Renewable Energy Technical Potential and Supply Curves for the Contiguous United States: 2024 Edition

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National Renewable Energy Laboratory

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List of Abbreviations and Acronyms

AC	alternating current
ATB	Annual Technology Baseline
BIA	Bureau of Indian Affairs
BLM	Bureau of Land Management
BOS	balance of system
CAISO	California Independent System Operator
CBI	Conservation Biology Institute
CONUS	contiguous United States
CRP	Conservation Reserve Program
DC	direct current
DOD	U.S. Department of Defense
EGS	enhanced geothermal systems
ERCOT	Electric Reliability Council of Texas
FEMA	Federal Emergency Management Agency
ft	feet
GAP	Gap Analysis Project
GETEM	Geothermal Electricity Technology Evaluation Model
GW	gigawatt
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
ISONE	Independent System Operator for New England
km	kilometer
kV	kilovolts
kW	kilowatt
LCOE	levelized cost of energy
LCOT	levelized cost of transmission
m	meter
MISO	Midcontinent Independent System Operator
MW	megawatt
MWh	megawatt-hour
NEXRAD	Next Generation Weather Radar
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Aerospace Defense Command
NPS	National Park Service
NRHP	National Register of Historic Places
NSRDB	National Solar Radiation Database
NYISO	New York Independent System Operator
OSW	offshore wind
PAD-US	Protected Areas Database of the United States
POI	point of interconnection
psi	pounds per square inch
PV	photovoltaics
ReEDS	Regional Energy Deployment System
reV	Renewable Energy Potential

RIBITS	Regulatory In-Lieu Fee and Bank Information Tracking System
SAM	Systems Advisor Model
SCE	Southern California Edison
SPP	Southwest Power Pool
SROM	spatial reduced order model
TEPPC	Transmission Expansion Planning Policy Committee
TI	turbulence intensity
TWh	terawatt-hour
USACE	U.S. Army Corps of Engineers
USBOR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USFWS	U.S. Fish & Wildlife Services
USGS	U.S. Geological Survey
WIND	Wind Integration National Dataset

Executive Summary

Estimates of the potential of renewable energy are essential for a broad understanding of energy generation costs, opportunities for local economies, energy related jobs, revenues from renewable energy, and power systems planning. These estimates provide key data for policymakers, land managers, and energy planners by defining the quantity, quality, and cost of renewable resources. However, estimating renewable energy potential is challenging and requires frequent updates because of rapid advances in technology, cost reductions, and uncertainties about developable land resulting from social, regulatory, and environmental factors. Additionally, the complex processes involved in renewable energy development require regular reviews of methods and assumptions, which can also impact our understanding of renewable potential.

In this 2024 edition, we present new estimates of the technical potential for land-based wind, offshore wind, geothermal, and solar photovoltaics (PV) for the lower 48 or contiguous United States (CONUS). We also provide cost estimates for the available resources, presenting representative supply curves that can be used in downstream modeling and analysis.

Several improvements and modifications to the data, assumptions, and model were made this year, including:

- Updated technology cost and design
- New offshore wind potential estimates
- New geothermal potential estimates
- Land-based wind spatial balance of system costs
- Land-based wind thrust curves and turbulence intensity
- Land-based wind icing and temperature cutoffs
- Solar PV economies of scale cost curves
- Regional capital cost multipliers
- Transmission cost and representation
- New siting datasets and assumptions.

Our developable area, capacity, and multiyear annual mean uncurtailed generation estimates for the CONUS are presented in Table ES-1. CONUS-level supply curves are presented in Figure ES-1. Additional results, including state-level estimates, can be found in Section 3 of this report.

Table ES-1. Developable Area, Capacity, and Multiyear Annual Mean Uncurtailed Generation Estimates for the CONUS

Technology	Siting Scenario	Developable Area (km^2)	Capacity (GW)	Generation (TWh)
Land-based wind	Open access	5,680,290	13,365	41,849
	Reference access	1,654,997	9,436	30,575
	Limited access	579,050	4,291	14,267
Solar PV	Open access	5,770,111	185,160	429,941
	Reference access	2,370,737	76,076	181,964
	Limited access	1,076,840	34,555	83,966
Offshore wind fixed	Open access	300,629	1,203	4,193
	Reference access	262,089	1,048	3,605
	Limited access	183,212	733	2,483
Offshore wind floating	Open access	583,052	2,332	8,200
	Reference access	480,638	1,923	6,873
	Limited access	369,999	1,480	5,210
Geothermal Technology	**Depth (km)**	**Developable Area (km^2)**	**Capacity (GW)**	**Generation (TWh)**
Hydrothermal binary	3.5	577,211	1,642	14,284
EGS binary	4.5	999,961	3,698	32,189
	5.5	1,623,779	7,018	61,088
EGS flash	6.5	701,062	6,500	56,663

All estimates are in AC.

EGS = enhanced geothermal systems; GW = gigawatts; km = kilometers; TWh = terawatt-hours.

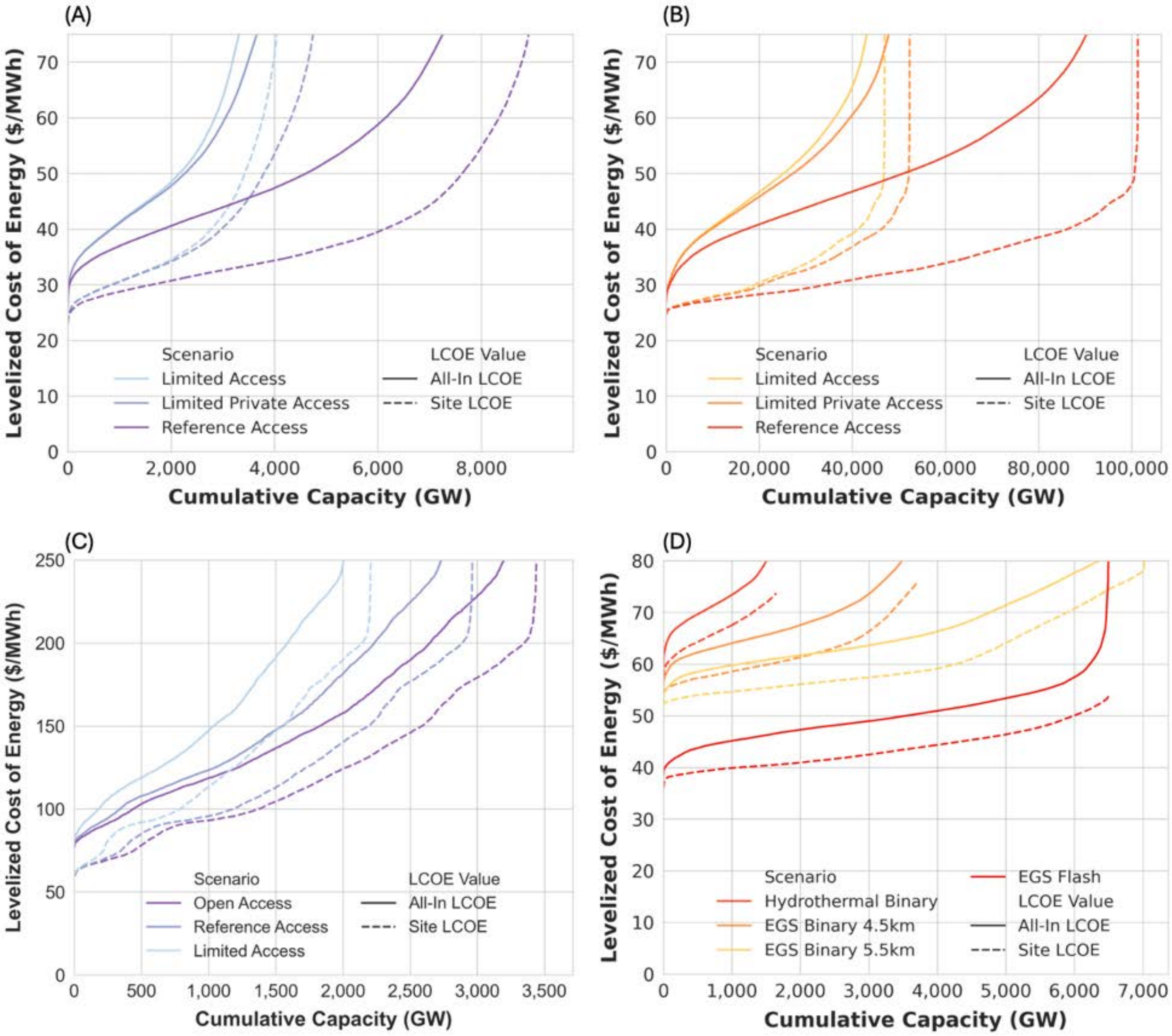

Figure ES-1. Levelized cost of energy (dollars per megawatt-hour, $/MWh) as a function of cumulative capacity (gigawatts, GW) for land-based wind energy (A), solar PV energy (B), offshore wind energy (C), and geothermal energy (D).

Graphs apply a cap on the y-axis to preserve resolution at lower costs and do not show the entire supply curve.

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1 Introduction

Estimates of the potential of renewable energy are essential for a broad understanding of energy generation costs, opportunities for local economies, energy related jobs, revenues from renewable energy, and power systems planning. They provide key data for policymakers, land managers, and energy planners by defining the quantity, quality, and cost of renewable resources. However, estimating renewable energy potential is challenging and requires frequent updates regarding the rapid advances in technology, cost reductions, and uncertainty about developable land that are the result of social, regulatory, and environmental factors. Additionally, the complex processes involved in renewable energy development require regular reviews of methods and assumptions, which can also impact our understanding of the potential for renewable energy.

In this study, we present new estimates of the technical potential for land-based wind, offshore wind, geothermal, and utility-scale solar photovoltaics (PV) for the contiguous United States (CONUS). We also provide cost estimates for the available resources, presenting representative supply curves that can be used in downstream modeling and analysis.

Several improvements and modifications to the data, assumptions, and model were made in 2024, including:

- Updated technology cost and design
- New offshore wind potential estimates
- New geothermal potential estimates
- Land-based wind spatial balance of system (BOS) costs
- Land-based wind thrust curves and turbulence intensity
- Land-based wind icing and temperature cutoffs
- Solar PV economies of scale cost curves
- Regional capital cost multipliers
- Transmission cost and representation
- New siting datasets and assumptions.

2 Methods and Modeling Framework

We used the Renewable Energy Potential (reV) model (version 0.9.4) to conduct our analysis (Maclaurin et al. 2019). Most of our modeling framework was the same as used in the report published by Maclaurin et al., but we made some incremental improvements and advancements to the modeling methods and core underlying data.

reV is a geospatial model that combines a variety of spatial and temporal data to estimate renewable energy potential at discrete sites across broad geographies. reV operates at multiple input resolutions and aggregates the results into approximately 67,000 11.5-kilometer (km) × 11.5-km candidate solar and wind sites, more than 10,000 15.8-km × 15.8-km candidate offshore wind sites, and approximately 38,000 11.5-km × 11.5-km candidate geothermal sites. The four primary components of data and assumptions we used to estimate resource potential were:

- Resources (wind speed, irradiance, temperature at depth)
- Technology design and finance assumptions
- Siting constraints and considerations
- Transmission costs and constraints.

2.1 Solar and Wind Resources

reV uses the National Solar Radiation Database (NSRDB) version 3 for solar resources (Sengupta et al. 2018). The NSRDB is a dataset of half-hourly solar irradiance with ancillary meteorological information at a 4-km spatial resolution. It spans the CONUS for more than 20 years (1998–2022). Land-based and offshore wind resources are represented using the Wind Integration National Dataset (WIND) Toolkit (Draxl et al. 2015). It provides 5-minute wind speed, direction, and ancillary meteorological data at a 2-km spatial resolution for a range of hub heights. It also spans the CONUS, but for a shorter period of record (2007–2013) than the solar data.

For both datasets, we sampled the resource at hourly intervals, specifically at on-the-hour times. Because both the NSRDB and WIND Toolkit datasets provide instantaneous estimates of resources, we used the hour value as the index.

2.2 Geothermal Resources

reV uses the temperature-at-depth datasets from Southern Methodist University (Blackwell et al. 2011) because they provide the most comprehensive representation of conterminous U.S. geothermal resources, in both spatial and depth dimensions. The original data from Southern Methodist University were preprocessed into an equal-area raster format at a 2.5-km spatial resolution before ingestion by reV. The geothermal resource data cover depths of 3.5 km to 9.5 km in 1-km depth increments. Temperatures are assumed to remain constant over time, thereby eliminating the need for a temporal component for the data.

2.3 Technology Design and Financial Assumptions

The reV model uses the Systems Advisor Model (SAM) to estimate hourly generation and levelized cost of energy given user-defined plant configurations and costs (Freeman et al. 2018a). For this study, we used SAM version 2022.11.21 (PySAM version 4.1.0).

Solar PV and wind turbine design and costs have been evolving at a rapid pace over the past several decades ("Land-Based Wind Market Report: 2023 Edition" 2023; "Utility-Scale Solar | Electricity Markets and Policy Group" 2023; McCoy et al. n.d.). Therefore, we leveraged the 2024 Annual Technology Baseline (ATB), which provides annual updates of typical and expected technology design and costs from the present year and into the future (NREL 2024).

For this study, we used the ATB technology and cost assumptions representative of the "Market Financial Case," a capital recovery period of 30 years, and costs from the year 2035.

We developed regional capital cost expenditures datasets to apply to wind and solar technologies capital cost to reflect the variations in labor, taxes, land value, and more. We sourced our capital costs primarily from the EIA/Leidos Engineering report (*Capital Cost Estimates for Utility Scale Electricity Generating Plants* 2016). We used these city data costs and spatially interpolated them to each reV site. In addition, offshore wind also applies regional multipliers, using cost data from the EIA (2023).

2.3.1 Land-Based Wind Technology

Assumptions specific to land-based wind technology are presented in Table 1. We then present model specifics and enhancements.

To better capture the ability of wind turbines placed in complex environments, we used the spatial reduced order model (SROM) methodology presented by Lopez et al. in 2023. The SROM methodology uses an optimization routine to place individual turbines, considering the turbine configuration, the cost and losses associated with the wind farm (e.g., wake losses), the wind resource at the site, and any restrictions (e.g., local ordinances) on where the turbines can be placed.

Traditional methods of calculating the technical potential of a wind farm require the input of a capacity density, which is the amount of wind capacity that can be installed per unit area. These capacity densities are often derived from empirical studies or roughly estimated using typical plant spacing requirements (Harrison-Atlas, Lopez, and Lantz 2022). However, the SROM methodology calculates site-dependent capacity densities, which consider the cost of building and operating the wind farm and the amount of land available. Therefore, capacity density is an output of the model and not an input assumption.

Table 1. Land-Based Wind Technology Characteristics Used in Supply Curves

Wind Turbine Characteristic	ATB Moderate Case
Turbine nameplate (megawatt, MW)	6
Rotor diameter (meter, m)	170
Hub height (m)	115
Losses (%)[a]	Endogenous
Capacity density (MW/km^2)[b]	Endogenous
Capital expenditures (2022$/kilowatt, kW)[c]	1,109[d]
Fixed operational expenditures (2022$/kW)	28
Fixed charge rate (%)	7.14

[a] We used a static loss rate of 11%, Intra-power plant wake losses were determined endogenously and ranged from 0.05% to 25%. Additionally, outages from icing and cold temperatures were also captured. The static loss rate includes maintenance and forced outages, electrical losses, turbine performance losses (i.e., energy not produced compared to the original equipment manufacturer, or OEM, power curve), and environmental losses. Profiles from reV assumed no grid curtailment.

[b] Capacity density was endogenous. We calculated two forms of capacity density based on the results. Included area capacity density had a median of 7.6 MW/km^2, and the convex hull capacity density had a median of 2.4 MW/km^2. See Lopez et al. (2023) for details regarding capacity density.

[c] The ATB assumes $1,159/kW for a 200-MW wind power plant. We applied an economies of scale cost curve in our siting optimization, in which capital expenditures ranged from $1,111/kW to 2,374/kW, depending on the number of turbines sited.

[d] The ATB costs assume about $50/kW for roads and electrical collection systems (as part of balance of system costs). Since these costs are modeled endogenously in reV, we reduce the ATB capital costs by $50/kW but add in site-specific costs for roads and collections. These costs range from $23/kW to $150/kW.

In 2024, we made several enhancements to the SROM model to improve our representation of wind farm wake losses. The improvements included improved wake decay constants using site-specific turbulence intensity (TI). TI is defined as the ratio of the standard deviation of wind speed to the mean wind speed within a specified time frame, typically 10 minutes (Ren et al. 2018) and can have a significant impact on wake losses. We sourced our TI spatial data from the Danish Technical Institute Global Atlas for Siting Parameters (Figure 1).[1] The Danish Technical Institute TI data are estimated with a numerical weather prediction model at 50-, 100-, and 150-m heights at 250-m horizontal spatial resolution. We interpolated these values onto the WTK grid by averaging all TI values within a distance threshold from each resource location. This threshold was set as 105% of half of the diagonal distance between the closest WTK resource points. Once all TI values had been re-gridded, we interpolated to the hub height of the modeled turbine by fitting a quadratic function to the values of TI at 50 m, 100 m, and 150 m for each of the 11.5-km reV cells. Finally, we converted the data into a wake decay constant by halving the interpolated TI value at each location.

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[1] https://orbit.dtu.dk/en/projects/global-atlas-for-siting-parameters

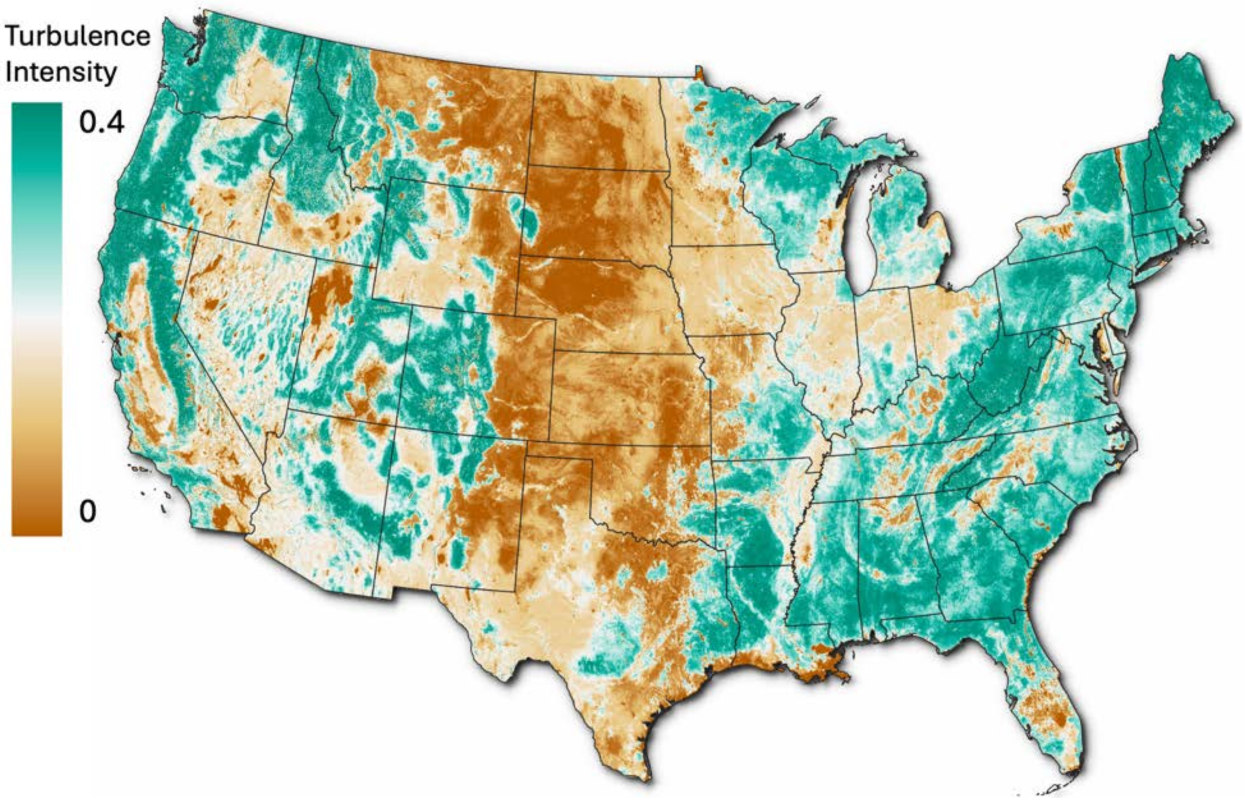

Figure 1. Danish Technical Institute turbulence intensity at 100-m hub height

We also added user-defined coefficient of thrust curves (C_t). The C_t is a nondimensional number that compares the axial force exerted on the flow by the turbine to the incoming momentum of the flow (Martínez-Tossas et al. 2022). Our previous methods used the SAM generic C_t approximation with a known bias, resulting in lower wake losses than expected. This is shown in Figure 2, where the SAM C_t approximation is in orange and the C_t curve for our turbine is in blue.

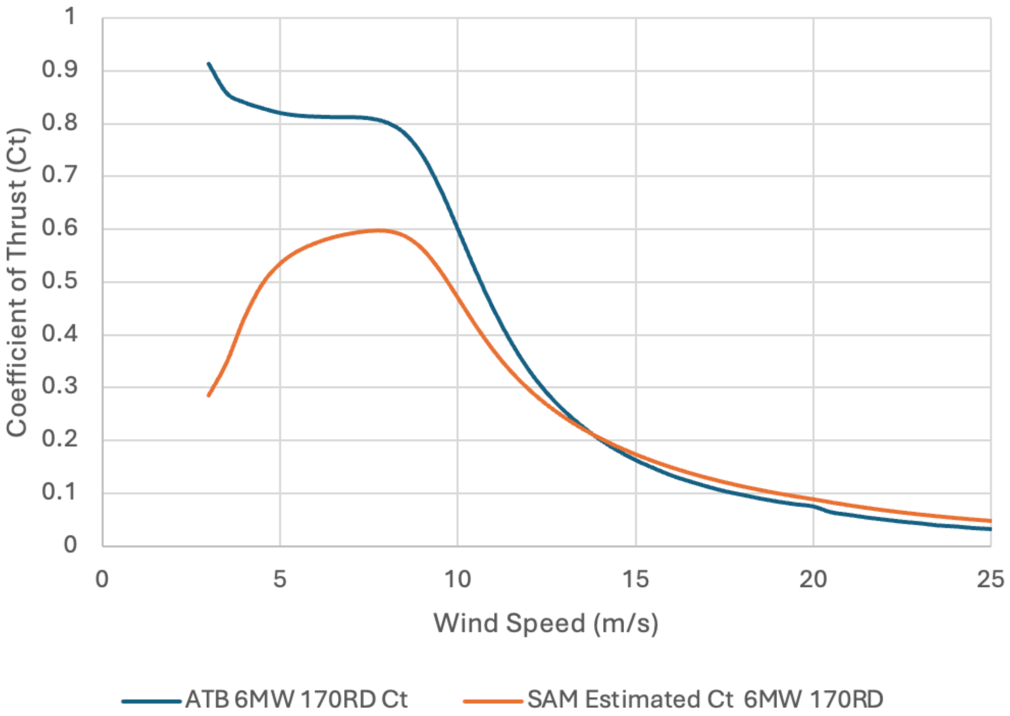

Figure 2. Comparison of SAM approximated C_t curve and our derivation of the C_t curve for the 6-MW 170-meter rotor diameter turbine

Figure 3 shows a comparison of the new method (orange line) with the old one (blue dot) with an empirical estimate for a single location (green dots). The empirical location was based on site C from the Wind Plant Performance Benchmarking (PRUF) study (Simley et al. forthcoming). In this comparison, turbine and plant configurations, as well as wind speed and temperature conditions, were harmonized to the extent possible. The old method underestimated wake losses by about 40% for this location, whereas the new method resulted in wake losses only slightly exceeding the empirical estimates. This harmonized comparison was conducted only for a single site where data were readily available.

In the latest reV analysis presented in this report, the new method was used for all locations and, in general, tended to increase estimated wake losses compared to those calculated by the old method. Figure 4 shows a map (panel A) and histogram (panel B) of estimated wake losses under the current Reference Access scenario. The median site had a wake loss of 6.7% and the interquartile range across all sites was 5% to 7.8%. Note that reV estimates only internal wakes, that is, wakes from other turbines within the same plant (reV grid cell). Future work is needed to estimate external wakes.

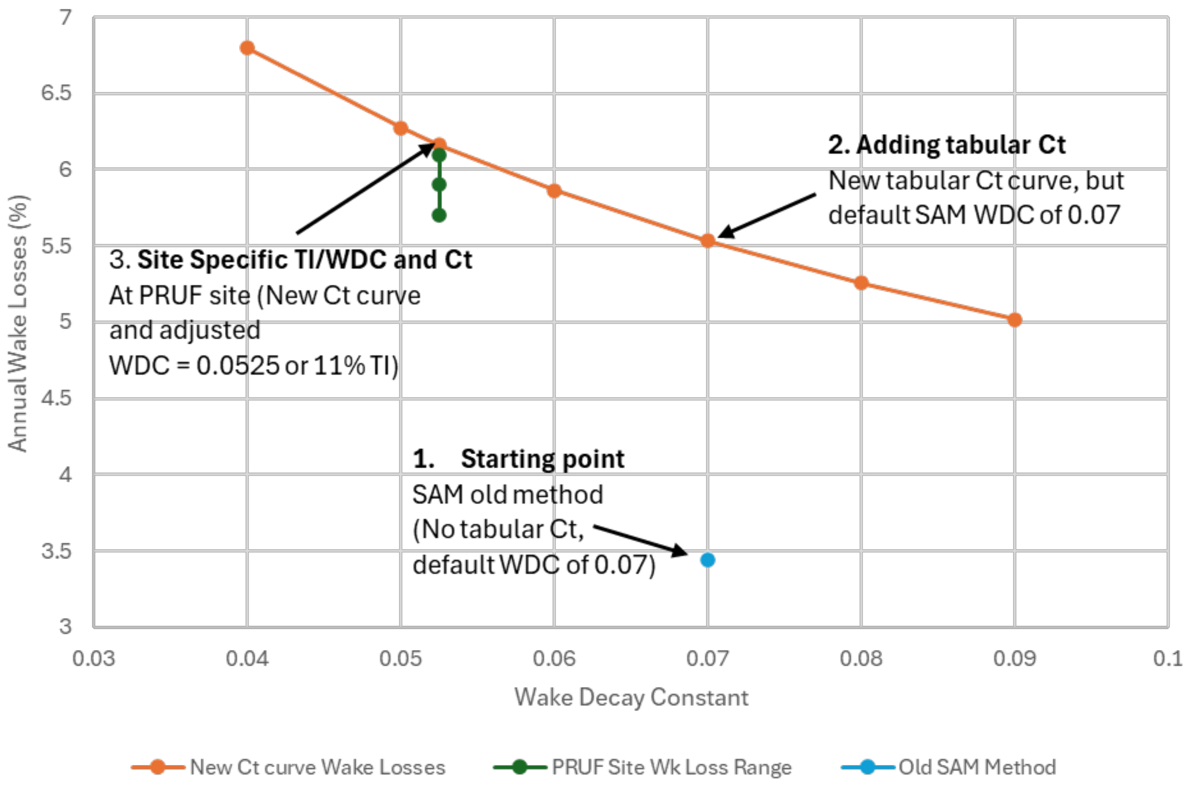

Figure 3. Comparison of old wake loss methods vs. new wake loss methods, which include custom C_t curves, site-dependent turbulence intensity (TI), and wake decay constants (WDC)

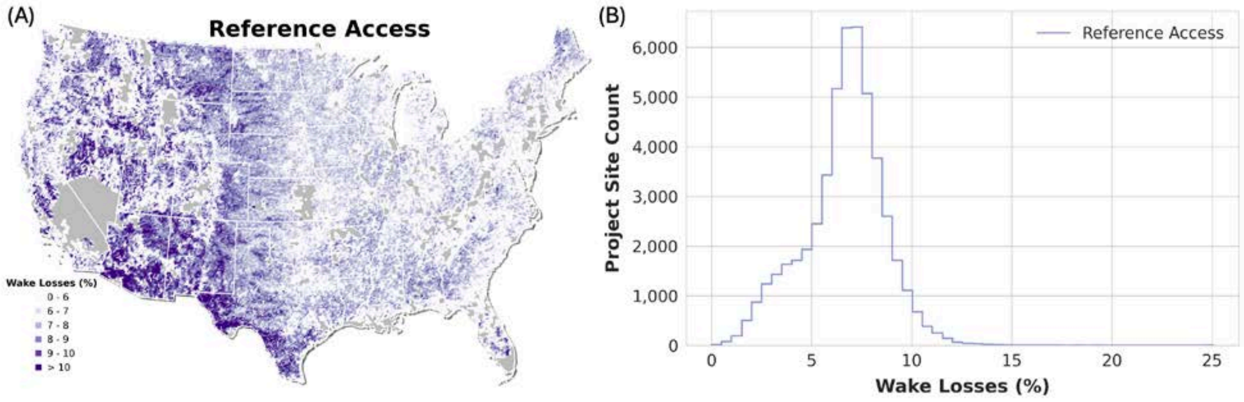

Figure 4. Map of annual mean wake losses for the Reference scenario (A), histogram of wake losses for the Reference scenario (B)

Figure 5 compares these reV wake loss estimates with other estimates for four additional sites (B, D, E, H) from the PRUF study. The dark blue bars show the range reported in Simley et al. (forthcoming), which includes various corrections applied. The light blue bars represent preconstruction estimates from consultants for the projects. And the orange range shows estimates from reV, where the range represents the lowest and highest estimates across four grid cells closest to the site and across all 7 weather years. Note that this comparison is imperfect for three important reasons: (1) different turbines are used, (2) the plant layout and size are not harmonized, and (3) different weather years are considered. The turbines assumed in reV have higher hub heights and larger capacity ratings. Differences in plant sizes can have material impacts to wake loss estimates—the reV estimates assume much larger plant sizes (approximately 200–250 MW), whereas the PRUF sites are much smaller (approximately 100–150 MW). In spite of these differences, the reV estimates fall within the broad range of consultant and corrected estimates. Specifically, Figure 5 shows how reV estimates tended to be lower than but similar to the consultant estimates but noticeably higher than the corrected values from Simley et al. (forthcoming). The higher values in reV were expected, given the larger plants modeled. Nonetheless, future work is needed to conduct a more harmonized comparison across a larger range of locations to improve future wake modeling in reV.

