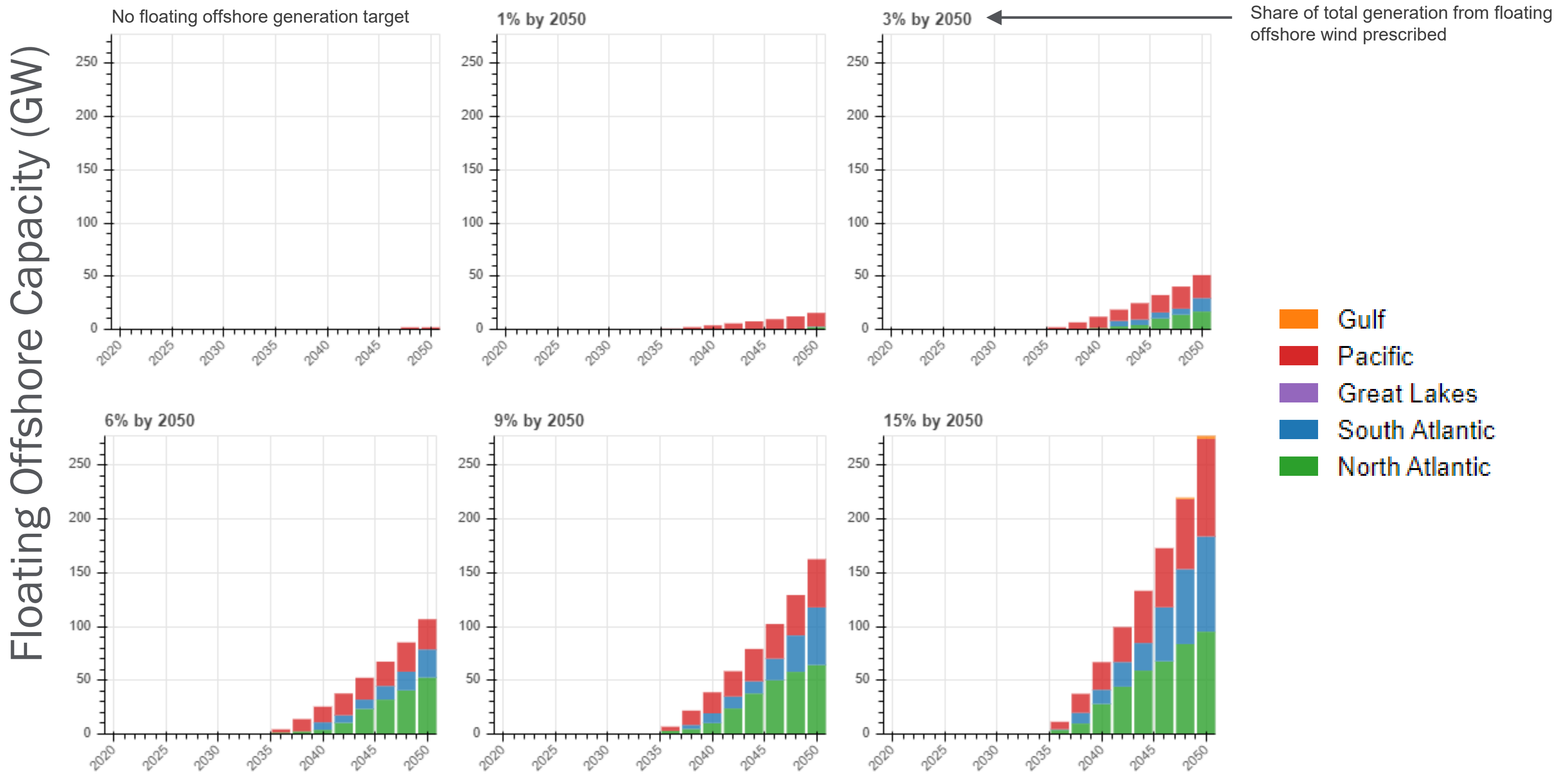
Approach: Prescribe Increasing Generation Shares From Floating Offshore Wind Energy



Increasing floating offshore wind energy mainly displaces a mix of fixed-bottom offshore wind, onshore wind, solar, and storage. Note that these scenarios assume ATB 2021 Moderate costs; the Floating Offshore Wind Shot would possibly yield some technology improvements for all wind technologies.

