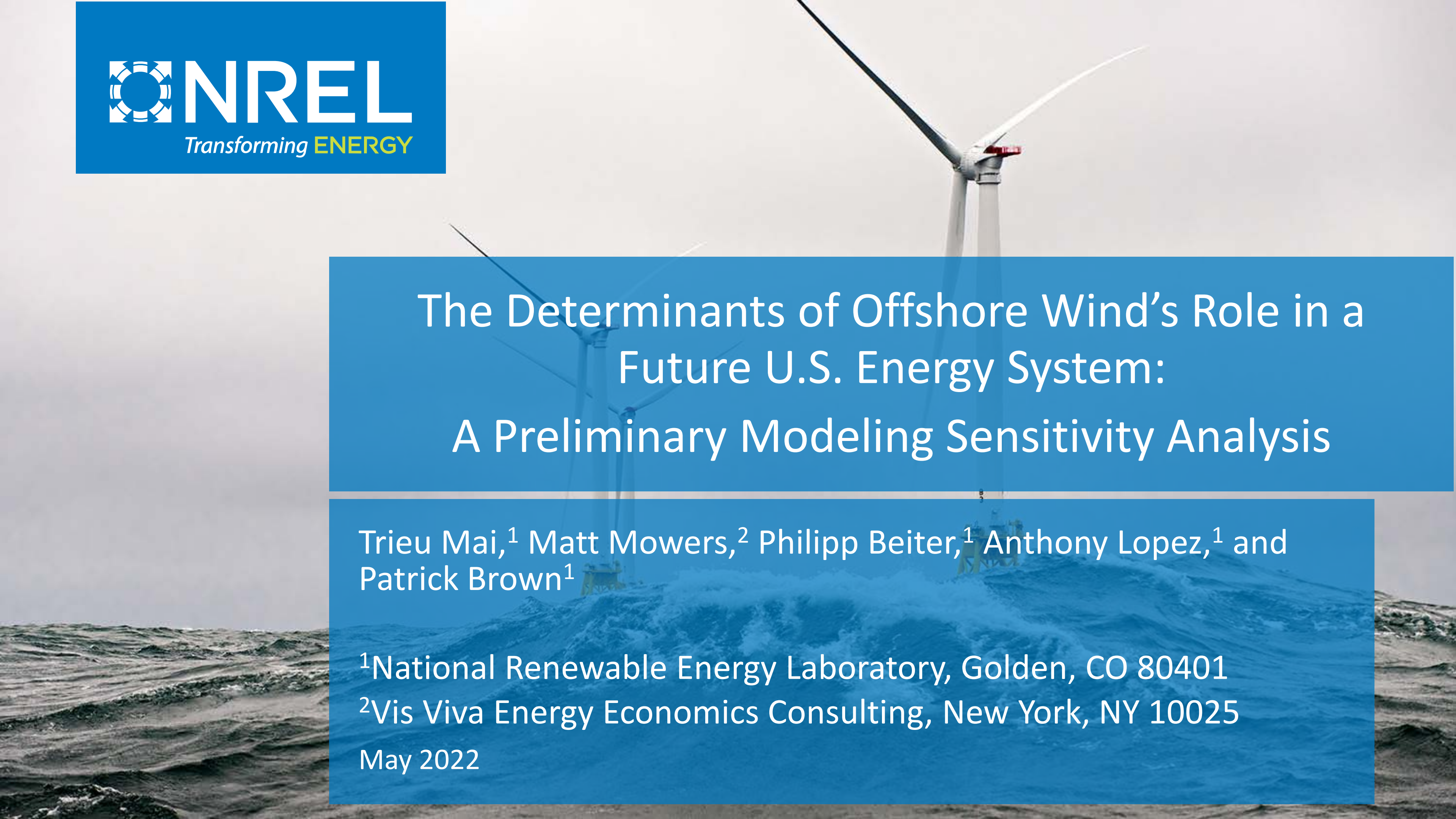


The Determinants of Offshore Wind's Role in a Future U.S. Energy System:

A Preliminary Modeling Sensitivity Analysis

Trieu Mai,[1] Matt Mowers,[2] Philipp Beiter,[1] Anthony Lopez,[1] and Patrick Brown[1]

[1]National Renewable Energy Laboratory, Golden, CO 80401
[2]Vis Viva Energy Economics Consulting, New York, NY 10025

May 2022

Outline

1. Background and Objectives
2. Methods, Scenario Definitions, and Assumptions
3. Results: Sensitivity Analysis
4. Results: Core Scenario
5. Future Work

Background and Objectives

Research Objectives

The study is designed to evaluate offshore wind's (OSW's) potential role in the future U.S. energy system. The analysis uses long-term power system models to assess a wide-range of future power system possibilities. Specific objectives include:

- Identify the determinants of OSW deployment under different scenarios
- Understand the impacts of substantial levels of offshore wind deployment on the power system

Background

- OSW is an emerging industry with new technology advancements and an accelerating global deployment.
- In the United States, OSW is at a more nascent stage with only seven turbines, totaling 42 megawatts (MW), installed through 2021.
- Over 35 gigawatts (GW) of OSW capacity are at various stages of development as of 2020, driven primarily by state targets (Musial et al. 2021).
- The growing interest in OSW development in the Northern Atlantic, in particular, has led to coordinated grid planning between states and regional transmission operators (RTOs) in the region.
- At the national level, OSW projects are financially incentivized by a 30% investment tax credit (ITC) for projects under construction before the end of 2025.[1]
- The Biden administration announced a goal to deploy 30 GW of OSW by 2030, along with broader goals for 100% carbon-free electricity by 2035 and net-zero, economywide greenhouse gas emissions by 2050 (The White House 2021a,b).
- There are significant uncertainties about the future deployment potential for OSW—especially in the time frame beyond the current project pipeline and state policies.

---

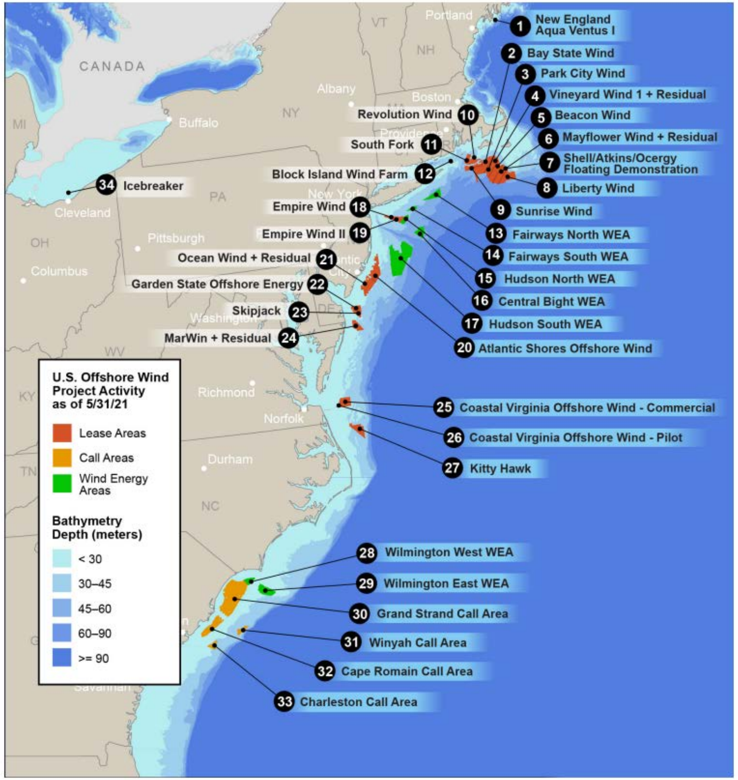
[1] Under the 5% Safe Harbor Rule, to qualify for the ITC, the facility needs to be placed into service within 10 calendar years after the calendar year during which construction of the project began (Musial et al. 2021).

State of Offshore Wind Industry in 2020

- **Global**
    - 33 GW of cumulative installed capacity
    - 5.5 GW of new capacity in 2020
    - 23.4 GW under construction

- **U.S.**
    - 42 MW of cumulative installed capacity
    - 35.3 GW in the pipeline

- **U.S. and state targets**
    - 30–40 GW targeted by states, in aggregate, by 2035–2040
    - 30 GW by 2030 Biden administration target (The White House, 2021)
    - Broader administration goals (The White House, 2021)
        - 50%–52% economywide greenhouse gas emissions by 2030
        - 100% carbon-free electricity by 2035
        - Net-zero economywide greenhouse gas emissions by 2050



Source: Figure and offshore data from Musial et al. (2021)

Methods, Scenario Definitions, and Assumptions

Methods

- The Regional Energy Deployment Scenario (ReEDS) is used for the capacity expansion modeling in this study.
  - Scope: Conterminous United States through 2050
  - Website: https://www.nrel.gov/analysis/reeds/
  - Latest model documentation: https://www.nrel.gov/docs/fy21osti/78195.pdf (Ho et al. 2021)
- The 2021 version of the model, used in the 2021 Standard Scenarios study (Cole et al. 2021), serves as the base model with several updates, including:
  - Updated land-based and offshore wind supply curves from Lopez et al. (forthcoming)
  - Transmission representation and cost assumptions (described in later slides)
  - Updated and new representation of several nonrenewable technologies based on Denholm et al. (forthcoming)
  - Direct modeling of individual wind sites rather than regional aggregates
  - Different default assumptions for the core scenario (see next slide).

Default Assumptions

- Default settings for core scenario:
  - **Technology costs**: Annual Technology Baseline (ATB) 2021 Moderate projections for all technologies, 30% offshore ITC through 2035.
  - **National carbon emissions constraint**: 80% reduction by 2035 (from 2005 levels) and 95% by 2050.
  - **Demand**: Electrification Futures Study (EFS) High scenario.[2]
  - **Renewable energy (RE) siting**: Limited Access siting regimes for land-based wind and utility photovoltaic (PV).[3]
  - **Transmission**: New transmission is allowed within each of the 12 regions only (see slide 24).
  - **Technology availability**: No carbon capture and storage (CCS), nuclear small-modular reactors (SMR), or carbon dioxide removal (CDR) technologies.

- Wide-ranging scenarios are modeled (next slide).

[2] The EFS High scenario assumes widespread vehicle electrification (~76% of all 2050 vehicle miles travels use electricity) along with electrification for buildings and industry. This results in 1.9% per year annual load growth from 2020 to 2050 (Mai et al. 2018; Murphy et al. 2021).

[3] Siting regimes are from the 2021 supply curve versions (https://www.nrel.gov/gis/wind-supply-curves.html).

Scenario Overview

Default assumptions in **bold red**

Policy and Demand

- Existing Policies, AEO demand*
- 75% by 2050, EFS demand
- 85% by 2050, EFS demand
- **95% by 2050, EFS demand**
- 95% by 2050, AEO demand
- 100% by 2035, ADE demand*

** Includes multiple sensitivities*

Technology

- **ATB 2021 Moderate**
- Low RE Costs
- Low OSW Costs
- OSW ITC Extension
- High Great Lakes Cost
- Expanded Tech (CCS, Nuclear-SMR)
- Limited Tech (no new CSP, geo, nuclear)

Transmission

- **Intraregional only**
- High Tx Cost
- Inter-regional Tx
- National HVDC
- Atlantic HVDC

Siting

- **Default***
- Higher Onshore Resource
- Lower Onshore Resource
- Lower Offshore Resource

** Default uses Limited Access supply curves for land-based wind and PV and Open Access supply curves for offshore.*

Not all combinations are modeled; most are single variations from the core default scenario. For example, most scenarios include the 95% emissions reduction constraint. The following slides provide additional details for scenario assumptions.

Acronyms

ADE = Accelerated Demand Electrification
AEO = Annual Energy Outlook
ATB = Annual Technology Baseline
CCS = carbon capture & sequestration
CSP = concentrating solar power
EFS = Electrification Futures Study
Geo = geothermal
HVDC = high-voltage direct current
ITC = investment tax credit
OSW = offshore wind energy
RE = renewable energy
SMR = small modular reactor
Tx = transmission

Key Assumptions – Policy and Demand Scenarios

Default settings for Core Scenario

- **Technology costs:** ATB 2021 Moderate projections for all technologies, 30% offshore ITC through 2035.
- **National carbon emissions constraint**: 80% reduction by 2035 (from 2005 levels) and 95% by 2050.
- **Demand**: EFS High scenario.
- **Renewable Energy Siting**: Limited Access siting regimes for land-based wind and utility (PV)
- **Transmission**: New transmission is allowed within each of the 12 regions only (see slide 24)
- **Tech availability**: No CCS, nuclear SMR, or CDR technologies.

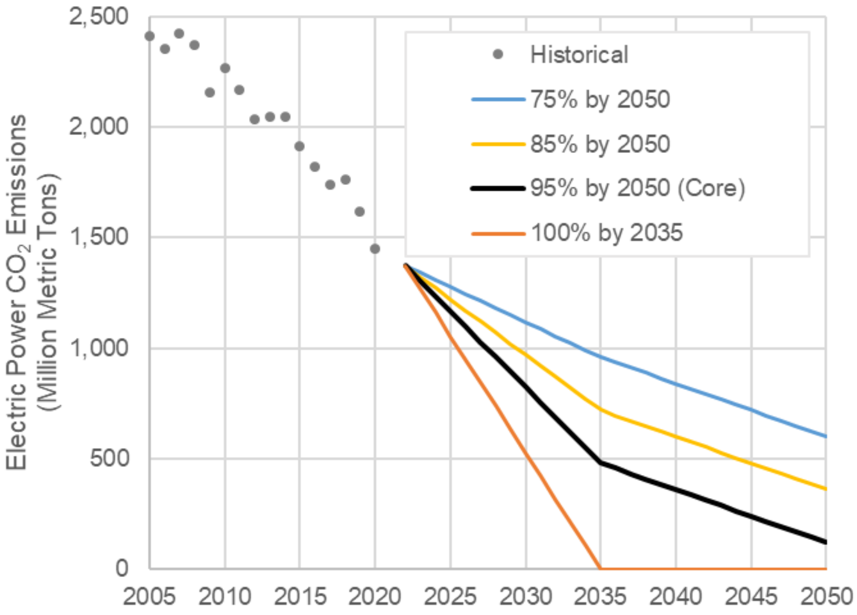
Scenario Name	Key Assumption (Differences From Default Core Scenario Assumptions)
Reference (Ref)	Existing (as of June 2021) policies only. These include state renewable portfolio standards, clean energy standards, and carbon caps. They also include federal tax incentives, including the ITC and production tax credit (PTC), based on existing phase-out schedule and safe-harbor provisions.
Ref – Low OSW Cost	Existing policies only. ATB 2021 Advanced projections for OSW only.
Ref – OSW ITC Ext	Existing policies only except for the 30% ITC for OSW, which is extended through 2050.
Ref – High Natural Gas (NG) Price	Existing policies only. NG prices based on the AEO 2021 Low Oil and Gas resource case.
Ref – High Demand	Existing policies only. Demand growth and demand profiles from the ADE case, which represents an end-use electrification consistent with a pathway to achieve U.S. economywide, net-zero greenhouse gas emissions by 2050 (Denholm et al. forthcoming).
75-by-2050	A national carbon emissions constraint that lowers U.S. power sector emissions to 75% below 2005 levels by 2050 (60% below by 2035).
85-by-2050	A national carbon emissions constraint that lowers U.S. power sector emissions to 85% below 2005 levels by 2050 (70% below by 2035).
95-by-2050 - Low Demand	Demand growth based on the AEO 2021 reference case. Demand profiles based on 2012 historical profiles.
Admin Target	A national carbon emissions constraint that achieves 100% emissions reductions by 2035. 30 GW offshore wind by 2030. Demand assumptions from the ADE case.
Admin Target – Exp Tech	A national carbon emissions constraint that achieves 100% emissions reductions by 2035. 30 GW offshore wind by 2030. Demand assumptions from the ADE case. Includes SMR, CCS, and CDR technologies as options. Model treatment and assumptions based on Denholm et al. (forthcoming).

Key Assumptions – All Other Scenarios

Scenario Name	Key Assumption (Differences From Default Core Scenario Assumptions)
Low OSW Cost	ATB 2021 Advanced assumptions for offshore wind only.
OSW ITC Ext	Extends the 30% ITC for OSW, which is extended through 2050.
Low RE Cost	ATB 2021 advanced assumptions for all renewable energy and battery technologies.
High Great Lakes Cost	Adds 25% to capital costs for Great Lakes OSW to represent potential logistics and weather challenges in the region.
Expanded Tech	Includes SMR, CCS, and CDR technologies as options. Model treatment and assumptions based on Denholm et al. forthcoming.
Limited Tech	Excludes deployment of *new* CSP, geothermal, and nuclear capacity.
Inter-regional Tx	Transmission expansion allowed between all regions, including RTOs, based on default AC transmission costs.
National HVDC	HVDC (voltage source converter) transmission options are available across the country with an upper limit of 20 GW of capacity between each pair of regions.
High Tx Cost	Transmission costs are 10 times the default costs representing undergrounding and other mitigation options associated with transmission siting.
Atlantic Transmission	HVDC lines between all Atlantic Coast model balancing areas from Maine to South Carolina are prescribed in 2040 (a minimum of 10 GW of capacity with an upper limit of 20 GW). 50% reduction in interconnection costs for all OSW sites. Interconnection costs include array cables, marine export cables, and onshore grid connections.
Higher Onshore Resource	Land-based wind and utility PV supply curves based on the Reference Access siting regime.
Lower Onshore Resource	Excludes critical biodiversity lands defined by The Nature Conservancy’s Resilient Connected Landscapes project in the land-based wind supply curves.
Lower Offshore Resource	OSW supply curve based on the Limited Access siting regime from Lopez et al. (forthcoming)

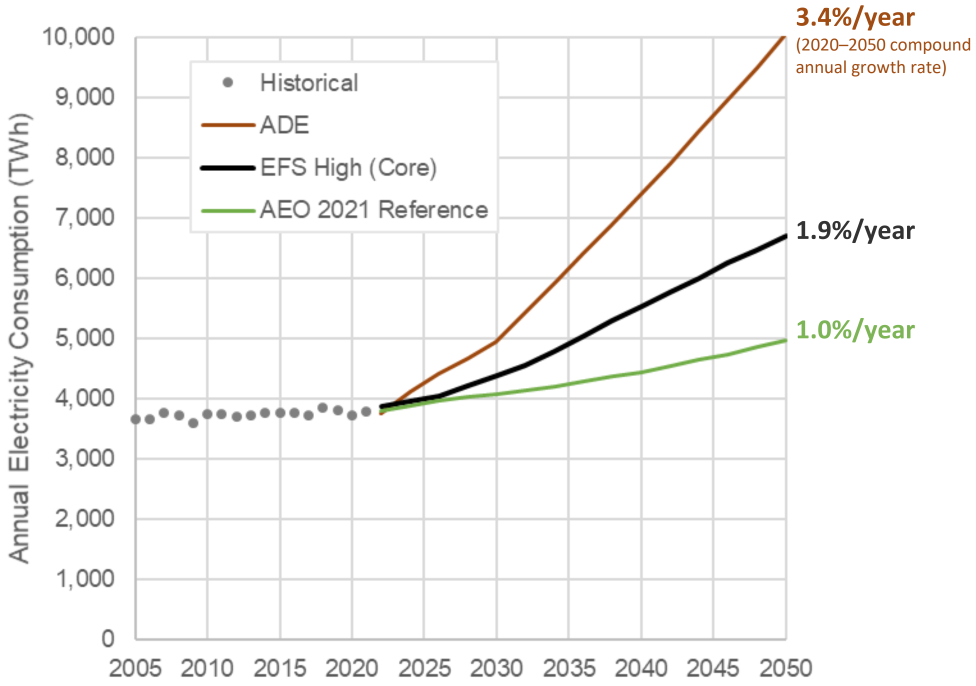
All scenarios on this slide achieve 80% power sector emissions reductions from 2005 levels in 2035 and 95% in 2050.

Emissions Constraints



- Existing policies as of July 2021 are included in all scenarios:
    - Includes state clean energy policies, OSW requirements, and federal tax incentives with current phase down schedule.
- Emission-constrained scenarios are modeled using a national annual constraint on CO_2 emissions.
    - The 100% by 2035 scenarios also includes a requirement to achieve 30 GW of OSW by 2030 based on the Administration target (The White House, 2021a).

Electricity Demand



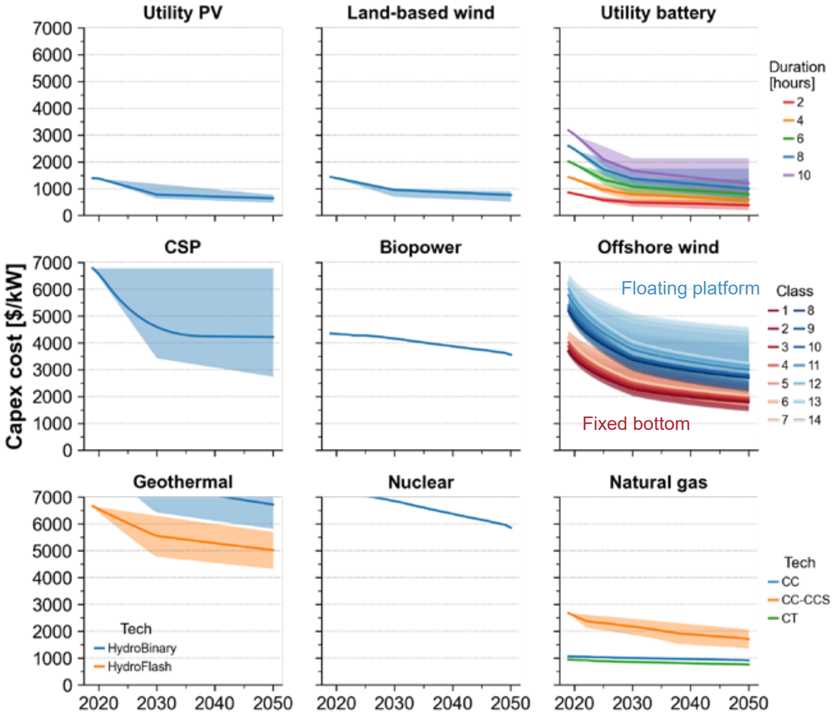
- Electricity demand growth is exogenously specified. Three scenarios modeled are:
  - AEO 2021 Reference case (EIA 2021) with demand profiles from 2012 weather year
  - EFS High (Mai et al. 2018)
  - Accelerated Demand Electrification (ADE) (Denholm et al. forthcoming).