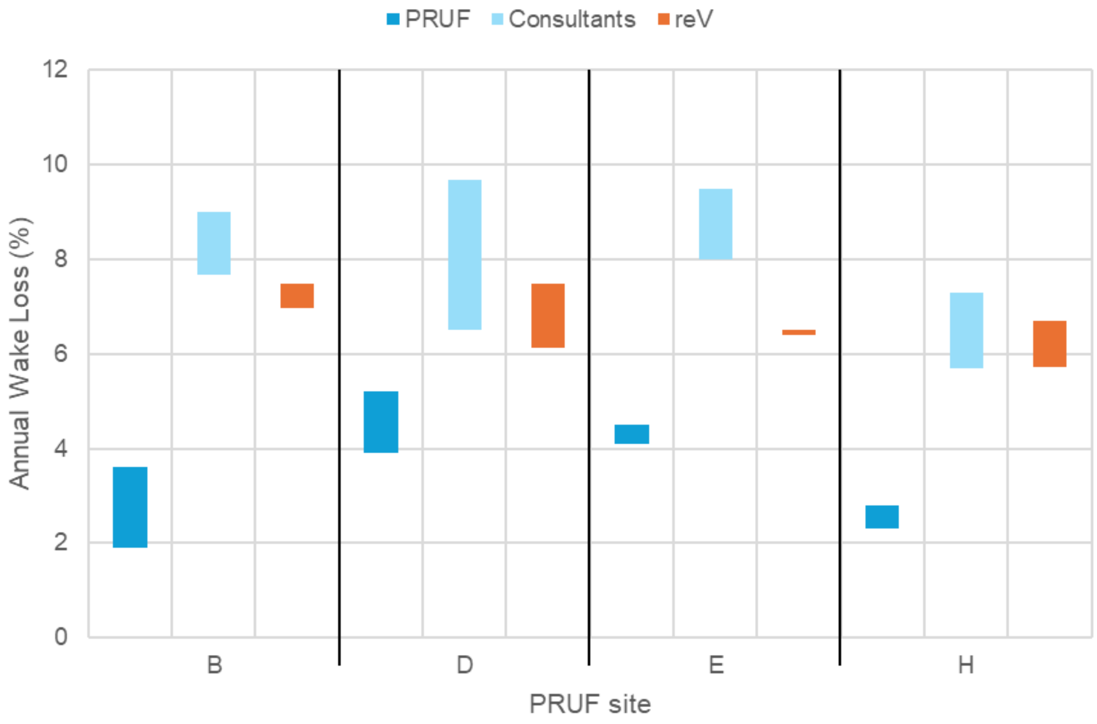

Figure 5. Wake loss comparison between PRUF sites and reV

In addition to the wake loss improvements, we implemented two additional weather-driven losses for land-based wind. The first was an absolute temperature cutoff set at –20°C, which is a common threshold for non-cold-weather packaged turbines. Most modern turbines likely to be deployed in the United States in the near future have a minimum operational temperature between –20°C and –30°C (e.g., Vestas V163[2], V150[3], SGRE 5.0-145[4], SGRE4.4-164[5]). The minimum operational temperature for the GE Sierra is –15°C[6], but cold climate packages are

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[2] https://www.vestas.com/en/energy-solutions/onshore-wind-turbines/4-mw-platform/V163-4-5-MW.

[3] https://www.vestas.com/en/energy-solutions/onshore-wind-turbines/4-mw-platform/v150-4-5-mw.

[4] https://www.siemensgamesa.com/global/en/home/products-and-services/onshore/wind-turbine-sg-5-0-145.html.

[5] https://www.siemensgamesa.com/global/en/home/products-and-services/onshore/wind-turbine-sg-4-4-164.html.

[6] https://www.leecountyil.com/DocumentCenter/View/3190/D---11---General_Description_Sierra-154_60Hz_EN_Doc-0086887_r01.

available[7] with a –30°C minimum operational temperature. Older GE turbines have a low temperature cutoff of –15°C, but many of these older turbines have been upgraded with lower minimum operating temperatures.

The other weather-driven loss was an icing cutoff, in which the wind facility stops generating when the temperature reaches 0°C and the relative humidity exceeds 95%, which represents a conservative threshold for icing events.

To capture the additional cost and spatial dependency of the relative proximity of turbines within a wind farm, we developed a spatial BOS cost function that was integrated into the SROM. Without this constraint, the SROM is incentivized to place turbines as far apart as possible to minimize losses resulting from wakes. The newly added spatial BOS cost function helped counteract this tendency by accounting for the increased costs (roads, cabling, land lease, etc.) associated with spreading turbines further apart. Table 2 summarizes the incremental cost of adding or removing distance between turbines.

Table 2. Assumed Road and Collection Costs at 204 MW

	Cost Scenario	$/m
Roads	Low	68
	Mid	88
	High	175
Collection	Low	91
	Mid	130
	High	260
Combined cost	Low	159
	Mid	**218**
	High	436

To compute the BOS distance, we implemented a greedy algorithm that ran for every layout considered by the SROM. The algorithm started by labeling the medoid turbine location as the substation collection point. It then selected the next closest turbine (determined via straight-line distance to any of the already-connected turbine locations) that had not yet been connected. The distance to that turbine was recorded, and the new turbine location was added to the set of connected turbines. This algorithm ran until all turbine locations had been connected. The total distance was recorded, and the BOS cost was computed as the product of that distance and the $218/m cost from Table 2.

Figure 6 visualizes the connections made by this algorithm. This method for computing BOS costs did not decrease the number of turbines placed in a reV cell. Rather, the BOS cost

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[7] https://www.gevernova.com/wind-power/sites/default/files/related_documents/GEA35089-Cold-Weather-Solutions-Brochure_R3.pdf.

minimized the separation between turbines such that isolated clusters of turbines were heavily penalized. The appendix demonstrates the effect of the BOS cost function on the addition of turbines to an existing layout.

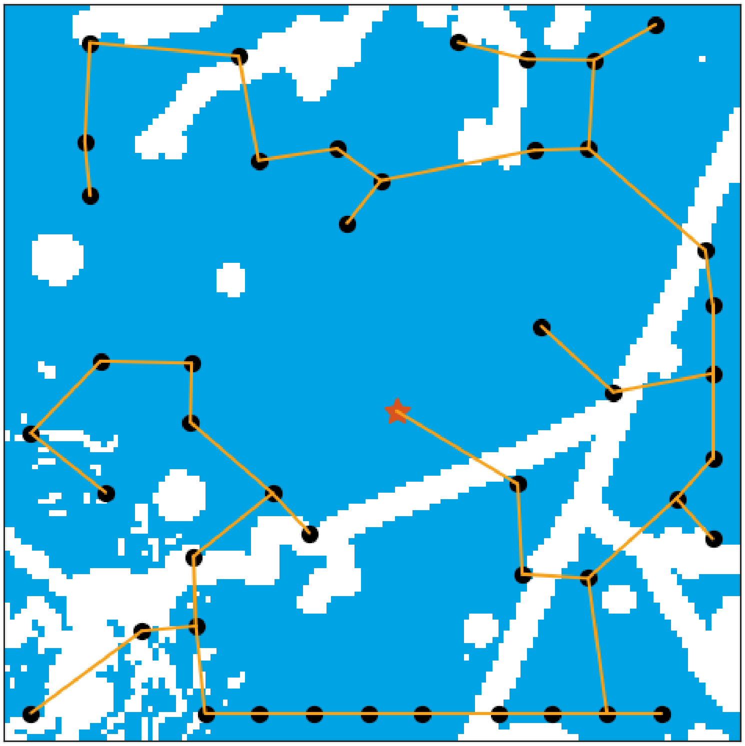

Figure 6. Connections made by the spatial reduced order model balance of system (SROM BOS) algorithm for a sample layout.

Turbine locations are indicated by the black dots, whereas connections are shown using orange lines. The red star represents the medoid turbine location, which is treated as the collection substation. White areas represent exclusions for this reV cell.

Non-wake wind generation losses are implemented via a transformation of the turbine power curve. Unlike haircut losses, which result in a flat reduction in total output, this transformation decreases the power generated nonuniformly across the power curve wind speeds. reV offers several different power curve transformation options, all of which are described in detail in the reV documentation (Maclaurin et al. 2019). For this study, we applied the default transformation, which is functionally given as

$$P_{transformed}(u) \;=\; P_{original}\left(u^{1/t}\right),$$

where $P_{transformed}$ is the transformed power curve, $P_{original}$ is the original power curve, u is the wind speed, and t is the transformation variable that controls the total losses applied. This transformation was chosen because the losses are distributed primarily across regions 2 and 3 of the power curve (Figure 7).

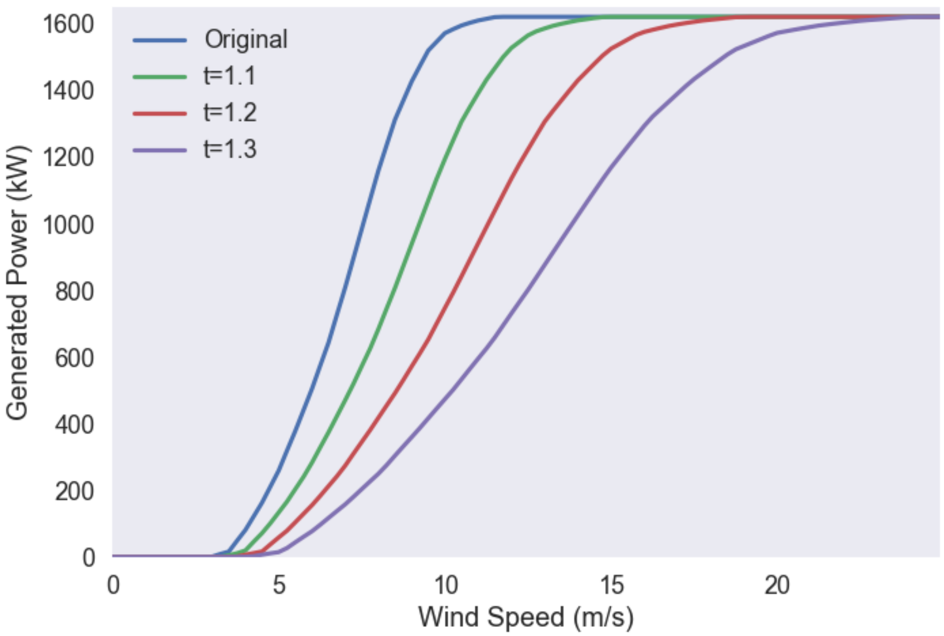

Figure 7. Power curve loss transformations of varying strengths

The strength of the transformation t was uniquely computed for each reV site such that the total annual generation at each individual location decreased by the total loss target. The transformed power curve was then passed to SAM for the rest of the technoeconomic computations.

Notably, the transformed power curve still reached rated power at high wind speeds, which was not possible with simple haircut losses. Figure 8 illustrates this point by comparing the original power curve (blue line) with both the transformed power curve (green line) and the power curve with haircut losses (red line) for a sample site with a 20% loss target. Note that the transformed power curve produced less power than the haircut loss power curve for wind speeds under approximately 9.5 meters per second (m/s) and did not reach rated power until approximately 13 m/s. This reduction in generation accounted for the 20% total annual losses at the site. The hourly generation profile was similarly affected, yielding less power than the haircut loss profile in some cases. However, the transformed power curve profile still reached rated power at high wind speeds (Figure 9), which was a significant improvement over the haircut loss approach, especially for downstream modeling efforts. Figure 9 shows a generation profile for each of the loss methods.

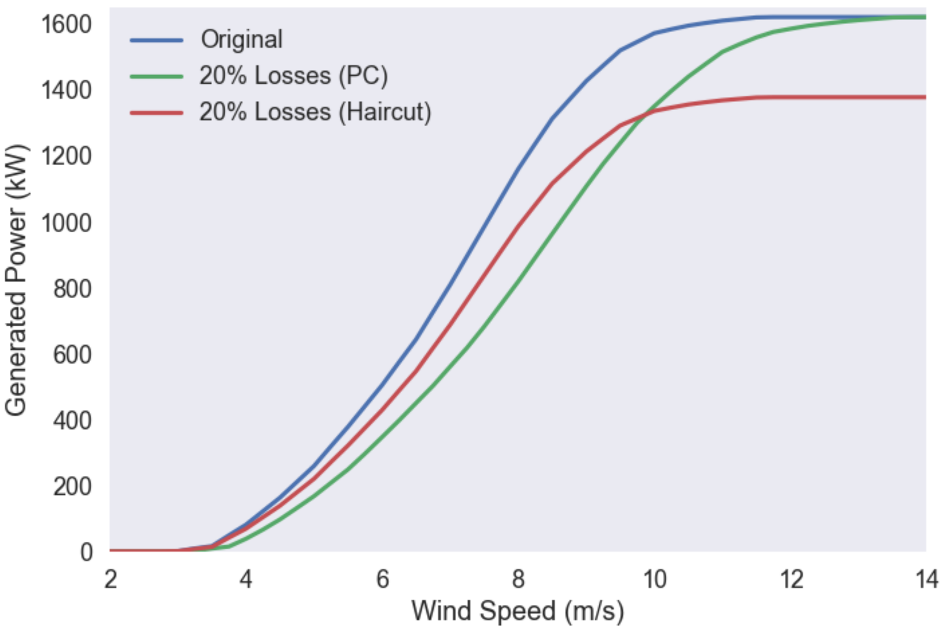

Figure 8. Example of power curve (PC) loss transformation

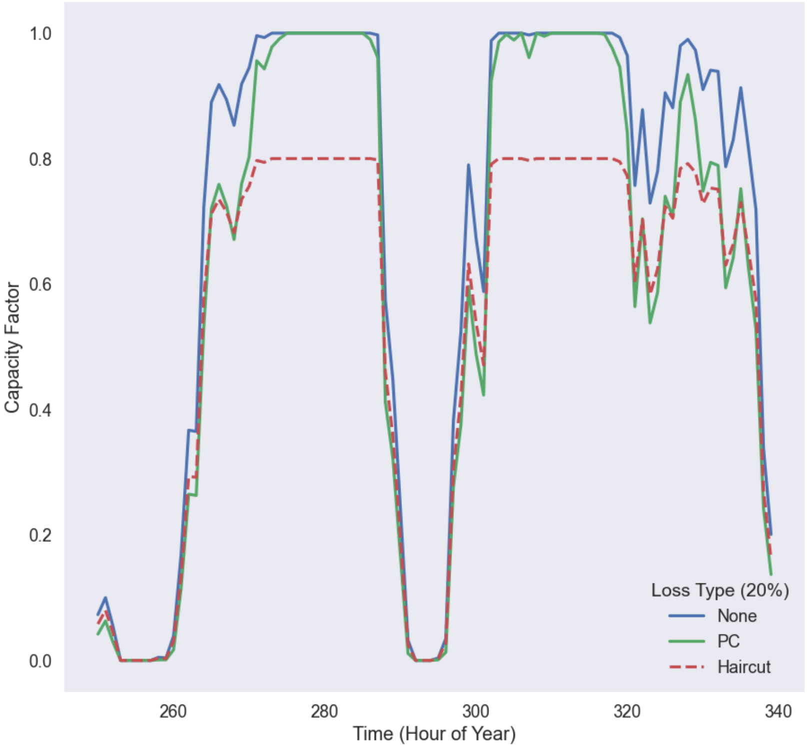

Figure 9. Sample generation output for various loss methods

2.3.2 Offshore Wind Technology

Offshore wind technology and cost assumptions are presented in Table 3. We assumed fixed-bottom turbines were deployed in waters less than 60 m deep, and floating turbines in waters deeper than 60 m. Costs and loss assumptions varied between fixed-bottom and floating, but they were treated similarly otherwise.

Table 3. Offshore Wind Technology Characteristics Used in Supply Curves

Wind Turbine Characteristic	ATB Moderate Case	
Turbine nameplate (MW)	12	
Rotor-diameter (m)	216	
Hub-height (m)	137	
Losses (%)[a]	Endogenous	
Capacity density (MW/km^2)	4	
Capital expenditures (2022$/kW)[b]	Fixed: 3,648	Floating: 6,036
Fixed operational expenditures (2022$/kW)[c]	Fixed: 74	Floating: 60
Fixed charge rate (%)	6.1	

[a] Losses are site specific. See details in following text.

[b] These are the 2035 representative sites' overnight capital costs, which include regional and economies of scale multipliers.

[c] These are the 2035 representative sites' fixed operational costs.

Unlike land-based wind, we did not use an SROM approach to site turbines. Turbine placement was assumed to be in an evenly spaced grid within the 15.84-km × 15.84-km supply curve cell, with a capacity density of 4 MW/km^2 and a full-size wind plant around 1 gigawatt (GW).

For offshore wind, we had five loss categories: technical, environmental, availability, wake, and electrical loss (see Table 4). Technical losses, accounting for power curve hysteresis (shutdown and restart near cutout wind speed), onboard equipment power usage, and rotor misalignments, were 1% for fixed-bottom and 1.2% for floating (Fuchs et al. 2024). Environmental losses accounted for hurricane, lightning, and temperature-related issues (Fuchs et al. 2024). Availability losses were site specific, varying based on significant wave height (as a proxy for weather) and distance to the operating port, to account for maintenance and repair, as well as other system shutdowns (Fuchs et al. 2024). Technical, environmental, and availability losses were applied as a power curve transformation, using the methodology described previously.

Wake losses were site-specific values calculated using the Python version of SAM's implementation of the Park wake model and were applied after the power curve transformation (Freeman et al. 2018b). Electrical losses were applied as a 3.5% haircut loss to account for losses during conversion between alternating current (AC) and direct current (DC) (Papadopoulos et al. 2015).

Table 4. Offshore Wind Loss Statistics

	Minimum	Maximum	Median
Electrical	3.5%	3.5%	3.5%
Technical	Floating: 1.2% Fixed:1%	Floating: 1.2% Fixed:1%	Floating: 1.2% Fixed:1%
Environmental	1.59%	1.59%	1.59%
Availability	1.5%	13.2%	5.6%
Wake	4.4%	22%	11.6%
TOTAL	7.7%	24.7%	14.6%

2.3.3 Solar PV Technology

Solar PV technology and cost assumptions are presented in Table 5.

Solar PV losses were applied via fixed losses, which reduced the power generated at each time-step in the generation profile by a fixed percentage. For example, in the ATB Moderate case, 10.4% haircut losses were applied by multiplying the solar generation profile by a factor of 0.896. SAM performs this calculation internally, and reV reports the result. These losses were applied on the DC side before computing the capacity factor, meaning that a solar plant can still reach a capacity factor of 1 with the inverter loading ratio set at 1.34.

Table 5. Solar PV Characteristics Used in Supply Curves

Solar PV Characteristic	ATB Moderate Case
PV array nameplate (MW_{DC})	100
PV array type	1-axis tracking
PV module type	Standard
Tilt (degrees)	0
Losses (%)[a]	10.4
Inverter loading ratio	1.34
Capacity density (MW_{DC}/km^2)	43
Ground cover ratio	0.4
Capital expenditures (2022$/$kW_{AC}$)	1,044
Fixed operational expenditures (2022$/$kW_{AC}$/year)	17.99
Fixed charge rate (%)	6.41

[a]Losses include electrical and soiling losses. Shading losses and planned and maintenance outages are not considered. reV outputs assume no grid curtailment.

The solar PV capacity density assumption remained at the same level as the 2023 technical potential report (Lopez et al. 2024). Bolinger and Bolinger (2022) report a 0.24 MW_{DC}/acre capacity density for a single-axis tracking panel. However, this accounts only for the array area and does not capture other PV system land use, such as service roads, inverters, fencing, and so on. For the supply curves, we modeled total land-use requirements and thus needed to account for area associated with the total land use of a solar PV facility. To estimate total land use from the Bolinger and Bolinger (2022) report, we determined the ratio between direct and total land use from Ong et al. 2013. We used the reported values for small PV (>1 MW, <20 MW) because the sample size for large PV was not sufficient. Ong et al. reported 6.3 acres of direct land use for an 8.7-acre facility. Using that ratio, we obtained a density of 42.9 MW_{DC}/km^2:

$$43\ MW_{DC}/km^2 = 0.24\ MW_{DC}/acre * 247.105\ acres/km^2 * 6.3\ acres/MW_{AC}\ /\ 8.7\ acres/MW_{AC}$$

This year, we incorporated a cost scaling function into the solar PV site capital expenditures to account for cost variations driven by economies of scale related to plant size. We sourced our large plant costs from Ramasamy et al. 2021 and our small plant costs from Barbose et al. 2023 and fit these into an equation to relate the plant size to the relative cost of the plant. The resulting cost multiplier equation (as follows) was applied to each solar PV site. When a site multiplier was less than 1.0, we set it to 1.0. A cost multiplier is shown in Figure 10.

$$\text{Economies of scale cost multiplier} = 1.841 * (kW_{DC})^{-0.1345}$$

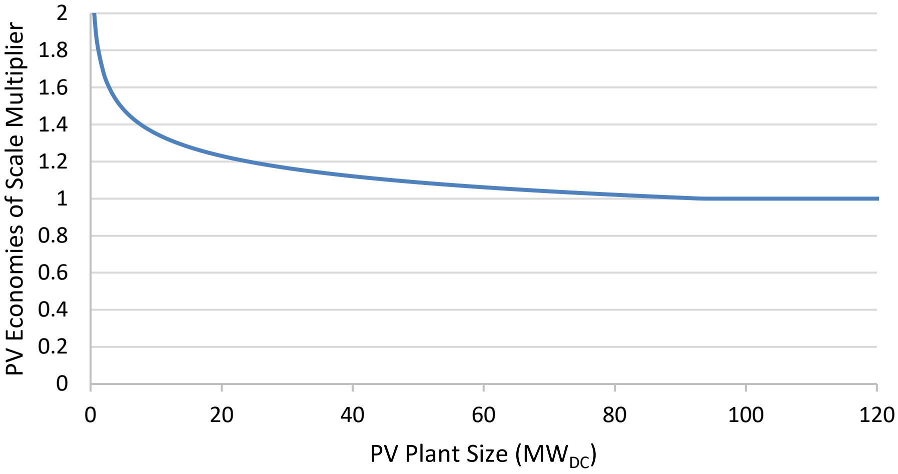

Figure 10. PV economies of scale multiplier

2.3.4 Geothermal Technology

Geothermal deployment potential across the United States is estimated using the reV geothermal module (Pinchuk et al. 2023). reV geothermal relies on the underlying coupling between SAM and the Geothermal Electricity Technology Evaluation Model (GETEM). Geothermal technology and cost assumptions are presented in Table 6. We assumed ATB Advanced cost assumptions because several demonstration projects have already proven to be more cost effective than the most aggressive cost reduction trajectories (Norbeck, Gradl, and Latimer 2024; McClure 2024).

Table 6. Geothermal Technology Characteristics Used in Supply Curves

Geothermal Plant Characteristic	ATB Advanced Case			
	Hydrothermal Binary	**Enhanced Geothermal Systems (EGS) Binary 4.5 km**	**EGS Binary 5.5 km**	**EGS Flash**
Resource depth (m)	3,500	4,500	5,500	6,500
Plant conversion type	Binary			Flash
Operational temperature range (°C)[a]	120–250			182–343
Drilling cost ($/well)[b]	3,130,258	3,864,018	4,592,983	5,317,153
Capital expenditures (2022$/kW)[c]	4,479.83	4,538.36		2,756.22
Fixed operational expenditures (2022$/kW)[d]	126	119		99
Fixed charge rate (%)	6.348			
Capacity density (MW/km^2)[e]	Endogenous			

Geothermal Plant Characteristic	ATB Advanced Case			
	Hydrothermal Binary	**Enhanced Geothermal Systems (EGS) Binary 4.5 km**	**EGS Binary 5.5 km**	**EGS Flash**
Plant efficiency (%)	80			
Change in pressure across the reservoir (psi-h/1000 lb)	0.4			
Wet bulb temperature (°C)	15			
Ambient pressure (psi)	14.7			
Production well flow rate (kg/s per well)	110			
Pump efficiency (%)	67.5			
Pressure difference across surface equipment (psi)	40			
Excess pressure at pump suction (psi)	50			
Production well diameter (inches)	12.25			
Production pump casing size (inches)	9.625			
Injection well diameter (inches)	12.25			
Injection Pump Casing Size (inches)	11.5			
Number of Confirmation Wells	0			
Ratio of Injection Wells to Production Wells	0.75			

[a] Locations with temperatures outside of this range do not conform with the assumptions of the underlying Geothermal Electricity Technology Evaluation Model (GETEM) and are therefore excluded from consideration.

[b] Calculated using the “Ideal” GETEM drilling cost curve. See details in following text.

[c] These are the 2035 representative sites overnight capital costs reduced by the drilling costs for the default ATB geothermal plant, calculated using the “Ideal” GETEM drilling cost curve. No regional or economies of scale multipliers were applied.

[d] These are the 2035 representative sites fixed operational costs.

[e] Capacity density is endogenous. We calculated the variable capacity density at each location using the temperature estimate from the resource. See details in following text.