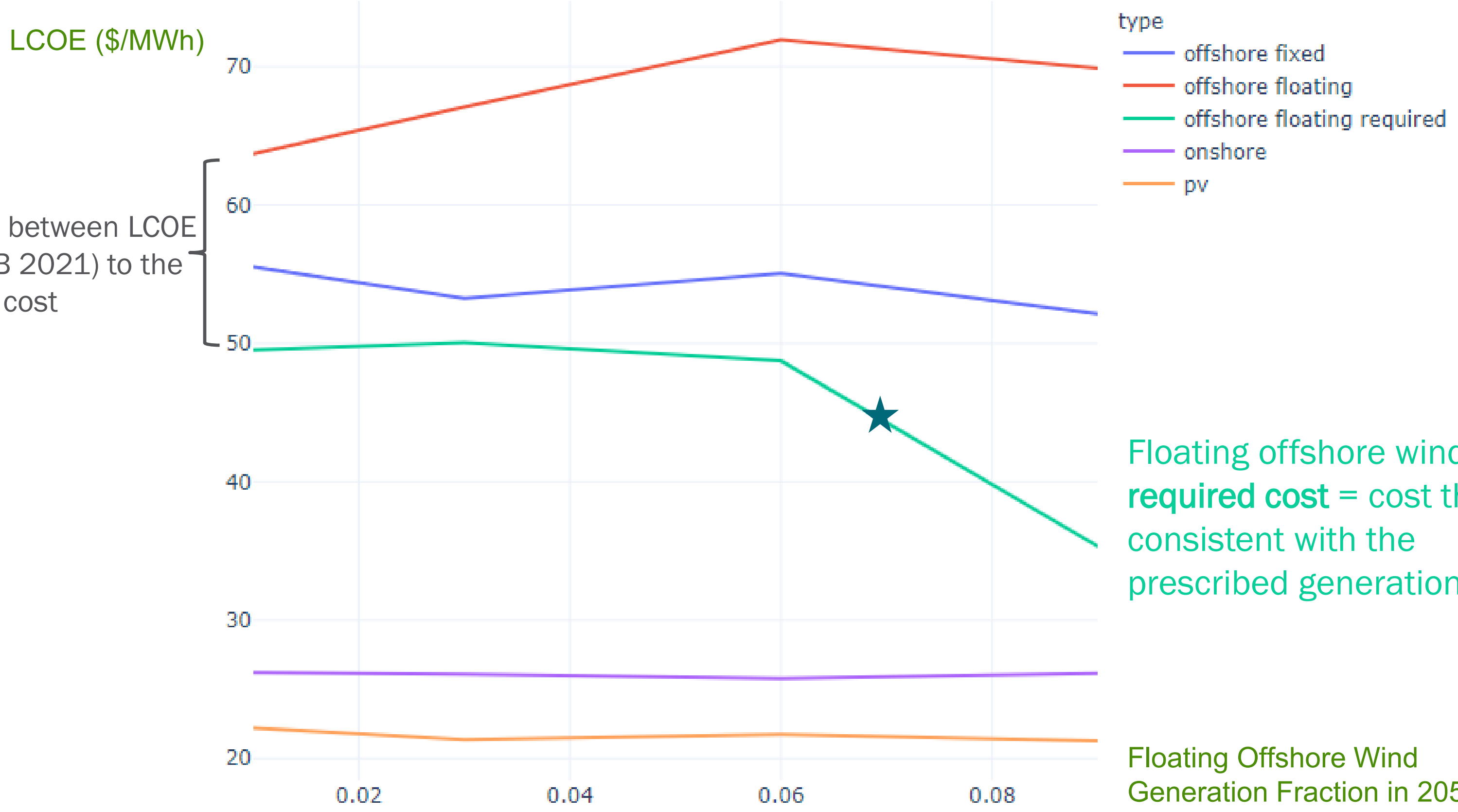
Scenarios With Greater Amounts of Floating Offshore Wind Lead to More Geographically Diverse Deployment

Varying shares of floating offshore wind of total U.S. generating capacity and its regional representation.