- Demand profiles:
  - AEO scenarios use historical (2012) demand profiles;
  - EFS and ADE scenarios include changing demand profiles from electrification (using 2012 weather year); and
  - Demand flexibility for EFS and ADE scenarios are from EFS Base assumptions (Sun et al. 2020).

Technology Cost Assumptions

The figure shows capital costs from ATB 2021. Assumptions also include improvements to capacity factors, operation and maintenance (O&M) costs, and heat rates.

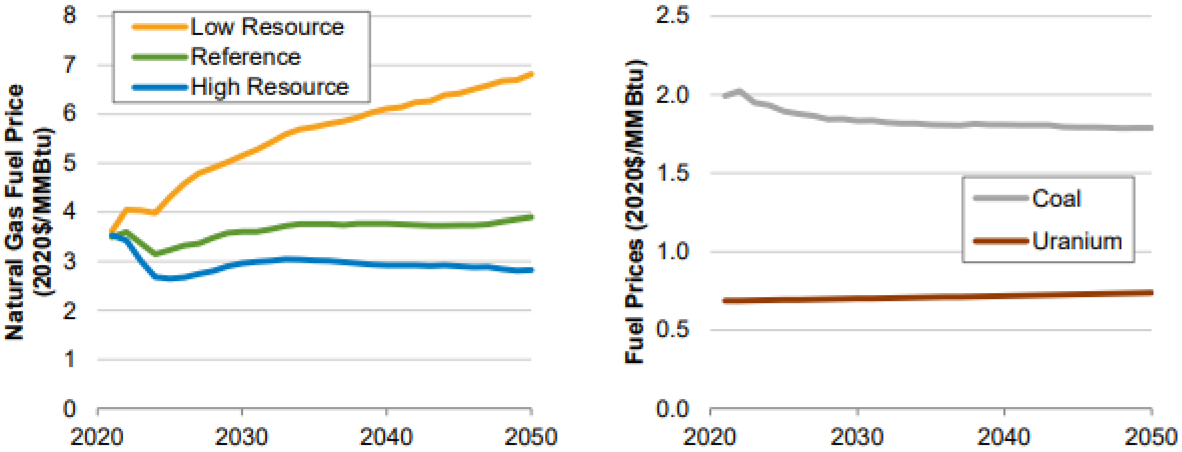
- Technology cost and performance projections are primarily from the NREL ATB 2021 (see Figure).
    - Moderate and Advanced trajectories are used.
- Regional cost and performance differences are also modeled.
    - Regional capital cost multipliers are applied.
    - Additional grid interconnection costs are modeled for wind and solar technologies; costs include array costs, marine export cables, and land-based connection costs.
    - Land-based wind and OSW costs and annual capacity factors also vary by each site.
    - A sensitivity raises capital costs for Great Lakes OSW by 25% to reflect potential logistics and weather challenges in the region.
- Assumptions for direct air capture, bioenergy with CCS (BECCS), hydrogen (H2) production technologies, and Nuclear-SMR are from Denholm et al. (forthcoming).



Natural gas technologies modeled include combined cycle (CC), combustion turbine (CT), and combined cycle with carbon capture and sequestration (CC-CCS)

Fuel Prices From AEO 2021

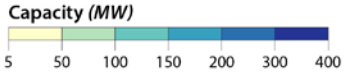
Figure from 2021 Standard Scenarios (Cole et al. 2021).



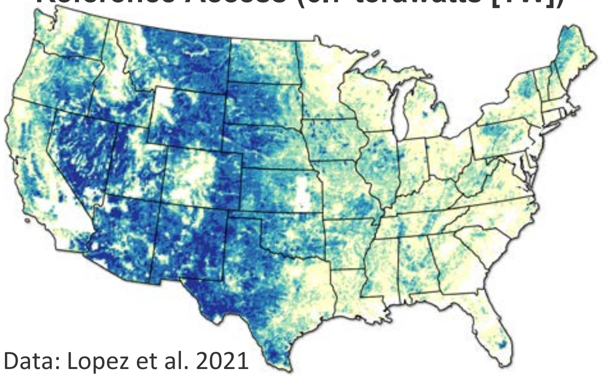
- Nearly all scenarios use the AEO 2021 Reference case NG prices except a single Existing Policies scenario that uses the Low Resource price trajectory.
- No fuel elasticity is modeled, given uncertainty with future fuel prices under a decarbonization trajectory that includes high electrification.

Wind Resource Potential

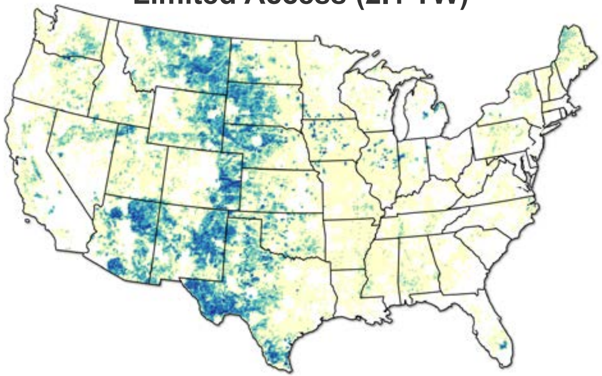
Land-Based Wind



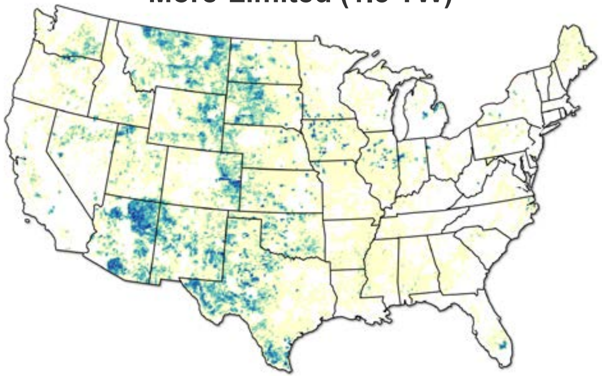
Reference Access (6.7 terawatts [TW])



Limited Access (2.1 TW)



More-Limited (1.3 TW)

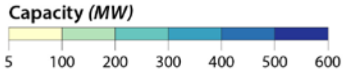


Data: Lopez et al. 2021

Open Access
(1.2 TW Fixed, 2.6 TW Floating)

Limited Access
(0.5 TW fixed, 1.5 TW floating)

Offshore Wind

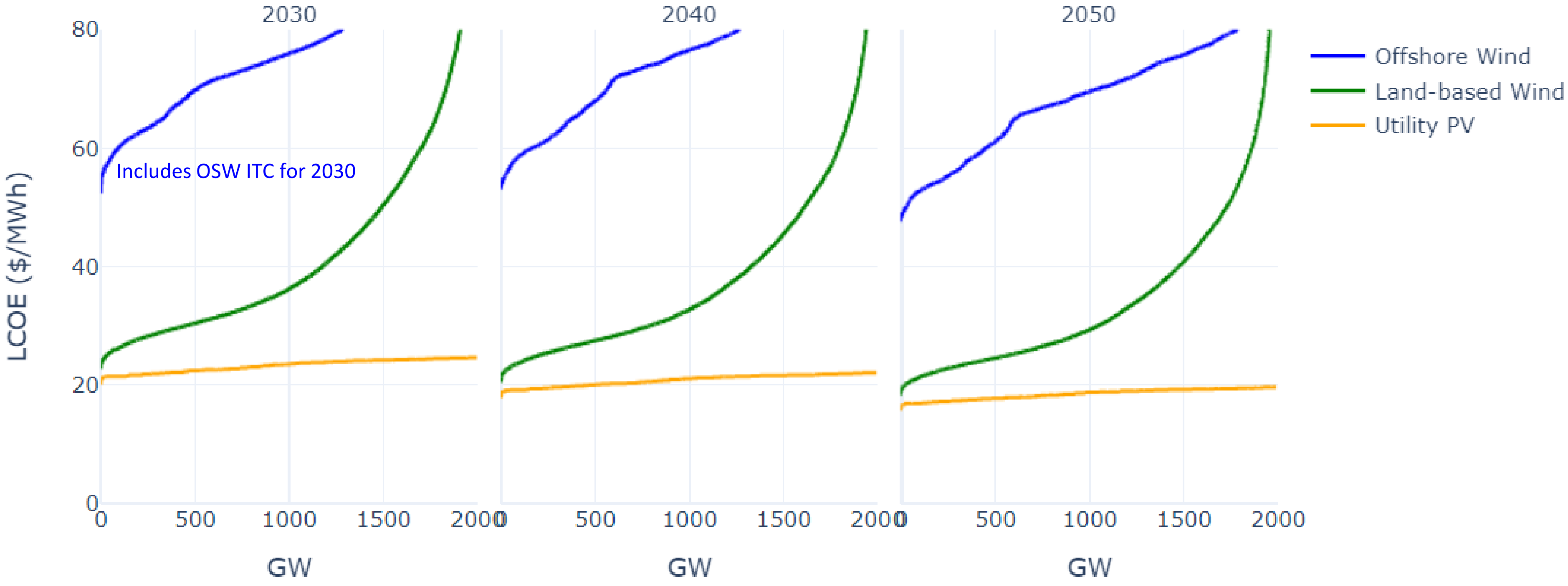


Default uses Limited Access for land-based wind and Open Access for OSW.

Data: Lopez et al. 2022

Core Supply Curves

ReEDS finds the *system*wide, least-cost solution that considers technology cost and characteristics (e.g., generation profiles, capital, O&M, and fuel costs) but does not rely on lowest cost of energy (LCOE). Implied LCOE values are shown simply to illustrate cost differentials between technologies for all sites (including sites chosen by the model and those not chosen at a point in time). LCOE values shown include interconnection costs and are based on available energy.



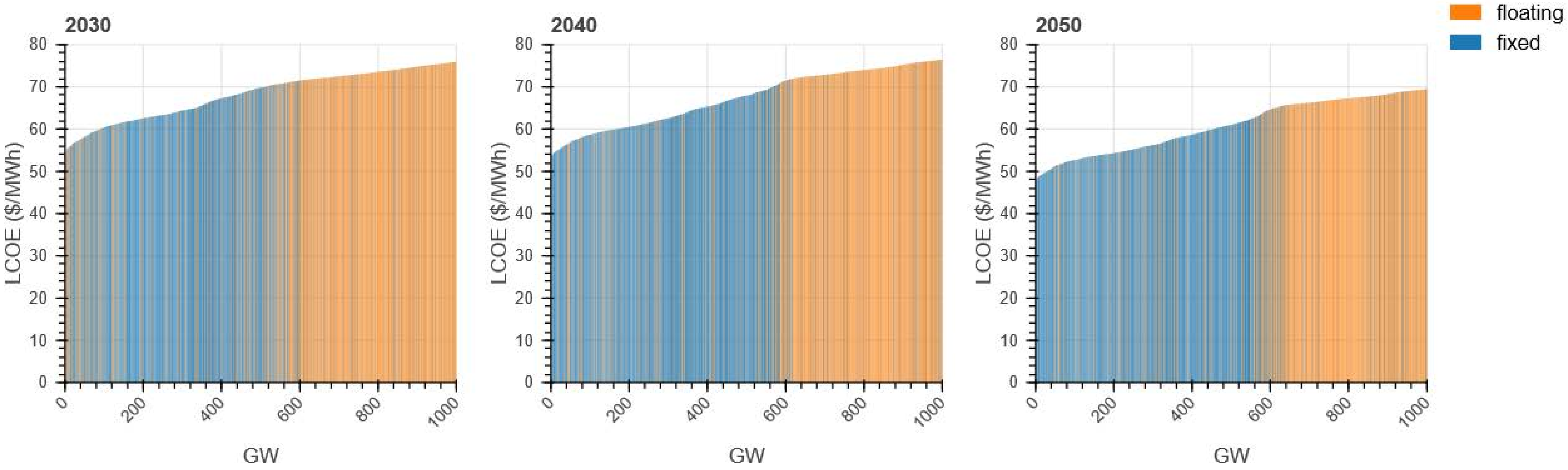
Core Regional Supply Curves – 2040

ReEDS finds the *system*wide, least-cost solution that considers technology cost and characteristics (e.g., generation profiles, capital, O&M, and fuel costs) but does not rely on LCOE values. Implied LCOE values are shown simply to illustrate cost differentials between technologies for all sites (including sites chosen by the model and those not chosen at a point in time). LCOE values shown include interconnection costs and are based on available energy.

Acronyms
ISO = Independent System Operator
CAISO = California ISO
ERCOT = Electric Reliability Council of Texas
ISO-NE = ISO New England
MISO = Midcontinent ISO
NYISO = New York ISO
PJM Interconnection

Offshore Wind Assumptions

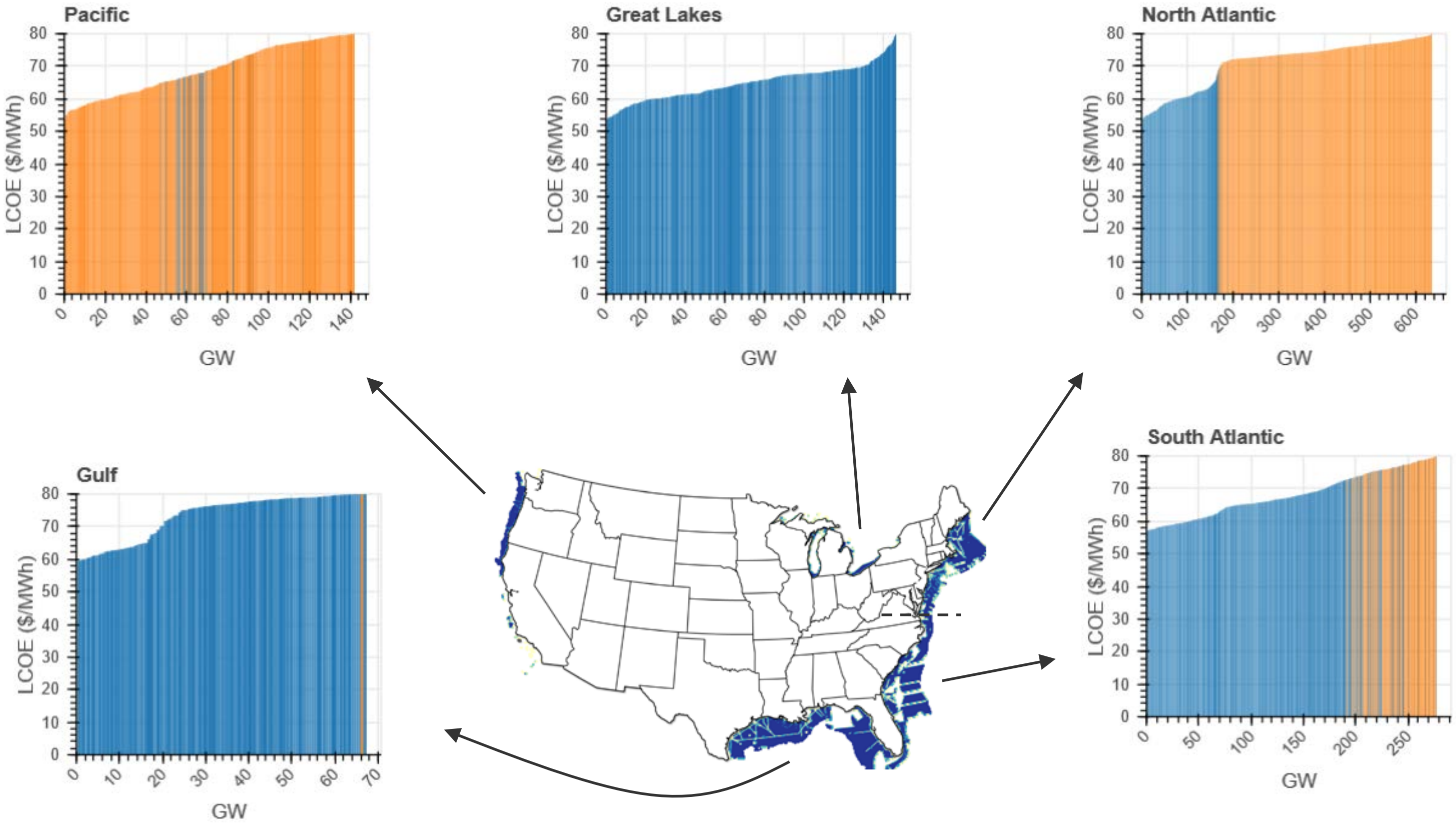
ReEDS finds the *system*wide, least-cost solution that considers technology cost and characteristics (e.g., generation profiles, capital, O&M, and fuel costs) but does not rely on LCOE values. Implied LCOE values are shown simply to illustrate cost differentials between technologies for all sites (including sites chosen by the model and those not chosen at a point in time). LCOE values shown include interconnection costs and are based on available energy.



The chart uses 600-MW wide bars for each site (actual resource potential modeled in ReEDS varies between sites, so bars may overlap). Blue bars reflect fixed-bottom resources, and orange ones reflect floating-platform resources.

Offshore Wind Assumptions – 2040

ReEDS finds the *system*wide, least-cost solution that considers technology cost and characteristics (e.g., generation profiles, capital, O&M, and fuel costs) but does not rely on LCOE values. Implied LCOE values are shown simply to illustrate cost differentials between technologies for all sites (including sites chosen by the model and those not chosen at a point in time). LCOE values shown include interconnection costs and are based on available energy.



🟧 floating
🟦 fixed

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

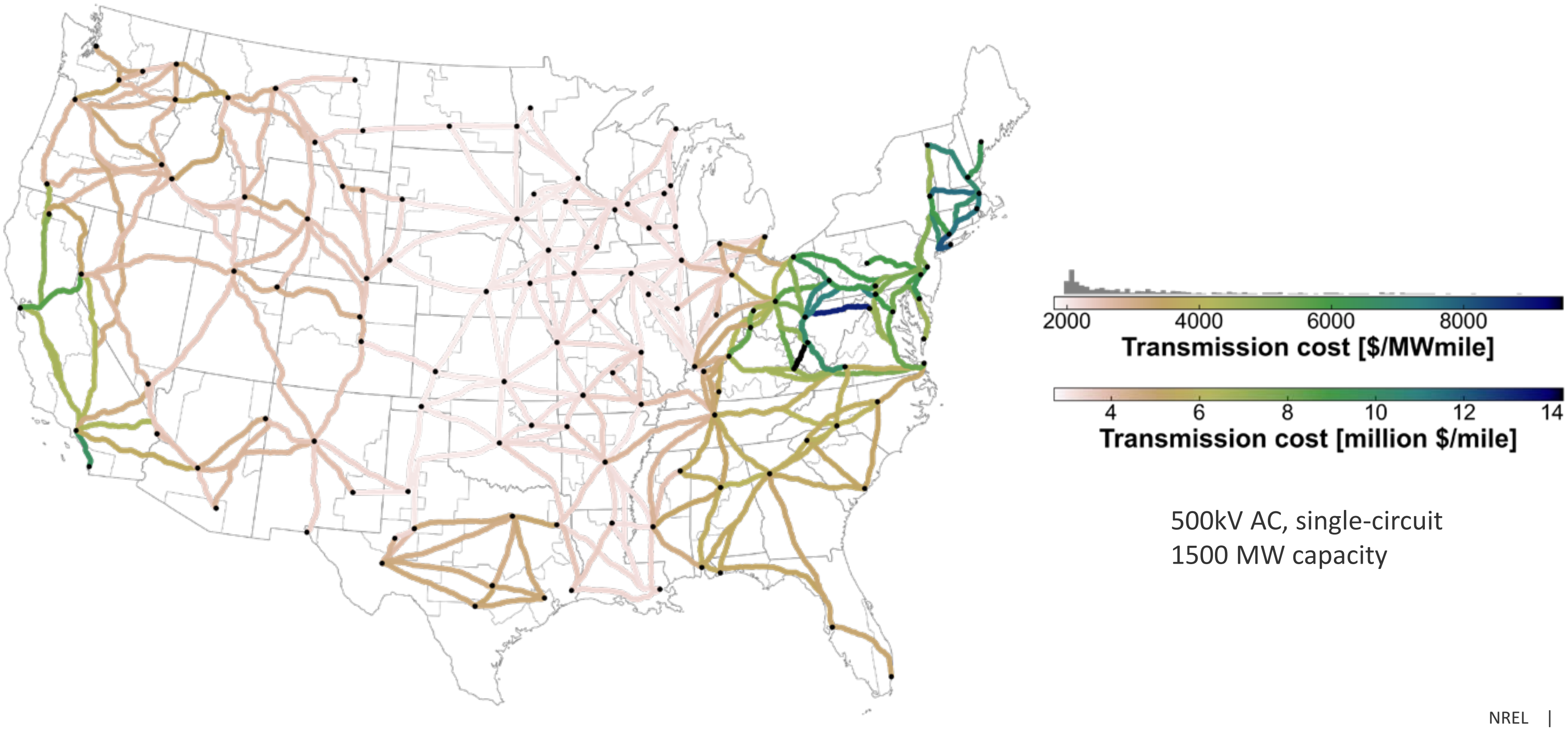
Data only includes sites with LCOE values <$80/MWh.

Transmission Assumptions

- Interconnection assumptions:
  - From the Renewable Energy Potential (reV) model (Lopez et al. forthcoming).
  - Interconnection cost assumptions are broken down by “hard costs” and “soft costs” from data from WECC, SCE, MISO, and others (Lopez et al., forthcoming). A least-cost-path method is used to determine spur-transmission right-of-way. Constraints avoid legally or administratively protected lands and apply additional “friction” to routes around likely sensitive areas.