Most of the geothermal plant technology assumptions align with the default technology values set in the SAM software interface. However, as advised by the SAM developers, we increased the “Ratio of Injection Wells to Production Wells” from the EGS default value of 0.5 to 0.75. In addition, when computing reV generation for EGS, we set the “plant design temperature” to 200°C. This extra step ensured that the EGS plant design temperature never deviated from the resource temperature, allowing modeling to proceed without any errors.

To account for depth-dependent drilling costs, we first calculated the drilling costs associated with the sample plant assumed by the 2024 ATB using GETEM depth cost curves. Specifically, we assumed the “Ideal” cost curve with a vertical open hole well type and a large well diameter. The drilling costs were then subtracted from the base ATB capital cost for each example plant. Finally, with the reV model, we calculated the depth-dependent drilling cost at each location based on the number of wells required at each site (this value is dictated by the geothermal resource). This value was added to the capital cost presented in Table 6 to obtain the total capital cost of a geothermal plant at each location.

We estimated the capacity density at each location using the exponential relationship formulated by Wilmarth, Stimac, and Ganefianto (2021):

$$CD = 0.408\, e^{0.014\, T}$$

where CD is the capacity density (MW/km^2) and T is the temperature (°C). This empirical model related the reservoir temperature to a power density value for 103 preexisting geothermal plants globally. The final capacity density reported at each supply curve location represented the exclusion-weighted mean of the capacity density of one or more resource cells that overlap spatially with the supply curve point location.

2.4 Siting Constraints and Considerations

Siting constraints and certain siting considerations, including existing or potential competing uses, may restrict or prevent renewable energy development. Though known clear obstructions preclude development, such as interstate highways and buildings, many other competing land uses are more complex when evaluating potential development.

To capture the uncertainty associated with siting criteria, we used a scenario-based approach introduced by Lopez et al. (2021). Specifically, we used three scenarios: Open Access, Reference Access, and Limited Access, which together capture a range of plausible restrictiveness to development and provide bounds for resource potential.

- *Open Access* (Open) is the least restrictive scenario. It applies only physical obstacles and excludes development on legally or administrated protected lands.
- *Reference Access* (Reference) is a moderate scenario. It applies existing ordinances and regulations, known preclusions, and current industry practices for siting.
- *Limited Access* (Limited) is the most restrictive scenario. It applies a combination of the most restrictive setbacks, environmental constraints, and national defense concerns.

We also applied solar PV and wind regulations from wind and solar ordinances databases (Lopez et al. 2023). These regulations were grouped and categorized by 50th and 90th percentiles. We applied the existing regulations as written in both the Reference and Limited scenarios. However, to capture possible restrictions based on the expansion of ordinances, we extrapolated them to the rest of the country. In the Reference scenario, we used the median of existing ordinances. In the Limited scenario, we used the 90th percentile of ordinances across the country.

For solar PV setbacks, we calculated a percentage of area available within a 90-m grid-cell. This was used to estimate the developable land given the resolution of solar setbacks was smaller than the native resolution of reV.

We made several changes to our land-based wind and solar PV siting assumptions in 2024. The changes are primarily on better representation of federal lands managed by the Bureau of Land Management, Forest Service, Department of Defense, Fish and Wildlife Serice, and the Department of Energy. The additions are noted in the respective tables. Further documentation of the new assumptions are presented in Mai et al (2025).

Note that resource (temperature-at-depth) is a much larger driver for geothermal development than the typical wind and solar siting constraints. For this reason, we only report geothermal potential at the “Reference Access” level and instead focus on the differences in development potential across various depths and geothermal plant types.

The full suite of siting constraints by scenario is presented in Table 7 for land-based wind, Table 8 for offshore wind, Table 9 for solar PV, and Table 10 for geothermal.

Table 7. Land-Based Wind Siting Constraints

Category	Dataset	Open	Reference	Limited	Source
Airspace/Defense	Airport and heliport setbacks (variable)		x	x	Federal Aviation Administration—AIS (2022); also see Appendix A.2
Airspace/Defense	Airport footprints	x	x	x	“Airports and Heliports” (2010)
Airspace/Defense	U.S. Department of Defense (DOD, 9-km) and Next Generation Weather Radar (NEXRAD) radar setback (4-km)		x	x	Official-use-only communication with North American Aerospace Defense Command (NORAD)
Airspace/Defense	U.S. Department of Defense and NEXRAD radar line-of-sight exclusion			x	See Appendix A.6
Airspace/Defense	Intercontinental ballistic missile silo setback (3.7-km)		x	x	“ICBM Sites” (2019)
Airspace/Defense	Risk of adverse impact on military operations and readiness areas (RAIMORA)		x	x	Kiernan (2016)
Airspace/Defense	U.S. Department of Defense Lands (military bases)*			x	Office of the Assistant Secretary of Defense for Energy, Installations, and Environment (2022)
Airspace/Defense	DOD Readiness and Environmental Protection Integration (REPI) Opportunity Areas*			x	Readiness and Environmental Protection Integration Program (2020)
Airspace/Defense	DOD Clear Zones and Accident Potential Zones*	x	x	x	Readiness and Environmental Protection Integration Program (2020)
Environmental	Bureau of Land Management (BLM) Oil and Gas or Geothermal No Surface Occupancy areas*			x	Laura Fox, Argonne National Laboratory, personal communication, April 9, 2024
Environmental	Desert Renewable Energy Conservation	x	x	x	Bureau of Land Management (2016a)

Category	Dataset	Open	Reference	Limited	Source
	Plan Lands closed to Wind on BLM Lands*				
Environmental	USFWS-administered lands (except for Wetland and Grassland Wildfowl Production Area easements)	x	x	x	U.S. Fish & Wildlife Service (2024)
Environmental	U.S. Department of Energy Cleanup to Clean Energy Wind Exclusion Areas*	x	x	x	Bureau of Land Management (2024a); Department of Energy, Office of Management, Sustainability Performance Office (2023); Department of Energy (2023); U.S. Department of Energy (2023a, 2023b, 2024a, 2024b, 2024c, 2024d)
Environmental	Karst depressions*	x	x	x	Jones et al. (2021)
Environmental	U.S. Forest Service (USFS) GAP Status 3 and 4 (excluding National Forests)*		x	x	U.S. Geological Survey (2024)
Environmental	USFS active grazing allotments*			x	U.S. Forest Service (2024b)
Environmental	Mature and Old Growth Forests (USFS and BLM lands only)*		x	x	DellaSala et al. (2022); U.S. Forest Service (2024a); Mai et al. (2025)
Environmental	USFS modeled Recreational Opportunity Spectrum (ROS) excluded categories*		x	x	Mai et al. (2025)
Environmental	BLM Resource Management Plan Amendment (RMPA) / Draft Environmental Impact Statement (DEIS) Sage Grouse Priority Habitat Management Area Avoidance Areas—alternative 5 (BLM lands only)*	x	x		Bureau of Land Management (2024c)
Environmental	BLM RMPA/DEIS Sage Grouse Priority Habitat			x	Bureau of Land Management (2024c)

Category	Dataset	Open	Reference	Limited	Source
	Management Area Exclusion Areas—alternative 3 (BLM lands only)*				
Environmental	Sagebrush Core and Growth habitat on federal lands*			x	Doherty et al. (2022)
Environmental	Federal Emergency Management Agency (FEMA) 100-year floodplains*		x	x	Federal Emergency Management Agency (2024)
Environmental	USFWS Regulatory In-lieu Fee and Bank Information Tracking System (RIBITS) Mitigation Banks and In-lieu Fee Program lands*	x	x	x	U.S. Army Corp of Engineers (2024)
Environmental	Bat hibernacula		Priority 1, 2	Priority 1, 2, 3	Lopez et al. (forthcoming)
Environmental	National Land Cover Dataset Water, Woody/Herbaceous Wetlands	x	x	x	U.S. Geological Survey (2021)
Environmental	Lesser Prairie Chicken core habitat			x	U.S. Fish & Wildlife Service (2023)
Mixed	West-Wide Wind Mapping Project composite exclusion areas*			x	Bureau of Land Management (2016b)
Mixed	West-Wide Wind Mapping Project composite high level of siting consideration areas*			x	Bureau of Land Management (2016b)
Mixed	West-Wide Wind Mapping Project composite medium level of siting consideration areas*			x	Bureau of Land Management (2016b)
Environmental	BLM Resource Management Plan (RMP) wind exclusions*	x	x	x	Bureau of Land Management (2016b)
Environmental	BLM wind exclusions based on Solar Draft Programatic Solar Environmental Impact	x	x	x	Bureau of Land Management (2024b)

Category	Dataset	Open	Reference	Limited	Source
	Statement (DPEIS) resource based exclusions*				
Environmental	USFS Wild and Scenic Rivers 10-mile buffer for viewshed protection*			x	U.S. Forest Service (2024c)
Environmental	Scenic and Historic Trails 10-mile buffer for viewshed protection*			x	Bureau of Land Management (2022a); National Park Service (2018)
Environmental	Threatened and Endangered Species core habitat (USGS subset BLM lands only)*		x	x	Lopez et al. (forthcoming)
Environmental	U.S. Fish & Wildlife Service National Wetlands Inventory	x	x	x	U.S. Fish & Wildlife Service (n.d.)
Environmental	American Farm Trust conservation lands	x	x	x	American Farmland Trust (2023)
Environmental	BLM Areas of Critical Environmental Concern	x	x	x	Bureau of Land Management (2022b)
Environmental	National Forest Service Inventoried Roadless Areas	x	x	x	U.S. Forest Service, Geospatial Service and Technology Center (2001)
Environmental	National Conservation Easement Database (Gap Analysis Project [GAP] Status 1, 2)	x	x	x	National Conservation Easement Database (2017)
Environmental	Protected Areas Database (GAP Status 1, 2)	x	x	x	U.S. Geological Survey (2024)
Infrastructure	Oil and gas well footprints	x	x	x	Oak Ridge National Laboratory (2019)
Infrastructure	Railroads	x	x	x	U.S. Census Bureau (2021)
Infrastructure	Roads	x	x	x	Homeland Security Infrastructure Program (2018)
Infrastructure	Building structures	x	x	x	Microsoft (2018)
Infrastructure	Transmission right-of-way	x	x	x	Oak Ridge National Laboratory et al. (2022); Lopez et al. (2021)

Category	Dataset	Open	Reference	Limited	Source
Infrastructure	Oil and gas pipeline right-of-way	x	x	x	Federal Communications Commission and Oak Ridge National Laboratory (2018)
Infrastructure	Urbanized areas	x	x	x	U.S. Census Bureau (2018)
Infrastructure	Existing solar PV facilities	x	x	x	Fujita et al. (2023)
Infrastructure	368 designated (2009) transmission corridors*	x	x	x	Bureau of Land Management (2022c)
Infrastructure	Wind facility bans or moratoriums		x	x	Lopez et al. (2022)
Regulatory	Wind facility height limits (exceeding current turbine height assumption)		x	x	Lopez et al. (2022)
Regulatory	Oil and gas pipeline setback		220 m	400 m	Lopez et al. (2022)
Regulatory	Railroad setback		220 m	400 m	Lopez et al. (2022)
Regulatory	Road setback		220 m	400 m	Lopez et al. (2022)
Regulatory	Structure setback		220 m	400 m	Lopez et al. (2022)
Regulatory	Transmission setback		400 m	1,000 m	Lopez et al. (2022)
Regulatory	Water setback		220 m	400 m	Lopez et al. (2022)
Terrain	Slope exclusion(s)		>25%	>13%	Jarvis et al. (2008)
Terrain	Elevation (>9,000 ft) and mountainous landforms	x	x	x	Karagulle et al. (2017)

x denotes where a layer is used to exclude land; * denotes a new layer or assumption.

Table 8**. Offshore Wind Siting Constraints**

Category	Dataset	Open	Ref	Lim	Source
Airspace/Defense	Danger zones and restricted areas	x	x	x	"Marine Cadastre Hub" (n.d.)
Airspace/Defense	U.S. Department of Defense offshore wind exclusions		x	x	"Marine Cadastre Hub" (n.d.); (Preacher 2024)
Airspace/Defense	Submarine transit lanes	x	x	x	"Marine Cadastre Hub" (n.d.)
Airspace/Defense	Unexploded ordinance setback	100 m	100 m	200 m	"Marine Cadastre Hub" (n.d.)
Airspace/Defense	Military ship shock boxes	x	x	x	"Marine Cadastre Hub" (n.d.)
Environmental	Marine protected areas	x	x	x (also excludes proposed MPAs)	"The MPA Inventory | National Marine Protected Areas Center" (n.d.)
Environmental	Artificial reefs	x	x	x	"Marine Cadastre Hub" (n.d.)
Environmental/Technical	Canyons		x	x	Harris et al. (2014)
Infrastructure	Oil/Gas pipeline setback	61 m	61 m	122 m	"HIFLD Open" (n.d.)
Infrastructure	Oil/Gas platform setback	250 m	250 m	500 m	"HIFLD Open" (n.d.)
Infrastructure	Submarine cables setback	500 m	500 m	1000 m	"Marine Cadastre Hub" (n.d.)
Infrastructure	Active oil/gas leases	Force Include	Force Include	Force Include	"Marine Cadastre Hub" (n.d.)
Infrastructure	Shipwreck setback	50 m	50 m	100 m	"Marine Cadastre Hub" (n.d.)
Regulatory	Bureau of Ocean Energy Management (BOEM) lease and planning areas	Force Include	Force Include	Force Include	Bureau of Ocean Energy Management (n.d.)
Regulatory	Shipping lanes		x	x	"Marine Cadastre Hub" (n.d.); (Moriarty 2023)
Regulatory	State waters		x	x	"Marine Cadastre Hub" (n.d.)
Regulatory	Ocean disposal sites	x	x	x	"Marine Cadastre Hub" (n.d.)

Category	Dataset	Open	Ref	Lim	Source
Regulatory	Atlantic outer continental shelf aliquots	x	x	x	“Marine Cadastre Hub” (n.d.)
Regulatory	Coast guard anchorages	x	x	x	(Moriarty 2023)
Regulatory	Tribal usual and accustomed fishing areas		x	x	Schlosser (2012)
Regulatory	Crabber and tug lanes		x	x	(Moriarty 2023)
Regulatory	Distance to shore		<5,556 m	<30,000 m	Derived
Regulatory	Outer continental shelf sand and gravel borrow areas	x	x	x	U.S. Army Corps of Engineers (n.d.)
Technical	Water depth	>1,300 m	>1,300 m	>1,000 m	GEBCO (n.d.)

x denotes where a layer is used to exclude land; * denotes a new layer or assumption.

Table 9**. Solar PV Siting Constraints**

Category	Dataset	Open	Reference	Limited	Source
Airspace/Defense	Intercontinental ballistic missile silo setback (3.7 km)		x	x	“ICBM Sites” (2019)
Airspace/Defense	Airports and runways*	x	x	x	“Airports and Heliports” (2010); U.S. Department of Transportation (2024)
Airspace/Defense	U.S. Department of Defense Lands (military bases)*			x	Office of the Assistant Secretary of Defense for Energy, Installations, and Environment (2022)
Airspace/Defense	DOD Readiness and Environmental Protection Integration (REPI) Opportunity areas*			x	Readiness and Environmental Protection Integration Program (2020)
Airspace/Defense	DOD Clear Zones and Accident Potential Zones*	x	x	x	Readiness and Environmental Protection Integration Program (2020)
Environmental	BLM Oil and Gas or Geothermal No Surface Occupancy areas*	x	x	x	Laura Fox, Argonne National Laboratory, personal

Category	Dataset	Open	Reference	Limited	Source
					communication, April 9, 2024
Environmental	Desert Renewable Energy Conservation Plan lands closed to solar on BLM lands*	x	x	x	Bureau of Land Management (2016a)
Environmental	USFWS administered lands*	x	x	x	U.S. Fish & Wildlife Service (2024)
Mixed	BLM Solar Draft Programmatic Environmental Impact Statement Alternative 3*	x	x		Bureau of Land Management (2024b)
Mixed	BLM Solar Draft Programmatic Environmental Impact Statement Alternative 5*			x	Bureau of Land Management (2024b)
Mixed	U.S. Department of Energy Clean-up To Clean Energy Solar Exclusion Areas*	x	x	x	Bureau of Land Management (2024a); Department of Energy, Office of Management, Sustainability Performance Office (2023); Department of Energy (2023); U.S. Department of Energy (2023a, 2023b, 2024a, 2024c, 2024d, 2024b)
Environmental	Bat hibernacula setbacks*		805 m	805 m	Lopez et al. (n.d.)
Environmental	Karst depressions*	x	x	x	Jones et al. (2021)
Environmental	USFS GAP Status 3 and 4 (excluding National Forests)*		x	x	U.S. Geological Survey (2024)
Environmental	USFS active grazing allotments*			x	U.S. Forest Service (2024b)
Environmental	USFS and BLM Mature and Old Growth Forests (USFS and BLM lands only)*		x	x	DellaSala et al. (2022); U.S. Forest Service (2024a)
Environmental	USFS modeled Recreational Opportunity Spectrum (ROS) excluded categories*		x	x	Mai et al. (2025)

Category	Dataset	Open	Reference	Limited	Source
Environmental	National Land Cover Dataset Water, Woody/Herbaceous Wetlands	x	x	x	U.S. Geological Survey (2021)
Environmental	Lesser Prairie Chicken core habitat			x	U.S. Fish & Wildlife Service (2023)
Environmental	BLM RMPA/DEIS Sage Grouse Priority Habitat Management Area Avoidance Areas - alternative 5 (BLM lands only)*	x	x		Bureau of Land Management (2024c)
Environmental	BLM RMPA/DEIS Sage Grouse Priority Habitat Management Area Exclusion Areas - alternative 3 (BLM lands only)*			x	Bureau of Land Management (2024c)
Environmental	Sagebrush Core and Growth habitat on federal lands*			x	Doherty et al. (2022)
Environmental	FEMA 100-year floodplains*		x	x	Federal Emergency Management Agency (2024)
Environmental	USFWS RIBITS Mitigation Banks and In-lieu Fee Program lands*	x	x	x	U.S. Army Corp of Engineers (2024)
Environmental	Department of Interior defined ridgelines*			x	Mai et al. (2025)
Environmental	Threatened and Endangered Species core habitat (federal lands only)		x	x	Lopez et al. (forthcoming)
Environmental	United States Fish and Wildlife Service National Wetlands Inventory	x	x	x	U.S. Fish & Wildlife Service (n.d.)
Environmental	Nationally Significant Agricultural Lands*		10% available	5% available	Conservation Science Partners and American Farmland Trust (2016)
Environmental	Simulated Conservation Reserve Program lands		x	x	See Appendix A.1
Environmental	American Farm Trust conservation lands	x	x	x	American Farmland Trust (2023)

Category	Dataset	Open	Reference	Limited	Source
Environmental	BLM Areas of Critical Environmental Concern	x	x	x	Bureau of Land Management (2022b)
Environmental	National Forest Service Inventoried Roadless Areas	x	x	x	U.S. Forest Service, Geospatial Service and Technology Center (2001)
Environmental	National Conservation Easement Database (GAP Status 1, 2)	x	x	x	National Conservation Easement Database (2017)
Environmental	Protected Areas Database (GAP Status 1, 2)	x	x	x	U.S. Geological Survey Gap Analysis Project [GAP] (2022)
Environmental	Big game migration corridors		50% available	x	Kauffman et al. (2020); Kauffman, Lowrey, Beck, et al. (2022); Kauffman, Lowrey, Berg, et al. (2022)
Infrastructure	368 designated (2009) transmission corridors*	x	x	x	Bureau of Land Management (2022c)
Infrastructure	Existing wind turbine pads (45.7 m) setback*	x	x	x	Hoen et al. (2023)
Infrastructure	Oil and gas well footprints	x	x	x	Oak Ridge National Laboratory (2019)
Infrastructure	Railroads	x	x	x	U.S. Census Bureau (2021)
Infrastructure	Roads	x	x	x	Homeland Security Infrastructure Program (2018)
Infrastructure	Building structures	x	x	x	Microsoft (2018)
Infrastructure	Transmission right-of-way	x	x	x	Oak Ridge National Laboratory et al. (2022); Lopez et al. (2021)
Infrastructure	Oil and gas pipeline right-of-way	x	x	x	Federal Communications Commission and Oak Ridge National Laboratory (2018)
Regulatory	Solar existing bans or moratoriums		x	x	Lopez et al. (2022)
Regulatory	Oil and gas pipeline setback		30 m	76 m	Lopez et al. (2022)

Category	Dataset	Open	Reference	Limited	Source
Regulatory	Property line setback		15 m	46 m	Lopez et al. (2022)
Regulatory	Rail setback		30 m	76 m	Lopez et al. (2022)
Regulatory	Road setback		30 m	76 m	Lopez et al. (2022)
Regulatory	Building structure setback		61 m	152 m	Lopez et al. (2022)
Regulatory	Transmission setback		30 m	76 m	Lopez et al. (2022)
Regulatory	Water setback		30 m	76 m	Lopez et al. (2022)
Terrain	Slope exclusion		>10%	>5%	Jarvis et al. (2008)
Terrain	Elevation (>9,000 ft) and mountainous landforms	x	x	x	Karagulle et al. (2017)
Other	Contiguous area filter (8,100 m^2)	x	x	x	Endogenous

x denotes where a layer is used to exclude land; * denotes a new layer or assumption.

Table 10. Geothermal Siting Constraints

Category	Dataset	Ref	Source
Airspace/Defense	Intercontinental ballistic missile silo setback (3.7 km)	x	"ICBM Sites" (2019)
Airspace/Defense	Airports and runways*	x	"Airports and Heliports" (2010); U.S. Department of Transportation (2024)
Airspace/Defense	DOD Clear Zones and Accident Potential Zones*	x	Readiness and Environmental Protection Integration Program (2020)
Environmental	BLM Oil and Gas or Geothermal No Surface Occupancy*	x	Laura Fox, Argonne National Laboratory, personal communication, April 9, 2024.
Environmental	Desert Renewable Energy Conservation Plan lands closed to solar on BLM lands*	x	Bureau of Land Management (2016a)
Environmental	Bat hibernacula setbacks*	805 m	Lopez et al. (forthcoming)
Environmental	Karst depressions*	x	Jones et al. (2021)
Environmental	USFS GAP Status 3 and 4 (excluding National Forests)*	x	U.S. Geological Survey (2024)
Environmental	USFS active grazing allotments*	x	U.S. Forest Service (2024b)
Environmental	USFS and BLM Mature and Old Growth Forests (USFS and BLM lands only)*	x	DellaSala et al. (2022); U.S. Forest Service (2024a)

Category	Dataset	Ref	Source
Environmental	USFS modeled Recreational Opportunity Spectrum (ROS) excluded categories*	x	Mai et al. (2025)
Environmental	National Land Cover Dataset Water, Woody/Herbaceous Wetlands	x	U.S. Geological Survey (2021)
Environmental	Lesser Prairie Chicken core habitat		“Conserving the Lesser Prairie-Chicken | U.S. Fish and Wildlife Service” (2023)
Environmental	Greater Prairie Chicken habitat	x	(Prior-Magee and McKerrow 2018)
Environmental	Dixie Valley Toad	x	Meadows and County (n.d.)
Environmental	Desert Tortoise	x	Davidson and Schueck (2020)
Environmental	Tiehm’s Buckwheat	x	“Endangered and Threatened Wildlife and Plants; Endangered Species Status and Designation of Critical Habitat for Tiehm’s Buckwheat” (2022)
Environmental	BLM RMPA/DEIS Sage Grouse Priority Habitat Management Area Avoidance Areas—alternative 5 (BLM lands only)*	x	Bureau of Land Management (2024c)
Environmental	BLM RMPA/DEIS Sage Grouse Priority Habitat Management Area Exclusion Areas—alternative 3 (BLM lands only)*	x	Bureau of Land Management (2024c)
Environmental	FEMA 100-year floodplains*	x	Federal Emergency Management Agency (2024)
Environmental	Department of Interior-defined ridgelines*	x	Mai et al. (2025)
Environmental	Threatened and Endangered Species core habitat (federal lands only)	x	Lopez et al. (forthcoming)
Environmental	U.S. Fish and Wildlife Service National Wetlands Inventory	x	U.S. Fish & Wildlife Service (n.d.)
Environmental	Nationally Significant Agricultural Lands*	10% available	Conservation Science Partners and American Farmland Trust (2016)
Environmental	Simulated Conservation Reserve Program Lands	x	See Appendix A.1
Environmental	American Farm Trust Conservation Lands	x	American Farmland Trust (2023)
Environmental	BLM Areas of Critical Environmental Concern	x	Bureau of Land Management (2022b)

Category	Dataset	Ref	Source
Environmental	National Forest Service Inventoried Roadless Areas	x	U.S. Forest Service, Geospatial Service and Technology Center (2001)
Environmental	National Conservation Easement Database (GAP Status 1, 2)	x	National Conservation Easement Database (2017)
Environmental	Protected Areas Database (GAP Status 1, 2)	x	U.S. Geological Survey Gap Analysis Project [GAP] (2022)
Environmental	Big game migration corridors	50% available	Kauffman et al. (2020); Kauffman, Lowrey, Beck, et al. (2022); Kauffman, Lowrey, Berg, et al. (2022)
Infrastructure	368 designated (2009) transmission corridors*	x	Bureau of Land Management (2022c)
Infrastructure	Existing wind turbine pads (45.7 m) setback*	x	Hoen et al. (2023)
Infrastructure	Oil and gas well footprints	x	Oak Ridge National Laboratory (2019)
Infrastructure	Railroads	x	U.S. Census Bureau (2021)
Infrastructure	Roads	x	Homeland Security Infrastructure Program (2018)
Infrastructure	Building structures	x	Microsoft [2018] (2018)
Infrastructure	Oil and gas pipeline right-of-way	x	Federal Communications Commission and Oak Ridge National Laboratory (2018)
Infrastructure	BLM National Geothermal Leases	x	“BLM Natl MLRS Geothermal Leases” (2023)
Infrastructure	Geothermal plant locations	x	Akindipe et al. (2025)
Regulatory	Oil and gas pipeline setback	30 m	Lopez et al. (2022)
Regulatory	Property line setback	15 m	Lopez et al. (2022)
Regulatory	Rail setback	30 m	Lopez et al. (2022)
Regulatory	Road setback	30 m	Lopez et al. (2022)
Regulatory	Building structure setback	61 m	Lopez et al. (2022)
Regulatory	Transmission setback	30 m	Lopez et al. (2022)
Regulatory	Water setback	30 m	Lopez et al. (2022)
Terrain	Slope exclusion	>25%	Jarvis et al. (2008)
Terrain	Elevation (>9,000 ft) and mountainous landforms	x	Karagulle et al. (2017)

x denotes where a layer is used to exclude land; * denotes a new layer or assumption.

2.5 Transmission Costs and Constraints

2.5.1 Land-Based

In this 2024 version of the supply curves, we made some adjustments and simplifications to the methods and data used to estimate the transmission infrastructure required to connect new renewable energy projects to the electric grid. Specifically, we removed the voltage requirements for each project site and thus have a single voltage cost applied, adjusted the region boundaries used for the regional transmission costs, and applied a mitigation cost based on the natural and cultural constraint categories detailed in this section.[8]

We used a least-cost-path methodology that considered the six components in the following list. In addition, we used a methodology for capturing network upgrade requirements as part of the total interconnection cost requirement. The main components of our transmission method were:

- Siting constraints
- Natural and cultural mitigation costs
- Regional component costs
- Land composition costs
- Point-of-interconnection (POI) costs
- Network upgrade costs.

We obtained our regional transmission costs from the Transmission Expansion Planning Policy Committee (TEPPC)[9], Southern California Edison (SCE)[10], the Midcontinent Independent System Operator (MISO)[11], and an undisclosed utility in the Southeastern United States. Some regions, such as Southwest Power Pool (SPP), the Electric Reliability Council of Texas (ERCOT), California Independent System Operator (CAISO), Independent System Operator for New England (ISONE), PJM Interconnectio, and NYISO (The New York Independent System Operator), do not have publicly available transmission costs. For those regions, we used the costs from another region, as shown in Table 11. Note that regional costs do not follow exact footprints of each independent service operator.