Required Costs in 2050 for Different Shares of Floating Offshore Wind From Total System Generation

Cost gap between LCOE (from ATB 2021) to the required cost



Floating offshore wind **required cost** = cost that is consistent with the prescribed generation level

4. How would floating offshore wind energy deployment change with cost assumptions based on the Floating Offshore Wind Shot goal?

Approach

We modeled three scenarios that all use the same reference assumptions (Slide 19) except for wind technologies, which differ by achievement of the Floating Offshore Wind Shot cost targets:

1. No Floating Offshore Wind Shot

Costs of floating offshore wind correspond to the “reference” scenario (i.e., ATB 2021 Moderate).

2. Floating Offshore Wind Shot

Lower floating offshore wind costs that correspond to the Floating Offshore Wind Shot cost goal.[1]

3. Floating Offshore Wind Shot Extended

The cost reduction effects of the Floating Offshore Wind Shot extend to fixed-bottom and land-based wind energy.[2]

---

[1] Only capital costs of fixed-bottom and land-based wind are adjusted, but they represent the combined impact of cost reductions and performance improvements. For floating technologies, we assume capital costs are ~47% lower than ATB 2021 Moderate for all years after 2035 for the “Floating Offshore Wind Shot” and “Floating Offshore Wind Shot Extended” sensitivities.

47% cost reductions reflect ATB costs × 8/15, where 8/15 = 2/3 × 4/5 (2/3 from capital costs and 4/5 representing 25% higher capacity factor).

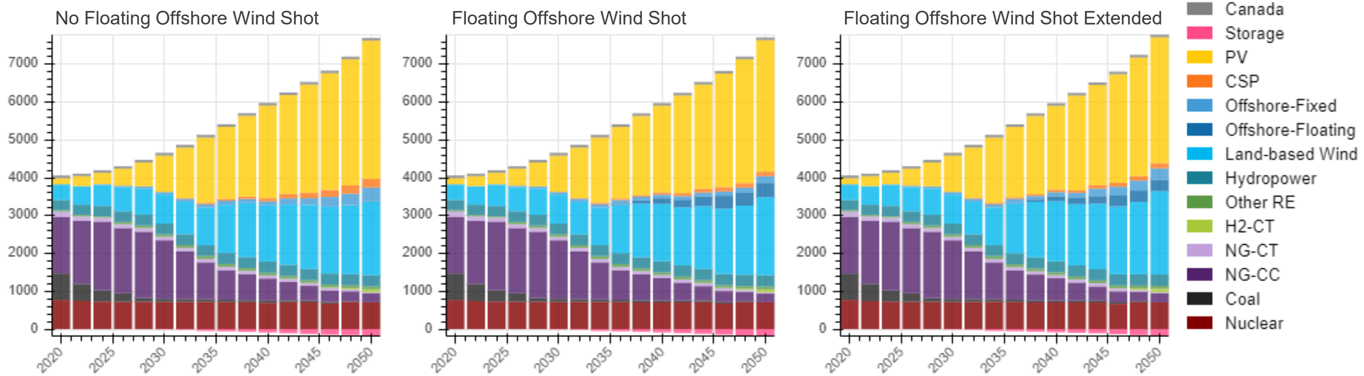
[2] For the “Floating Offshore Wind Shot Extended” sensitivity, we assume fixed-bottom offshore wind and land-based wind respectively achieve half and a quarter the cost reductions as floating (i.e., ~23% lower than ATB for fixed-bottom, ~12% lower for land-based).