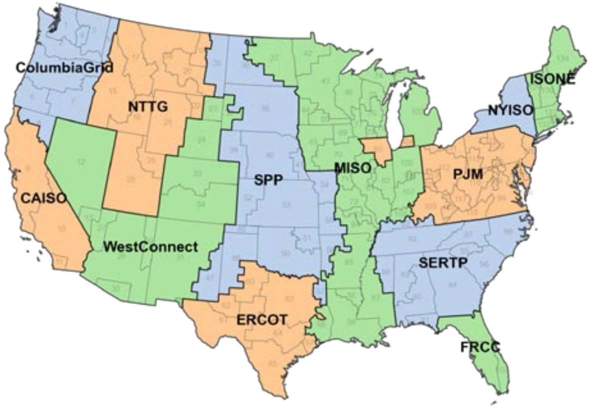
- Inter-BA transmission expansions:
  - Optimized using ReEDS.
  - Effective costs and distances are also based on a least-cost path method as with interconnection costs
    - DC line and converter costs from MISO cost estimation guide: DC $/MW-mile cost = ~41% of AC cost, $182/kW AC/DC voltage source converter (VSC) & $141/kW line-commutated converter (LCC).
  - Transmission losses:
    - 1%/100 miles for AC transmission; 0.5%/100 miles for DC transmission
    - 1% AC/DC conversion losses for VSC and 0.7% for LCC.

Inter-zonal transmission cost inputs



500kV AC, single-circuit
1500 MW capacity

Transmission Scenarios



Default: New AC only within transmission planning regions
based approximately on regions of *Federal Energy Regulatory Commission Order 1000*

+ Sensitivity case with 10× higher cost for new transmission.

HVDC-VSC macrogrid + new interregional AC
Up to 20 GW allowed for each HVDC line and Voltage Source Converter (VSC)

Atlantic Transmission
10-20 GW of HVDC capacity between all Atlantic model BAs from Maine to South Carolina in 2040, 50% lower OSW interconnection costs

Key Caveats and Limitations

- ReEDS considers some aspects of reliability, but more detailed analyses (e.g., probabilistic resource adequacy, power flow assessments) are required to verify the reliability of future grids modeled.

- Supply chain and logistics requirements are not directly modeled for any of the modeled power assets, including OSW.

- The model applies a systemwide optimization approach that considers direct costs to the power system and does not consider market and cost recovery uncertainties. Other factors, such as local economic development and workforce impacts, are also not considered.

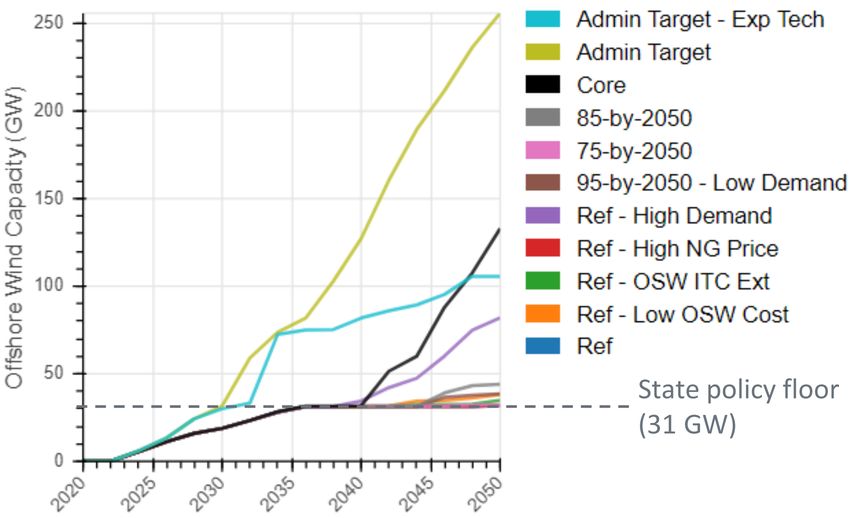
- Grid interconnection cost estimates inform the investment decisions in ReEDS, but a detailed point of interconnection analysis is not conducted in this study.

- A wide range of scenarios and constraints are modeled, but the analysis is not comprehensive of all possibilities.

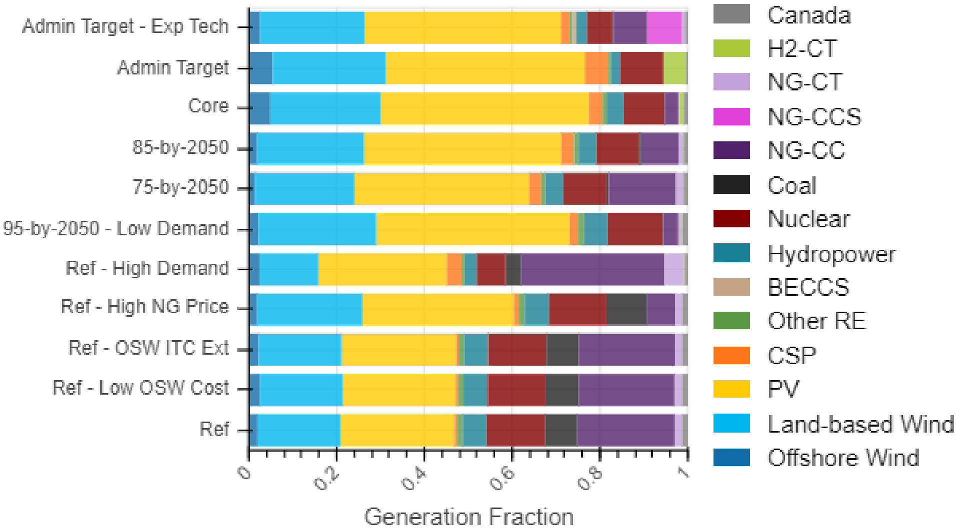
Results: Sensitivity Analysis

Policy and Demand Sensitivities

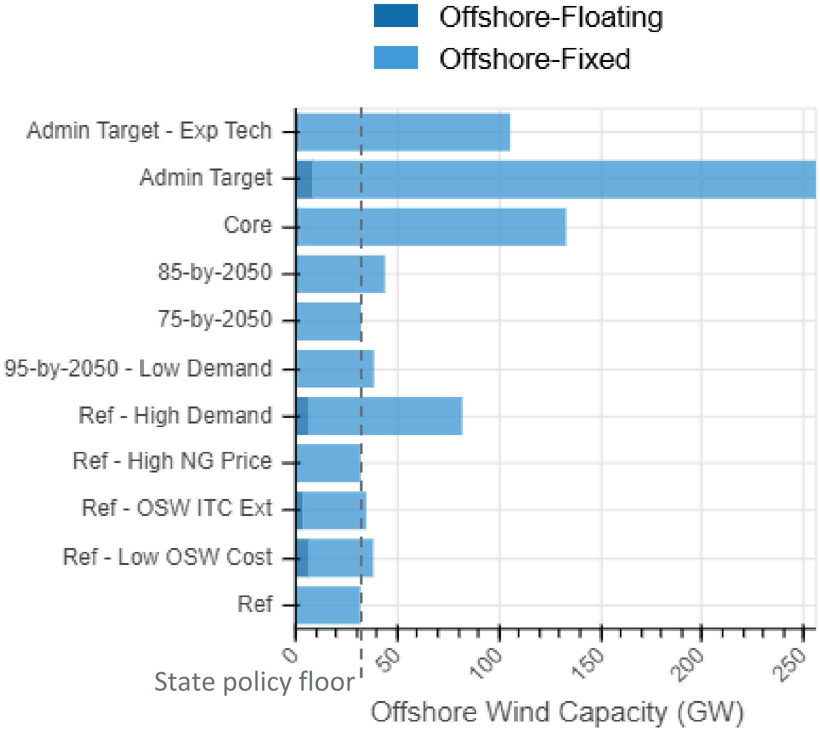
OSW Capacity

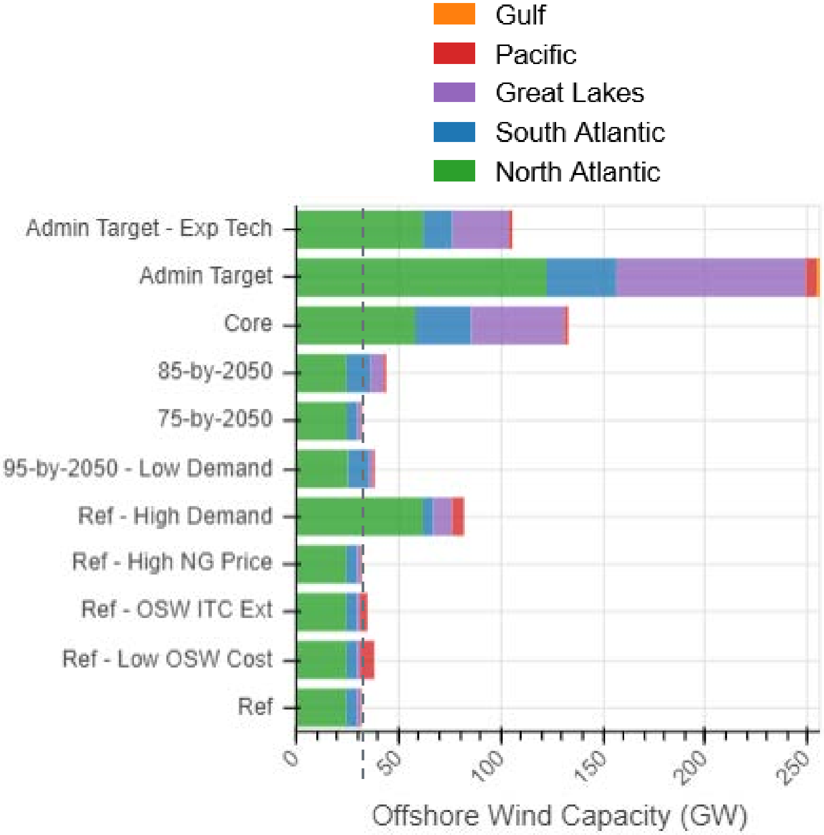


Generation Fraction

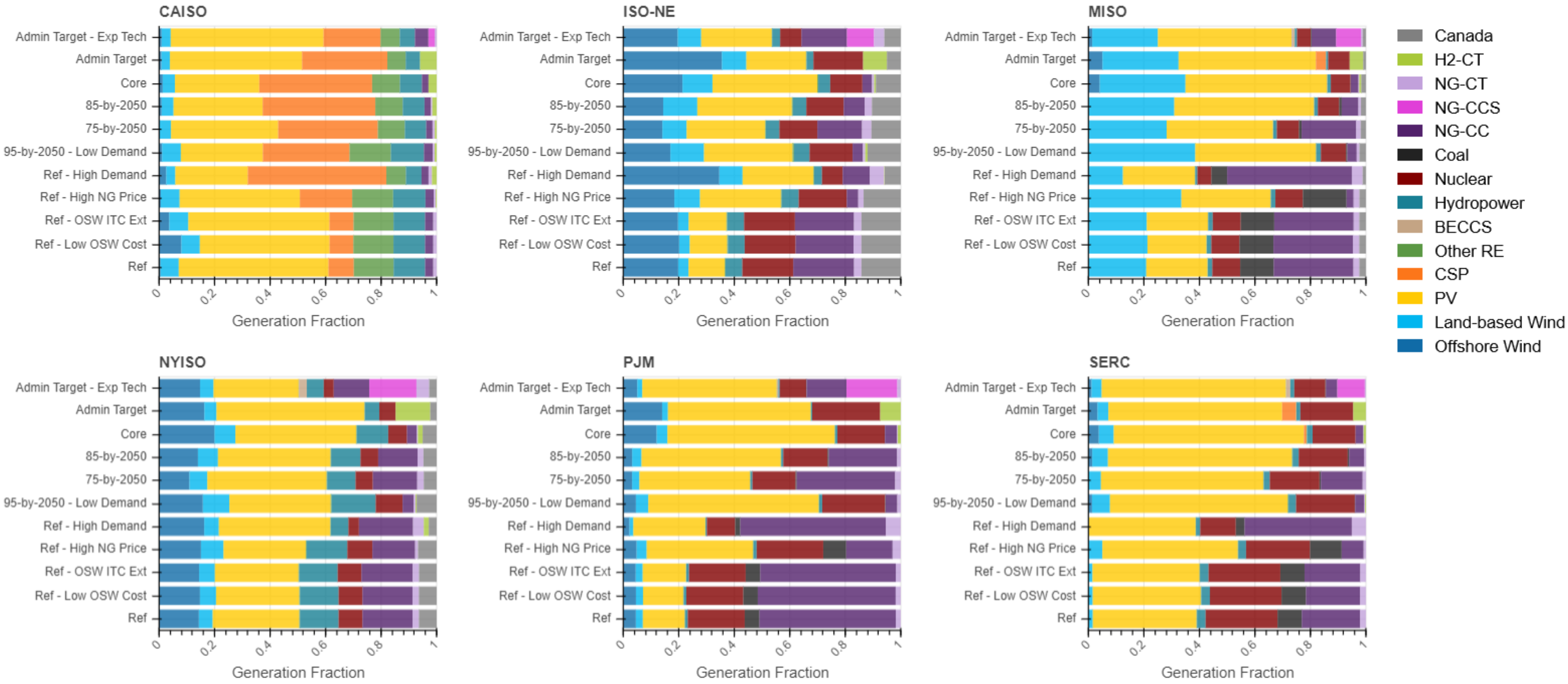


OSW deployment through the mid-2030s is driven primarily by state policies in most scenarios. In the long term, a wide range of possible OSW deployment outcomes are found due to uncertainties with future clean energy policy and load growth driven by electrification.



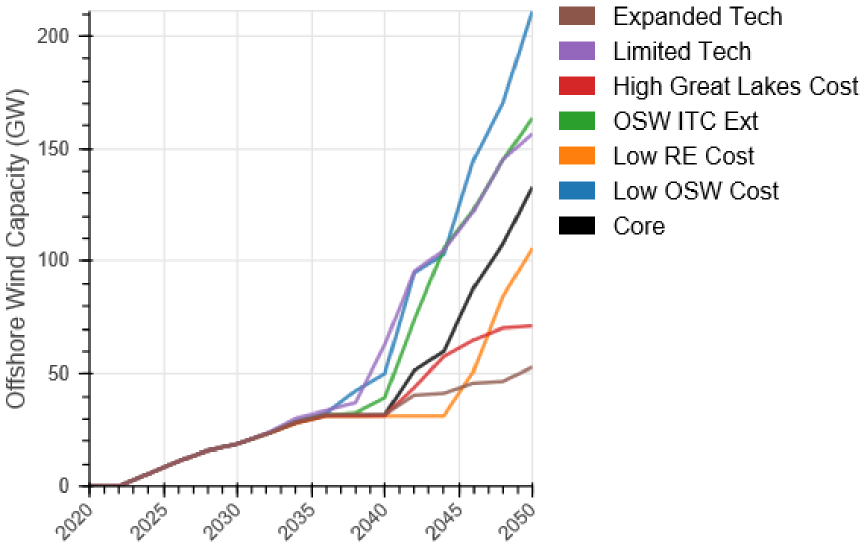


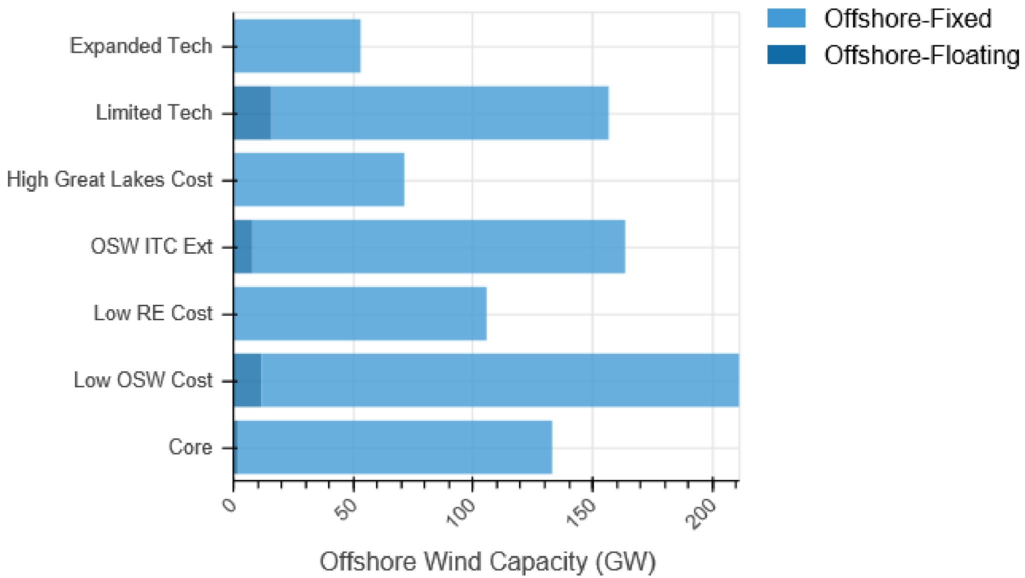
Under default assumptions, a combination of stringent power sector emissions reductions (>80%) and high electrification induce OSW deployment in the long term.



OSW contributes <10% to total U.S. generation in all scenarios but is a much more significant contributor (>~ 20%) in some regional grids.

Technology Sensitivities

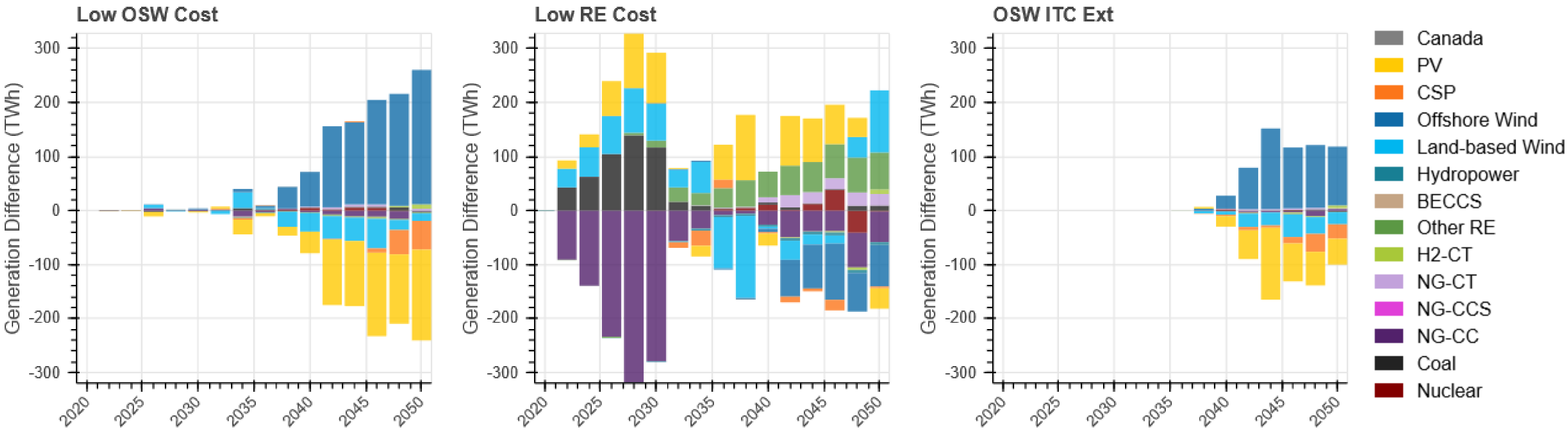




Relative costs (and/or financial incentives) between OSW and other renewable technologies, as well as the commercial availability of other low-emission technologies, are among the most significant determinants of future OSW.

National Difference in Generation From the Core Scenario

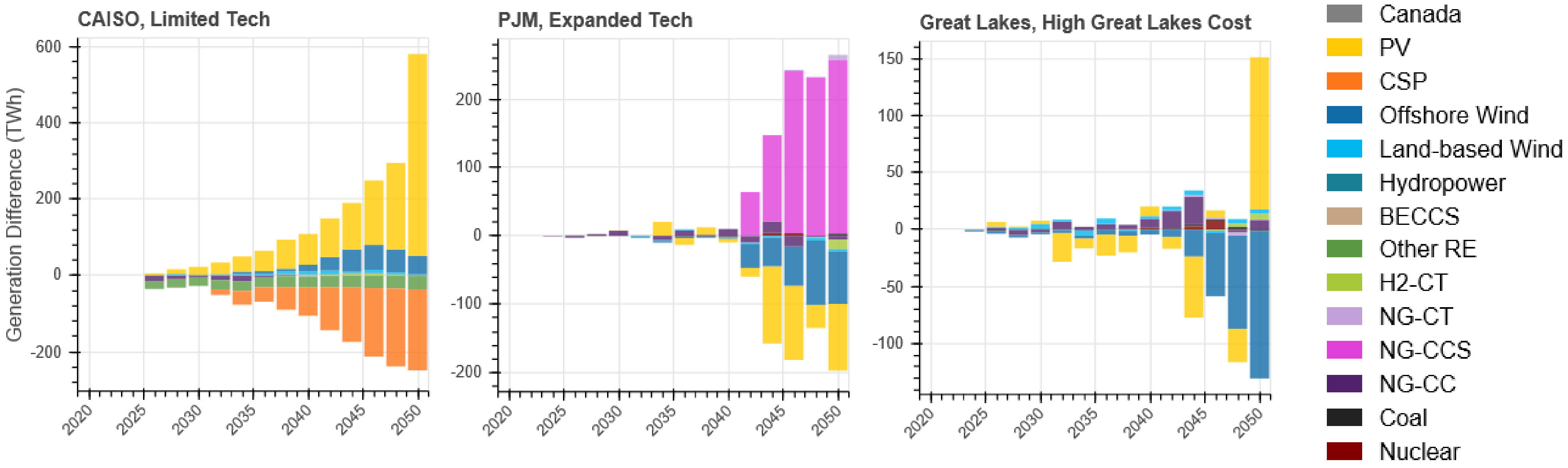
(Negative values represent greater generation in the core scenario.)



Technology cost sensitivities reveal trade-offs between OSW generation and generation from land-based renewable resources, particularly land-based wind and solar but also other renewable options, such as geothermal.

Regional Difference in Generation From the Core Scenario

(Negative values represent greater generation in the core scenario.)