We used regional land composition cost multipliers (Table 12) to represent the relative ease or difficulty with developing transmission on different land use and land cover types.

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[8] Mitigation costs were sourced from the Western Electricity Coordinating Council Environmental Data Viewer. https://ecosystems.azurewebsites.net/WECC/Environmental/.

[9] https://www.wecc.org/Administrative/TEPPC_TransCapCostCalculator_E3_2019_Update.xlsx.

[10] http://www.caiso.com/Documents/SCE2021FinalPerUnitCostGuide.xlsx.

[11] https://cdn.misoenergy.org/20210209%20PSC%20Item%2006a%20Transmission%20Cost%20Estimation%20Guide%20for%20MTEP21519525.pdf.

Table 11. Regional Baseline Transmission Costs (2022/mile)

Voltage	Prospective Site Capacity (MW)	TEPPC	SCE (CAISO, NYISO, ISONE, PJM)	MISO (SPP)	Southeast (ERCOT)
138	205	$1,317,993	$2,327,709	$1,615,100	$1,099,072

Costs are per mile and assume pastureland terrain for the groundcover cost multiplier.

Table 12. Transmission Cost Multipliers

Land Composition	TEPPC	SCE (CAISO, NYISO, ISONE, PJM)	MISO (SPP)	Southeast (ERCOT)
Pasture/Farmland	1.0	1.0	1.0	1.0
Suburban	1.3	2.0	1.1	1.8
Urban	1.6	3.0	1.2	1.1
Forest	2.3	3.0	1.2	1.5
Wetland	1.2	2.0	1.8	1.3
Hilly	1.4	1.5	1.1	1.2
Mountainous	1.8	2.0	1.2	1.6

We also applied estimated natural and cultural mitigation costs on a per-risk and per-mile basis (Table 13). The risk layers represent relative risk of cost escalation for mitigating effects of transmission development to known or presumed environmental and cultural resources. These risk layers were developed by SWCA Environmental Consultants and are documented in the appendix.

Table 10. Natural and Cultural Risk Mitigation Costs

Natural or Cultural Risk Level	$2022/mile
Least Risk (1)	$9,000
Low to Moderate Risk (2)	$10,000
High Risk (3)	$38,000

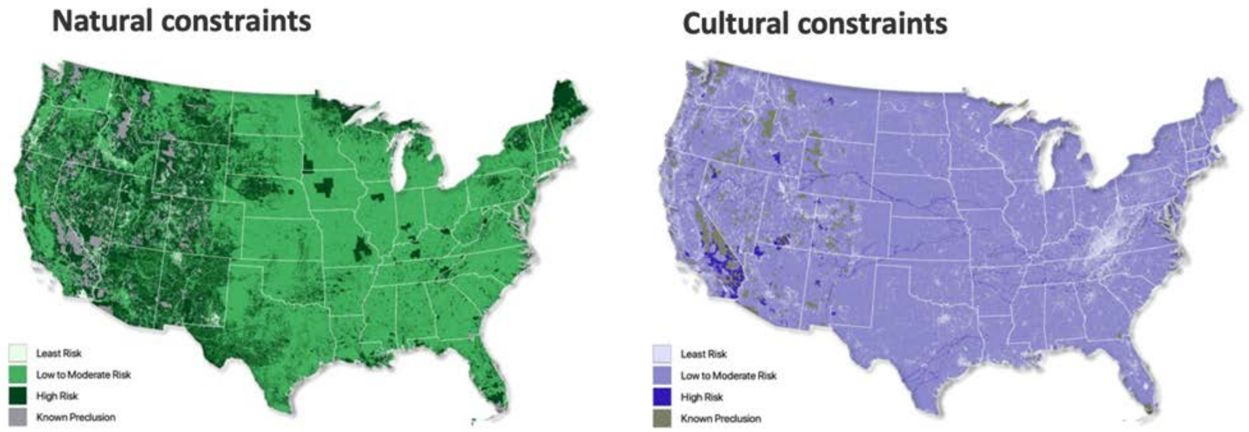

Figure 11. Transmission siting risk layers: natural constraints (left) and cultural constraints (right)

We applied spatial constraints to the cost raster, setting the cost to infinity in areas where development is prohibited. Prohibited, or excluded, areas are classified as risk level 4 (Known Preclusions) by SWCA. Additionally, we excluded PAD-US GAP Status 1 areas from transmission development. The result is a 90-m × 90-m raster that reflects the cumulative cost multiplier to build transmission in each pixel and is shown in Figure 11.

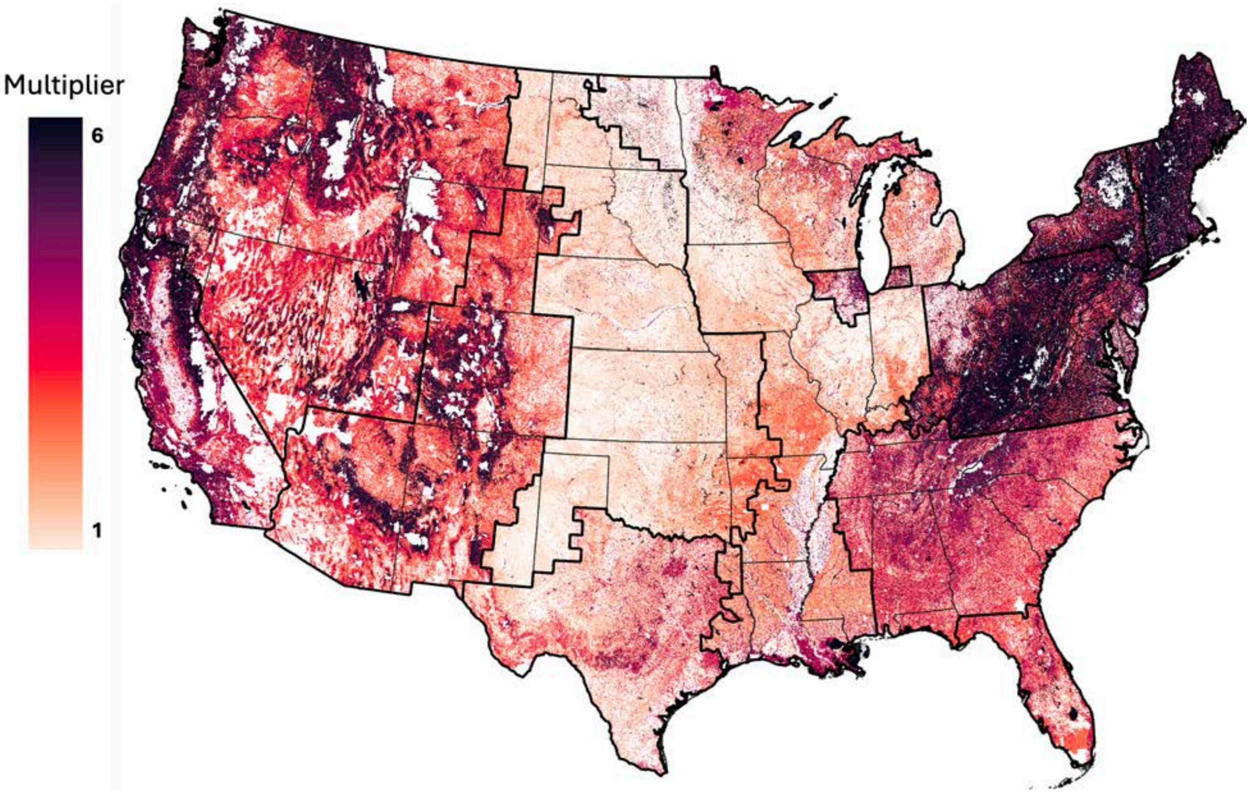

Figure 12. Regional transmission multipliers

Using the cost raster and for each prospective solar or wind site (~67,000 11.5-km sites), we ran a least-cost-path algorithm (Walt et al. 2014) to find the lowest-cost route from the prospective site to an existing electrical substation ("NREL/reVX: reV 0.8.0 Compatibility + Misc Updates" n.d.). Each prospective site has a list of possible substation connections or existing transmission lines. The list of possible connections was created by searching for substations or lines within 25 kilometers (km), within the same state, limited to features greater than or equal to 100 kilovolts (kV). If the search returned no possible connections, the 25-km constraint was relaxed. If the spur line connects to an existing substation, then an upgrade cost of $15/kW was applied; otherwise, a new substation cost of $35/kW was applied.

To account for the broader infrastructure needs beyond the connecting electrical substation, we estimated network upgrade costs as part of the overall interconnection cost requirements for a prospective solar or wind site. Network upgrades have been identified as a major contributor to the rising interconnection costs in recent years (Seel and Kemp n.d.). To capture this cost, we first defined load centers as locations with the highest electricity demand within a region. The default regions for the CONUS supply curves are the 134 model regions in the Regional Energy Deployment System (ReEDS) model (Ho et al. 2021)[12]. For these regions, the load centers were approximated as the largest population center in each region, and a few manual adjustments were made to them based on an analyst's judgment of where the load center should be located for a region.[13]

For each connecting substation, we determined the shortest path along existing transmission lines to the nearest "load center." The shortest path may be to a neighboring balancing authority area but was restricted to within the same state. Network upgrade costs were estimated as 50% of the greenfield costs (Table 11).

A conceptual diagram of the transmission methodology and resulting topology is presented in Figure 13.

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[12] https://www.nrel.gov/analysis/reeds

[13] For example, some regions with very small populations might have a tiny (but largest in the region) load center far removed from the actual transmission system, so the load center would be manually moved to be align with the transmission infrastructure.

Figure 13. Conceptual diagram of transmission routing.

Image by Billy J. Roberts, National Renewable Energy Laboratory

2.5.2 Offshore

Offshore cable routing takes a similar approach to land-based technologies. Cables are routed from the offshore wind plant to the POI, although an export cable is used in the water and then is converted to a spur line when it hits land. The spur line moves power to the POI, and from there, network upgrades/reinforcement are required from the POI to the load center. Given this, the land-based cost surface can be used in conjunction with a new offshore surface to route cables and calculate the levelized cost of transmission.

The integrated cost surface was created by joining the land-based cost surface with and new offshore cost surface. The offshore costs were determined by water depth and cable type. We routed both 425-kV high-voltage alternating current (HVAC) and 525-kV high-voltage direct current (HVDC) offshore cables and used the cable that results in the least cost. HVAC cables have a higher dollar-per-kilometer cost, though they have a lower conversion cost given that the grid operates in alternating current. By contrast, HVDC cables have a lower dollar-per-kilometer cost, but a higher conversion cost. Typically, the crossover point occurs around 80 km of cable length. To incorporate the costs associated with laying cable in deeper waters, such as additional material and longer installation times, we increased costs for 500 m of water depth by 10% (see Table 14). Table 15 details the one-time costs associated with constructing an export system.

Table 11. Site-Specific Cable Costs

Water Depth	425-kV HVAC Cost ($/90-m segment)	525-kV HVDC Cost ($/90-m segment)
0–500 m	1,017,900	357,750
500–1000 m	1,119,690	393,525
1000–1500 m	1,231,659	432,878
1500–2000 m	1,354,825	476,165
2000–2500 m	1,490,307	523,782
2500–3000 m	1,639,338	576,160
3000–3500 m	1,803,272	633,776
3500–4000 m	1,983,599	697,154

Costs are taken from Douville et al. (forthcoming), assuming 1.5-GW capacity. Costs are in 2022 USD.

Table 12. Offshore Substation, Platform, and Converter Costs

425-kV HVAC Cost ($)	525-kV HVDC Cost ($)
894,000,000	1,398,000,000

Costs are taken from Douville et al. (forthcoming), assuming 1.5-GW capacity. Costs are in 2022 USD.

With the new offshore cost surfaces comes a new layer type: friction. Friction is used when mitigation or additional costs would likely be required but the dollar amount is unknown. To this effect, friction functions as a spatial deprioritization to reduce the likelihood of incurring increased costs. Because friction does not impact the cost of transmission, we created two cost surfaces: one on which cables are routed (using the least-cost-path algorithm described previously) and one from which costs are extracted. The routing surface takes the values from the cost surface and modulates them by friction. Low friction increases routing costs by 33%, medium friction increases routing costs by 67%, and high friction increases routing costs by 100%. We determined that high friction should double routing costs in a given pixel, effectively serving as an expensive, but still viable, option should the overall cable costs be lower passing through that pixel compared to not passing through it. With high friction set at a doubling of costs in a given pixel, it followed naturally to make low and medium frictions a 33% and 67% increase, respectively. Once the route is determined, we can extract the costs by overlaying the route onto the cost surface. The export cable costs are added with one-time costs in Table 15 along with the spur line, POI costs, and network upgrades to calculate offshore levelized cost of transmission.

Table 16 details the offshore friction and exclusion siting assumptions used in conjunction with the land-based siting constraints. See Figure 14 for offshore routing cost surface, including exclusions and friction.

Table 16. Offshore Transmission Siting Constraints

Category	Layer	Treatment	Sources
Physical	Seafloor slope	10–15 degrees: medium friction >15 degrees: excluded	GEBCO (n.d.)
	Water depth	>4,000 m: excluded	GEBCO (n.d.)
	Seafloor sediment	Bedrock/hard: excluded Mixed/gravel: medium friction Mud/clay: low friction	"U.S. West Coast Seafloor Induration [v. 2017]—Overview" (n.d.) Buczkowski, Reid, and Jenkins (2020) Wang et al. (2015) "Gulf of Mexico Data Atlas" (n.d.)
	Canyons	Excluded	Harris et al. (2014)
	Rocky shorelines	High friction	("Environmental Sensitivity Index (ESI) Maps and Data | Response.Restoration.Noaa.Gov," n.d.)
	Artificial reefs	Excluded	("Artificial Reefs | InPort," n.d.)
	Shipwrecks	Excluded	("U.S. Office of Coast Survey," n.d.)
Infrastructure	Oil and gas pipelines and platforms	Medium friction	"HIFLD Open" (n.d.)
	Submarine cables	Low friction	"Marine Cadastre Hub" (n.d.)
Military	Danger zones and restricted areas	Excluded	"Marine Cadastre Hub" (n.d.)
	Unexploded ordinances	Excluded	"Marine Cadastre Hub" (n.d.)
	Oregon restricted area	Excluded	(Preacher 2024)
	Ship shock boxes	Excluded	"Marine Cadastre Hub" (n.d.)
Shipping / Navigation	U.S, Coast Guard Anchorage sites	Excluded	(Moriarty 2023)
	Shipping lanes	Shipping fairways/traffic lanes: medium friction Traffic separation schemes: excluded	"Marine Cadastre Hub" (n.d.) (Moriarty 2023)
	Crabber and tug lanes	Medium friction	(Moriarty 2023)

Category	Layer	Treatment	Sources
Regulatory	Usual and accustomed tribal fishing areas	Excluded	Schlosser (2012)
	Ocean disposal areas	Excluded	“Marine Cadastre Hub” (n.d.)
	Sand borrow areas	Excluded	U.S. Army Corps of Engineers (n.d.)
	State waters	Low friction	“US Marine Waters Boundaries” (n.d.)
	Bureau of Ocean Energy Management lease and planning areas	Force included	Bureau of Ocean Energy Management (n.d.)
Conservation	Marine protected areas	No take, no impact, and no access national marine protected areas: excluded Uniformed and zoned multiple use marine protected areas: medium friction Proposed Chumash National Marine Sanctuary: medium friction	“The MPA Inventory” (n.d.)

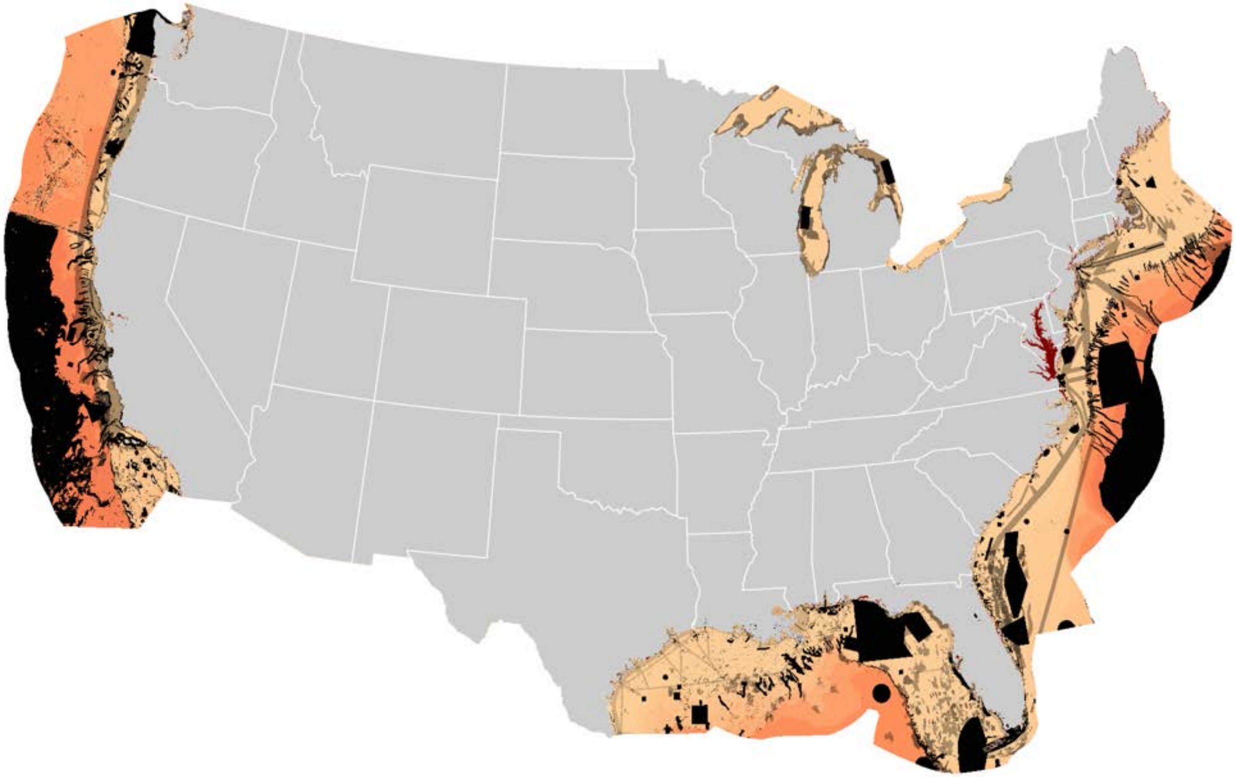


Figure 14. Offshore cable routing cost surface.

The darker the red-orange surface, the higher the cost. Grey areas represent friction, with lighter grey less friction, and darker grey are more friction. Black areas are excluded.

3 Results

In this section, we present results from the study. We first show CONUS-wide results in Table 17 for each technology and siting regime (or depth for geothermal; see Section 2.3.4). We then use maps and graphs to present critical dimensions of the supply curve results. Finally, we present state-level summary tables (18–22) of the results. For all results, we present capacity and generation in alternating current.

Table 17. National Summary of Capacity and Generation Potential for Wind and Solar Based on Siting Scenarios

Technology	Siting Scenario	Developable Area (km^2)	Capacity (GW)	Generation (TWh)
Land-based wind	Open access	5,680,290	13,365	41,849
	Reference access	1,654,997	9,436	30,575
	Limited access	579,050	4,291	14,267
Solar PV	Open access	5,770,111	185,160	429,941
	Reference access	2,370,737	76,076	181,964
	Limited access	1,076,840	34,555	83,966
Offshore wind fixed	Open access	300,629	1,203	4,193
	Reference access	262,089	1,048	3,605
	Limited access	183,212	733	2,483
Offshore wind floating	Open access	583,052	2,332	8,200
	Reference access	480,638	1,923	6,873
	Limited access	369,999	1,480	5,210
Geothermal Technology	**Depth (km)**	**Developable Area (km^2)**	**Capacity (GW)**	**Generation (TWh)**
Hydrothermal binary	3.5	577,211	1,642	14,284
EGS binary	4.5	999,961	3,698	32,189
	5.5	1,623,779	7,018	61,088
EGS flash	6.5	701,062	6,500	56,663

All estimates are in AC.

EGS = enhanced geothermal systems; GW = gigawatts; km = kilometers; TWh = terawatt-hours.

3.1 Capacity and Area

The developable area (or water) for energy projects is determined by siting exclusions and varies depending on the specific siting regime.

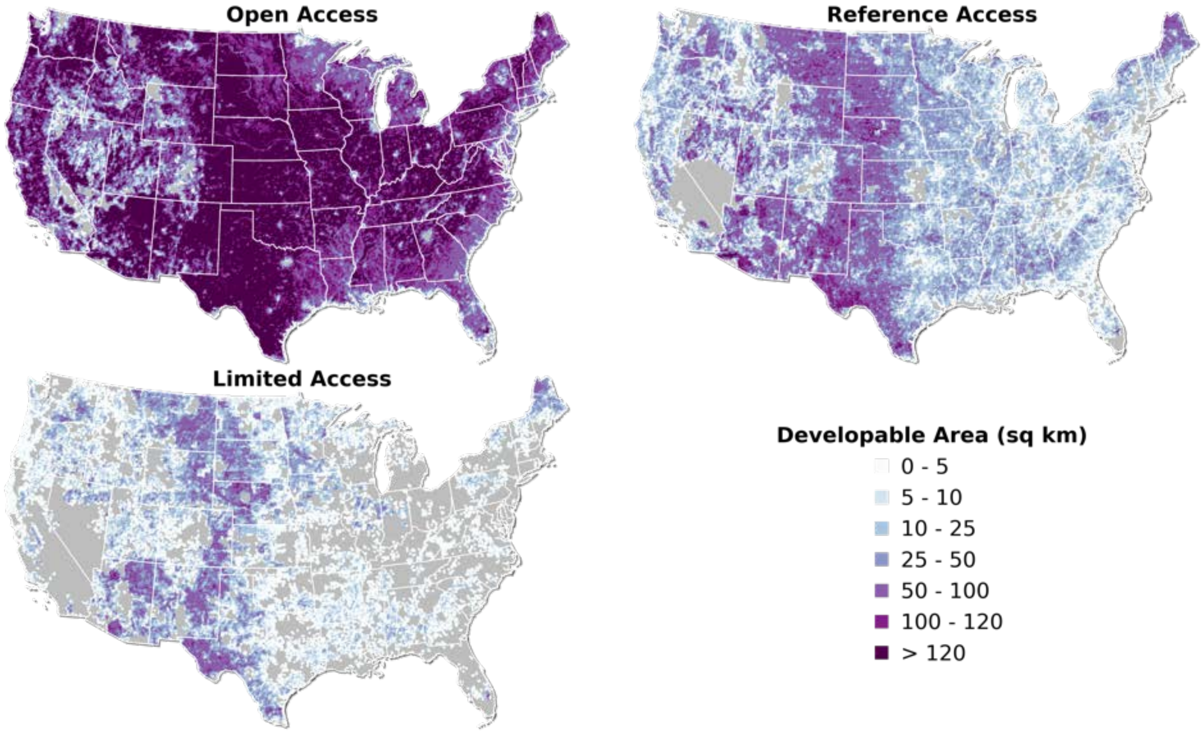


Figure 15. Developable area for land-based wind in Open Access, Reference Access, and Limited Access siting regimes

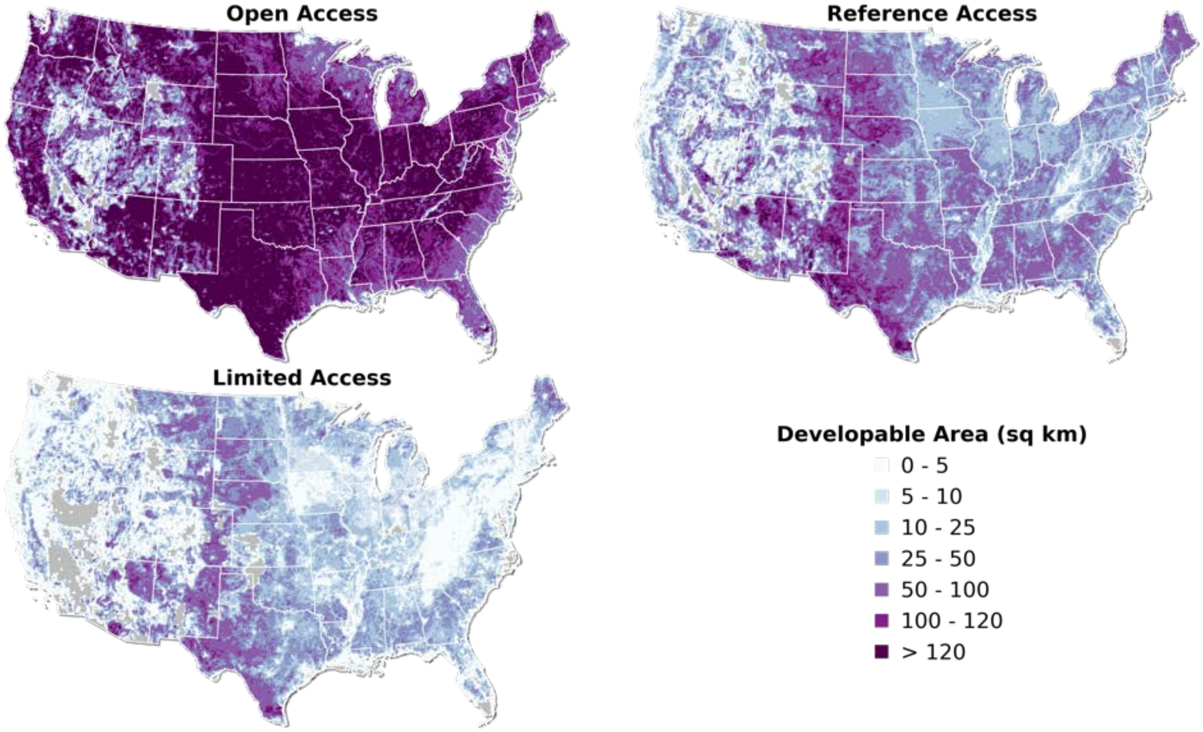


Figure 16. Developable area for solar PV in Open Access, Reference Access, and Limited Access siting regimes