Floating Offshore Wind Generation Compared to Other Technologies

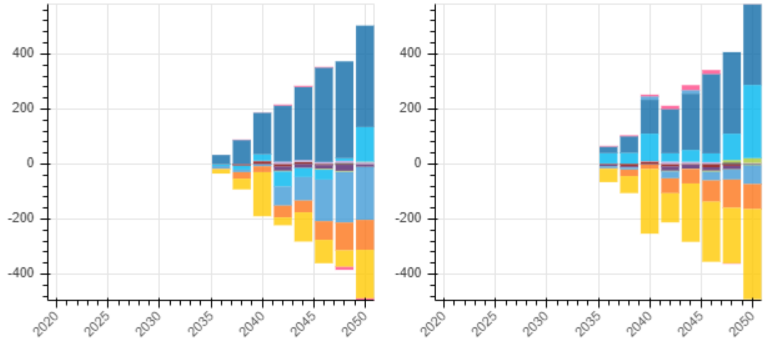
ATB 2021 Moderate

Only floating reductions (~47%)

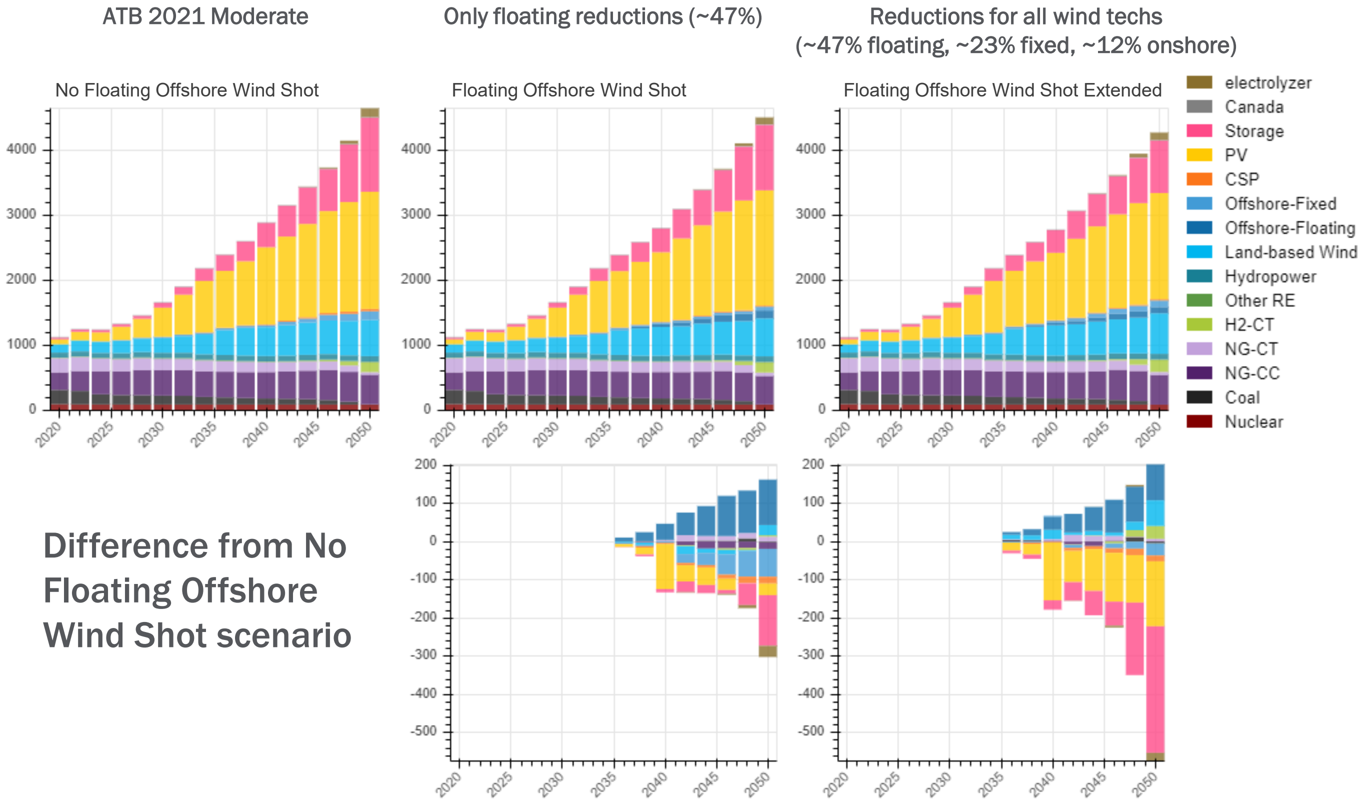
Reductions for all wind techs
(~47% floating, ~23% fixed, ~12% onshore)