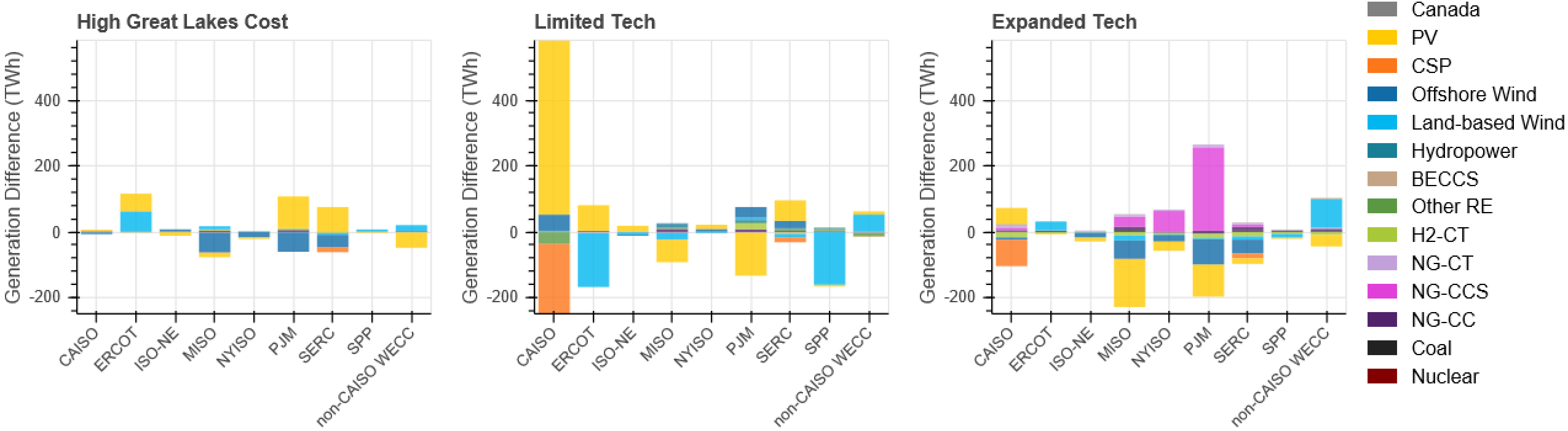


Great Lakes includes the following states: MN, WI, MI, IL, ON, OH, PA, NY (excluding Long Island).

Technology availability can have a major impact on OSW deployment in regional grids. For example, in the absence of concentrating solar power and geothermal, OSW (and solar PV) can play more prominent roles in California. The availability of CCS can reduce the need for OSW.

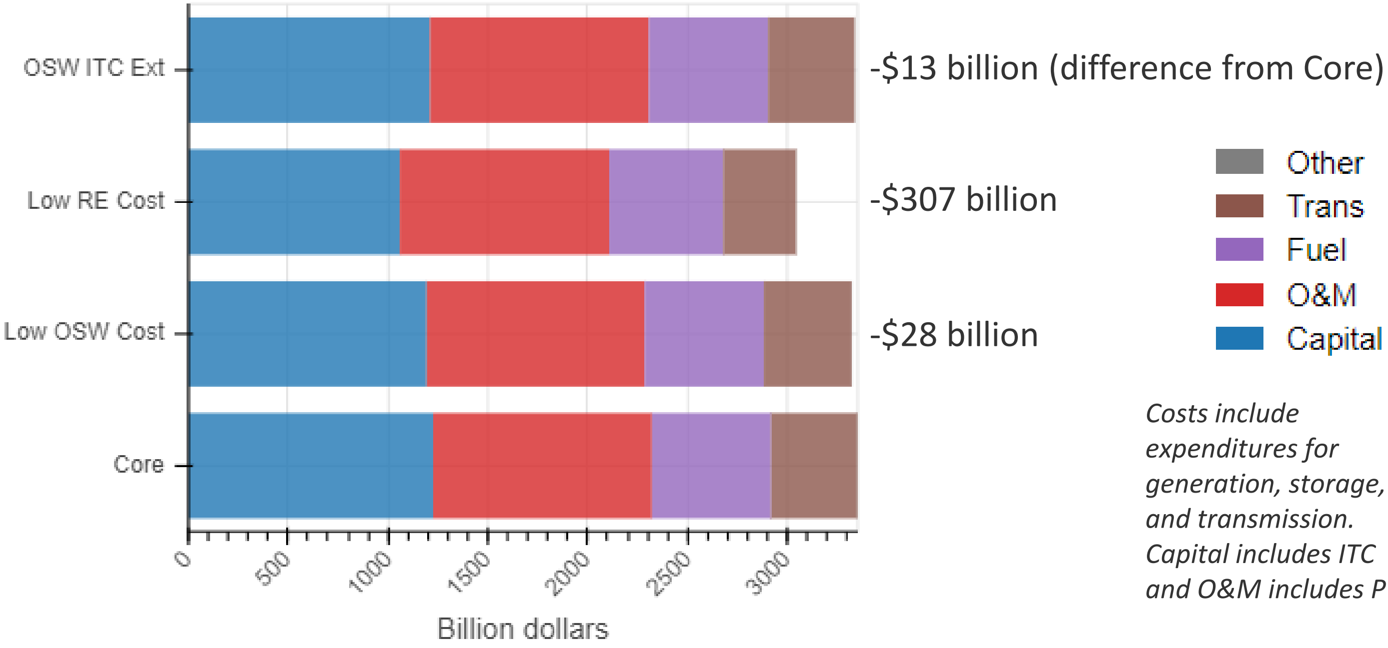
Regional Difference in 2050 Generation From the Core Scenario

(Negative values represent greater generation in the core scenario.)



Technology availability can have a major impact on OSW deployment in regional grids.

Present Value System Costs
(2022–2050, 5% Discount Rate)



-$13 billion (difference from Core)

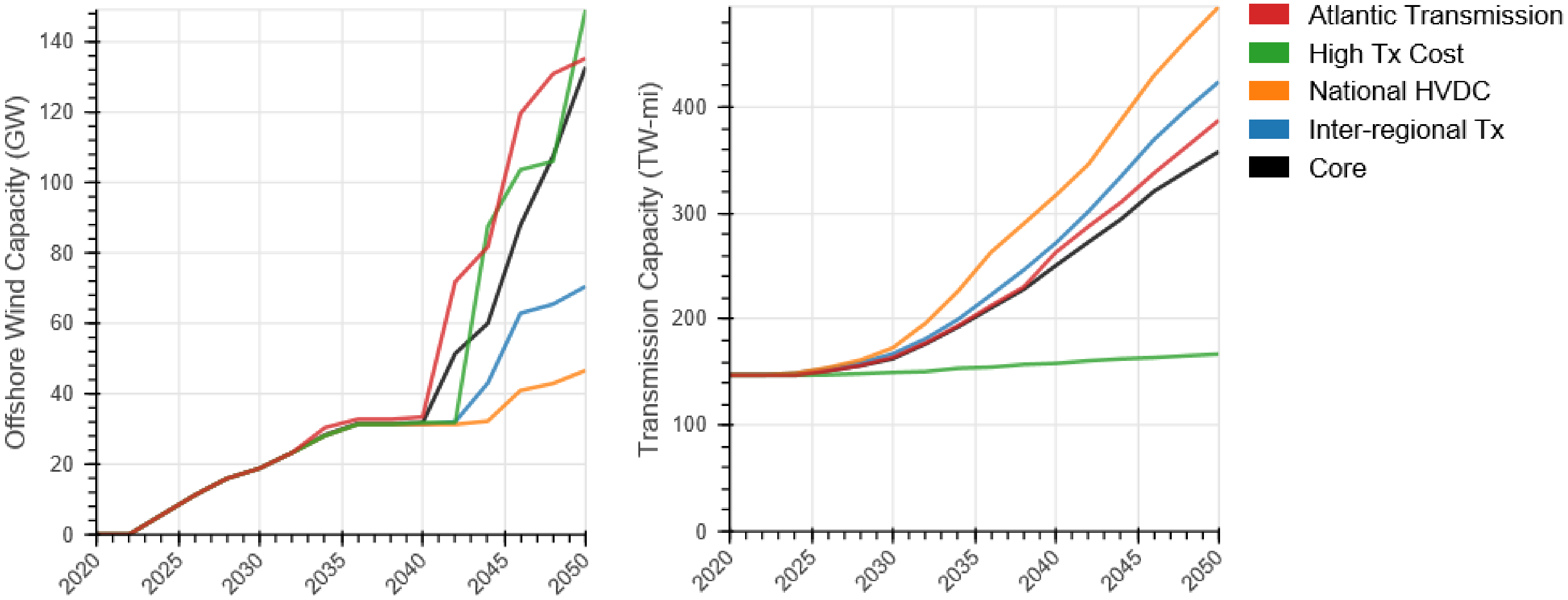
-$307 billion

-$28 billion

Costs include expenditures for generation, storage, and transmission. Capital includes ITC and O&M includes PTC

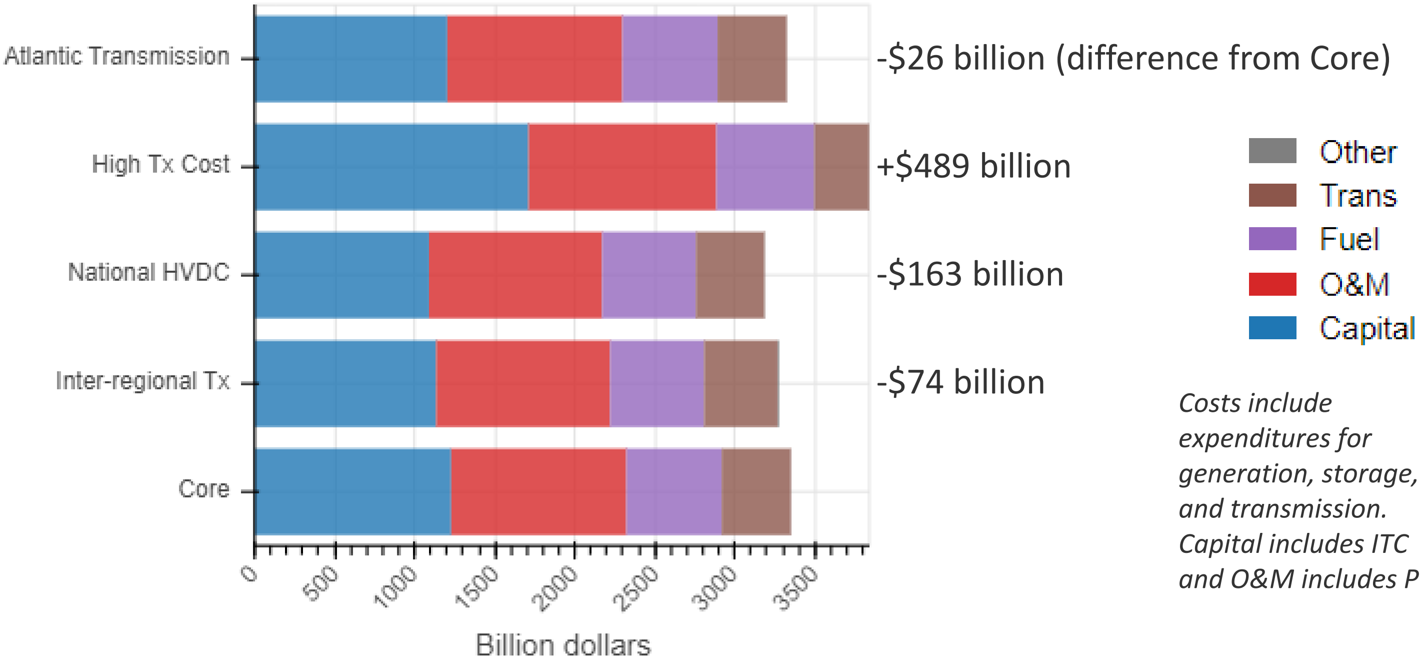
Extent of future technology advancement can influence electric system costs and the emissions abatement costs in the power sector.

Transmission Sensitivities



Widespread expansion of interregional transmission, including a HVDC macrogrid, enables access to high-quality land-based resources, thus reducing the need for OSW. Conversely, higher-cost or more-constrained transmission expansion could yield greater OSW development.

Present Value System Costs
(2022–2050, 5% Discount Rate)



-$26 billion (difference from Core)

+$489 billion

-$163 billion

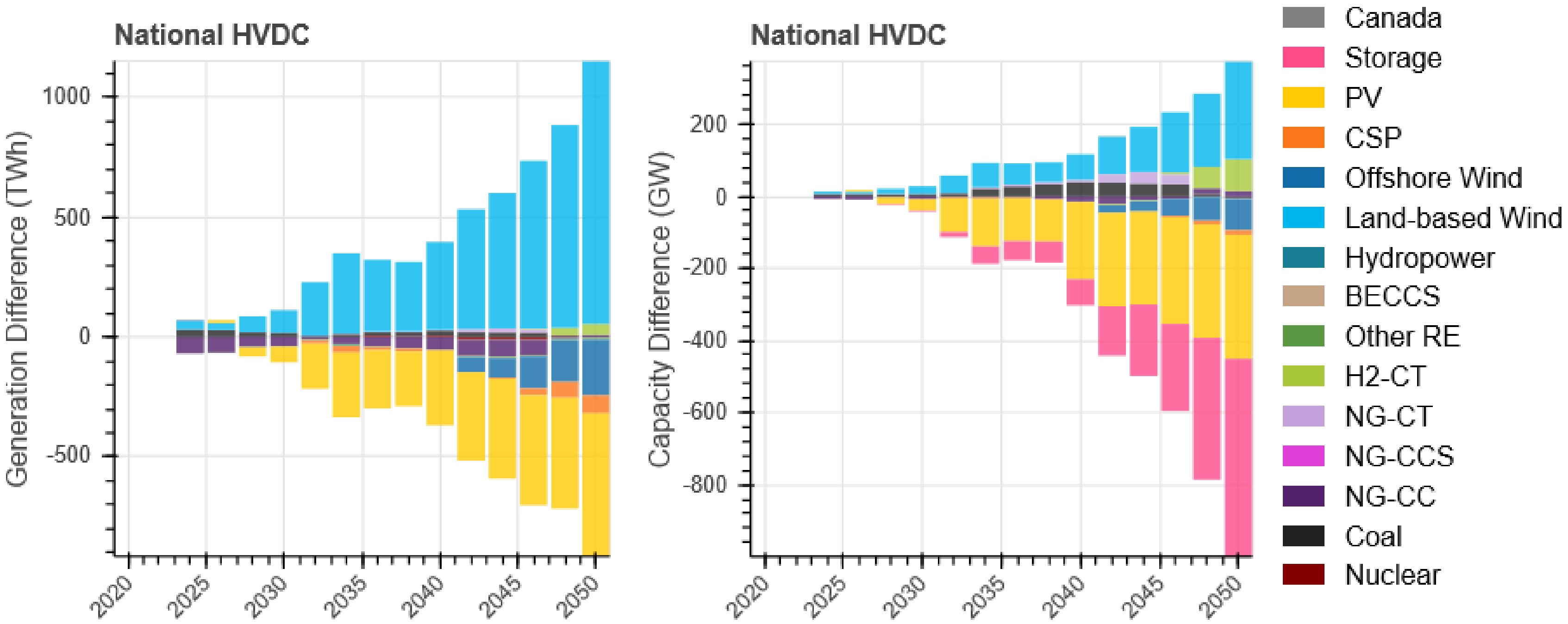
-$74 billion

Costs include expenditures for generation, storage, and transmission. Capital includes ITC and O&M includes PTC

Long-distance high-capacity interregional transmission can help lower total power system costs by enabling access to the lowest-cost clean energy resources and greater coordination between regions.

National Difference From the Core Scenario

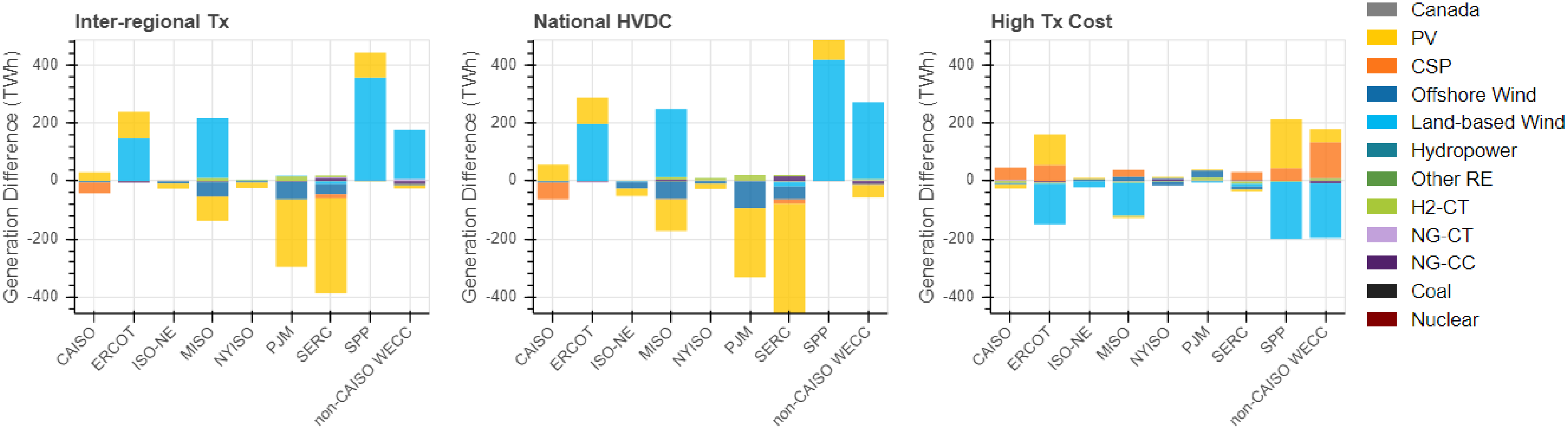
(Negative values represent greater generation and capacity in the core scenario.)



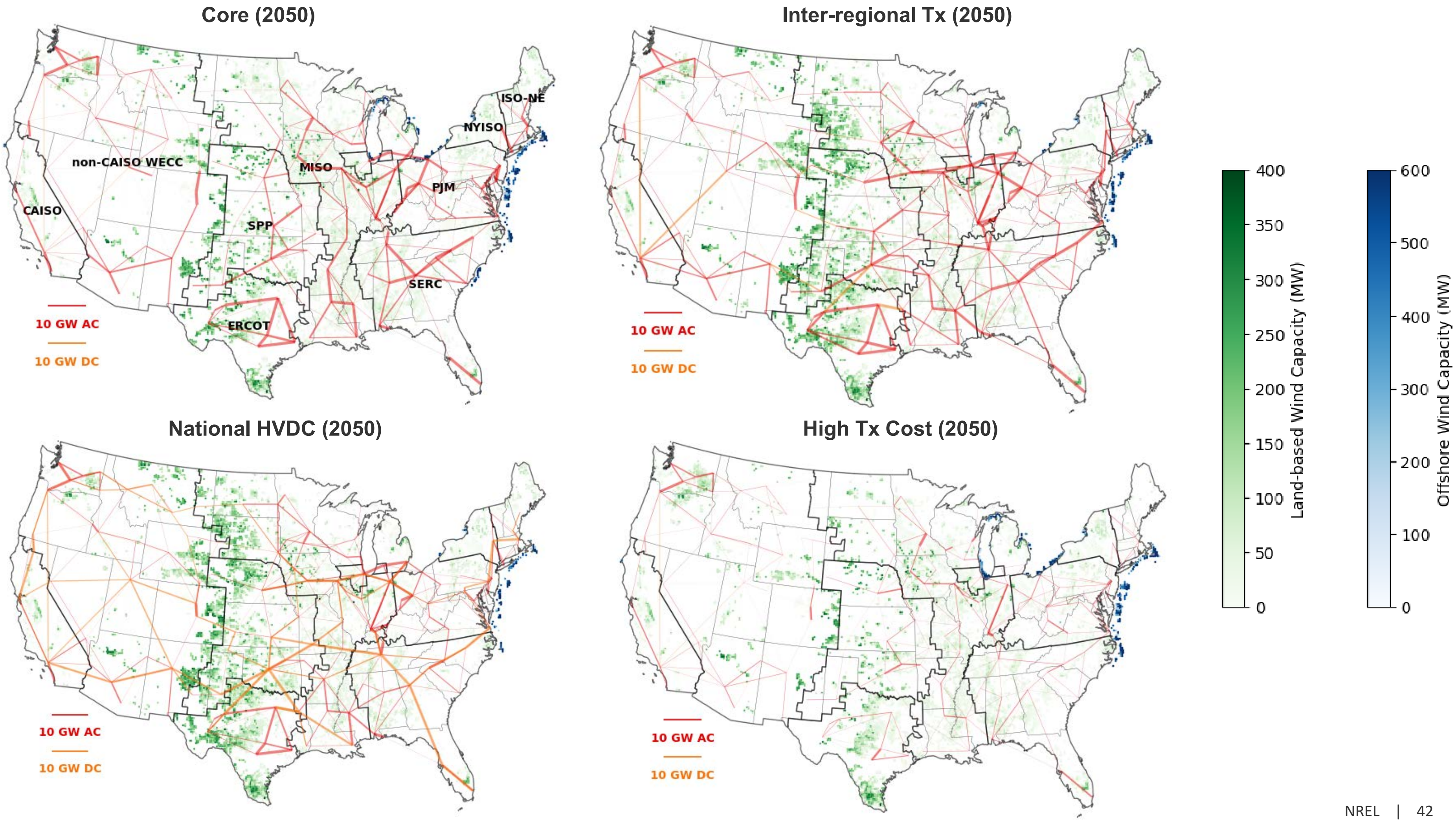
Increased long-distance (high-capacity AC or HVDC) transmission leads to greater wind development in the interior primarily at the expense of solar and OSW on the coastal regions.

Regional Difference in 2050 Generation From the Core Scenario

(Negative values represent greater generation in the core scenario.)



Increased long-distance (AC or HVDC) transmission leads to greater wind development in the interior primarily at the expense of solar and OSW on the coastal regions.