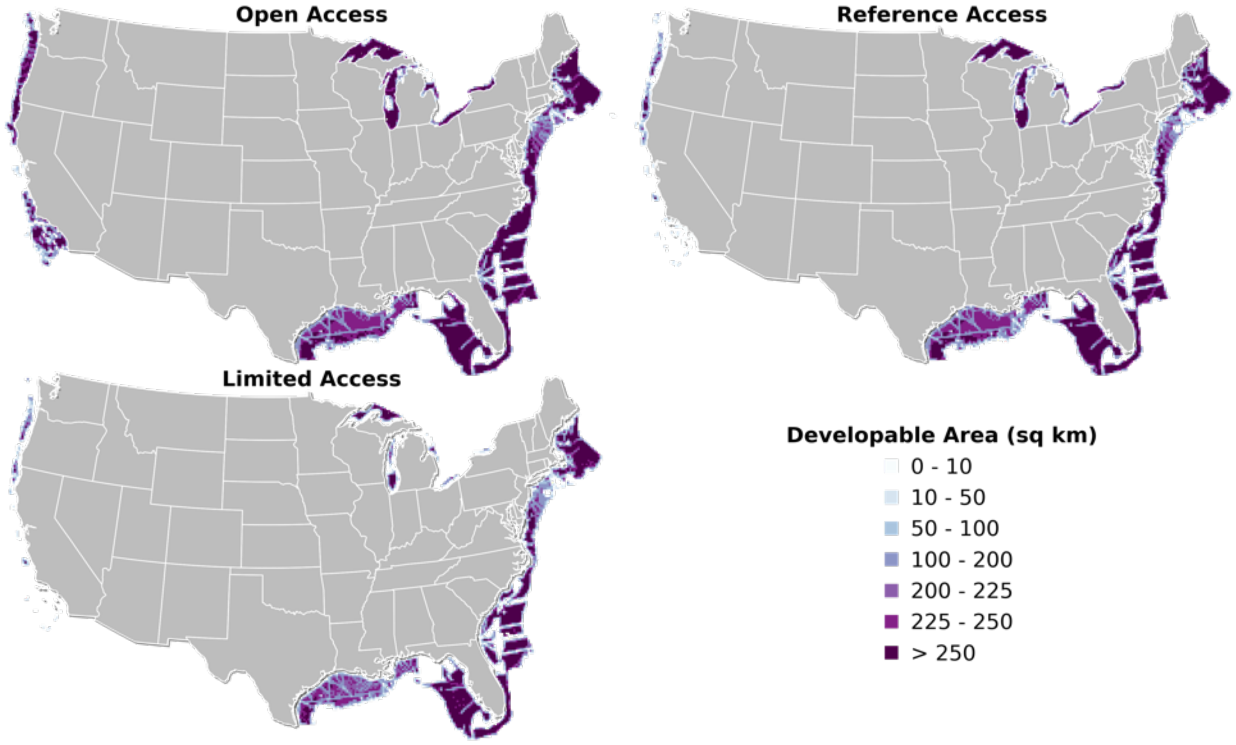


Figure 17. Developable area for offshore wind in Open, Reference, and Limited siting regimes

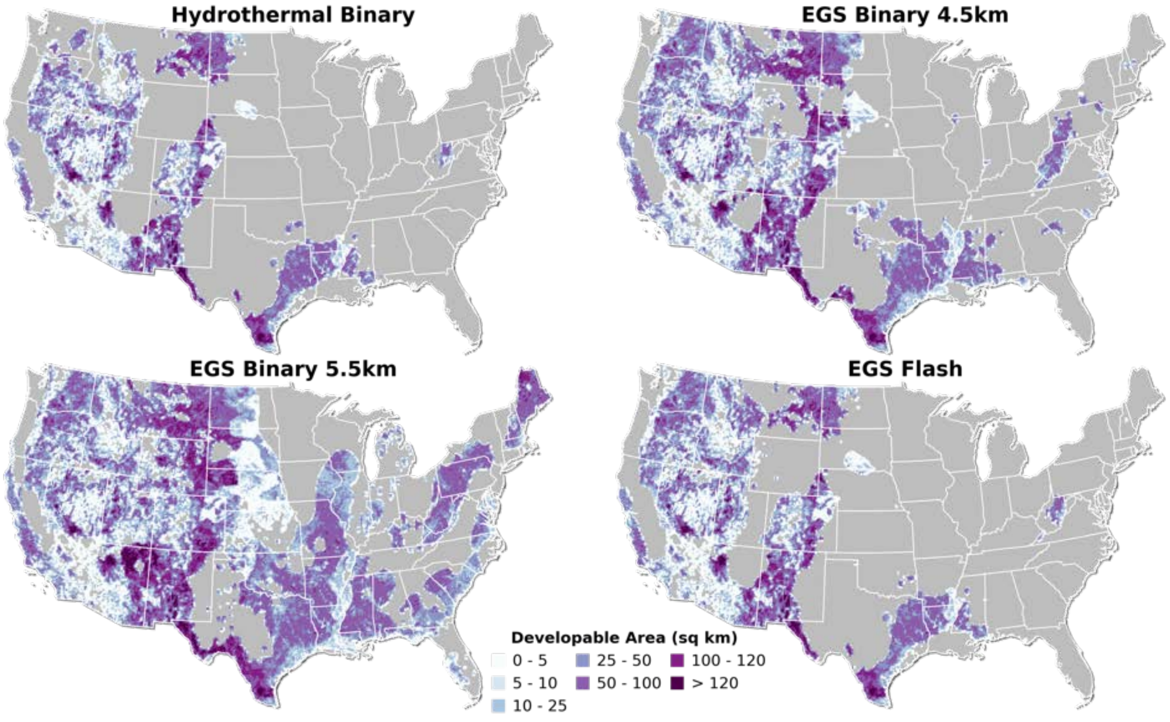


Figure 18. Developable area for geothermal across depths and plant types

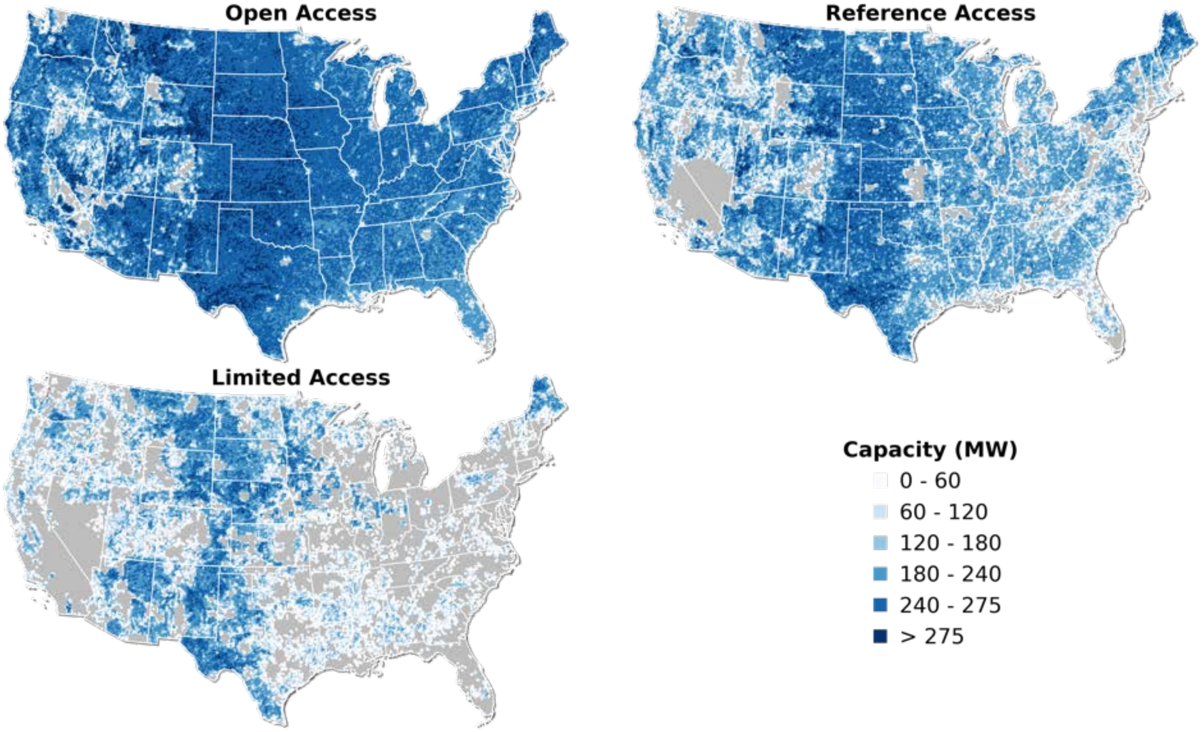


Figure 19. Available wind capacity in the three siting regimes

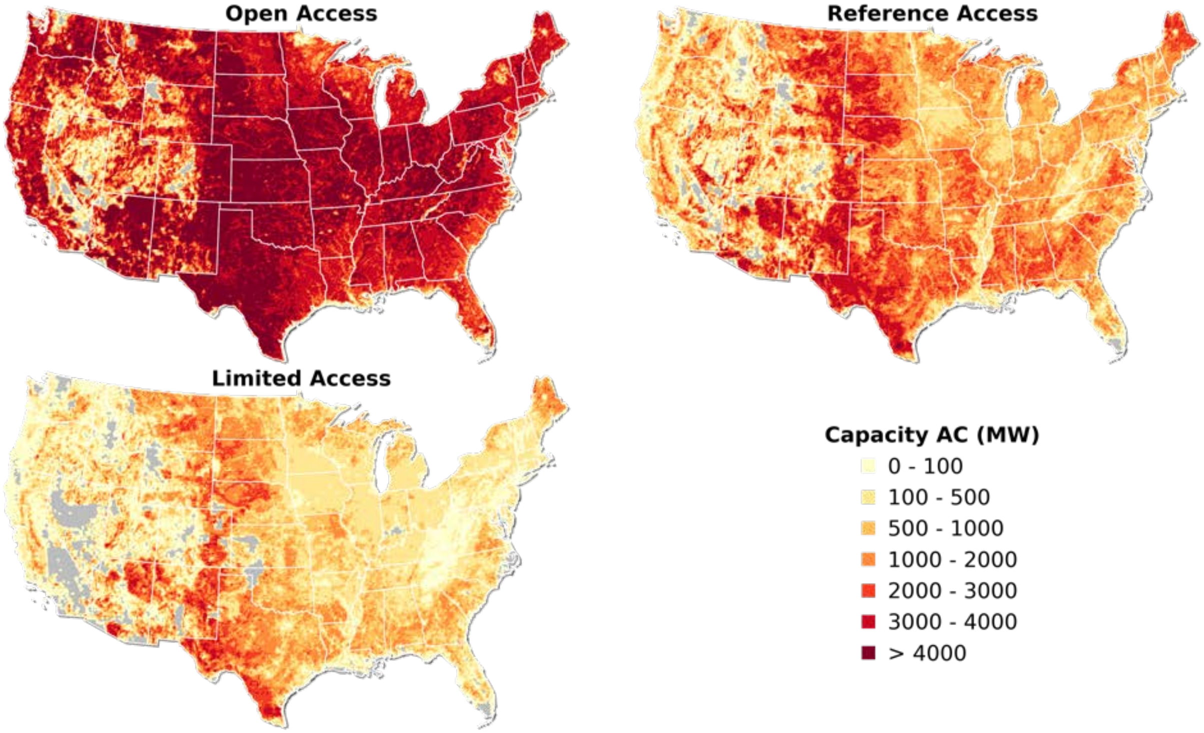


Figure 20. Available solar PV capacity (in AC) in the three siting regimes

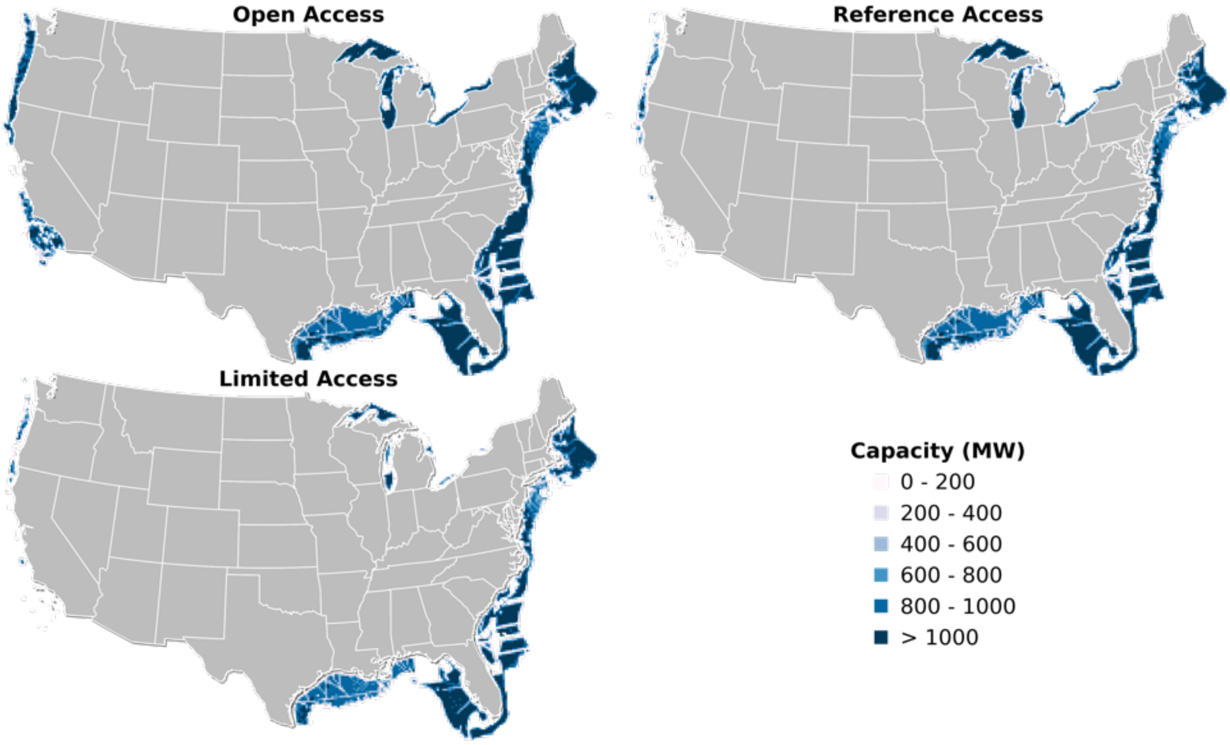


Figure 21. Available offshore wind capacity in the three siting regimes

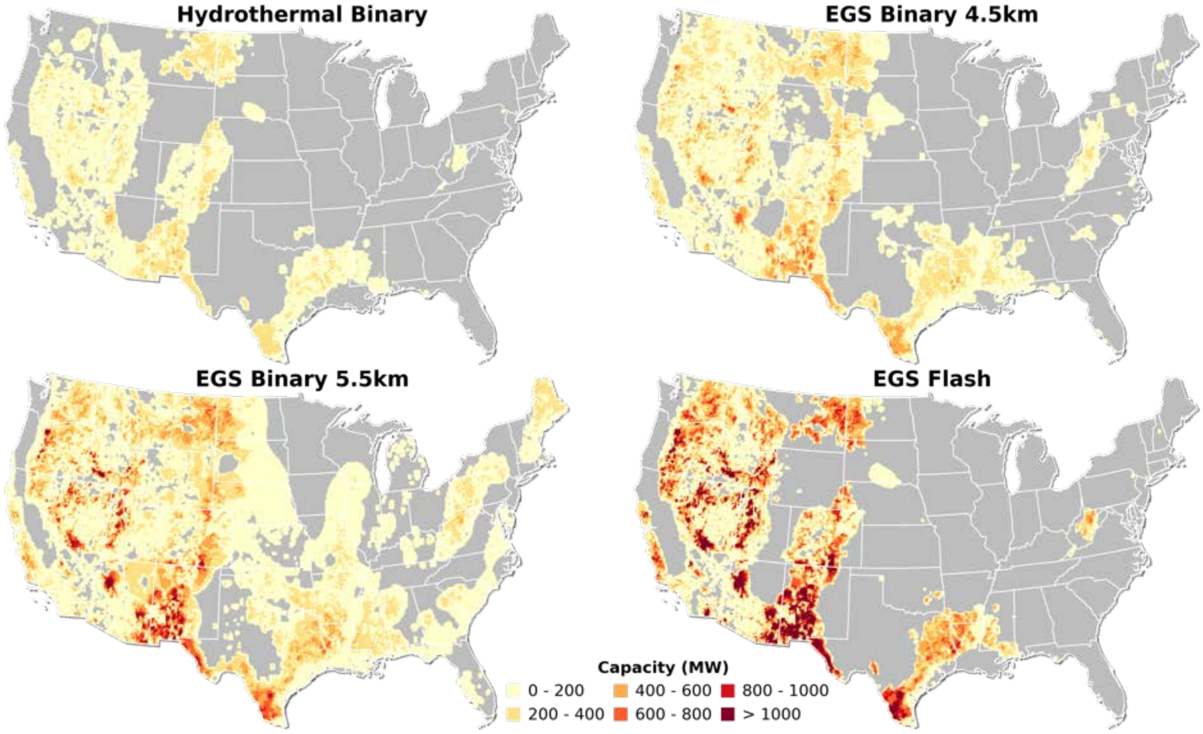


Figure 22. Available geothermal capacity across depths and plant types

3.2 Transmission Distance and Cost

Our transmission requirements were determined using a least-cost-path approach for each potential development site. The POI costs include the spur-transmission cost and substation upgrade cost requirement. Our reinforcement costs and distances are driven by the location of the POI and its proximity to the regional load center. Our results are comparable to recent literature that shows recent (2018–2021) total interconnection costs for all (completed and withdrawn) wind and PV projects at roughly $400,000/MW and $200,000/MW, respectively (Seel and Kemp n.d.). The following figures show maps of these costs on a levelized basis, referred to as levelized cost of transmission (LCOT), for each of the three siting regimes. The LCOT is like the levelized cost of energy (LCOE), but it includes only costs related to transmission, including spur-transmission, substation upgrade, and reinforcement.

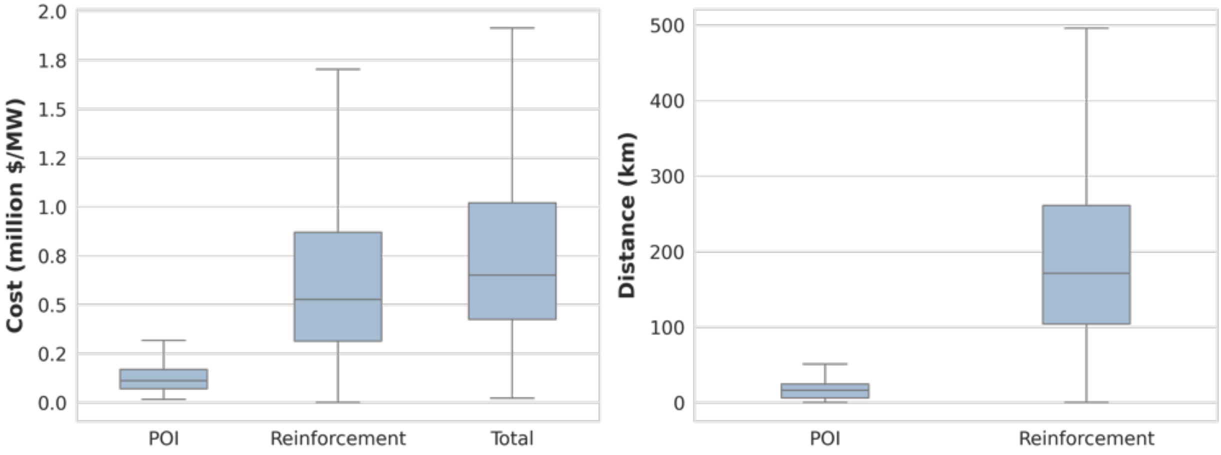


Figure 23. Transmission cost and distance distributions for the wind Reference Access siting regime

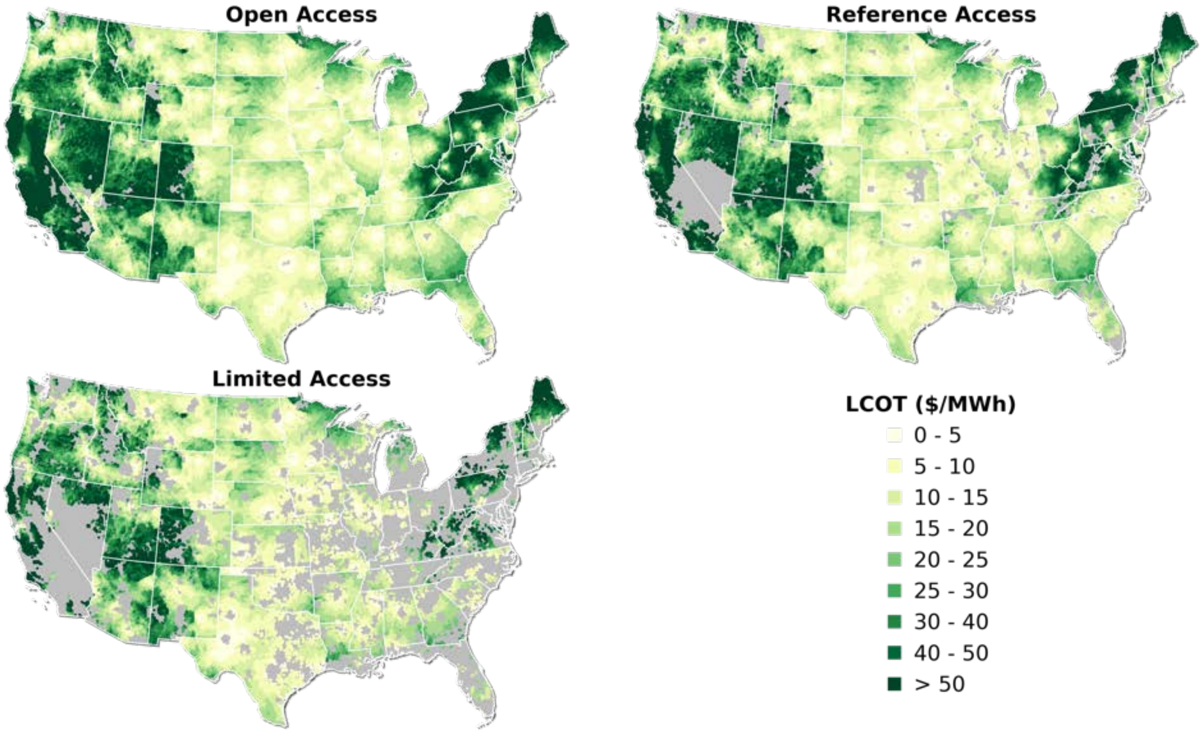


Figure 24. Levelized cost of transmission (LCOT) for the three wind siting regimes

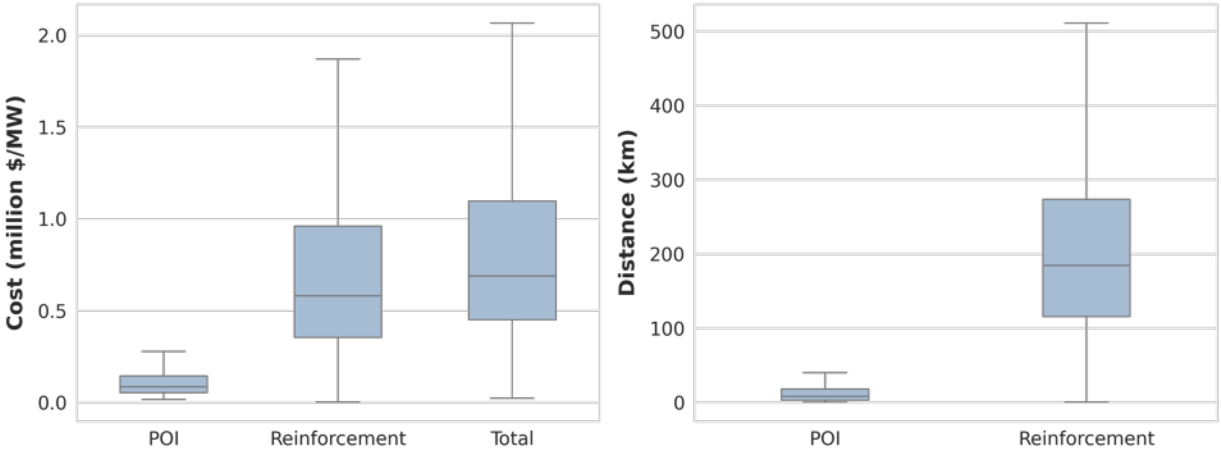


Figure 25. Transmission cost and distance distributions for the PV Reference Access siting regime

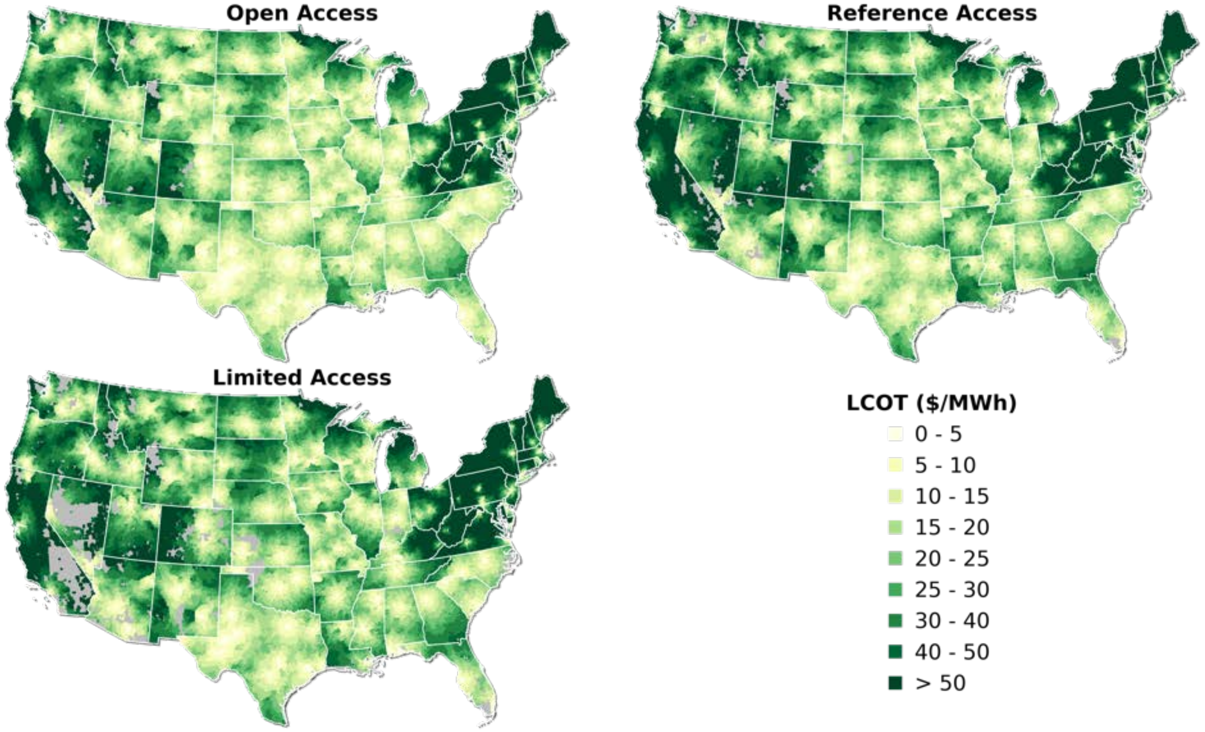


Figure 26. Levelized cost of transmission for the three PV siting regimes

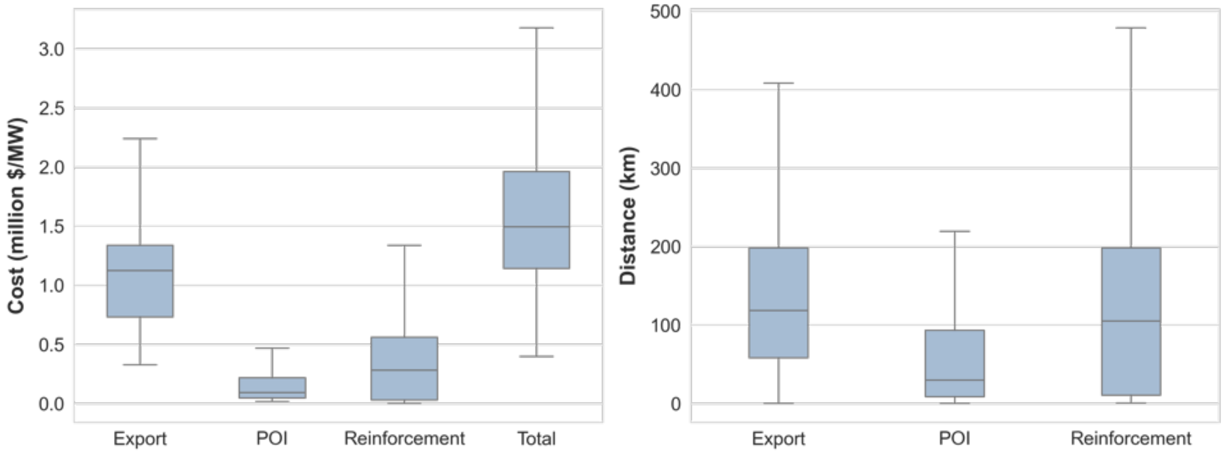


Figure 27. Transmission cost and distance distributions for the offshore wind (OSW) Reference siting regime