Difference from No Floating Offshore Wind Shot scenario



Floating Offshore Wind Capacity Compared to Other Technologies


ATB 2021 Moderate

Only floating reductions (~47%)

Reductions for all wind techs
(~47% floating, ~23% fixed, ~12% onshore)

Difference from No Floating Offshore Wind Shot scenario

Wind Capacity Under the Floating Offshore Wind Shot Scenarios

2040 | 2050 (GW)	No Floating Offshore Wind Shot	Floating Offshore Wind Shot	Floating Offshore Wind Shot "Extended"
Onshore	442 | 556	443 | 583	467 | 623
Fixed	32 | 131	28 | 58	34 | 100
Floating	0 | 2	42 | 121	34 | 96
All Offshore	32 | 133	70 | 179	68 | 196
All Wind	474 | 689	513 | 762	535 | 819

Initial Conclusions

- NREL analyzed a floating offshore wind cost of $45 per MWh by 2035 as a highly ambitious yet attainable DOE Floating Offshore Wind Shot goal; this cost level falls below LCOE typically estimated for floating offshore wind.
- Achieving the Floating Offshore Wind Shot goal could yield 96–121 GW of floating offshore wind capacity by 2050.
- We found very limited floating offshore wind deployment of 2 GW projected by 2050 in the absence of the DOE Floating Offshore Wind Shot. This limited deployment does not take into account the aspirational offshore wind goals by U.S. states (e.g., CA and OR).
- Increasing floating offshore wind energy mainly displaces a mix of fixed-bottom offshore wind, land-based wind, solar, and storage.

References

References

Beiter, P., T. Mai, M. Mowers, J. Bistline. Forthcoming. “Expanded Modeling Scenarios Show an Important Role for Offshore Wind in Decarbonizing the United States.” In peer review.

Brown, Austin, Philipp Beiter, Donna Heimiller, Carolyn Davidson, Paul Denholm, Jennifer Melius, Anthony Lopez, Dylan Hettinger, David Mulcahy, and Gian Porro. 2016. *Estimating Renewable Energy Economic Potential in the United States. Methodology and Initial Results*. Golden, CO: National Renewable Energy Laboratory NREL/TP-6A20-64503. https://doi.org/10.2172/1215323.

Cole, Wesley, Vincent Carag, Maxwell Brown, Patrick Brown, Stuart Cohen, Kelly Eurek, Will Frazier, et al. 2021. *2021 Standard Scenarios Report: A U.S. Electricity Sector Outlook*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-80641. https://www.nrel.gov/docs/fy22osti/80641.pdf.

Ho, Jonathan, Jonathon Becker, Maxwell Brown, Patrick Brown, Ilya Chernyakhovskiy, Stuart Cohen, and Wesley Cole. 2021. *Regional Energy Deployment System (ReEDS) Model Documentation: Version 2020*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-78195. https://www.nrel.gov/docs/fy21osti/78195.pdf.

Lopez, Anthony, Trieu Mai, Eric Lantz, Dylan Harrison-Atlas, Travis Williams, and Galen Maclaurin. 2021. “Land Use and Turbine Technology Influences on Wind Potential in the United States.” *Energy* 223 (May): 120044. https://doi.org/10.1016/j.energy.2021.120044.

Lopez, Anthony, Rebecca Green, Travis Williams, Eric Lantz, Grant Buster, Billy Roberts. 2022. “Offshore Wind Energy Technical Potential for the Contiguous United States.” Presentation, August 15, 2022. https://www.nrel.gov/docs/fy22osti/83650.pdf.

Mai, Trieu, John Bistline, Yinong Sun, Wesley Cole, Cara Marcy, Chris Namovicz, and David Young. 2018. “The Role of Input Assumptions and Model Structures in Projections of Variable Renewable Energy: A Multi-Model Perspective of the U.S. Electricity System.” *Energy Economics* 76 (October): 313–324. https://doi.org/10.1016/j.eneco.2018.10.019.