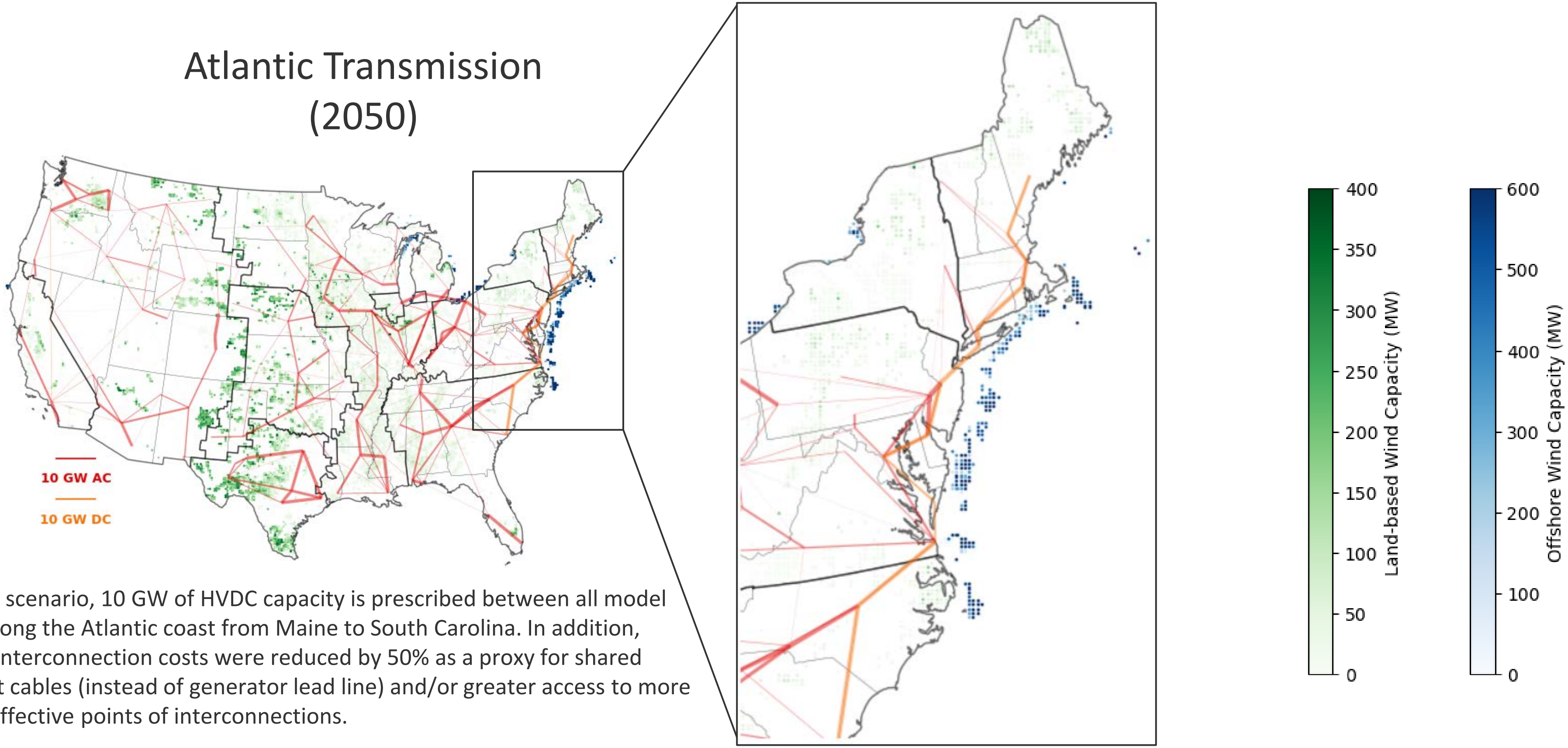
Core (2050)

Inter-regional Tx (2050)

National HVDC (2050)

High Tx Cost (2050)

Atlantic Transmission (2050)



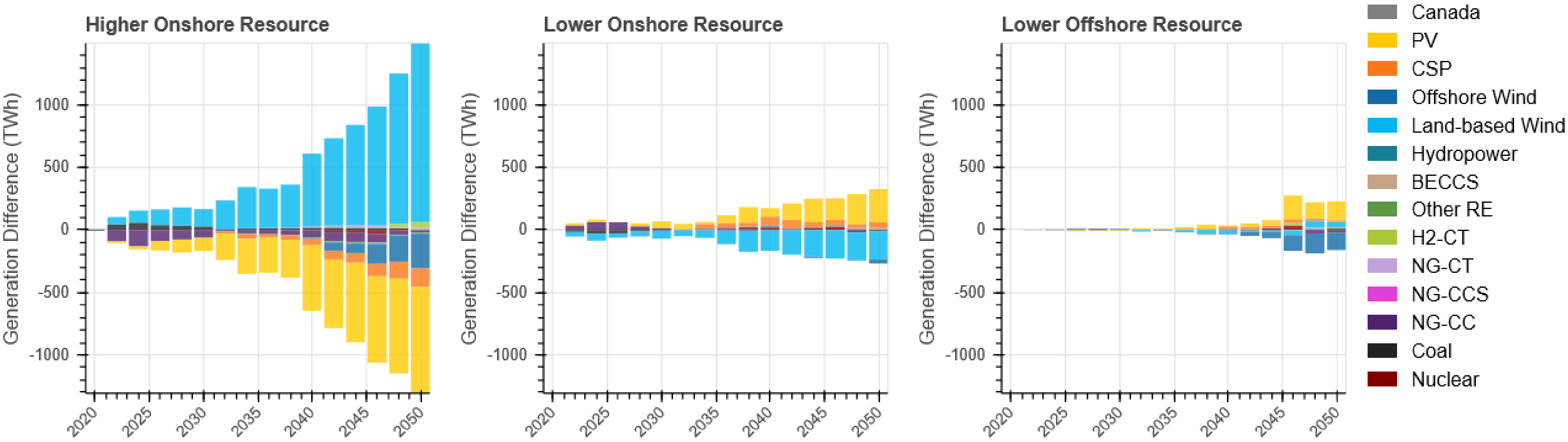
In this scenario, 10 GW of HVDC capacity is prescribed between all model BAs along the Atlantic coast from Maine to South Carolina. In addition, OSW interconnection costs were reduced by 50% as a proxy for shared export cables (instead of generator lead line) and/or greater access to more cost-effective points of interconnections.

An Atlantic HVDC backbone can support multiple resources (incl. offshore wind and solar PV) and modestly increases offshore wind deployment. More study is needed to assess the reliability and economic impacts of interregional transmission and offshore interconnections, e.g., Atlantic Offshore Wind Transmission Study.

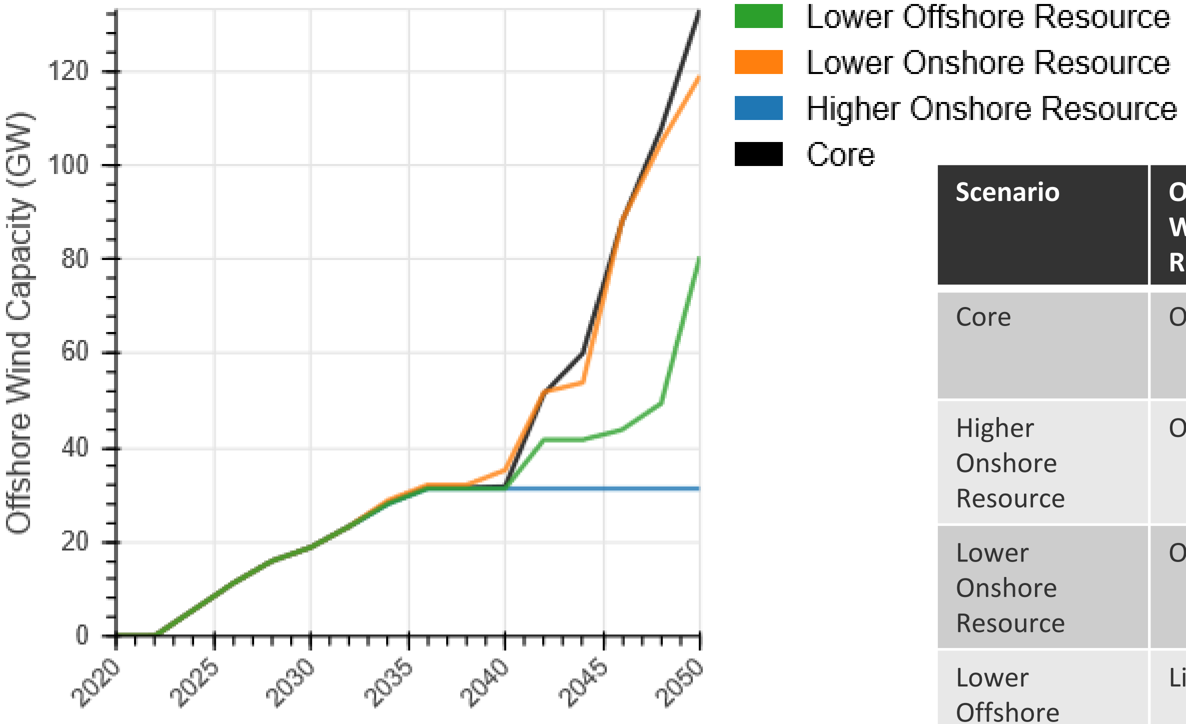
Renewable Energy Siting Sensitivities

National Difference in Generation From the Core Scenario

(Negative values represent greater generation in the core scenario.)



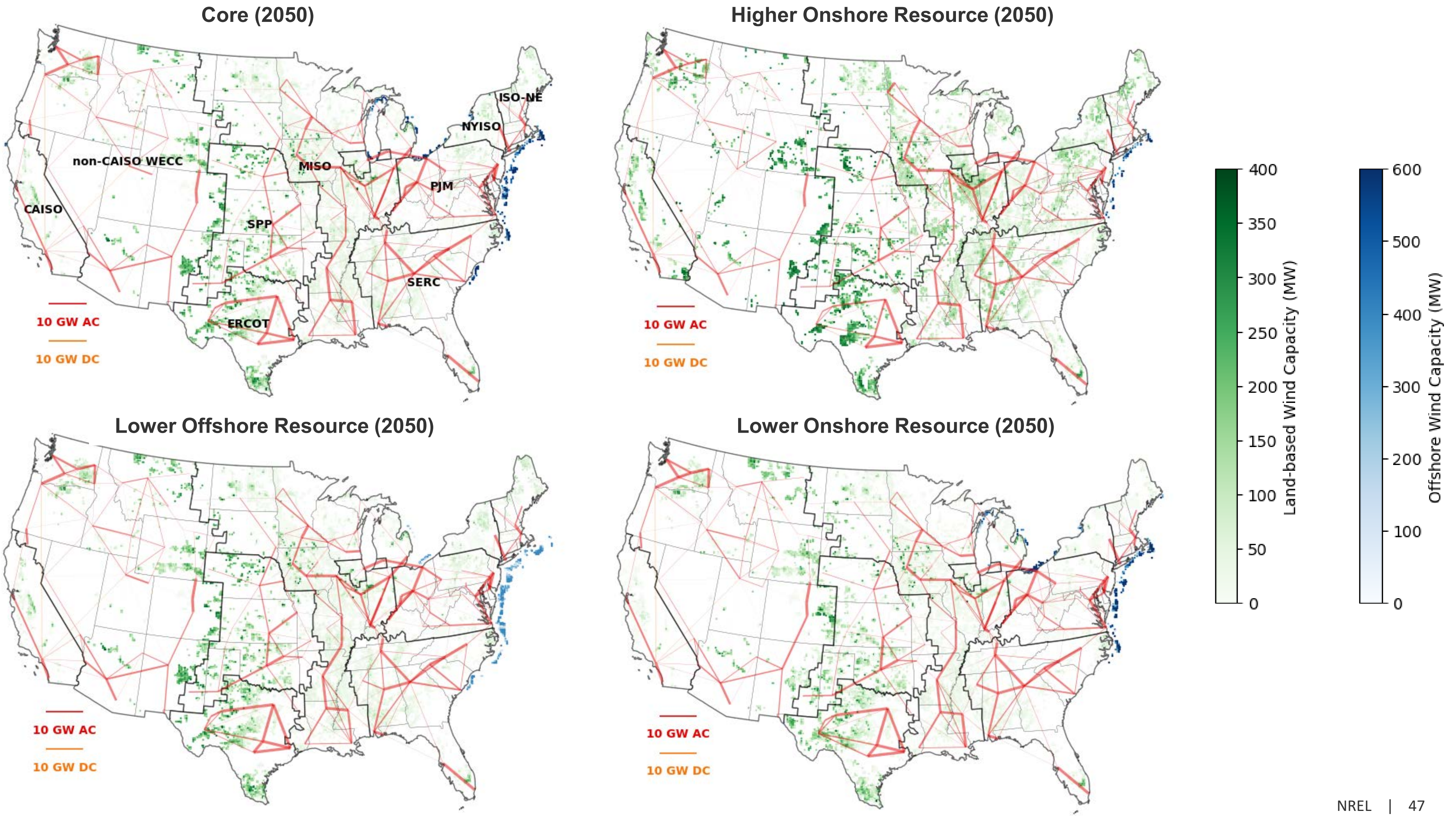
Siting considerations can influence the development between OSW, land-based wind, and solar resources in meeting a low-carbon grid.



See slide 17 for details

Scenario	Offshore Wind Siting Regime	Land-Based Wind Siting Regime	Utility PV Siting Regime
Core	Open Access	Limited Access	Limited Access
Higher Onshore Resource	Open Access	Reference Access	Reference Access
Lower Onshore Resource	Open Access	More-Limited Access	Limited Access
Lower Offshore Resource	Limited Access	Limited Access	Limited Access

Greater developability of land-based wind and solar sites can diminish the need for offshore resources. Note that the Core scenario uses a limited-access land-based wind siting regime (Lopez et al. 2021). The marginal impact of even more constraints to land-based wind siting driven by biodiversity factors has a limited impact on offshore wind under the scenarios modeled.

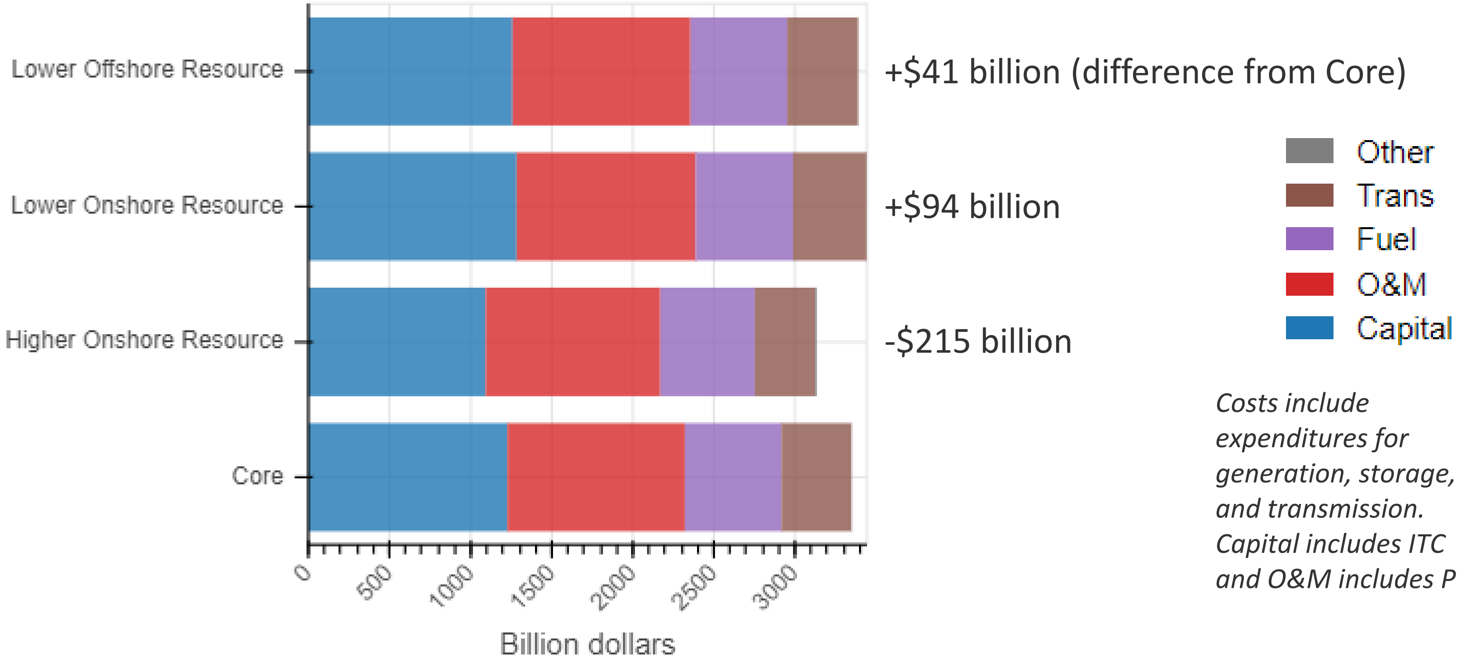

Core (2050)

Higher Onshore Resource (2050)

Lower Offshore Resource (2050)

Lower Onshore Resource (2050)

Present Value System Costs
(2022−2050, 5% Discount Rate)



+$41 billion (difference from Core)

+$94 billion

-$215 billion

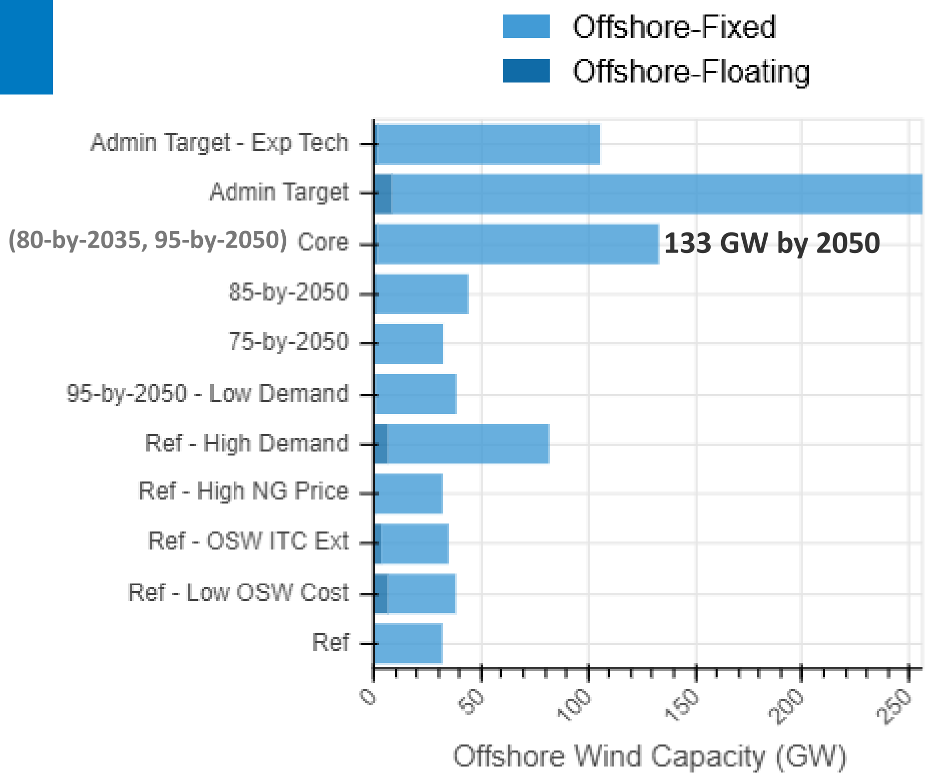
Costs include expenditures for generation, storage, and transmission. Capital includes ITC and O&M includes PTC

Siting can have a sizeable impact on total system costs. Fewer onshore siting restrictions can yield over $200 billion in cost savings, whereas more stringent onshore and offshore siting restrictions can increase costs by up to nearly $100 billion.

Summary of Sensitivity Analysis

Summary Findings (1)

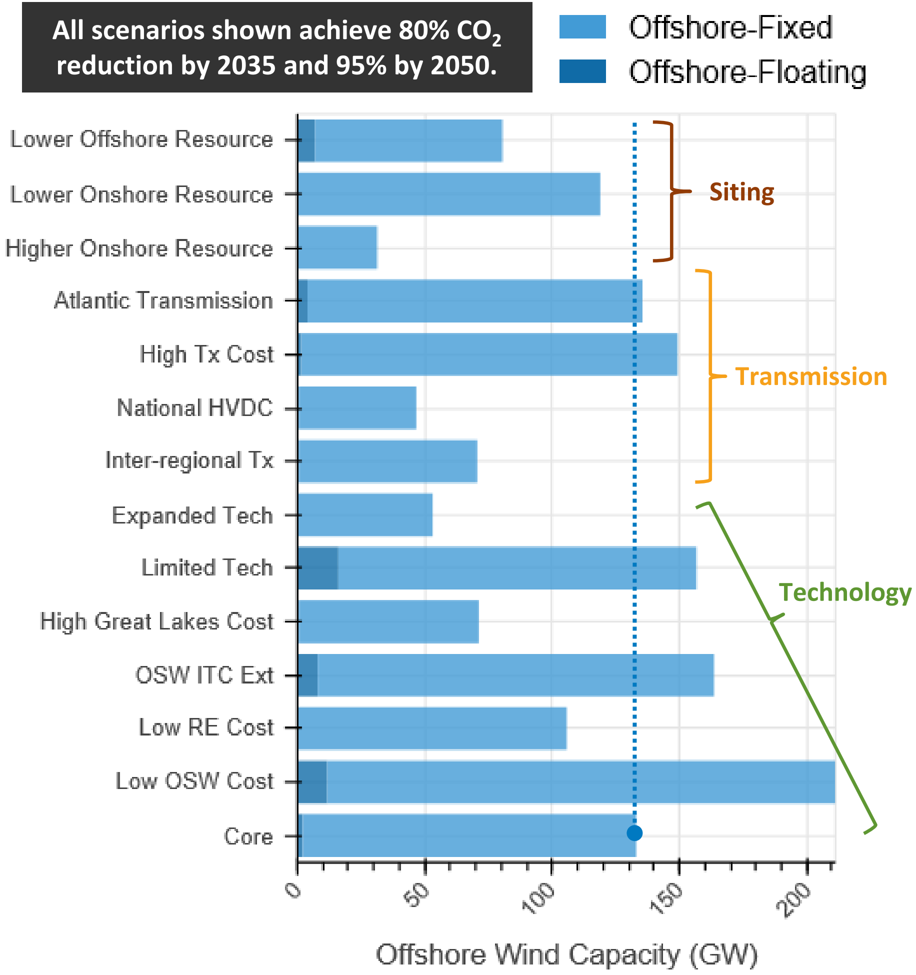
- State policies drive offshore development in the near-term and under “no new policy” conditions.
- A combination of concerted electricity emissions reductions (>80%) and electrification is needed for robust OSW deployment. These factors include:
    - Increase demand for clean electricity
    - Demand shifts to periods with higher offshore production.