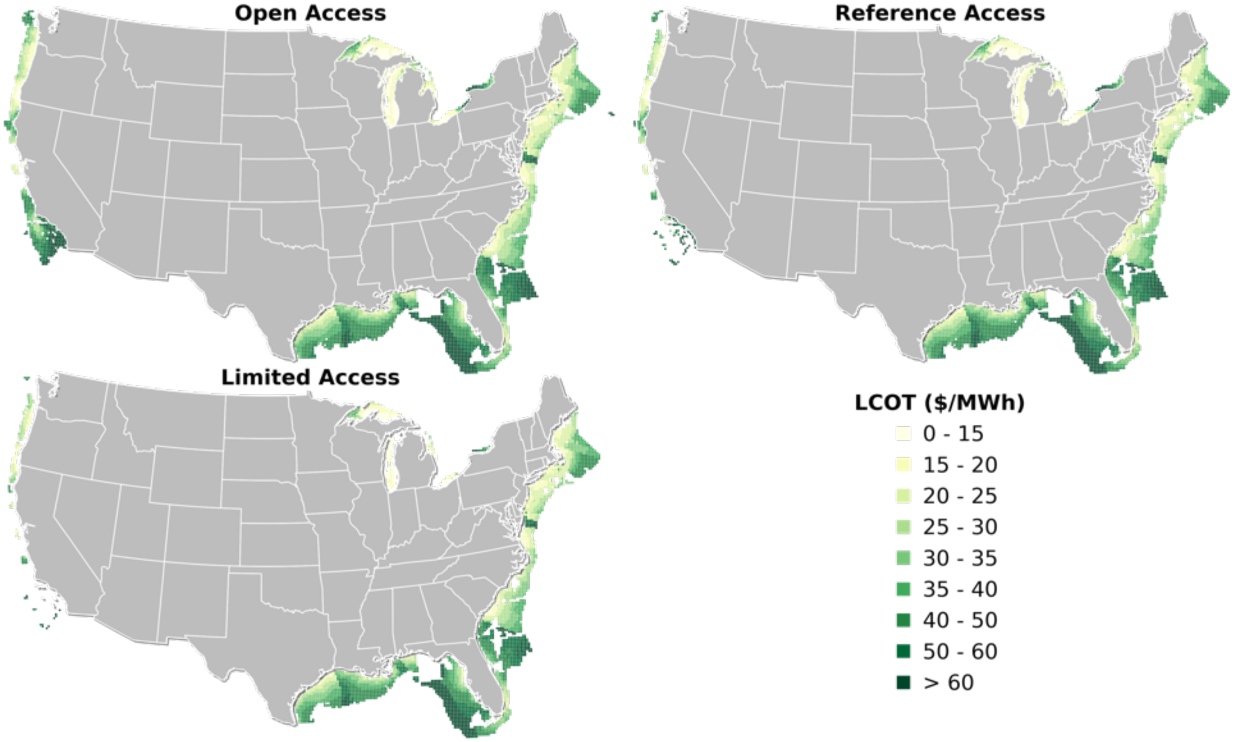


Figure 28. Levelized cost of transmission for the three OSW siting regimes

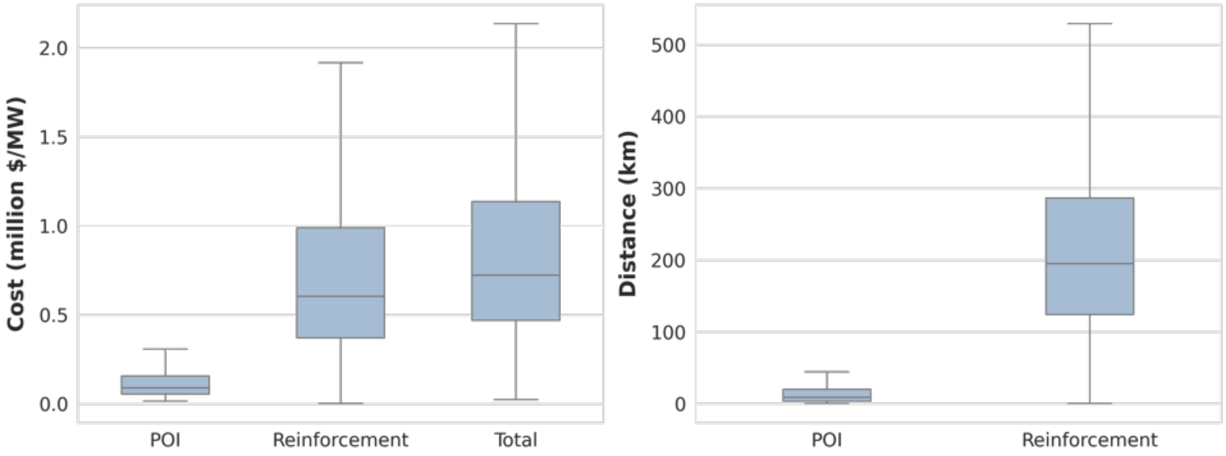


Figure 29. Transmission cost and distance distributions for the EGS binary 5.5-km scenario

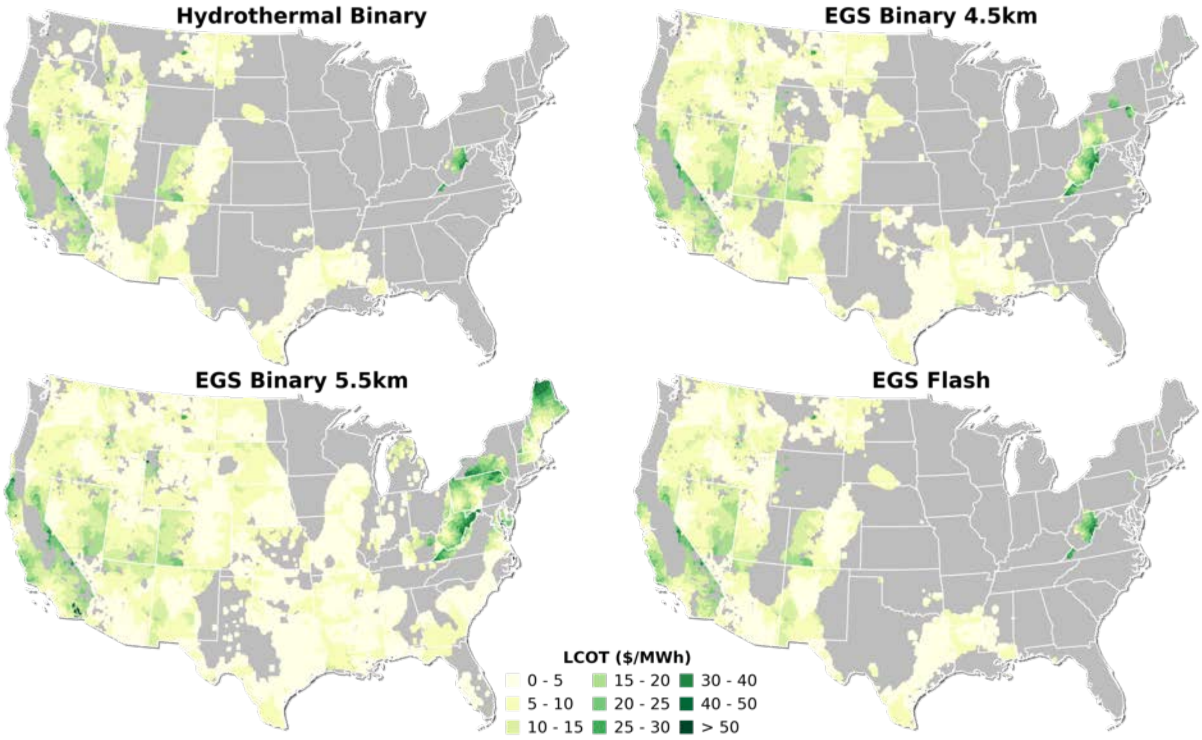


Figure 30. Levelized cost of transmission across depths and geothermal plant types

3.3 Supply Curves

Supply curves represent the quantity and cost of renewable resources. In Figure 31 through Figure 34, we partition the supply curves into “all-in” and “site” LCOE. All-in LCOE incorporates the cost of building transmission to interconnect a development site to the electric grid. In both cases, we exclude policies that might otherwise reduce the cost of development—for example, investment tax credit or production tax credit. Although site LCOE does not incorporate transmission costs and is largely driven by resource quality, we limit the maximum value in the graphs to preserve resolution at lower-cost resources.

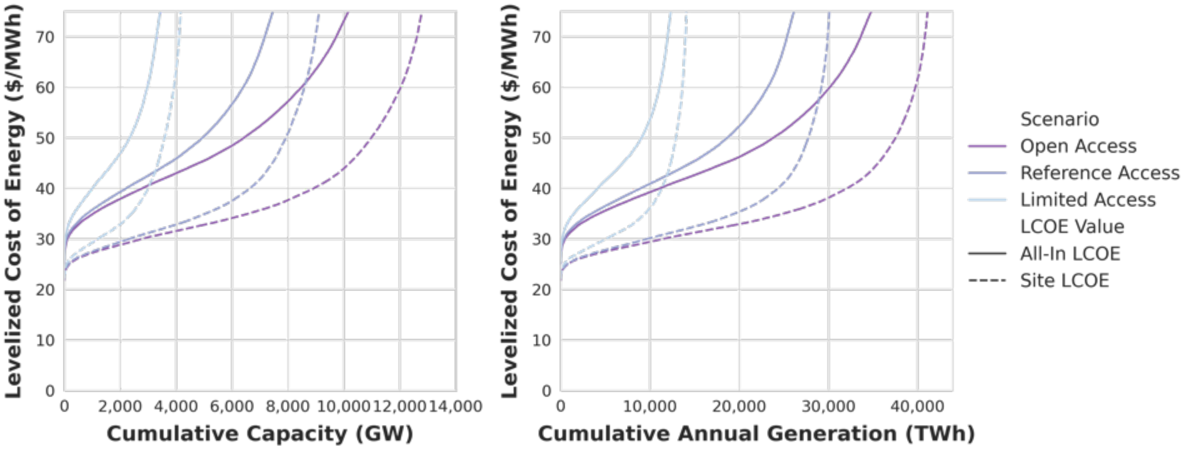


Figure 31. LCOE for wind supply curves as a function of cumulative capacity (left) and energy (right).

The graphs show both the all-in LCOE and the site LCOE for all siting regimes.
Values above $70/MWh are not shown.

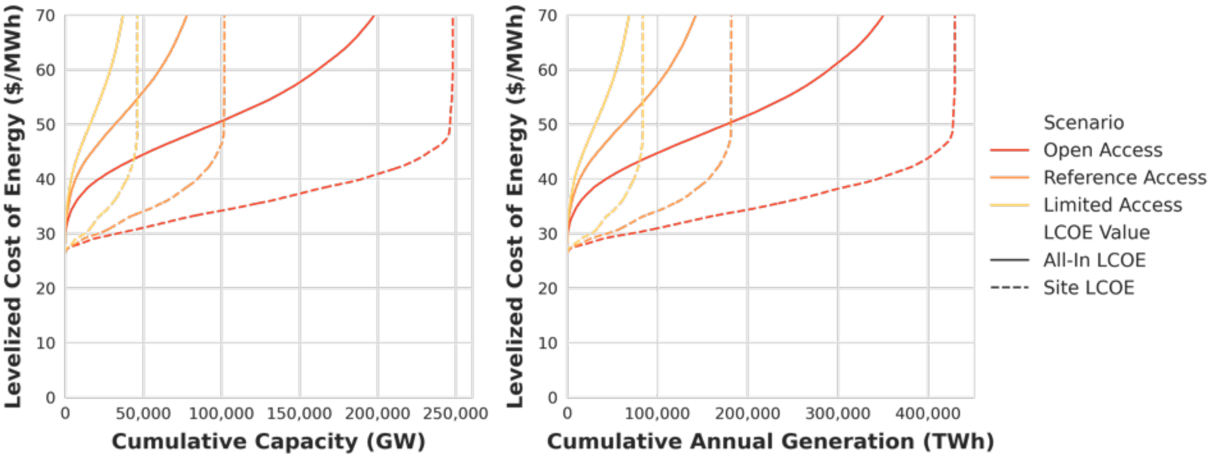


Figure 32. LCOE for PV supply curves as a function of cumulative capacity (left) and energy (right).

The graphs show both the all-in LCOE and the site LCOE for all siting regimes.
Values above $70/MWh are not shown.

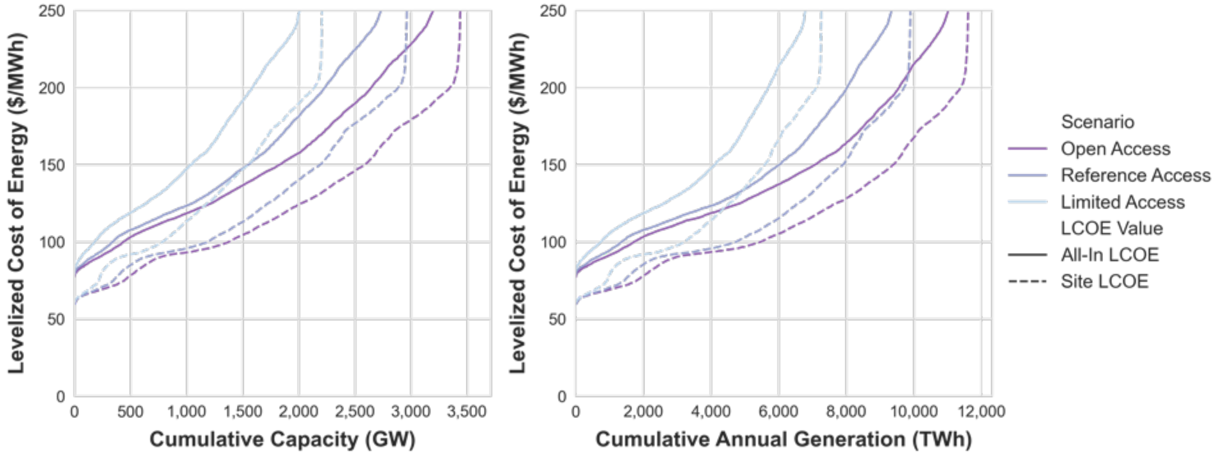


Figure 33. LCOE for OSW supply curves as a function of cumulative capacity (left) and energy (right)

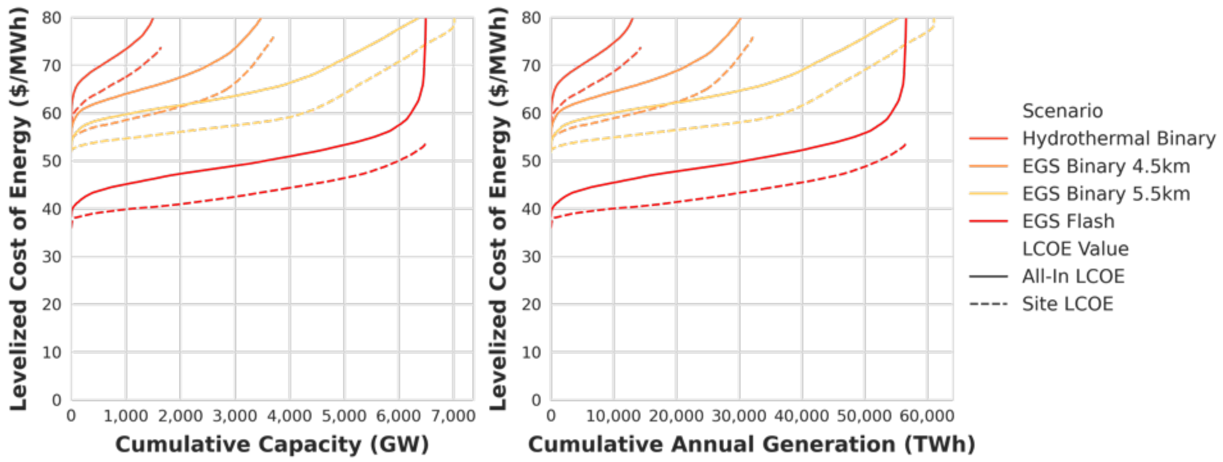


Figure 34. LCOE for geothermal supply curves as a function of cumulative capacity (left) and energy (right).

The graphs show both the all-in LCOE and the site LCOE for depth/plant type scenarios.
Values above $80/MWh are not shown.

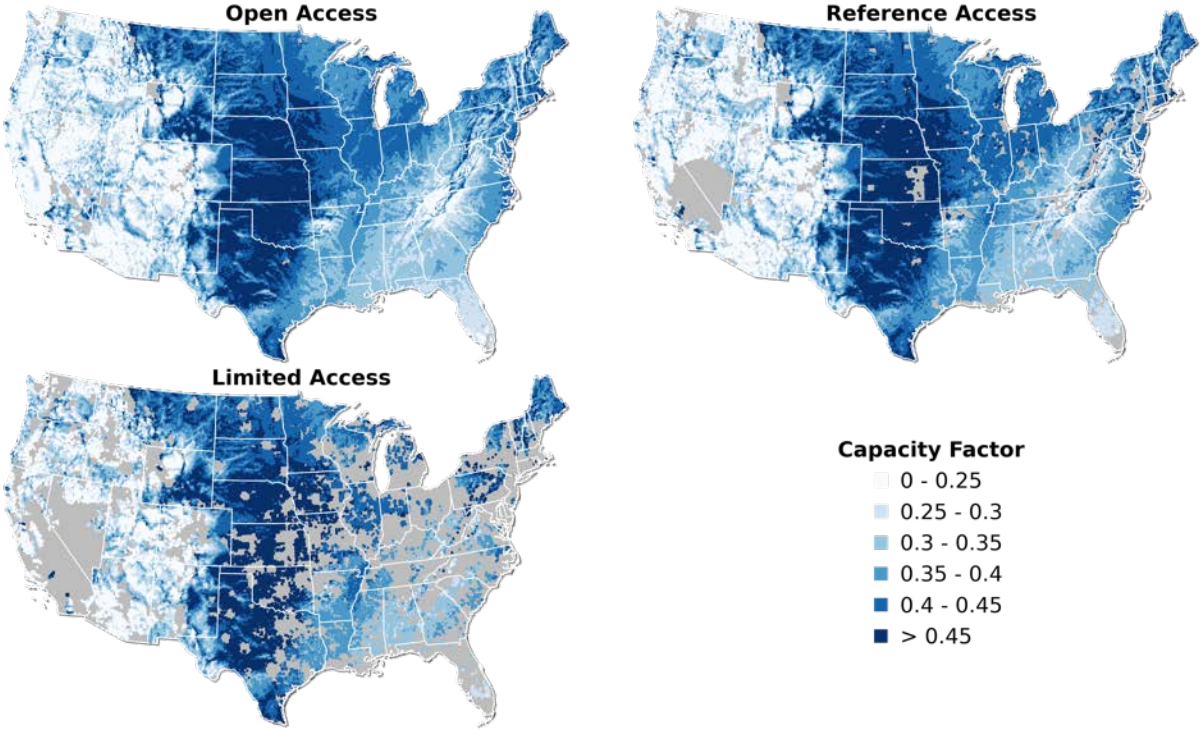


Figure 35. Wind capacity factor maps for the three siting regimes

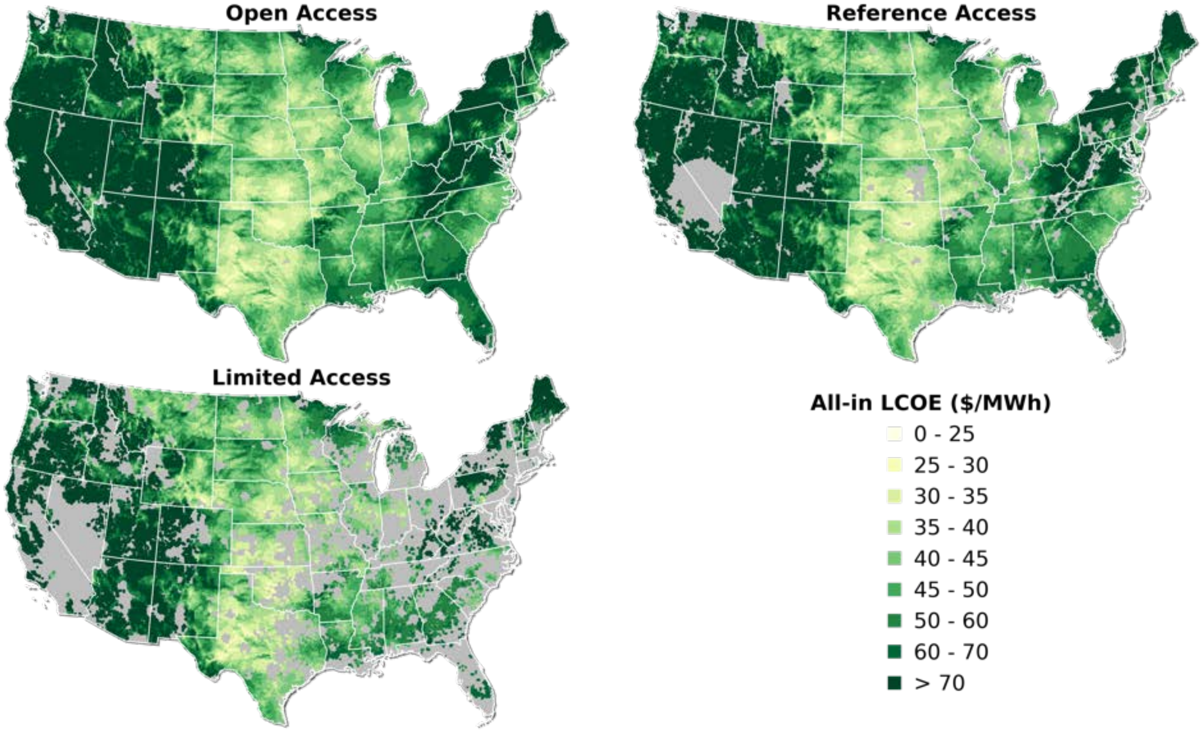
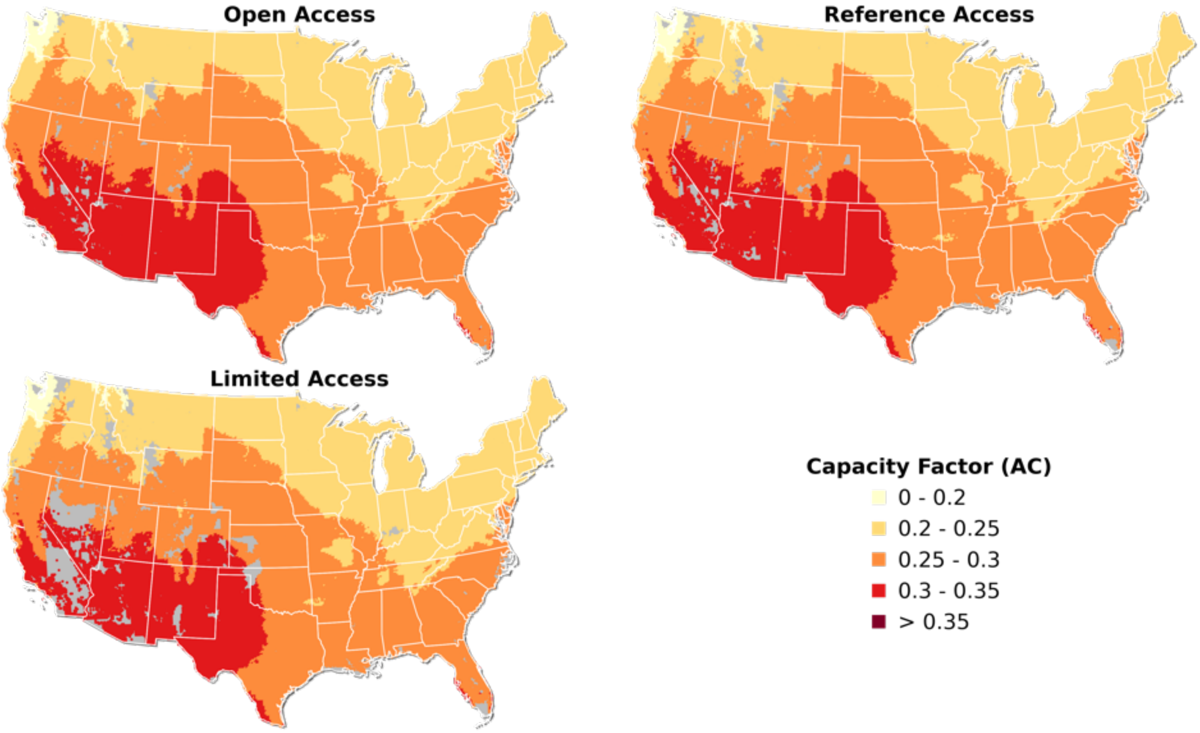


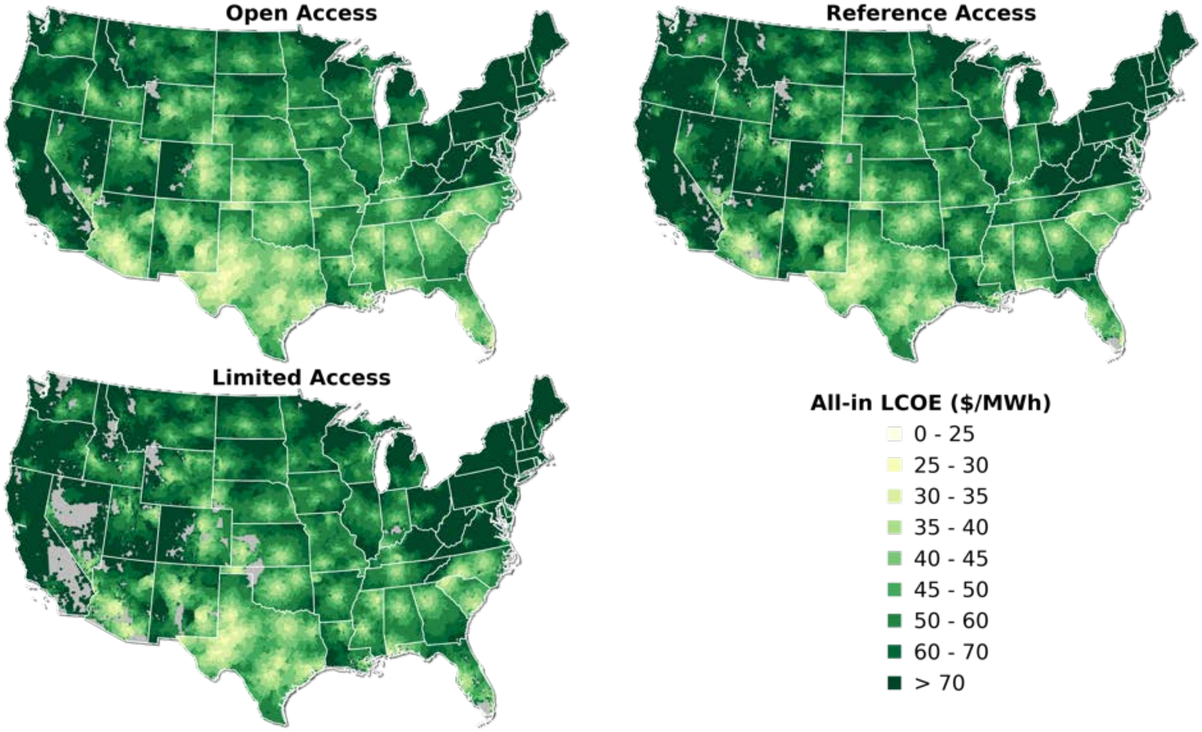
Figure 36. Wind all-in LCOE values for the three siting regimes