Mai, Trieu, Wesley Cole, Andrew Reimers. 2019. “Setting Cost Targets for Zero-Emission Electricity Generation Technologies.” *Applied Energy* 250 (15): 582–592. https://www.sciencedirect.com/science/article/abs/pii/S0306261919308542.

National Renewable Energy Laboratory. 2021. “2021 Annual Technology Baseline.” https://atb.nrel.gov/.

National Renewable Energy Laboratory. 2019. “The Renewable Energy Potential (reV) Model: A Geospatial Platform for Technical Potential and Supply Curve Modeling” NREL Technical Report. https://www.nrel.gov/docs/fy19osti/73067.pdf.

References

Shields, Matt, Philipp Beiter, and Jake Nunemaker. 2022. “A Systematic Framework for Projecting the Future Cost of Offshore Wind Energy.” Technical Report NREL/TP-5000-81819. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy23osti/81819.pdf.

U.S. Department of Energy. 2023. “Advancing Offshore Wind Energy in the United States, U.S. Department of Energy Strategic Contributions Toward 30 Gigawatts and Beyond.” https://www.energy.gov/sites/default/files/2023-03/advancing-offshore-wind-energy-full-report.pdf.

Appendix

Deployment Forecasts for Floating Offshore Wind

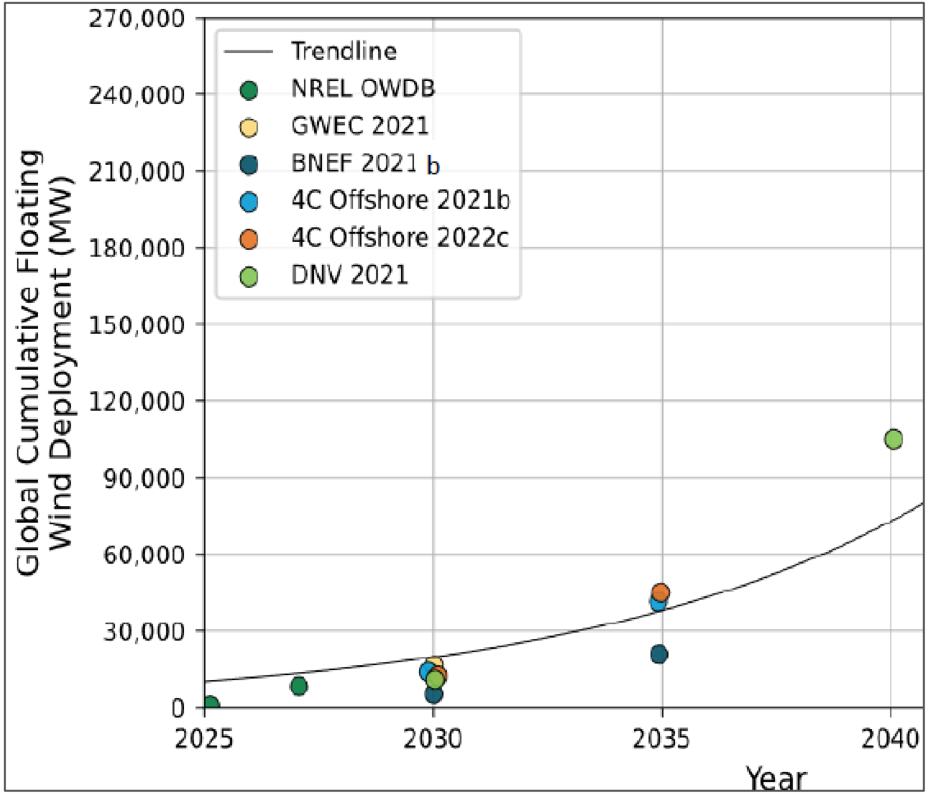
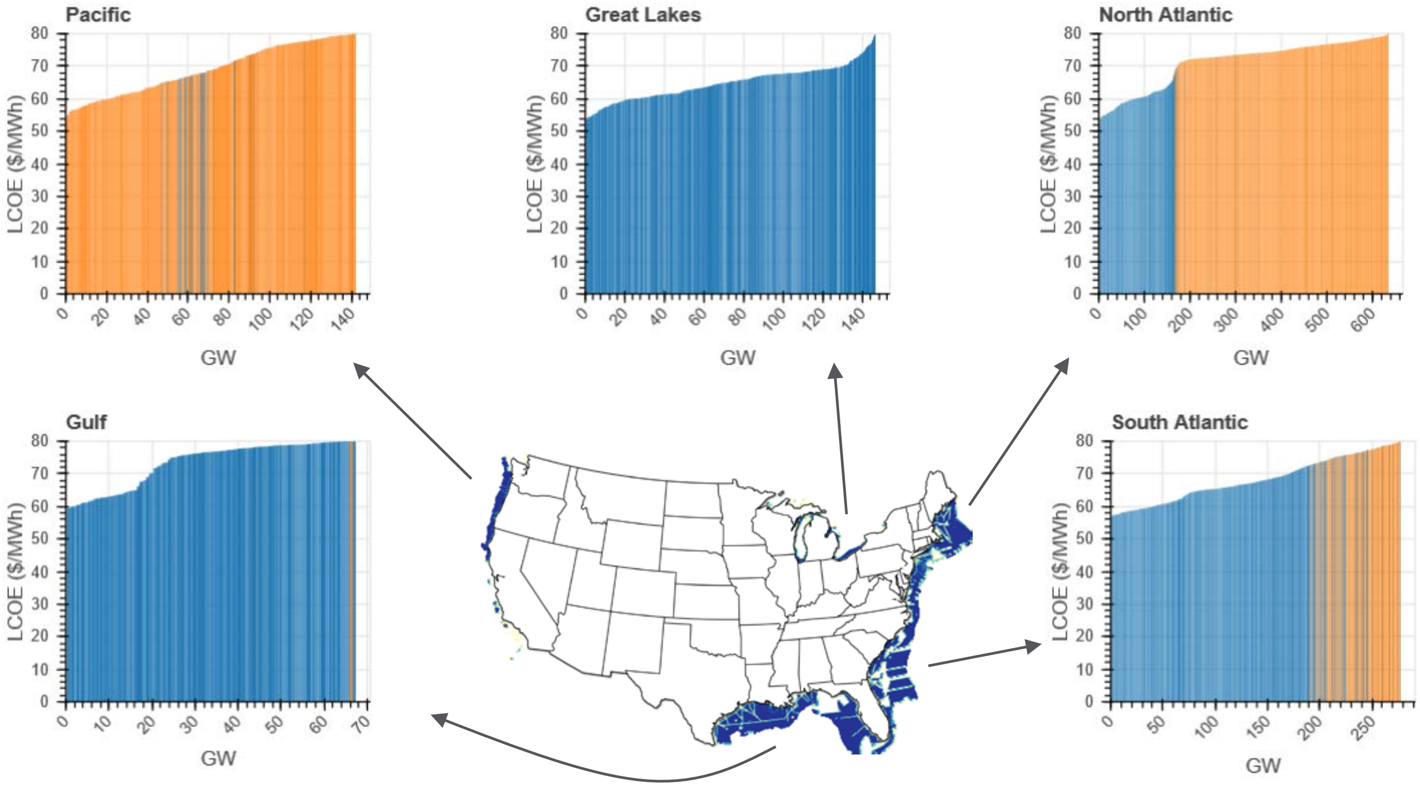


Figure Source: Musial et al. (2022) Notes: OWDB = Offshore Wind Database; GWEC = Global Wind Energy Council; BNEF = Bloomberg New Energy Finance

Baseline Projected Offshore Wind Costs for 2040 (Without Floating Offshore Wind Shot)

LCOEs reflect input data to ReEDS modeling, using technology assumptions from the Annual Technology Baseline (ATB) 2021 Moderate case (NREL 2021), developable potential from Renewable Energy Potential (reV) modeling (NREL 2019), and financing assumptions used in ReEDS. LCOEs shown include interconnection costs and are based on available energy.