133 GW by 2050

Summary Findings (2)

- Relative costs, incentives, and siting barriers with land-based resources are strong drivers of future U.S. OSW.
- Transmission expansion greatly enables land-based wind at the expense of offshore; more study is needed on offshore-specific transmission expansion (e.g., [Atlantic Offshore Wind Transmission Study]()).
- Availability of other low-carbon techs (including CCS and other renewable energy) can affect the role of OSW.
- Significant uncertainties with regional and technology (fixed vs. floating) OSW outcomes.



All scenarios shown achieve 80% CO_2 reduction by 2035 and 95% by 2050.

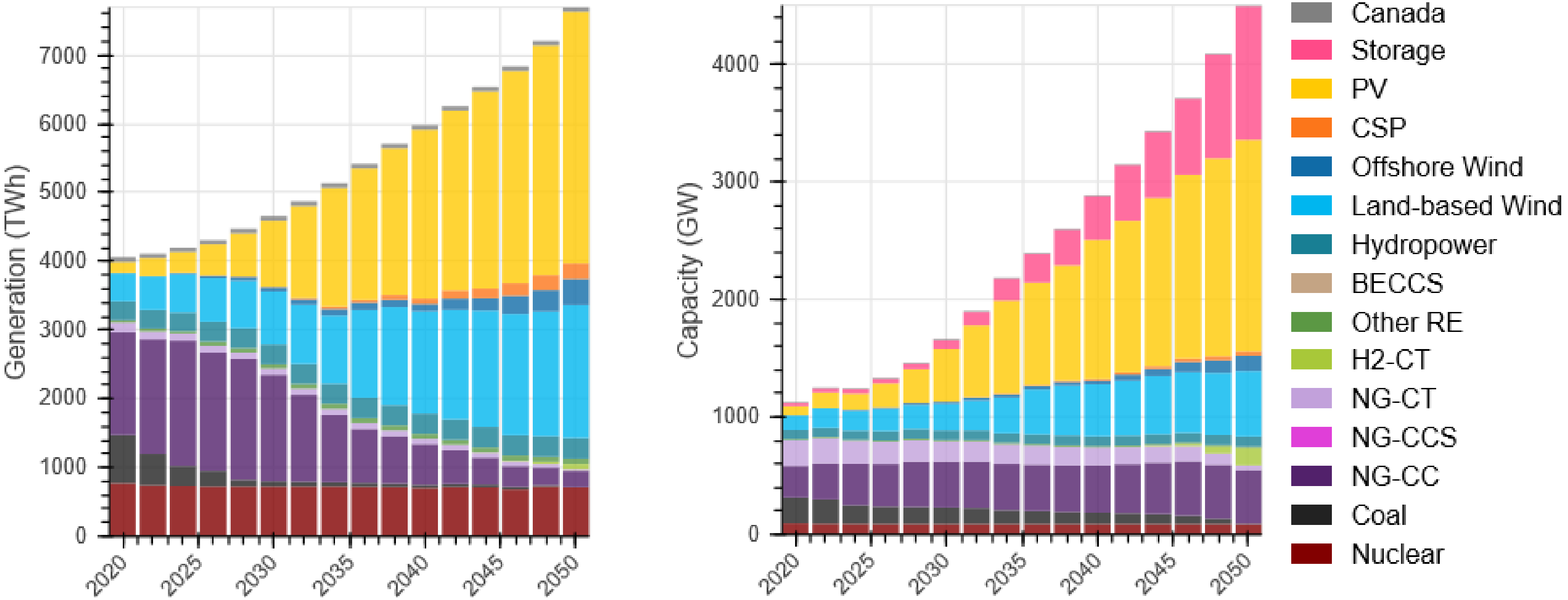
Results: Core Scenario

Deeper Dive of the Core Scenario

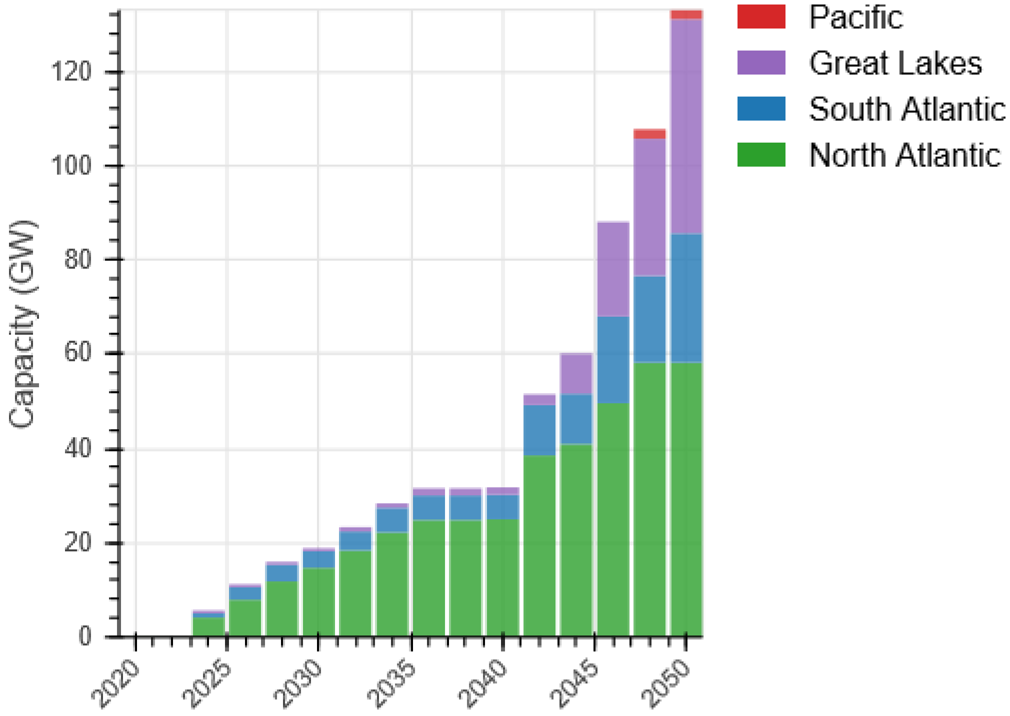
- Default settings for core scenario:
  - **Technology costs**: Annual Technology Baseline (ATB) 2021 Moderate projections for all technologies, 30% offshore ITC through 2035.
  - **National carbon emissions constraint**: 80% reduction by 2035 (from 2005 levels) and 95% by 2050.
  - **Demand**: Electrification Futures Study (EFS) High scenario.[2]
  - **Renewable energy (RE) siting**: Limited Access siting regimes for land-based wind and utility photovoltaic (PV).[3]
  - **Transmission**: New transmission is allowed within each of the 12 regions only (see slide 24).
  - **Technology availability**: No carbon capture and storage (CCS), nuclear small-modular reactors (SMR), or carbon dioxide removal (CDR) technologies.

[2] The EFS High scenario assumes widespread vehicle electrification (~76% of all 2050 vehicle miles travels use electricity) along with electrification for buildings and industry. This results in 1.9% per year annual load growth from 2020 to 2050 (Mai et al. 2018; Murphy et al. 2021).

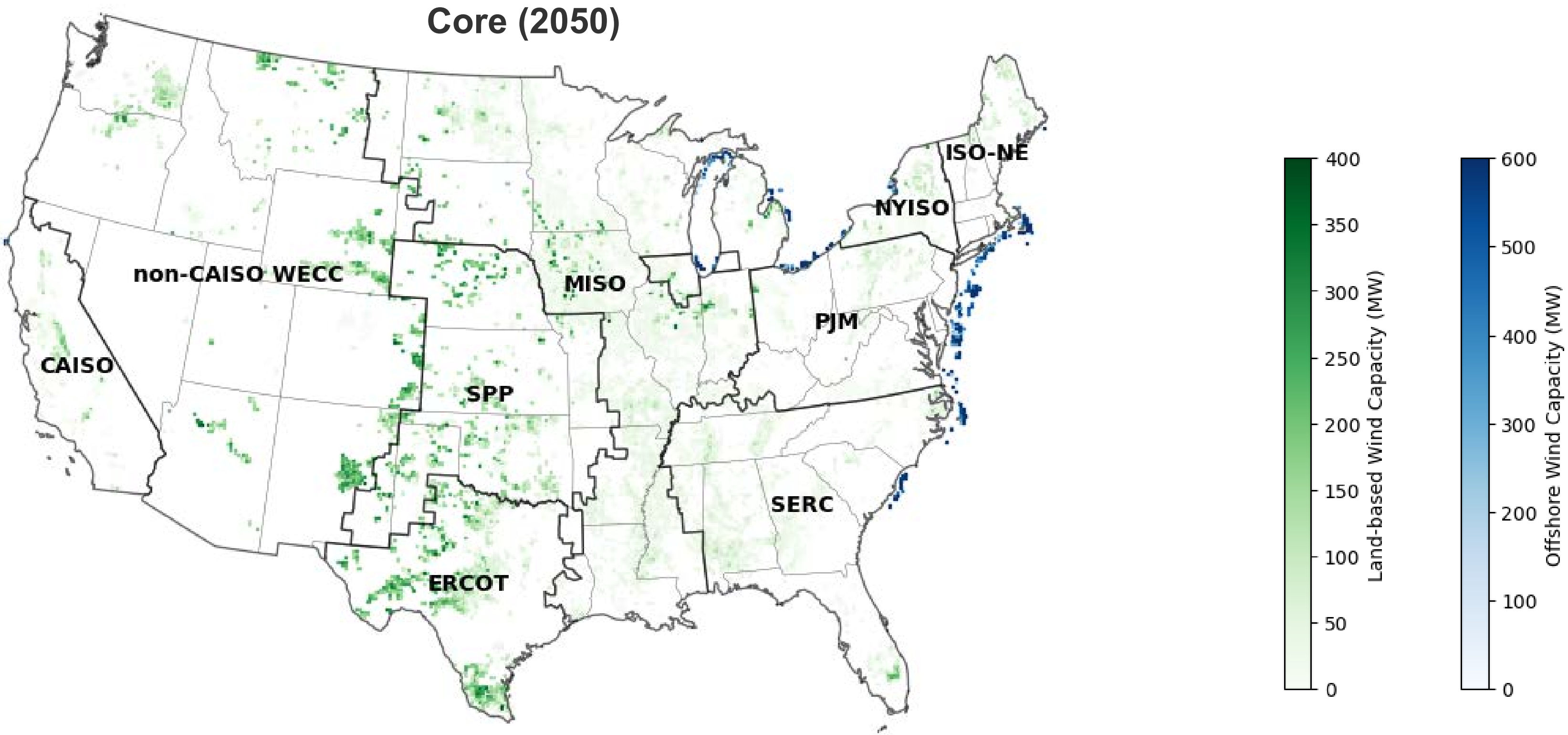
[3] Siting regimes are from the 2021 supply curve versions (https://www.nrel.gov/gis/wind-supply-curves.html).



In the core scenario, meeting new demand from electrification while lowering emissions requires transforming the U.S. electricity system primarily by expanding wind, solar, and battery capacity while reducing fossil fuel-based generation.



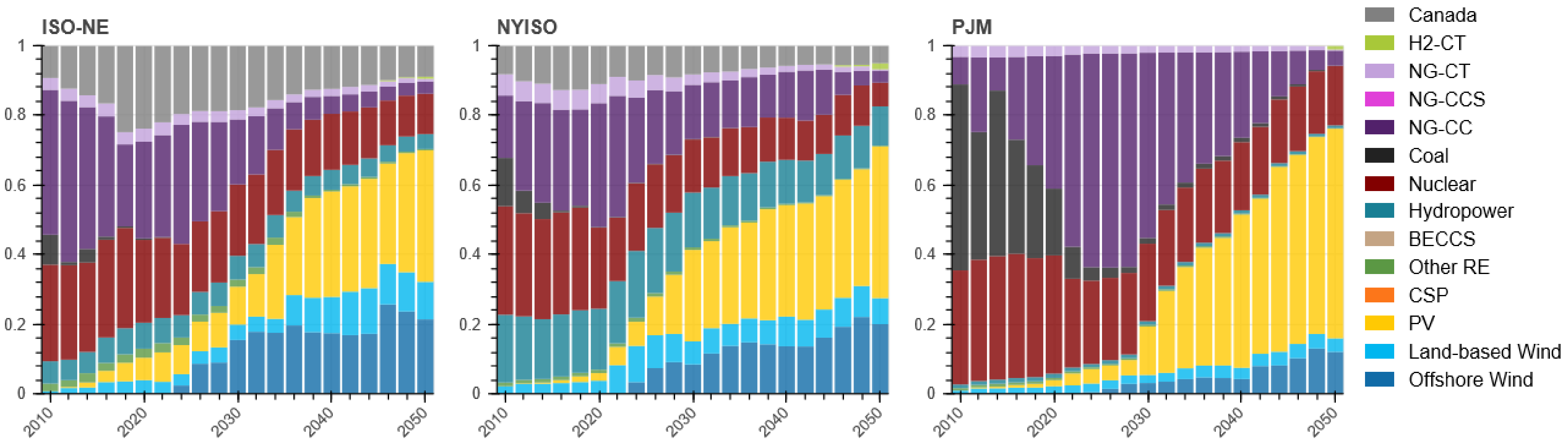
OSW development begins in the North Atlantic but expands south and to the Great Lakes over time and reaches 133 GW by 2050. Offshore development is more limited in the Pacific and Gulf—but significant offshore resources in these regions come very close to economic viability in the 2040s (see discussion starting on slide 60).



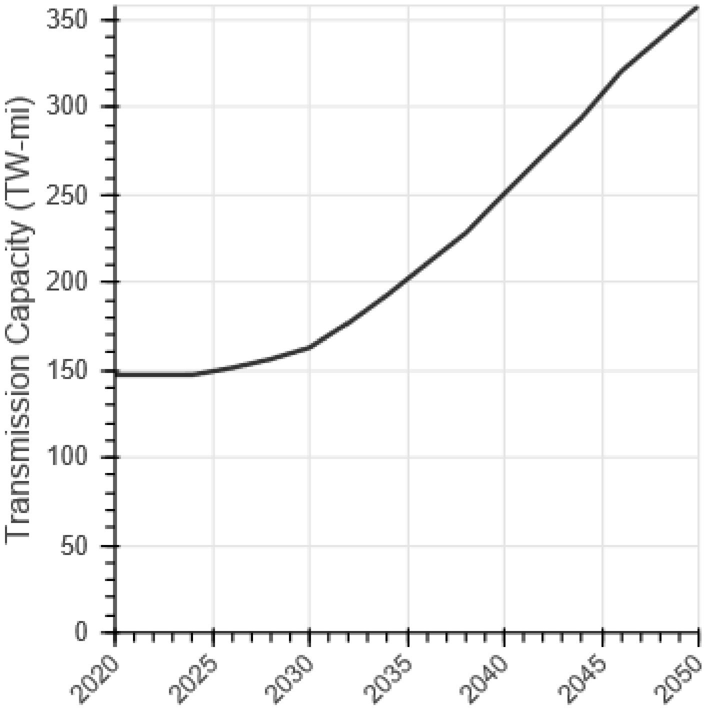
OSW development begins in the North Atlantic but expands south and to the Great Lakes over time and reaches 133 GW by 2050. Offshore development is more limited in the Pacific and Gulf—but significant offshore resources in these regions come very close to economic viability in the 2040s (see discussion starting on slide 59).

Regional Generation Share in the Core Scenario

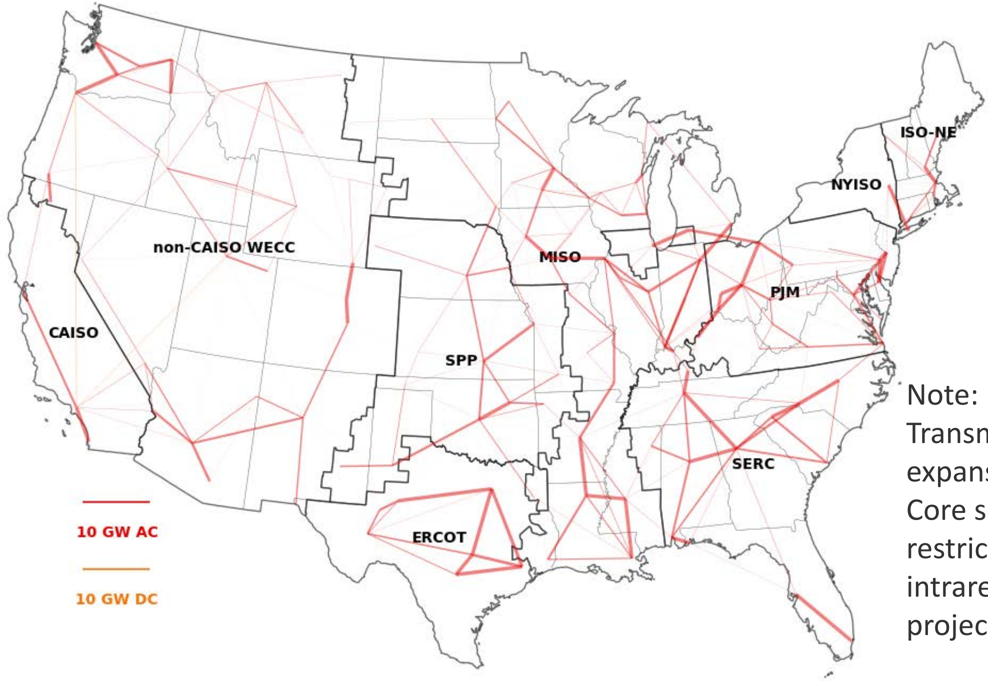
(Only in-state generation and imports from Canada are shown for each region.)



OSW contributes only 5% to total 2050 U.S. generation, but it is intrinsically a more regional resource. Over 20% of 2050 generation is from offshore in ISO-NE and NYISO and about 12% in PJM. OSW shares reach about 4% in MISO and SERC (excluding FRCC) and 1% in CAISO.



Core (2050)



Note: Transmission expansion in the Core scenario is restricted to intraregional projects only.

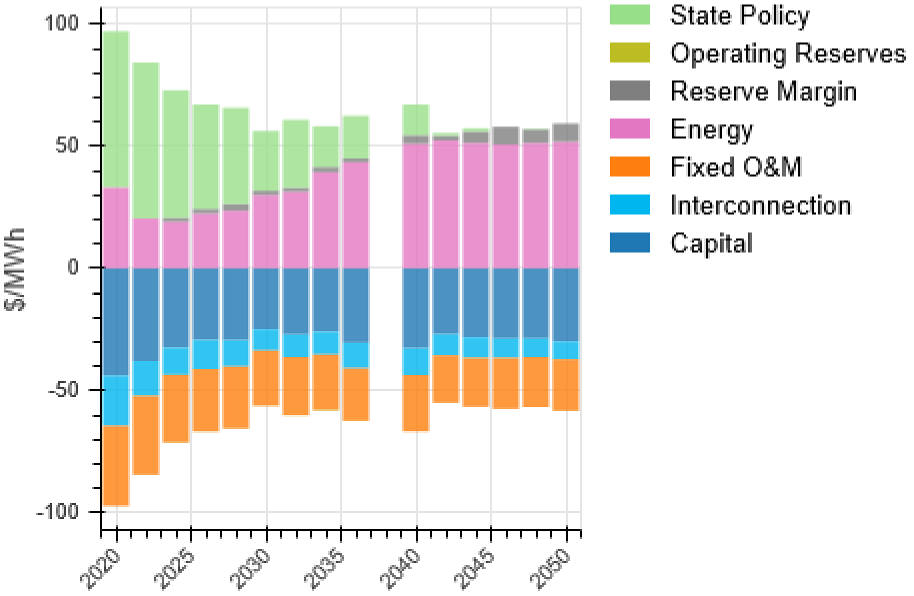
Growth in transmission reflects its systemwide benefits, but transmission expansion is constrained to be within region only (e.g., within RTOs). With these constraints, high-voltage transmission capacity in 2050 is 2.4 times larger than in 2020 under the Core scenario.

Offshore Wind Costs and Value Streams

- The figure shows average levelized costs and value for all sites chosen in each investment period.
- State policies are a primary source of OSW's value in the first half of the period, but OSW's energy value increases over time.
- The capacity value (in \$/MWh units) of OSW increases over time but is significantly smaller than the energy value.

Note: A slightly different version of the model (at a lower resolution) was used to estimate these value streams. Years without bars do not have any new OSW development.

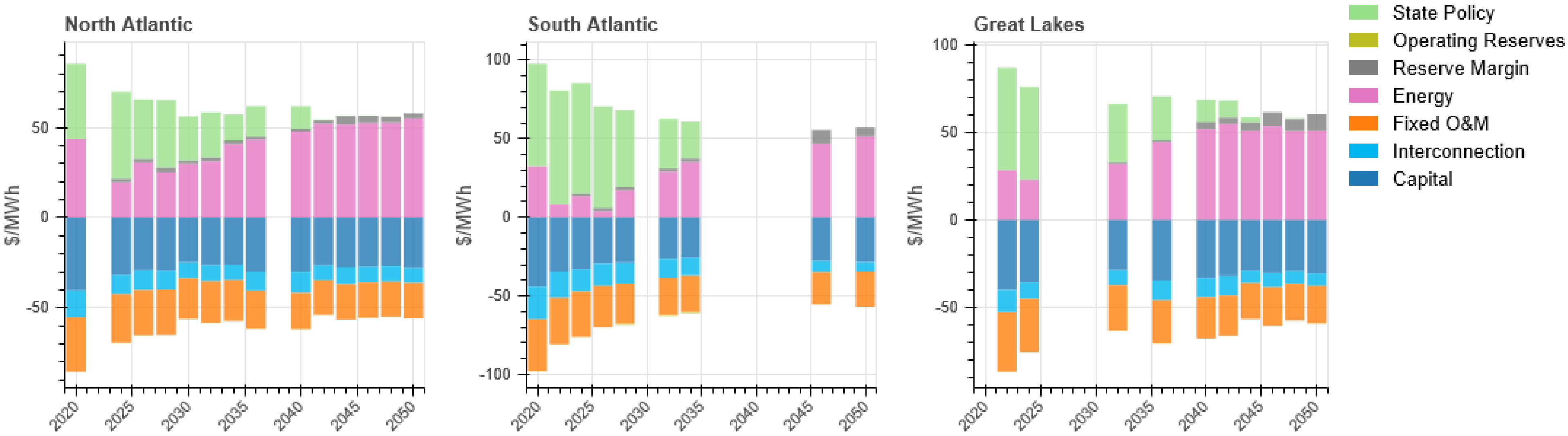
Positive values show the levelized value of energy for each grid service.