Open Access

Reference Access

Limited Access

Figure 37. Solar PV capacity factor maps for the three siting regimes


Open Access

Reference Access

Limited Access

Figure 38. Solar PV all-in LCOE values for the three siting regimes

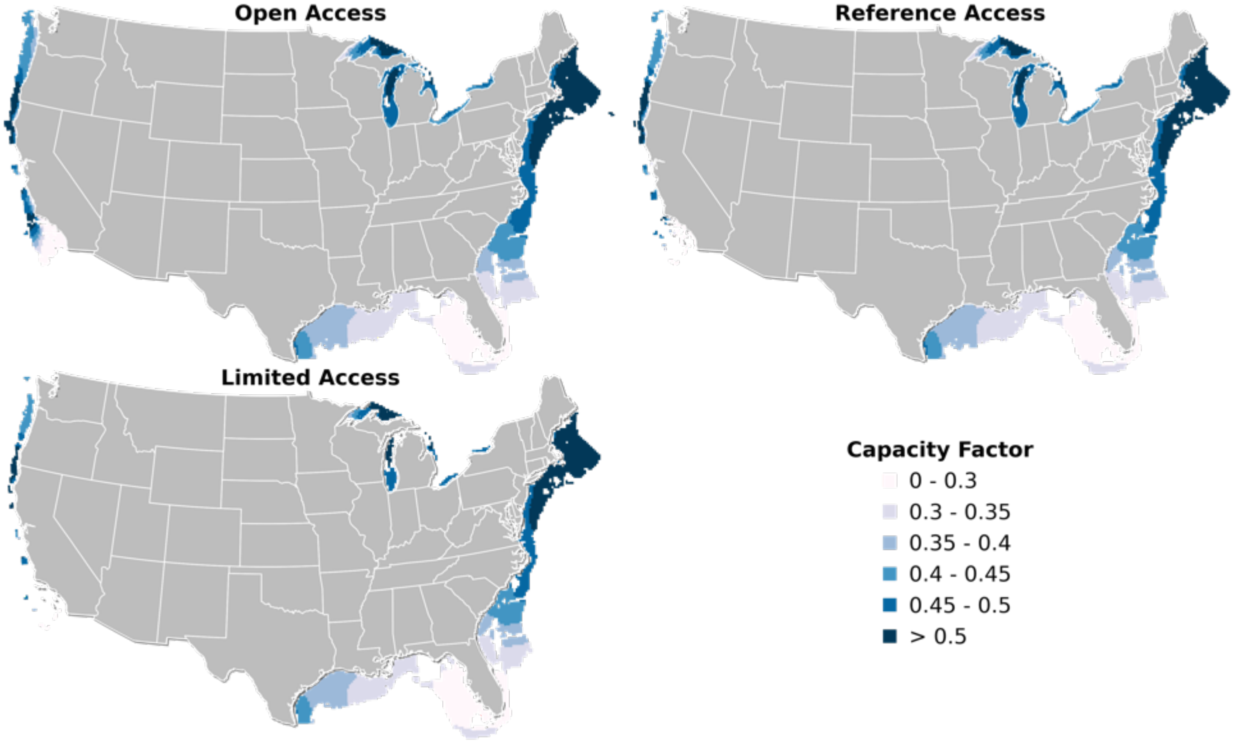


Figure 39. OSW capacity factor maps for the three siting regimes

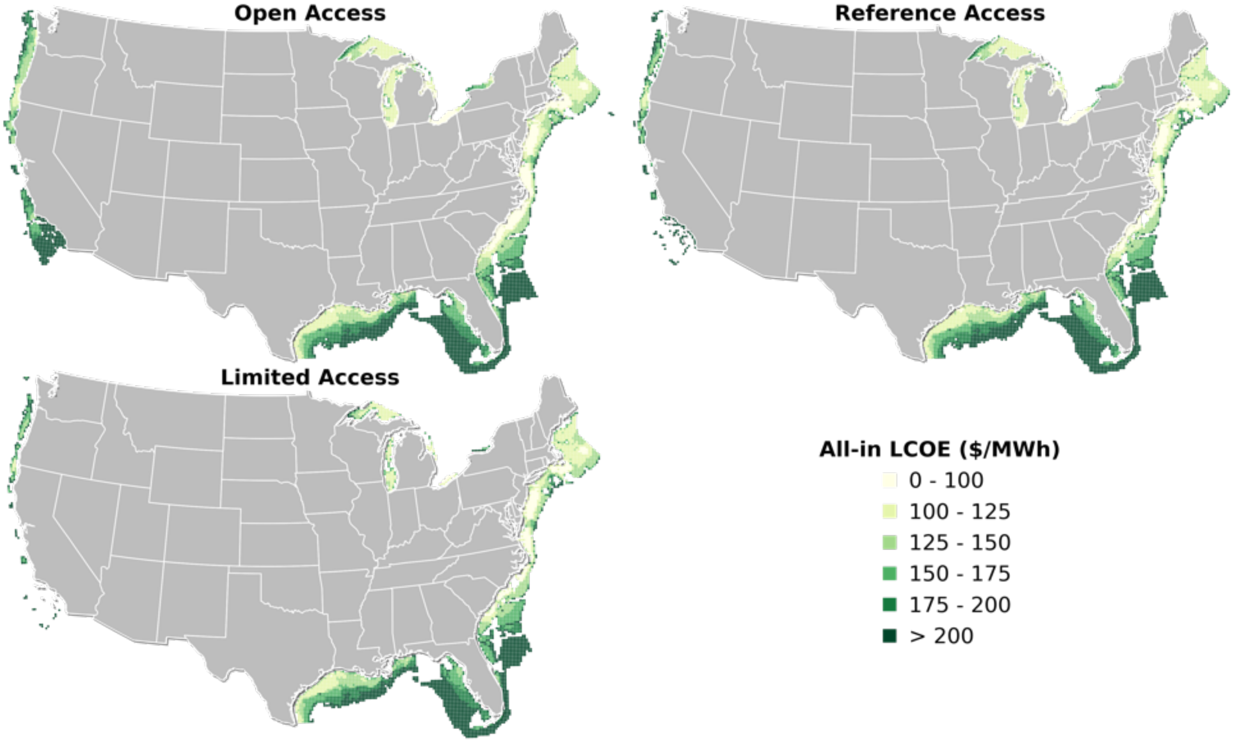


Figure 40. OSW all-in LCOE values for the three siting regimes

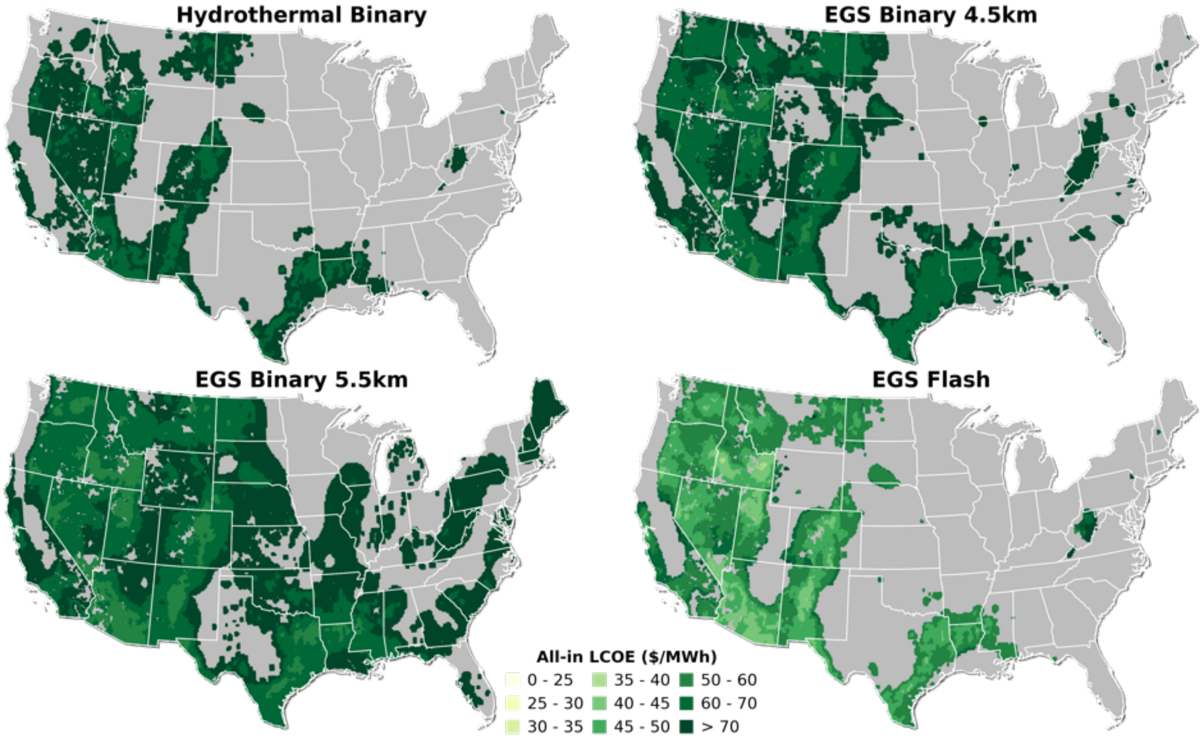


Figure 41. Geothermal all-in LCOE values across the depth/plant type scenarios

3.4 State-Level Results

Table 18 through Table 22 present state-level developable area, capacity, and generation for the respective technologies.

Table 138. State-Level Summary of Wind Reference Siting Regime Results

	Developable Area (km^2)			Capacity (MW)			Generation (TWh)		
State	**Open**	**Reference**	**Limited**	**Open**	**Reference**	**Limited**	**Open**	**Reference**	**Limited**
Alabama	106,532	23,276	4,494	238,668	162,018	46,140	638	443	130
Arizona	225,044	113,998	57,861	488,598	394,632	259,716	1,071	868	579
Arkansas	109,392	18,993	3,551	247,374	150,570	51,738	771	476	170
California	217,625	33,134	5,422	550,056	260,352	78,492	1,080	530	166
Colorado	171,875	71,555	27,489	417,006	341,964	182,598	1,117	951	543
Connecticut	6,362	248	5	18,702	4,800	156	66	18	1
D.C.	2,269	135	0	7,794	3,252	0	29	12	0
Delaware	63,120	4,771	886	189,972	61,308	6,294	480	160	15
Florida	103,199	17,084	1,951	254,436	169,956	27,528	704	482	79
Georgia	130,589	35,189	6,934	338,982	212,460	83,454	756	480	187
Idaho	125,032	17,214	5,293	265,044	153,744	50,544	951	561	188
Illinois	79,782	6,603	2,318	170,358	83,682	21,648	596	301	81
Indiana	134,925	24,855	8,810	285,648	223,506	99,858	1,109	882	400
Iowa	202,884	52,773	9,203	429,450	293,316	116,766	1,787	1,225	499
Kansas	94,370	9,786	324	193,884	124,050	8,052	577	377	24
Kentucky	61,260	12,059	2,061	167,436	107,886	27,396	504	332	87
Louisiana	60,081	27,732	12,261	155,322	131,448	81,750	539	465	296
Maine	13,679	677	23	40,026	12,528	426	135	44	2
Maryland	9,271	504	30	29,658	7,560	594	107	28	2
Massachusetts	89,746	10,636	1,331	262,098	152,322	21,264	928	552	80
Michigan	139,335	39,147	20,167	384,012	312,948	191,826	1,385	1,143	710
Minnesota	91,406	17,089	2,801	220,254	150,546	37,032	645	450	115
Mississippi	160,867	25,210	1,685	342,594	246,378	30,126	1,244	912	112
Missouri	288,951	150,098	69,248	690,984	588,156	430,530	2,240	1,942	1,466

	Developable Area (km^2)			Capacity (MW)			Generation (TWh)		
Montana	187,031	78,656	43,318	401,106	346,746	237,072	1,629	1,420	975
Nebraska	120,659	39,018	7,164	355,194	172,026	56,880	771	350	118
Nevada	17,756	2,954	393	44,670	25,290	6,174	146	88	23
New Hampshire	5,570	261	16	23,670	4,872	282	81	17	1
New Jersey	259,879	140,046	62,560	577,566	501,798	347,964	1,663	1,472	1,047
New Mexico	84,399	12,972	1,196	211,770	130,290	16,296	699	449	58
New York	87,578	8,221	577	216,480	105,102	8,712	645	324	27
North Carolina	158,344	50,257	18,323	355,236	282,384	166,758	1,303	1,049	633
North Dakota	87,197	8,311	245	186,504	117,270	4,698	610	391	16
Ohio	164,675	39,156	5,742	357,834	285,576	76,482	1,458	1,184	325
Oklahoma	163,566	37,042	9,989	396,786	266,820	132,084	904	618	317
Oregon	94,171	10,576	1,853	208,740	96,528	26,388	667	330	98
Pennsylvania	1,040	59	1	3,654	1,524	18	14	6	0
Rhode Island	50,051	6,785	740	133,926	79,110	10,926	375	225	31
South Carolina	178,803	80,291	34,624	395,106	354,048	245,028	1,482	1,334	931
South Dakota	85,140	8,466	843	187,332	88,620	10,272	527	271	33
Tennessee	602,687	224,321	89,057	1,291,374	1,075,344	564,558	4,777	4,043	2,120
Texas	117,811	51,904	12,164	326,568	239,760	123,828	716	525	276
Utah	20,349	3,477	380	45,762	29,298	5,754	145	98	22
Vermont	83,911	8,190	490	183,096	97,956	10,476	528	294	30
Virginia	119,226	34,781	11,501	278,484	195,216	107,628	665	483	282
Washington	52,551	5,965	171	116,310	65,682	6,042	330	188	19
West Virginia	95,766	15,118	1,853	260,094	180,780	27,780	890	627	97
Wisconsin	155,168	76,869	35,092	417,192	344,412	245,124	1,359	1,154	853
Wyoming	106,532	23,276	4,494	238,668	162,018	46,140	638	443	130

Table 14. Fixed-Bottom State-Level Summary of Offshore Wind Reference Siting Regime Results

	Developable Area (km^2)			Capacity (MW)			Generation (TWh)		
State	**Open**	**Reference**	**Limited**	**Open**	**Reference**	**Limited**	**Open**	**Reference**	**Limited**
Alabama	2,896	2,893	2,060	11,585	11,572	8,239	33	33	23
California	190	150	0	759	599	0	2	2	0
Connecticut	3,675	3,657	4,959	14,701	14,627	4,959	67	66	23
Delaware	2,976	2,806	10,528	11,904	11,226	10,528	52	49	46
Florida	71,124	70,987	228,989	284,497	283,946	228,989	687	686	550
Georgia	11,602	7,007	20,144	46,409	28,029	20,144	148	90	65
Illinois	1,667	1,494	370	6,670	5,975	370	26	23	1
Indiana	721	604	4	2,886	2,418	4	11	9	0
Louisiana	34,446	34,483	97,074	137,784	137,932	97,074	413	414	293
Massachusetts	15,743	15,179	52,416	62,974	60,718	52,416	306	296	256
Maryland	3,956	3,795	12,486	15,824	15,181	12,486	69	66	54
Maine	1,362	1,342	4,483	5,448	5,369	4,483	26	26	22
Michigan	14,594	9,623	1,556	58,377	38,492	1,556	235	157	7
Mississippi	3,765	3,755	10,844	15,060	15,019	10,844	43	43	31
North Carolina	24,264	14,114	30,668	97,056	56,457	30,668	398	235	128
New Hampshire	5,269	5,269	21,080	21,076	21,076	21,080	105	105	105
New Jersey	9,629	9,252	29,614	38,517	37,009	29,614	168	162	130
New York	11,101	9,901	26,929	44,405	39,606	26,929	191	173	121
Ohio	7,744	6,741	6,621	30,974	26,965	6,621	121	106	27
Oregon	307	28	0	1,226	113	0	4	0	0
Pennsylvania	1,460	1,157	105	5,838	4,628	105	23	18	0
Rhode Island	2,979	2,961	6,201	11,914	11,842	6,201	56	56	29
South Carolina	21,838	15,488	40,437	87,351	61,951	40,437	318	224	146
Texas	28,123	28,074	92,023	112,492	112,298	92,023	381	380	309

	Developable Area (km^2)			Capacity (MW)			Generation (TWh)		
Virginia	10,450	7,692	27,079	41,798	30,769	27,079	177	131	116
Washington	1,102	3	0	4,406	10	0	15	0	0
Wisconsin	7,646	3,632	0	30,583	14,529	0	117	56	0

Table 20. Floating State-Level Summary of Offshore Wind Reference Siting Regime Results

	Developable Area (km^2)			Capacity (MW)			Generation (TWh)		
State	**Open**	**Reference**	**Limited**	**Open**	**Reference**	**Limited**	**Open**	**Reference**	**Limited**
Alabama	49,103	48,184	43,379	196,412	192,738	173,516	502	492	440
California	64,480	10,620	4,167	257,919	42,480	16,668	781	188	76
Connecticut	619	251	222	2,477	1,003	888	12	5	4
Delaware	2,336	1,914	1,693	9,342	7,658	6,771	42	34	30
Florida	99,430	99,407	89,346	397,719	397,627	357,384	1,080	1,080	963
Georgia	4,430	4,153	4,153	17,719	16,611	16,611	59	55	55
Illinois	1,255	1,255	833	5,018	5,018	3,332	21	21	14
Indiana	0	0	0	0	0	0	0	0	0
Louisiana	49,483	41,639	30,584	197,931	166,555	122,335	574	486	358
Massachusetts	25,707	24,853	23,387	102,830	99,414	93,547	499	483	455
Maryland	3,429	2,834	2,707	13,714	11,338	10,826	60	50	48
Maine	34,061	31,180	24,201	136,243	124,719	96,804	647	593	465
Michigan	46,120	45,423	20,716	184,481	181,691	82,865	798	787	367
Mississippi	5,283	4,473	854	21,130	17,892	3,416	65	57	12
North Carolina	3,525	3,426	1,992	14,101	13,703	7,969	40	39	23
New Hampshire	17,864	17,575	16,193	71,457	70,300	64,772	297	292	269
New Jersey	13,051	12,987	12,237	52,202	51,946	48,947	252	251	238
New York	4,905	4,451	3,751	19,621	17,805	15,005	88	80	67
Ohio	18,786	12,211	5,123	75,146	48,844	20,490	328	208	93
Oregon	25,970	10,299	7,233	103,880	41,196	28,933	410	168	113
Pennsylvania	0	0	0	0	0	0	0	0	0
Rhode Island	1,658	1,624	1,562	6,633	6,498	6,248	32	31	30
South Carolina	37,029	36,808	34,441	148,115	147,233	137,763	536	533	499
Texas	42,812	42,637	31,819	171,248	170,548	127,276	579	577	433

	Developable Area (km^2)			Capacity (MW)			Generation (TWh)		
Virginia	2,482	2,115	1,847	9,930	8,461	7,390	43	37	32
Washington	10,470	1,652	1,222	41,881	6,607	4,890	150	24	18
Wisconsin	18,765	18,666	6,338	75,060	74,666	25,351	305	304	108

Table 21. State-Level Summary of PV Reference Siting Regime Results

	Developable Area (km^2)			Capacity (MW)			Generation (TWh)		
State	**Open**	**Reference**	**Limited**	**Open**	**Reference**	**Limited**	**Open**	**Reference**	**Limited**
Alabama	111,043	53,367	19,637	3,563,311	1,712,529	630,136	8,143	3,921	1,448
Arizona	219,313	119,754	63,677	7,037,666	3,842,860	2,043,365	19,851	10,884	5,780
Arkansas	112,545	39,938	15,430	3,611,532	1,281,593	495,127	8,172	2,883	1,115
California	230,849	56,781	15,557	7,407,840	1,822,073	499,229	19,514	4,926	1,322
Colorado	168,159	83,886	42,348	5,396,148	2,691,854	1,358,940	13,816	6,999	3,558
Connecticut	9,607	2,554	404	308,287	81,943	12,973	629	167	27
D.C.	3,075	728	287	6,058	447	16	218	52	20
Delaware	189	14	1	98,676	23,368	9,195	13	1	0
Florida	76,367	24,358	10,635	2,450,571	781,631	341,281	6,112	1,934	848
Georgia	113,532	50,071	21,270	3,643,205	1,606,772	682,559	8,577	3,789	1,623
Idaho	128,326	32,348	13,031	4,117,908	1,038,022	418,159	8,733	2,303	936
Illinois	133,910	26,868	11,071	4,297,121	862,177	355,265	9,318	1,877	774
Indiana	85,366	20,560	6,243	2,739,370	659,747	200,349	5,782	1,394	422
Iowa	137,002	23,334	6,836	4,396,333	748,777	219,364	9,499	1,620	474
Kansas	205,520	66,892	24,837	6,595,058	2,146,530	797,002	16,250	5,314	1,951
Kentucky	97,218	24,908	5,261	3,119,686	799,297	168,809	6,600	1,706	363
Louisiana	65,078	25,149	12,296	2,088,322	807,016	394,564	4,864	1,854	907
Maine	60,453	37,304	17,541	1,939,921	1,197,054	562,872	3,695	2,273	1,065
Maryland	17,523	3,751	782	562,295	120,359	25,089	1,201	258	54
Massachusetts	15,093	4,240	801	484,314	136,053	25,710	976	274	52
Michigan	97,312	39,287	15,389	3,122,702	1,260,704	493,814	6,177	2,471	965
Minnesota	142,319	43,855	22,582	4,566,948	1,407,294	724,645	9,386	2,859	1,470
Mississippi	93,994	44,812	18,497	3,016,221	1,437,984	593,571	6,948	3,298	1,362
Missouri	164,228	66,059	23,445	5,270,007	2,119,805	752,331	11,724	4,705	1,672

	Developable Area (km^2)			Capacity (MW)			**Generation (TWh)**		
Montana	285,577	142,702	73,650	9,164,042	4,579,246	2,363,386	18,513	9,381	4,849
Nebraska	188,233	98,237	54,607	6,040,298	3,152,367	1,752,300	14,273	7,493	4,166
Nevada	79,236	49,903	10,625	2,542,660	1,601,380	340,937	6,687	4,247	878
New Hampshire	18,877	5,324	994	605,757	170,830	31,896	1,173	333	62
New Jersey	11,094	2,563	617	356,004	82,234	19,805	747	174	42
New Mexico	247,348	160,473	89,074	7,937,291	5,149,495	2,858,347	22,399	14,640	8,140
New York	93,426	30,036	8,390	2,997,998	963,828	269,235	5,670	1,815	506
North Carolina	98,027	24,657	7,992	3,145,641	791,225	256,444	7,166	1,812	588
North Dakota	157,881	64,196	33,822	5,066,340	2,060,024	1,085,346	10,584	4,333	2,279
Ohio	96,950	22,464	5,547	3,111,070	720,861	178,006	6,277	1,446	360
Oklahoma	166,571	73,540	30,807	5,345,186	2,359,853	988,577	13,300	5,900	2,474
Oregon	158,870	36,154	12,238	5,098,051	1,160,162	392,722	10,794	2,562	883
Pennsylvania	104,923	25,771	5,270	3,366,945	826,982	169,103	6,474	1,582	322
Rhode Island	1,927	648	147	61,828	20,786	4,722	128	43	10
South Carolina	54,811	24,587	10,114	1,758,858	789,000	324,553	4,122	1,846	760
South Dakota	179,033	94,555	51,670	5,745,086	3,034,235	1,658,078	12,846	6,825	3,725
Tennessee	92,478	31,192	8,793	2,967,567	1,000,934	282,176	6,500	2,198	623
Texas	619,677	354,325	211,318	19,885,169	11,370,130	6,781,103	52,612	30,364	18,231
Utah	96,064	45,906	20,774	3,082,665	1,473,090	666,641	7,783	3,760	1,709
Vermont	20,505	4,804	886	658,004	154,155	28,426	1,226	286	53
Virginia	88,528	27,757	8,308	2,840,838	890,701	266,612	6,110	1,931	582
Washington	122,475	26,784	9,055	3,930,154	859,489	290,576	7,560	1,685	589
West Virginia	53,442	6,852	761	1,714,914	219,892	24,414	3,383	434	48
Wisconsin	99,596	35,813	12,663	3,195,986	1,149,234	406,343	6,555	2,343	825
Wyoming	146,540	90,679	40,861	4,702,402	2,909,863	1,311,196	10,862	6,770	3,053

Table 22. State-Level Summary of Geothermal Results

State	Developable Area (km^2)				Capacity (MW)				Generation (TWh)			
	Hydro-thermal Binary	EGS Binary 4.5 km	EGS Binary 5.5 km	EGS Flash	Hydro-thermal Binary	EGS Binary 4.5 km	EGS Binary 5.5 km	EGS Flash	Hydro-thermal Binary	EGS Binary 4.5 km	EGS Binary 5.5 km	EGS Flash
Alabama	175	10,936	27,550	133	414	28,424	80,048	784	4	247	697	7
Arizona	27,027	39,622	82,227	32,014	80,432	161,915	362,264	345,551	700	1,410	3,155	3,012
Arkansas	7,585	15,478	41,011	8,170	20,166	49,246	134,246	58,609	175	429	1168	511
California	24,423	35,748	44,176	30,605	71,961	147,773	240,469	328,700	626	1,287	2,084	2,865
Colorado	42,392	65,246	72,904	46,983	122,504	246,895	377,326	428,314	1,066	2,149	3,284	3,734
Connecticut			203				474				4	
Delaware			109				259				2	
Florida	32	635	6,749	17	76	1,601	17,639	103	1	14	153	1
Georgia		852	22,436			1,974	57,106			17	497	
Idaho	24,517	34,567	34,544	34,206	75,237	154,547	244,346	388,526	655	1,346	2,123	3,387
Illinois		554	14,369			1,309	37,631			11	327	
Indiana		56	4,298			130	10,610			1	92	
Iowa			9,087				25,225				219	
Kansas			12,176				30,036				261	
Kentucky		277	7,463			720	18,525			6	161	
Louisiana	13,123	19,839	21,658	13,530	38,999	74,936	107,691	110,571	339	652	938	964
Maine		223	41,535			521	107,515			5	935	
Maryland		658	2,368	26		1,814	6,842	152		16	60	1
Massachusetts			2,979				7,578				66	
Michigan			3,266				7,921				69	
Mississippi	11,710	28,911	41,509	12,085	29,189	90,014	152,506	76,900	254	783	1,328	670
Missouri			50,342				121,879				1,060	
Montana	58,167	111,748	128,038	73,424	153,440	371,211	557,749	522,708	1,335	3,231	4,857	4,556