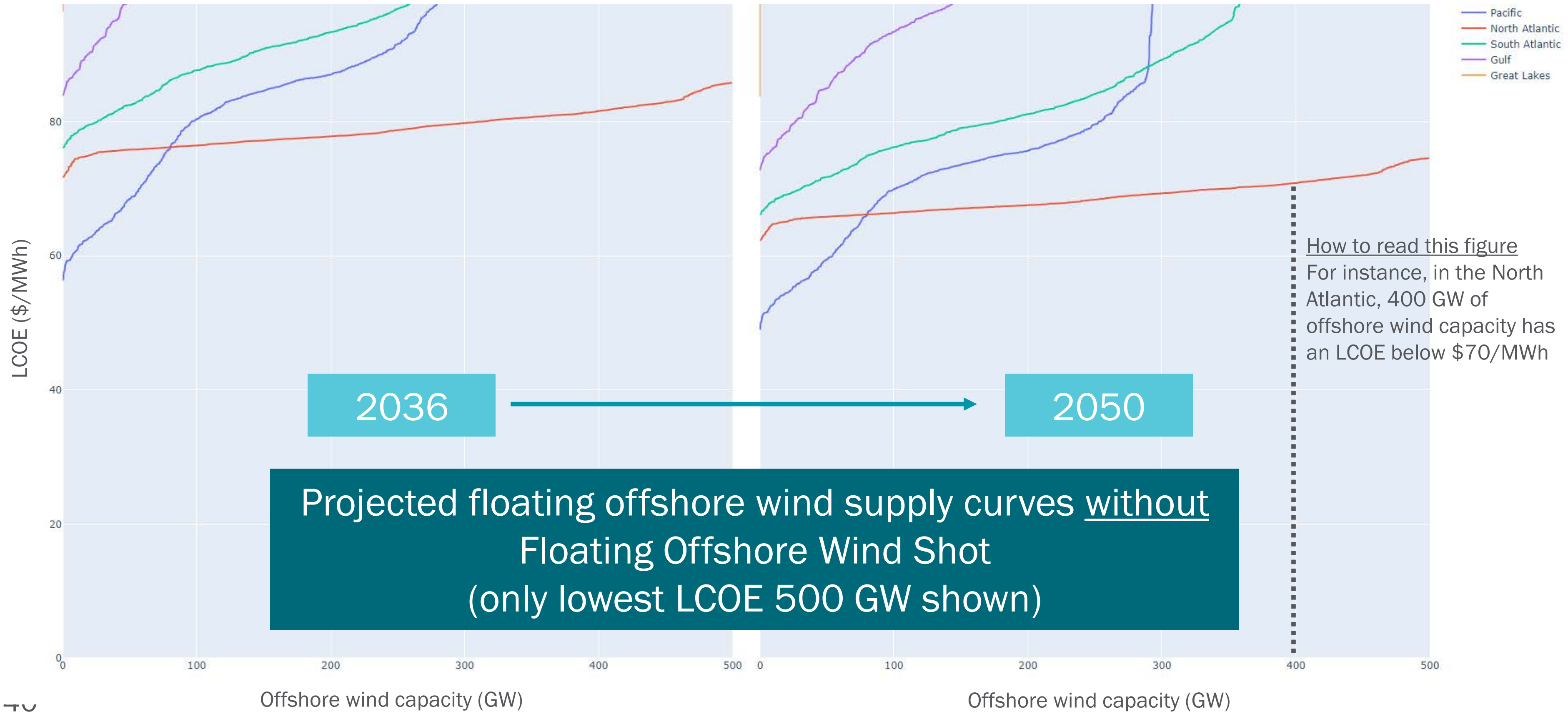
🟧 floating

🟦 fixed

North and South Atlantic regions are separated by the Maryland-Virginia border.

Data show the resource potential in each region for sites with LCOEs <$80/MWh.

Least-Cost Floating Sites Are in the Pacific Region With (ReEDS-Based) LCOEs of $56/MWh in 2036 and $49/MWh in 2050



2036 → 2050

Projected floating offshore wind supply curves <u>without</u> Floating Offshore Wind Shot
(only lowest LCOE 500 GW shown)

<u>How to read this figure</u>
For instance, in the North Atlantic, 400 GW of offshore wind capacity has an LCOE below $70/MWh

Thank you.

www.nrel.gov

NREL/PR-5000-86020

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL
Transforming ENERGY