Negative values show the levelized cost of energy by component.

Offshore Wind Costs and Value Stream by Region

Positive values show the levelized value of energy for each grid service.



Negative values show the levelized cost of energy by component.

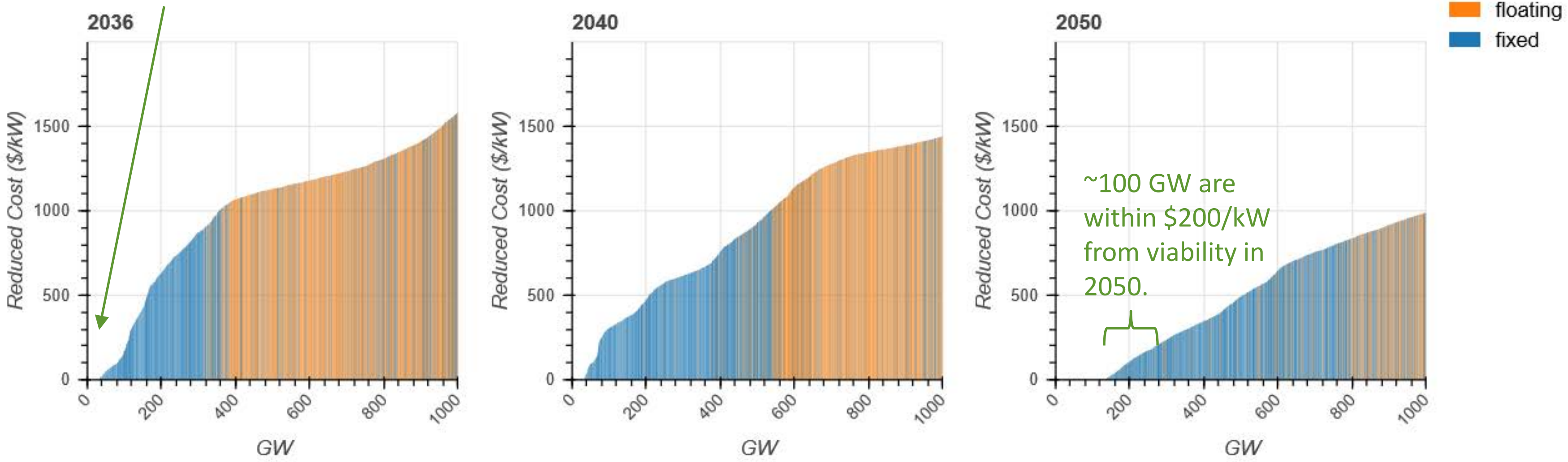
Note: A slightly different version of the model (at a lower resolution) was used to estimate these value streams. Years without bars do not have any new OSW development.

Offshore Wind *Reduced Cost* Supply Curves

Reduced cost = the amount that a resource's cost needs to be lowered for it to be economically viable considering all the resource's characteristics (e.g., direct costs, location, profile, reserve capabilities, interconnection costs).

Tens of GW beyond the state mandates are very close to economic viability.

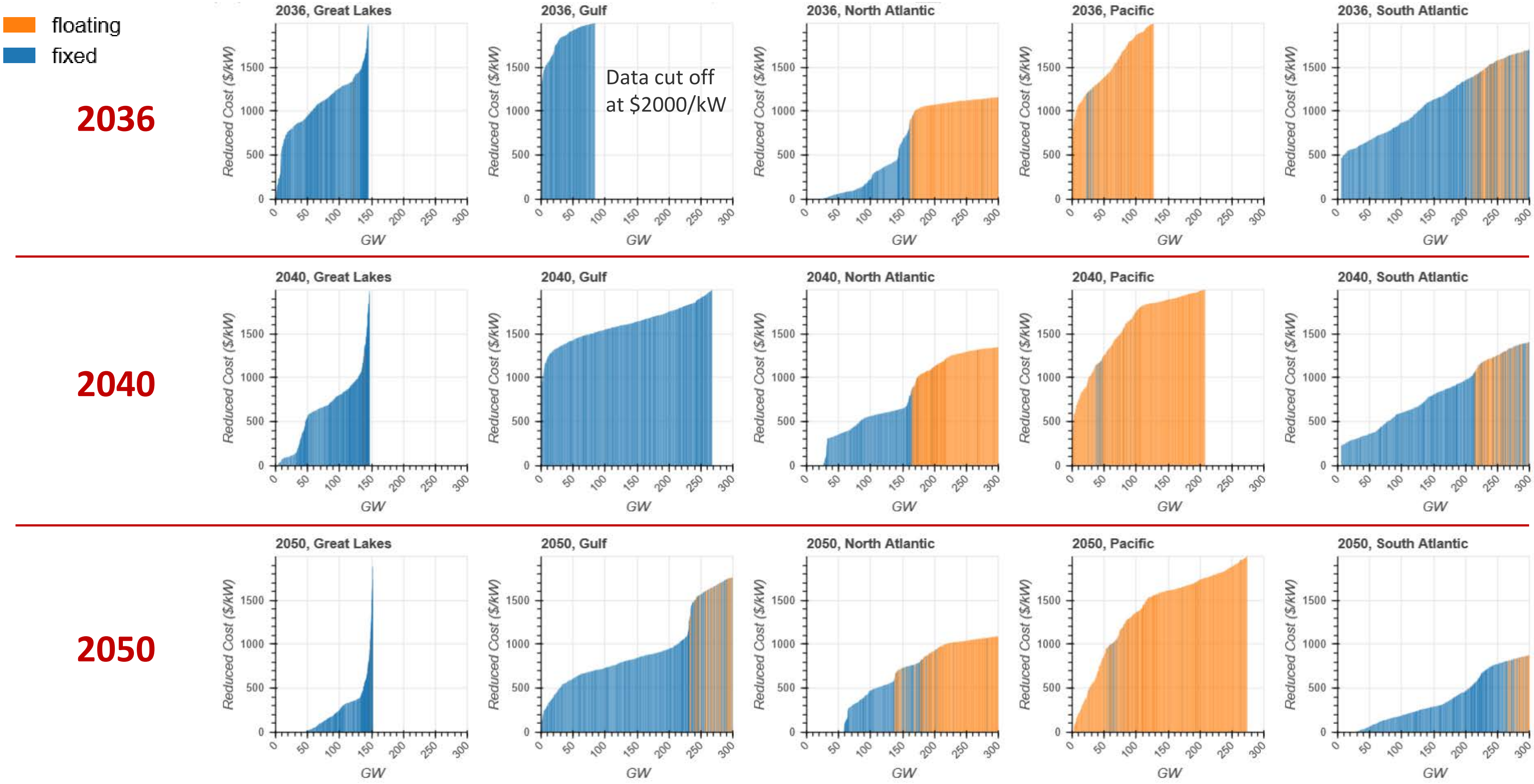
Shallower fixed-bottom locations are generally closer to economic viability than floating-platform sites in deeper waters.



~100 GW are within $200/kW from viability in 2050.

Note: Reported reduced costs are on a marginal basis only; if a resource is deployed, the reduced cost of other resources can change.

Regional *Reduced Cost* Supply Curves



2036

Data cut off at $2000/kW

2040

2050

Future Work

Future Work

The analysis provides initial modeling-based outlooks for U.S. OSW. The complexities and uncertainties with OSW and energy systems require additional research to improve upon this initial scenario assessment. Some key topics for further study include:

- Transmission and grid integration
  - What transmission designs could support OSW development and greater grid needs?
  - What points of interconnection are available and what new upgrades might be required for robust offshore deployment?
  - What grid services, beyond energy, can OSW provide? How might offshore's contributions to resource adequacy change with increasing deployment and as systems needs shift (e.g., changing from summer to winter peaking)?
- Local factors
  - What are the siting trade-offs between OSW and other uses (e.g., marine transportation, fishing, viewsheds)?
  - What are the local economic development and workforce impacts of OSW deployment?
  - What are the supply chain and manufacturing needs to support an expanding OSW industry? How might these factors impact future installation and maintenance costs for OSW?
- Energy system
  - How might competing technology options evolve relative to OSW technologies?
  - What role might OSW play for other future energy system needs (e.g., hydrogen production on energy islands)?

Corresponding author:
Trieu Mai, trieu.mai@nrel.gov

www.nrel.gov

NREL/PR-6A40-82101

Acknowledgments
This work was authored in part 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. We thank the following reviewers for their thoughtful comments and input: Jocelyn Brown-Saracino, Patrick Gilman, and Paul Spitsen (U.S. DOE); John Bistline (Electric Power Research Institute); Umed Paliwal and Amol Phadke (Lawrence Berkeley National Laboratory); and Gregory Brinkman, Jaquelin Cochran, Rebecca Green, Bethany Frew, Eric Lantz, Melinda Marquis, Walt Musial, Matt Shields, and Brian Smith (National Renewable Energy Laboratory). The views expressed in the article do not necessarily represent the views of the DOE, the U.S. Government, or the reviewers. Any errors or omissions are the sole responsibility of the authors. 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

References

Reports and Papers

Cole et al. 2021. *2021 Standard Scenarios Report: A U.S. Electricity Sector Outlook*. NREL/TP-6A40-80641. [link]

Denholm et al. Forthcoming. *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035.*

EIA. 2021. *Annual Energy Outlook 2021*. [link]

Ho et al. 2021. *Regional Energy Deployment System (ReEDS) Model Documentation: Version 2020*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-78195. [link]

Lopez et al. 2021. “Land use and turbine technology influences on wind potential in the United States.” *Energy* 223: 120044. [link]

Lopez et al. Forthcoming. *Offshore Wind Technical Potential of the Conterminous United States*.

Mai et al. 2021. “Interactions of wind energy project siting, wind resource potential, and the evolution of the U.S. power system.” *Energy* 223: 119998. [link]

Mai et al. 2018. *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States.* NREL/TP-6A20-71500. [link]

Musial et al. 2021. *Offshore Wind Market Report: 2021 Edition*. DOE/GO-102021-5614. [link]

Sun et al. *Electrification Futures Study: Methodological Approaches for Assessing Long-Term Power System Impacts of End-use Electrification.* NREL/TP-6A20-73336. [link]

The White House. 2021. “Fact Sheet: Biden Administration Jumpstarts Offshore Wind Energy Projects to Create Jobs”. Washington, D.C.

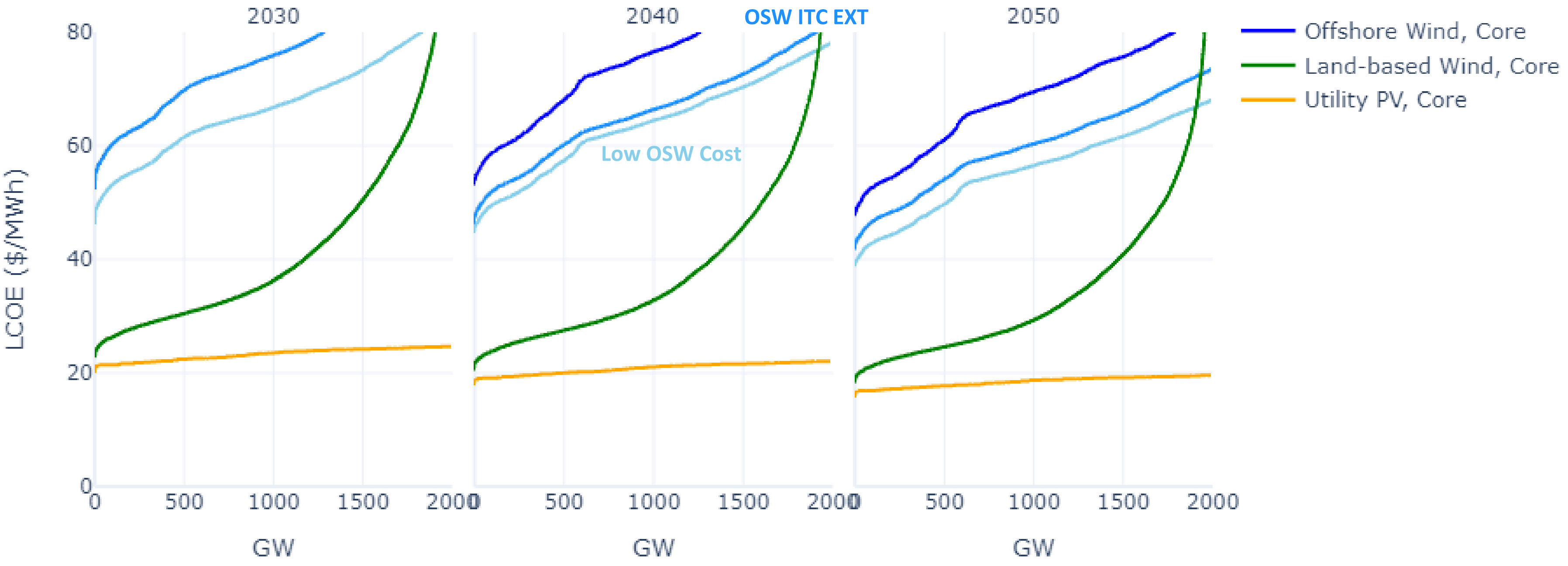
Other Resources

- ReEDS model [link]
- Renewable Energy Potential model [link]
- Renewable energy supply curve [link]
- Annual Technology Baseline [link]
- Electrification Futures Study [link]
- Energy Information Administration Annual Energy Outlook [link]

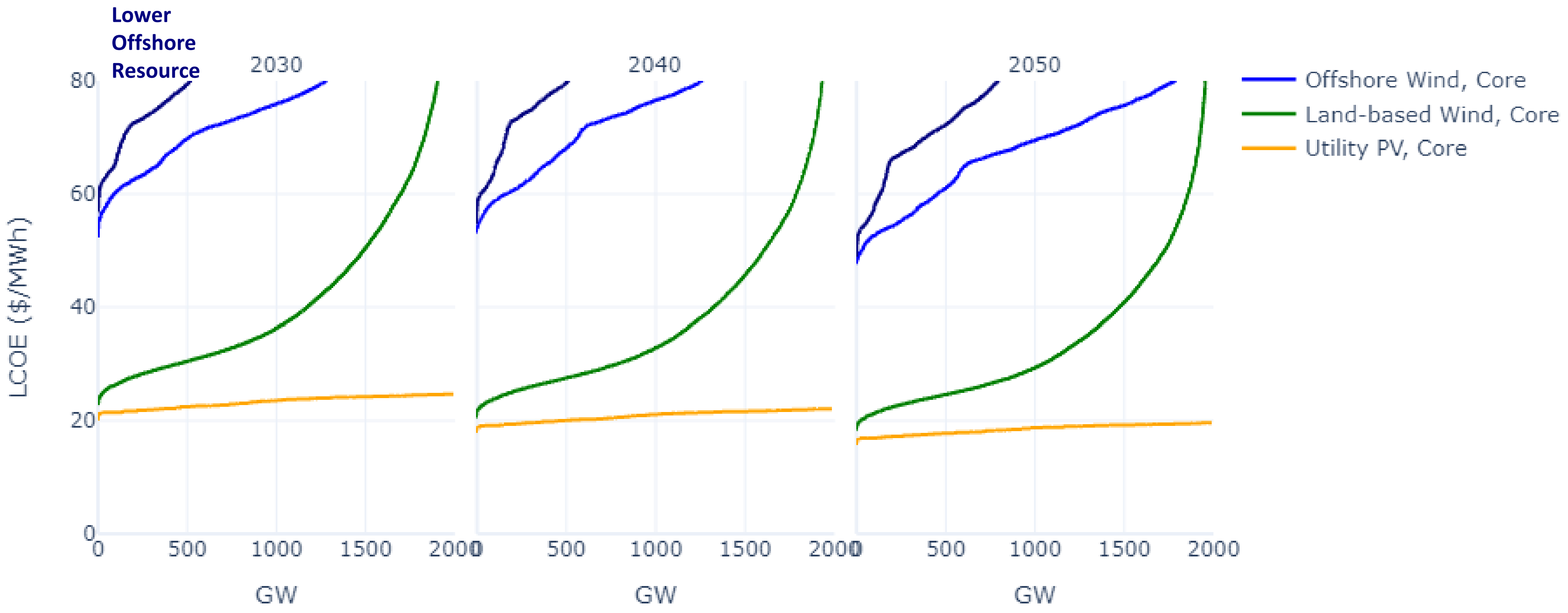
Additional Slides

Core Supply Curves

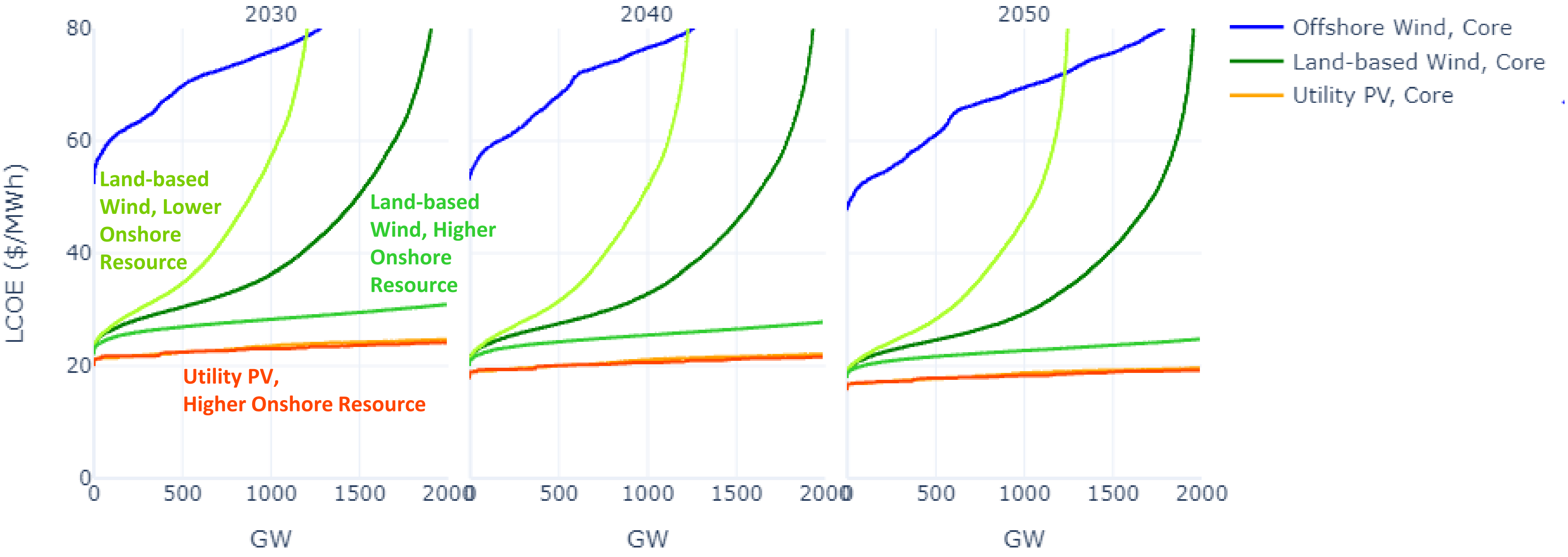
Supply Curves – OSW Cost



Supply Curves – Offshore Resource



Supply Curves – Land-based Resource

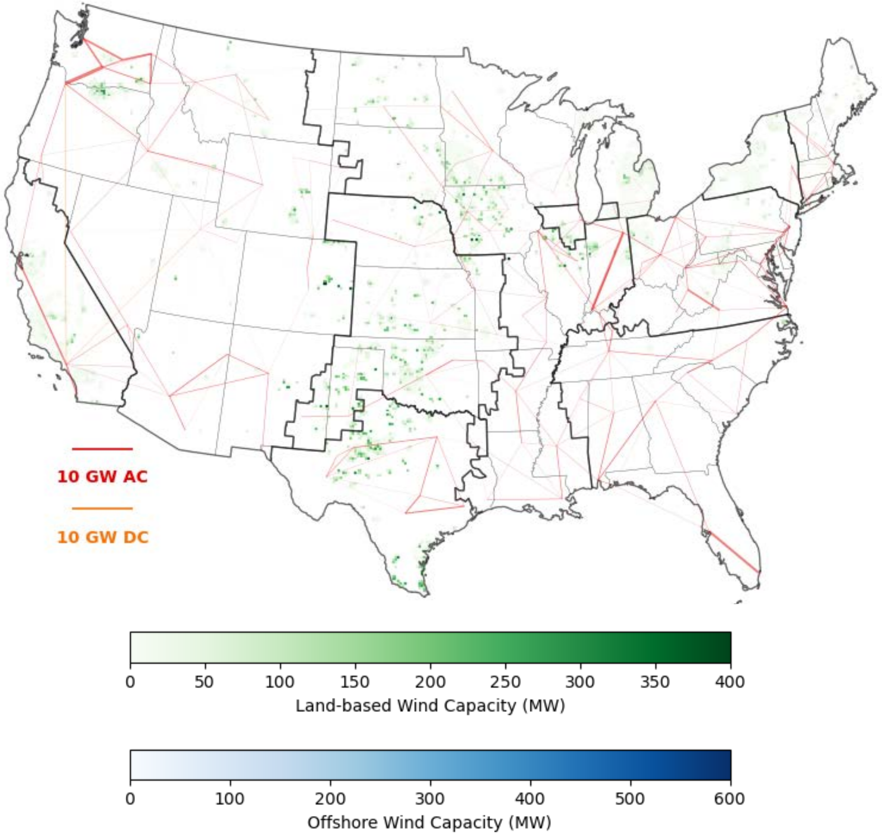


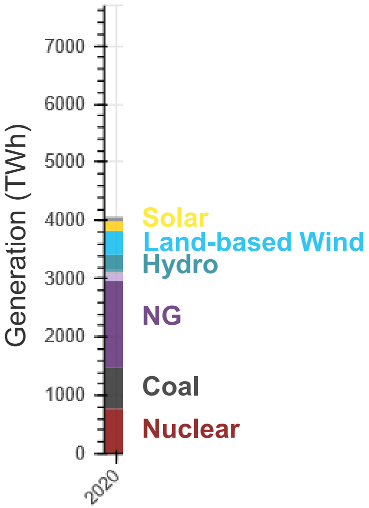
Land-based Wind, Lower Onshore Resource

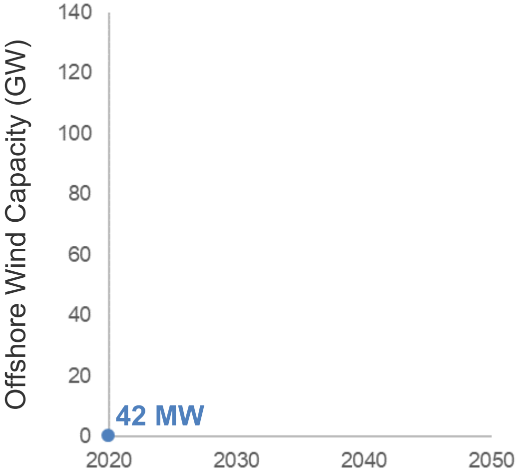
Land-based Wind, Higher Onshore Resource