State	Developable Area (km^2)				Capacity (MW)				Generation (TWh)			
	Hydro-thermal Binary	EGS Binary 4.5 km	EGS Binary 5.5 km	EGS Flash	Hydro-thermal Binary	EGS Binary 4.5 km	EGS Binary 5.5 km	EGS Flash	Hydro-thermal Binary	EGS Binary 4.5 km	EGS Binary 5.5 km	EGS Flash
Nebraska	7,074	25,515	43,102	7,402	19,026	73,880	146,919	47,719	166	643	1,279	416
Nevada	37,493	39,350	39,350	39,346	107,482	178,640	283,037	444,463	935	1,556	2,466	3,875
New Hampshire		224	4,469	2		544	11,794	14		5	103	<1
New Mexico	65,320	99,210	117,727	84,793	200,227	418,881	699,064	931,373	1,742	3,647	6,090	8,120
New York		1,887	12,437			4,692	33,211			41	289	
North Carolina		680	5,126			1,603	14,073			14	122	
North Dakota	26,566	36,699	40,779	26,252	71,879	132,766	190,008	187,853	625	1,156	1,655	1,637
Ohio		11	3,520			26	8,789			0	76	
Oklahoma	2,620	16,455	37,715	1,918	6,784	45,858	114,866	12,189	59	399	1,000	106
Oregon	30,472	43,843	44,759	43,578	86,110	181,557	287,457	443,600	749	1,581	2,504	3,867
Pennsylvania	88	11,319	32,173	225	211	28,880	93,235	1,413	2	251	811	12
South Carolina		2,005	13,294			4,714	35,928			41	313	
South Dakota	3,918	11,448	34,132	4,443	10,316	34,397	108,557	30,969	90	299	945	270
Tennessee		109	6,845			256	17,092			2	149	
Texas	93,845	131,804	181,068	97,346	262,513	491,590	814,612	790,863	2,284	4,280	7,094	6,894
Utah	26,253	37,981	48,008	30,442	75,955	154,313	267,574	335,214	661	1,344	2,331	2,922
Vermont			413				992				9	
Virginia	2	1,307	7,832	22	5	3,351	21,089	134	0	29	183	1
Washington	9,919	36,938	38,075	36,603	24,120	124,391	190,888	280,553	210	1,083	1,663	2,446
West Virginia	3,291	12,269	18,094	5,894	8,440	38,850	68,507	42,068	73	338	596	367
Wisconsin		301	9,135			706	23,642			6	206	
Wyoming	6,567	35,475	78,178	5,497	17,736	97,826	244,173	36,723	154	851	2,125	320

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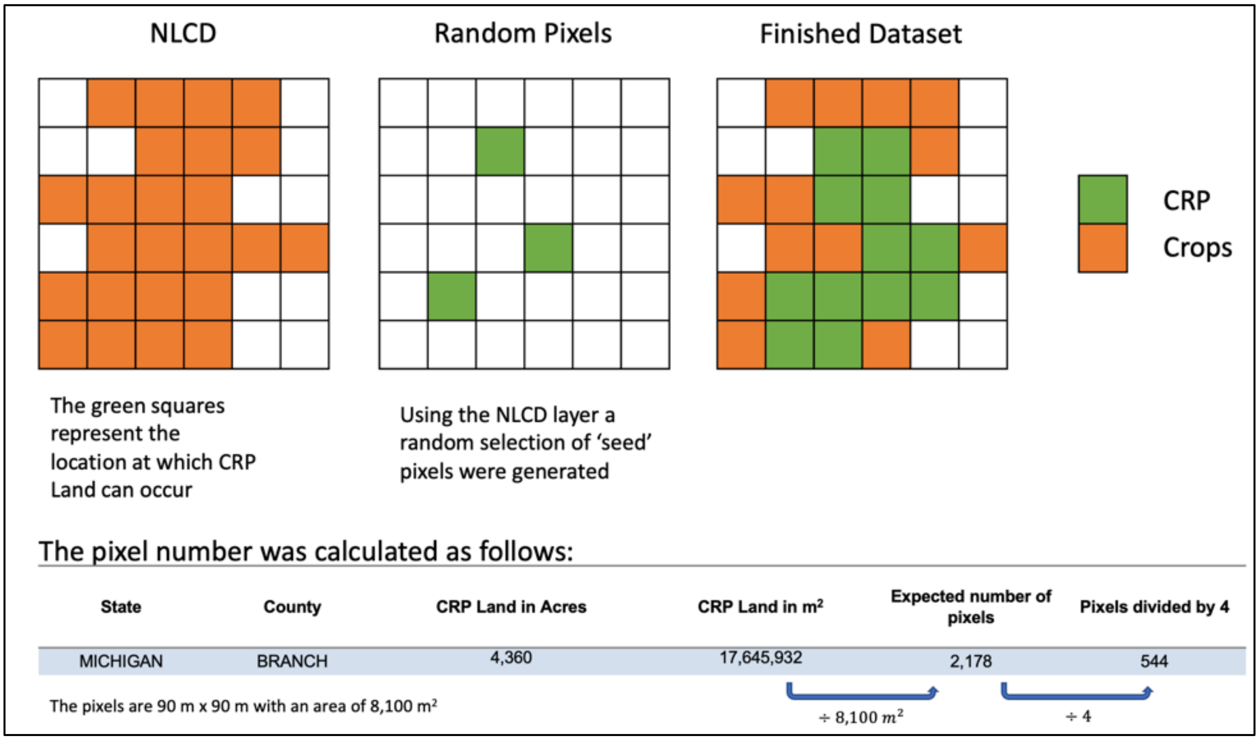
Appendix. Additional Details

A.1 Conservation Reserve Program Lands

The Conservation Reserve Program (CRP) is a land conservation program administered by the Farm Service Agency of the United States Department of Agriculture. This program allows agricultural land to be used to demarcate sensitive ecological land for *conservation* rather than agricultural use. Although the CRP publishes the total area of land by county, they do not publish the specific geographic location of the conserved land (because of privacy concerns). Therefore, a method for downscaling county-level data to a reV-compliant format was created. The intention was to capture the rough magnitude of lands that should be excluded from solar PV development on a per-county basis.

Hypothetical CRP land for our study was calculated based only in croplands as identified by the 2016 National Land Cover Database. It was assumed that the land set aside for CRP efforts is a small percentage of a landowner's land. Therefore, efforts were made to create many smaller areas rather than a few large areas. Each county was assigned several random seeds that were proportional to the target CRP area (see Figure A-1). The equation used was the total CRP land in square meters converted to 90-m^2 pixels and then divided by 4. These seeds were distributed randomly across the county's crop area, and then each seed pixel was expanded to encapsulate a 4-by-4-pixel area.



The green squares represent the location at which CRP Land can occur

Using the NLCD layer a random selection of 'seed' pixels were generated

The pixel number was calculated as follows:

State	County	CRP Land in Acres	CRP Land in m^2	Expected number of pixels	Pixels divided by 4
MICHIGAN	BRANCH	4,360	17,645,932	2,178	544

The pixels are 90 m x 90 m with an area of 8,100 m^2

Figure A-1. Process of creating synthetic Conservation Reserve Program lands

A.2 Airport and Heliport Setbacks

Accurately capturing airport airspace height constraints is site specific and requires aeronautical expertise with access and understanding to the following (not a comprehensive list):

- Digital-terminal procedures publication / airport diagrams (terminal procedures search)
- Minimum climb gradient and maneuvering airspace for engine failures
- Minimum sector altitudes, minimum safe altitudes, minimum crossing Height Altitudes
- Minimum vectoring altitude and minimum instrument flight rule altitude charts
- Visual flight rules raster charts (multiple charts exist and are typically accessed by flight expected in an area or region)
- Gross weight adjustment areas (emergency fuel dump)
- National Airspace System airspace classes (classes A-G and special airspace requirements).

Classifying airspace height limits for the United States with site-specific precision was not feasible for this assessment. However, there still was a need to quantify the amount of wind resource that may be impacted by Federal Aviation Administration height restrictions because of proximity to airports. As a first-order quantification of this potential impact, we used 14 CFR Part 77.9 as a guide to create proximity buffers from airports and heliports. It defines the following Federal Aviation Administration notice criteria that we used to create runway buffers and that intersect with the wind supply curve:

- **77.9 B.1:** Number of runways >3,200 feet (ft) long: 7,202
  100 to 1 for a horizontal distance of 20,000 ft from nearest point of nearest runway
- **77.9 B.2:** Number of runways <3,200 ft long: 16,894
  50 to 1 for a horizontal distance of 10,000 feet from nearest point of nearest runway
- **77.9 B.3:** Number of heliports: 5,576
  25 to 1 for a horizontal distance of 5,000 ft from nearest point of nearest landing and take-off area of each heliport.

A.3 Big Game

We used the spatial layers from the *USGS Ungulate Migrations of the Western United States*, Volumes 1–3 (Kauffman et al. 2020; Kauffman, Lowrey, Beck, et al. 2022; Kauffman, Lowrey, Berg, et al. 2022), which characterize big game migration. Data were grouped by herd and type (e.g., “winter range,” “route,” “stopover,” “corridor,” and “annual range”). We left all data types unmodified except for the route type. This data type was originally represented as lines, but we applied a 300-m buffer to account for movement uncertainties, based on discussion with a subject matter expert, Hall Sawyer of Western EcoSystem Technologies.

We did not exclude big game migration or seasonal range data, but rather we applied a reduced capacity density of 21.5 MW/km^2 (as opposed to the standard 43 MW/km^2) in all areas where big game migration data were present. Doing so enabled utility-scale PV development in big game habitat but allowed for array designs/plant layouts that maintain connectivity between key habitats.

A.4 Transmission Cultural Risk Model Details

The cultural risk and constraint layer was created by combining seven sources. Every layer was reclassified to represent the relative sensitivity for cultural resources, including estimates of both potential physical and visual effects. The following details present the steps SWCA took to create the layer.

Table A-1. Cultural Risk Model Input Datasets

Data Layers	Data Source
Digital elevation models	Esri
National Land Cover Database (NLCD)	U.S. Geological Survey (USGS)
National Register of Historic Places (NRHP) **Historic American Building Survey** **Historic American Engineering Record** **Historic American Landscapes Survey**	National Park Service (NPS)
NPS Boundaries-National Historic Trails	NPS
Protected Areas Database of the United States (PAD-US)	Conservation Biology Institute (CBI)
Transmission Line Data	Homeland Infrastructure Foundation-Level Data
U.S. Historic Sites	Esri

Digital Elevation Models: To derive slope, we used elevation data, which are ubiquitously used in cultural models. Elevation is typically one of the more significant factors in prehistoric and historic site placement because of the basic requirements of a stable surface for habitation and ease of movement. In contrast, some site types, such as rock art sites, rock shelters, and shrines, are located on very steep slopes and vertical cliff faces. Acknowledging that such significant resources can be associated with steep slopes, there remains value in considering—on a CONUS-scale analysis—that steep slopes are less likely to contain significant cultural resources than gentle slopes. To account for slope regarding general cultural sensitivity, slopes more than 30% grade were assigned to Level 1, and slopes less than 30 degrees were assigned to Level 2. Significant resources listed in the NRHP or are associated with otherwise protected areas (e.g., national monuments) were identified as more sensitive Levels 3 or 4 using NRHP and PAD-US data.

National Land Cover Database: The NLCD is used to approximate the likelihood that surface-associated archaeological material retains integrity of location. This contrasts with archaeological and architectural sites in certain ways. For example, the NLCD type called Developed, High Intensity may have a high likelihood of containing significant historical architectural resources and a low likelihood of containing significant surface-associated prehistoric archaeological material. This is not to suggest that archaeological material is not present beneath urban surfaces but that the archaeological material is likely unobservable and uninterpretable from the surface horizon. Developed areas unlikely to contain observable archaeological resources resulting from surface modifications were assigned to Level 1. Where other information was present to suggest significant historical buildings, structures, objects, or landscapes were present, these were identified through the NRHP and associated datasets.

National Register of Historic Places: The NRHP geospatial datasets contain center points of NRHP-listed locations, as well as Historic American Buildings Survey, Historic American Engineering Record, and Historic American Landscapes Survey locations, but it does not include sites whose location remains confidential because of sensitivity in disclosing site locations to the public. Still, the dataset contains most NRHP-listed sites in the CONUS, and these locations are buffered by 0.5 mile and assigned to Level 3 to provide an approximation of areas both physically and visually sensitive to transmission line developments. Of note, the integrity of some NRHP-listed resources may not be affected by visual impacts within 0.5 mile, whereas others may be affected by visual impacts at much greater distances. The 0.5-mile buffer is chosen as a compromise to indicate impacts may be likely within that area. Polygons are also present in the NRHP geospatial data, but a review of that dataset indicates those polygons are unreliable. For the actual footprints of NRHP locations where physical impacts are of primary concern, the USA Historic Sites data were used (discussed later).

Protected Areas Database of the United States: This dataset contains polygonal footprints of variously designated lands and places that allow for the identification of low- to high-risk areas (Levels 2–4). Given the nature of the attributes of this dataset, it is not used to identify Level 1 areas that are compatible with or encourage transmission development. In general, BLM and private lands are not assigned cultural risk levels, unless other information indicates some level of sensitivity. Level 2 is assigned to U.S. Forest Service land, Areas of Critical Environmental Concern, and state and national parks where cultural resources are not the primary protected resource. Archaeological or historic areas identified in PAD-US are assigned to Level 3. This includes state and national historic trails, landmarks, parks, sites, memorials, and other sites. Level 4 is limited to wilderness areas where there is compelling reason to suggest the land is incompatible with transmission line development.

Transmission Line Data: Transmission rights-of-way are modeled using a 0.1-mile buffer on the nationwide transmission line dataset. These buffers are assigned to Level 1, with the assumption that these areas are generally compatible with additional transmission line developments.

U.S. Historic Sites: This dataset is similar to PAD-US at certain locations, but it contains polygons representing historic sites not depicted in PAD-US. The dataset is a compilation of national historic parks, sites, trails, and preserves, as well as sites held in state and local trusts, and it represents the most accurate footprint for such areas. These were assigned to Level 4, given their accurate location and their designation specifically as historically significant sites. Though this dataset contains accurate boundaries of land of historical significance, it does not contain all NRHP site locations, and it complements both the NRHP and the PAD-US datasets.

In summary, cultural risk Level 1 areas can be summarized as those established transmission rights-of-way, designated corridors, developed areas, and steep slopes unlikely to contain significant cultural resources. Level 2 areas are those areas lacking specific restrictions in PAD-US, along with undeveloped or minimally developed or tilled land and slopes with a grade of less than 30%. Level 3 areas are those identified as PAD-US protected areas, national monuments, areas within 0.5 mile of national historic trails, or other NRHP, Historic American Engineering Record, Historic American Buildings Survey, and Historic American Landscapes Survey locations. Level 4 areas are limited to those specifically identified as wilderness areas or those historically significant in the PAD-US and U.S. Historic Sites.

A.5 Transmission Natural Risk Model Details

The environmental risk and constraint layer was created by combining the spatial layers documented in Table A-2.

Table A-2. Environmental Risk Model Input Datasets

Risk Class	WECC Area Type	Designation Authority	Administering Agency	Data Layers
1	Area Following Existing Linear Corridor	Federal Highway Administration	Federal Highway Administration	USA Railroads; Transmission Line Data; USA Major Highways
1	Designated Federal Energy Corridor	BLM	BLM	Easements and Right-of-Way
2	Area Following Existing Linear Corridor	Federal Railroad Administration	Federal Railroad Administration	USA Railroads; Transmission Line Data; USA Major Highways
2	Scenic Highway, Scenic Byway, and All-American Roads	Federal Highway Administration	Federal Highway Administration	America's Byways
2	Agricultural land (excluding prime farmland)	State Agency	Local government	National Land Cover Database (NLCD)
2	Areas that contain ecosystems or species at moderate risk	NatureServe	N/A	Natural Heritage Program Species Occurrence Program, Multi-Jurisdictional Database of Species Occurrence
2	Areas that contain ecosystems or species at moderate risk	NatureServe	N/A	Landscape Conditions
2	Greater sage-grouse general habitat management areas	BLM	Varies by state	Greater Sage Grouse
2	Conservation easements for "recreation" or "education"	Various	N/A	Conservation Easements

Risk Class	WECC Area Type	Designation Authority	Administering Agency	Data Layers
	purposes and for those “unknown purposes”			
2	U.S. Army Corps of Engineers (USACE) land	USACE	USACE	Protected Areas Database of the United States, PAD-US (CBI Edition)
2	Flood zones	FEMA	Applicable local government	National Flood Hazard Layer Database
2	Important Bird Areas	National Audubon Society	N/A	Important Bird Areas
2	National historic trails and other national trails	Statutory	BLM, NPS, USFWS	NPS boundaries - National Historic Trails
2	Native Allotment	Tribes/Bureau of Indian Affairs (BIA)	Tribes/BIA	Protected Areas Database of the United States, PAD-US (CBI Edition)
2	Other land administered by U.S. federal agencies	BLM, USFWS, USBOR, BIA, DOD	BLM, USFWS, USBOR, BIA, DOD	Protected Areas Database of the United States, PAD-US (CBI Edition)
2	Other private nonprofit land	N/A	N/A	Protected Areas Database of the United States, PAD-US (CBI Edition)
2	Other public land	N/A	N/A	Protected Areas Database of the United States, PAD-US (CBI Edition)
2	Other water district land	Various	Various	Protected Areas Database of the United States, PAD-US (CBI Edition)
2	Private land-unknown restrictions	N/A	N/A	Protected Areas Database of the United States, PAD-US (CBI Edition)
2	Private land restricted for development	N/A	N/A	Protected Areas Database of the United States, PAD-US (CBI Edition)
2	Private university land	N/A	N/A	Protected Areas Database of the

Risk Class	WECC Area Type	Designation Authority	Administering Agency	Data Layers
				United States, PAD-US (CBI Edition)
2	Urban fringe area	U.S. Census Bureau	N/A	Census Urban Areas Boundary
2	USDA Agricultural Research Center land	USDA	USDA	Protected Areas Database of the United States, PAD-US (CBI Edition)
2	USDA experimental range	USDA	USDA	Protected Areas Database of the United States, PAD-US (CBI Edition)
2	Wetlands	U.S. Fish & Wildlife Services (USFWS, National Wetlands Inventory), USACE	USACE, EPA	National Wetlands Inventory
2	American Indian/Native American Reservation	Statutory	Tribes/BIA	Protected Areas Database of the United States, PAD-US (CBI Edition)
3	Area of critical environmental concern	BLM	BLM	Protected Areas Database of the United States, PAD-US (CBI Edition)
3	Areas with irreplaceable natural or cultural resources	NatureServe	N/A	National Heritage Program Species Occurrence Data, Multi-Jurisdictional Database of Species Occurrence
3	Greater sage-grouse priority habitat management area	BLM	Varies by state	Greater Sage Grouse
3	Conservation easements for “environmental system,” “historic preservation,” “open space” purposes	Various federal agencies	Various federal agencies	Easements
3	Critical habitat	USFWS, National Oceanic and Atmospheric	USFWS, NOAA, NMFS	Critical Habitat for Threatened and Endangered

Risk Class	WECC Area Type	Designation Authority	Administering Agency	Data Layers
		Administration (NOAA), National Marine Fisheries Service (NMFS)		Species Composite Layer
3	Military range/installation	Statutory	DOD	Protected Areas Database of the United States, PAD-US (CBI Edition)
3	Research natural area	BLM, NPS, USFS, and USFWS	BLM, NPS, USFS, and USFWS	Protected Areas Database of the United States, PAD-US (CBI Edition)
3	Research natural area—proposed	BLM, NPS, USFS, and USFWS	BLM, NPS, USFS, and USFWS	Protected Areas Database of the United States, PAD-US (CBI Edition)
3	Special interest area	USFS	USFS	Protected Areas Database of the United States, PAD-US (CBI Edition)
3	State forest	Applicable state legislation	Applicable state agency	Protected Areas Database of the US, PAD-US (CBI Edition)
3	State park or state conservation area	Applicable state legislation	Applicable state agency	Protected Areas Database of the United States, PAD-US (CBI Edition)
3	State wildlife area	State	State	Protected Areas Database of the United States, PAD-US (CBI Edition)
3	USFS roadless area	USFS	USFS	National Inventoried Roadless Areas
3	Wild and Scenic River, National Rivers, and Wild and Scenic Riverways	Statutory	NPS, BLM, USFS	Wild and Scenic Rivers
4	National conservation area	Statutory	BLM	Protected Areas Database of the United States, PAD-US (CBI Edition)
4	National monument	Presidential Proclamation	BLM	Protected Areas Database of the United States, PAD-US (CBI Edition)

Risk Class	WECC Area Type	Designation Authority	Administering Agency	Data Layers
4	National recreation area	Statutory	BLM, NPS, USFWS	Protected Areas Database of the United States, PAD-US (CBI Edition)
4	National primitive area	USFS	USFS	Protected Areas Database of the United States, PAD-US (CBI Edition)
4	National wildlife refuge	USFWS	USFWS	Protected Areas Database of the United States, PAD-US (CBI Edition)
4	Units of the National Parks System (excluding National Recreation Areas and National Trails)	Statutory	NPS	Protected Areas Database of the United States, PAD-US (CBI Edition)
4	Wilderness area	Statutory	NPS	Protected Areas Database of the United States, PAD-US (CBI Edition)
4	Wilderness area (recommended)	USFS, BLM, NPS	USFS, BLM, NPS	Protected Areas Database of the United States, PAD-US (CBI Edition)
4	Wilderness study area	BLM, USFS	BLM, USFS	Protected Areas Database of the United States, PAD-US (CBI Edition)
4	Special management area (including wildlife management areas on federal land)	BLM, USFS	BLM, USFS	Protected Areas Database of the United States, PAD-US (CBI Edition)
4	National conservation area	Statutory	BLM	Protected Areas Database of the United States, PAD-US (CBI Edition)
4	National monument	Presidential Proclamation	BLM	Protected Areas Database of the United States, PAD-US (CBI Edition)
4	National recreation area	Statutory	BLM, NPS, USFWS	Protected Areas Database of the United States, PAD-US (CBI Edition)

Risk Class	WECC Area Type	Designation Authority	Administering Agency	Data Layers

BLM = Bureau of Land Management; EPA = Environmental Protection Agency; FEMA = Federal Emergency Management Agency; NMFS = National Marine Fisheries Service; NPS = National Park Service; USBOR = U.S. Bureau of Reclamation; DOD = U.S. Department of Defense; USFS = U.S. Forest Service; USFWS = U.S. Fish & Wildlife Services; WECC = Western Electricity Coordinating Council.

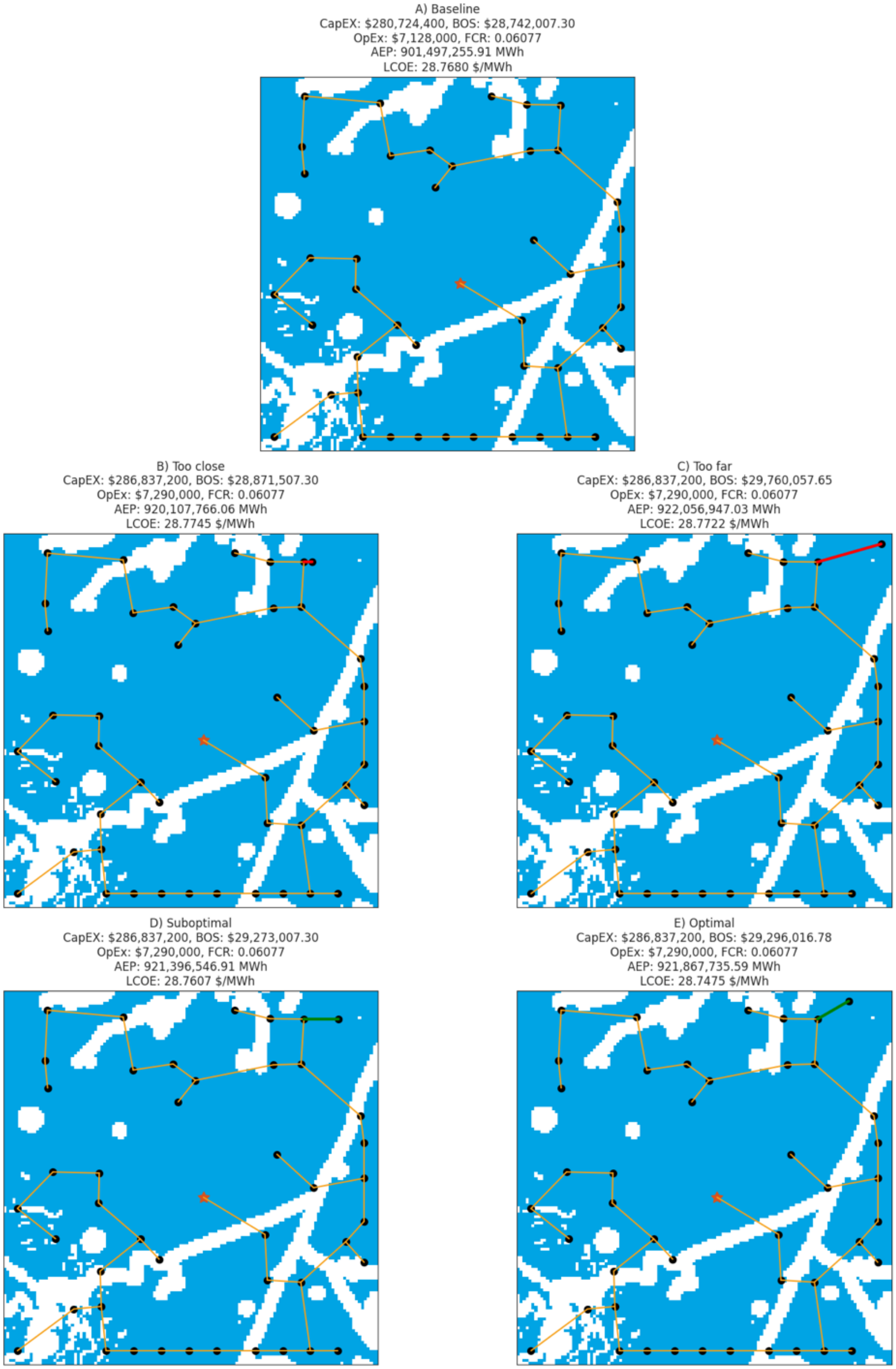
A.6 Radar Line-of-Sight

The U.S. Department of Defense and NEXRAD radar station locations are provided by the North American Aerospace Defense Command (NORAD). These locations were used to create line-of-sight exclusion polygons to represent plausible areas where radars may become saturated with too many wind turbines. To create the polygons, we used the Open-Source software, QGIS, and the Visibility Analysis plug-in with the following input parameters:

- **Radius**: Maximum distance of visibility testing (100,000 m)
- **Observer height**: Height of the observer (15 m)
- **Target height**: Value to be added to all terrain areas checked for visibility from the observer point (152.4 m).

A.7 SROM BOS Function

The newly added SROM BOS cost function does not reduce the number of turbines the model places. Rather, it regulates the spacing between turbines, adding a penalty for placing individual turbines too far apart. Figure A-2 demonstrates the effect of the BOS cost when adding a new turbine. The initial layout is shown in panel A, along with metrics such as the starting BOS cost, the annual energy production, and the resulting LCOE. Panel B demonstrates the case of adding a new turbine too close to an existing turbine location. In this case, wake losses dominate, and the resulting LCOE value is higher than the initial case. In panel C, the new turbine is placed too far away from an existing turbine location, so the BOS contribution drives the LCOE up too much. Note that older versions of the SROM would have preferred this placement, as it does reduce wake losses drastically (largest total annual energy production of all panels shown). Panels D and E both show potential locations for the new turbine that decrease the total LCOE compared with the original layout shown in panel A.



A) Baseline
CapEX: $280,724,400, BOS: $28,742,007.30
OpEx: $7,128,000, FCR: 0.06077
AEP: 901,497,255.91 MWh
LCOE: 28.7680 $/MWh

B) Too close
CapEX: $286,837,200, BOS: $28,871,507.30
OpEx: $7,290,000, FCR: 0.06077
AEP: 920,107,766.06 MWh
LCOE: 28.7745 $/MWh

C) Too far
CapEX: $286,837,200, BOS: $29,760,057.65
OpEx: $7,290,000, FCR: 0.06077
AEP: 922,056,947.03 MWh
LCOE: 28.7722 $/MWh

D) Suboptimal
CapEX: $286,837,200, BOS: $29,273,007.30
OpEx: $7,290,000, FCR: 0.06077
AEP: 921,396,546.91 MWh
LCOE: 28.7607 $/MWh

E) Optimal
CapEX: $286,837,200, BOS: $29,296,016.78
OpEx: $7,290,000, FCR: 0.06077
AEP: 921,867,735.59 MWh
LCOE: 28.7475 $/MWh

Figure A-2. Conceptual process of estimating spatial BOS costs