Utility PV, Higher Onshore Resource

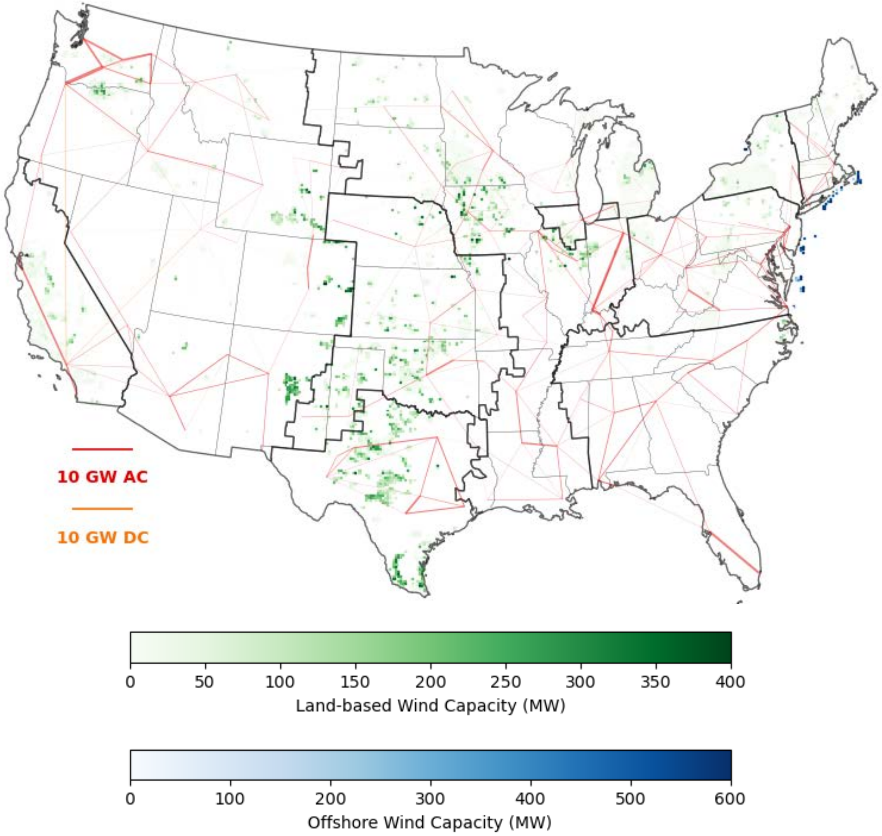
Core Scenario – 2020

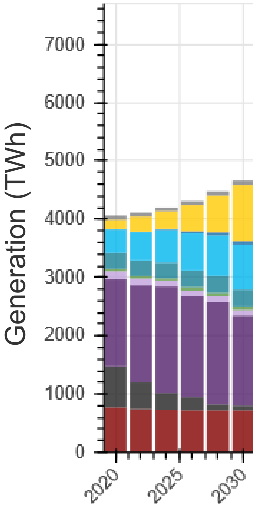


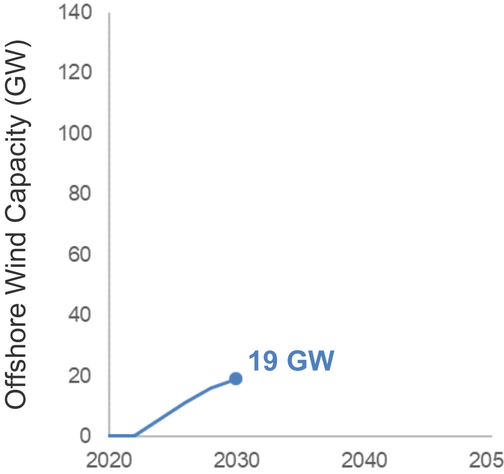




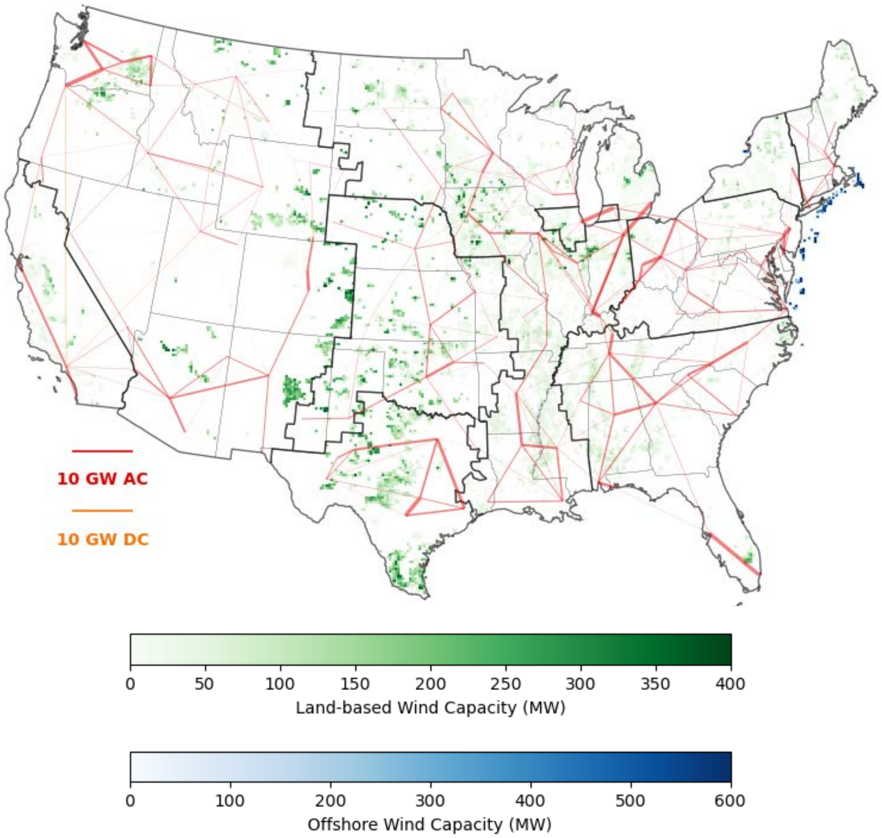
Core Scenario – 2030

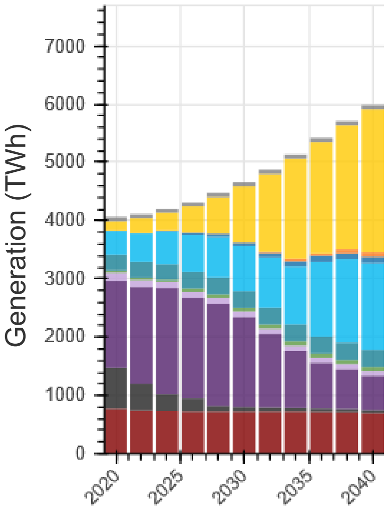


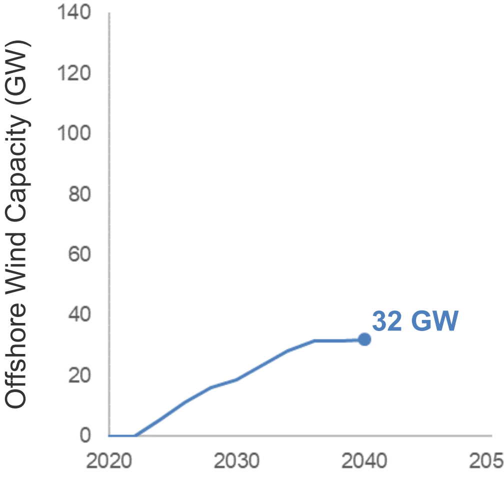




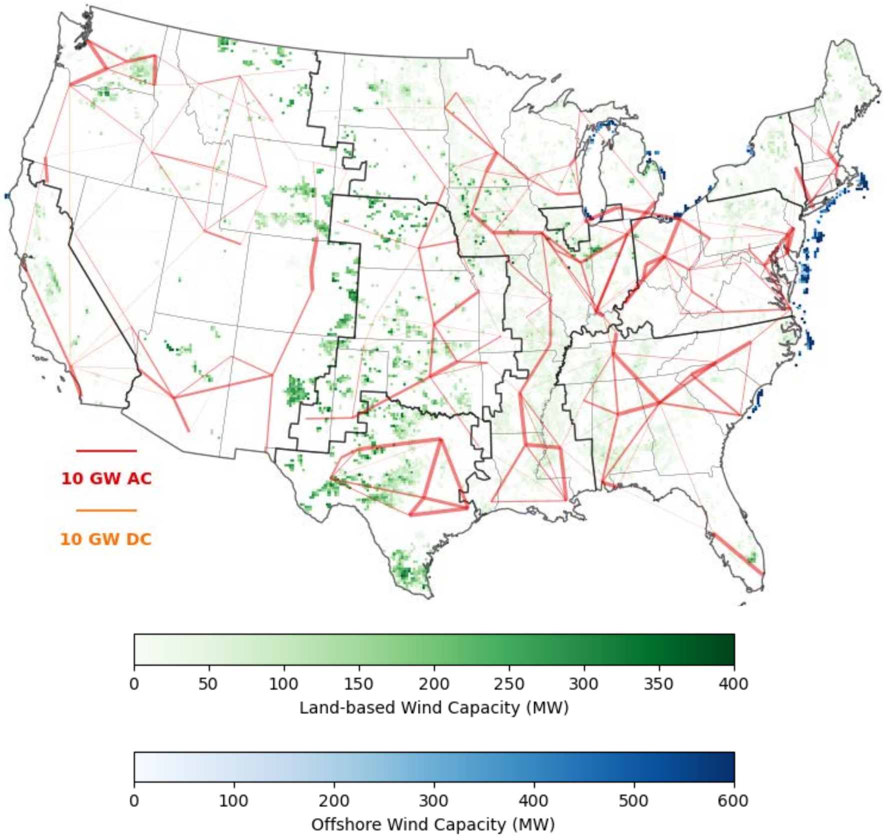
Core Scenario – 2040

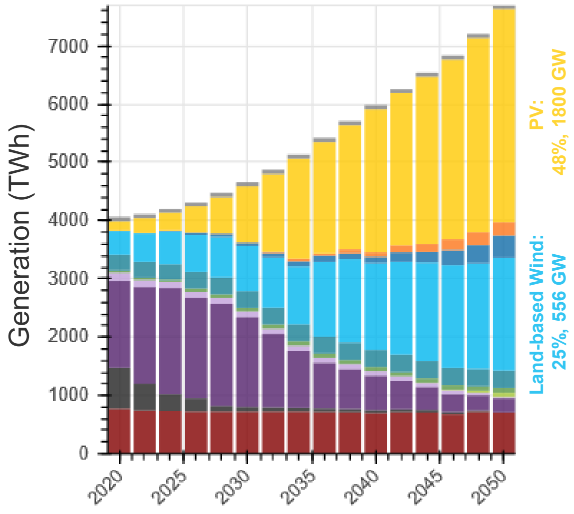


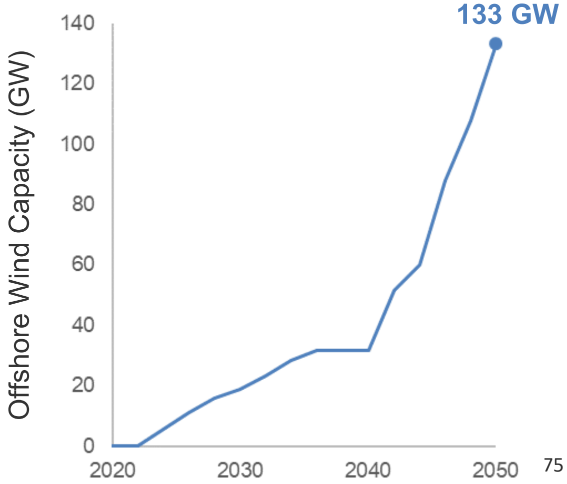




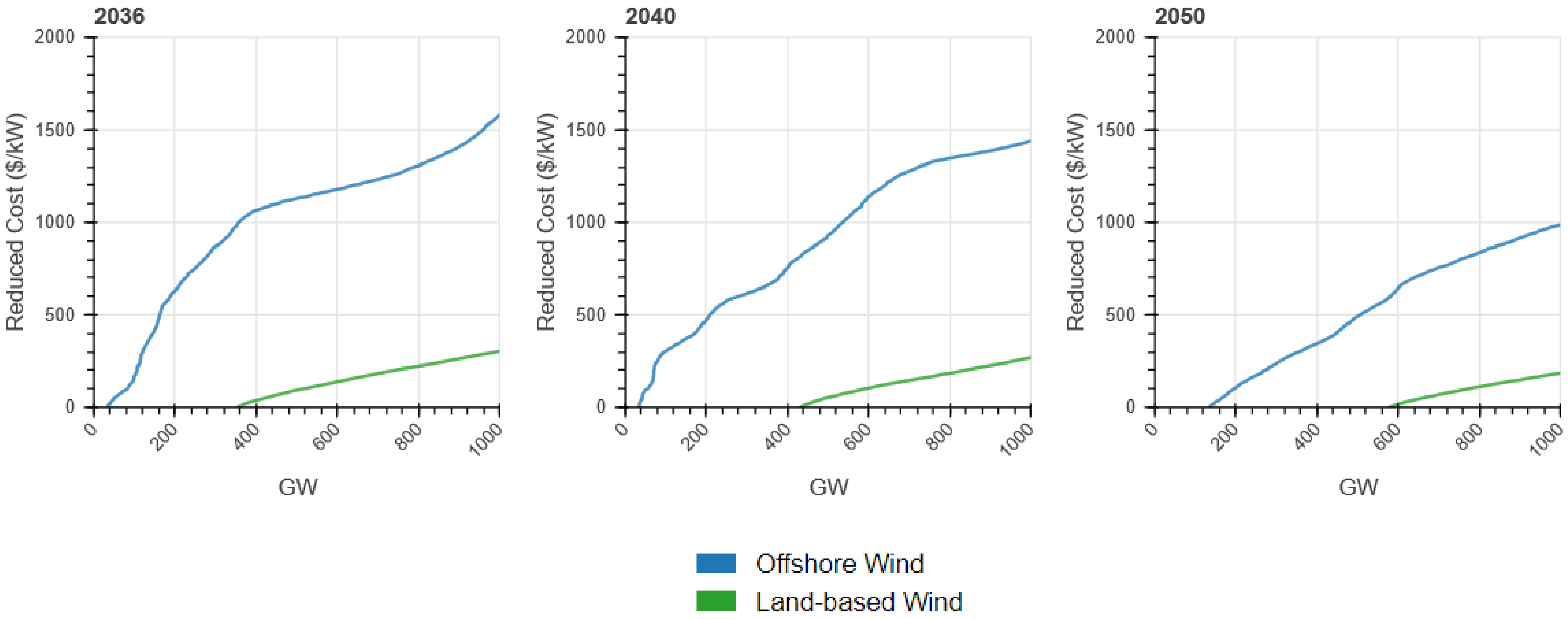
Core Scenario – 2050

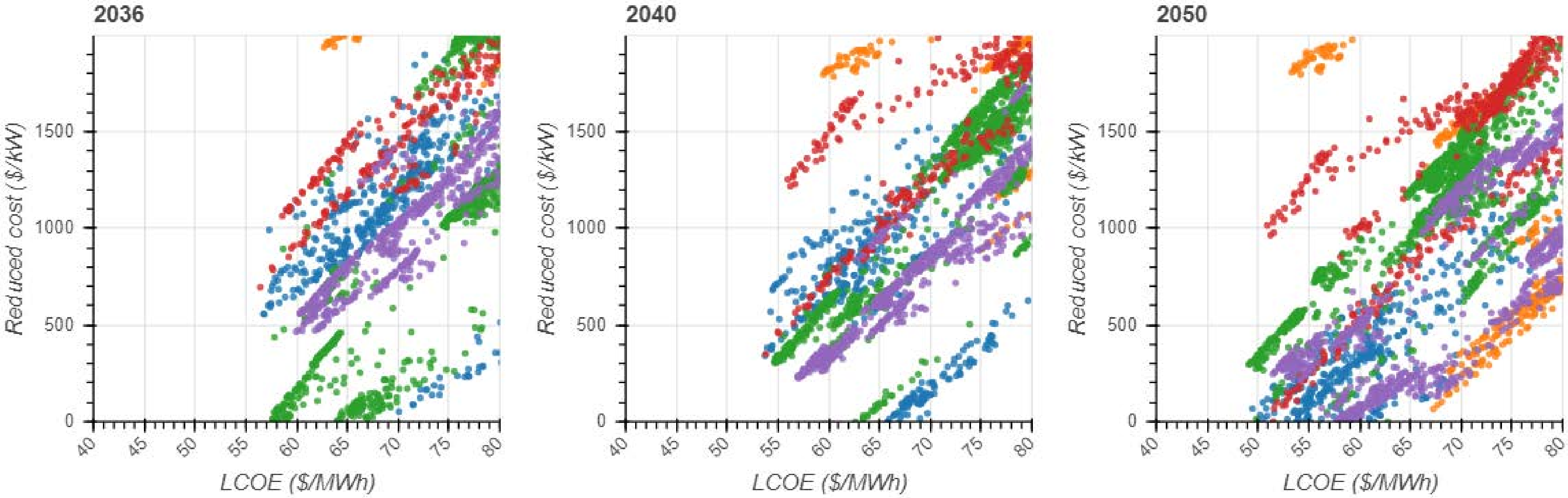






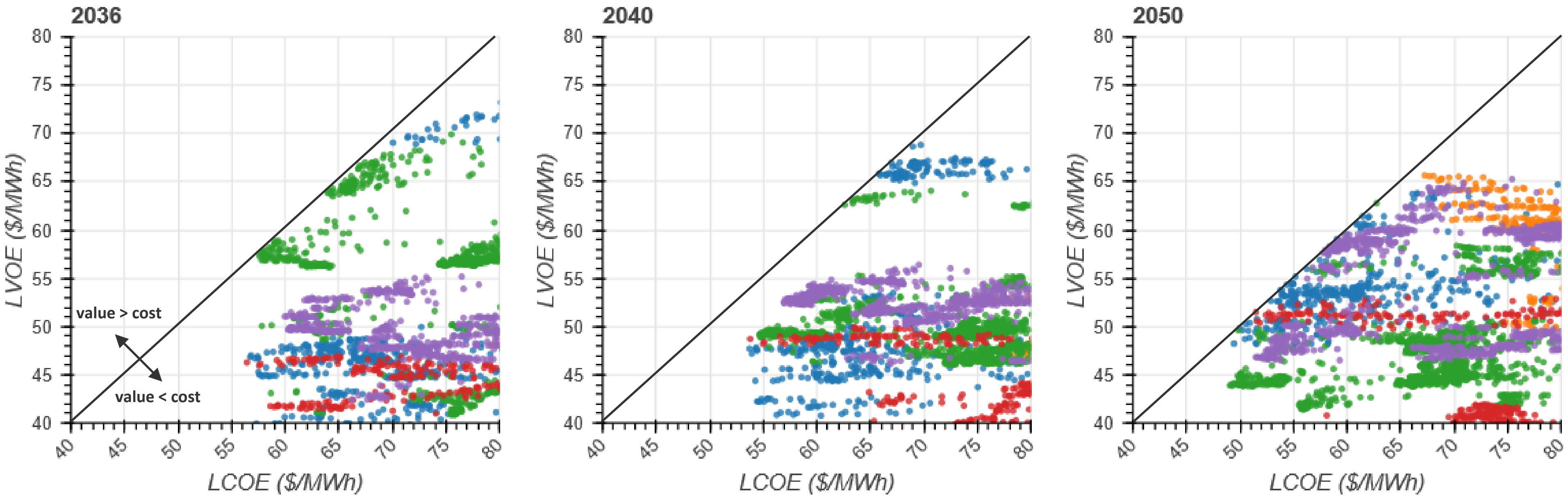
Reduced Cost Supply Curves Land-based and Offshore Wind





LCOE = levelized cost of energy

More sites in more diverse regions approach economic viability over time.



🟪 South Atlantic
🟥 Pacific
🟩 North Atlantic
🟧 Gulf
🟦 Great Lakes

LCOE = levelized cost of energy
LVOE = levelized value of energy

Sites chosen have LCOE = LVOE in the year deployed (the black diagonal line).