Solar Photovoltaics and Land-Based Wind Technical Potential and Supply Curves for the Contiguous United States: 2023 Edition

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National Renewable Energy Laboratory

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NOTICE

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List of Abbreviations and Acronyms

ATB	Annual Technology Baseline
BIA	Bureau of Indian Affairs
BLM	Bureau of Land Management
CAISO	California Independent System Operator
CBI	Conservation Biology Institute
CONUS	contiguous United States
EERE	Energy Efficiency and Renewable Energy
EPA	Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas
FEMA	Federal Emergency Management Agency
ft	feet
GAP	Gap Analysis Project
GSTC	Geospatial Service and Technology Center
GW	gigawatts
HIFLD	Homeland Infrastructure Foundation-Level Data
HSIP	Homeland Security Infrastructure Program
IFR	instrument flight rule
INL	Idaho National Laboratory
km	kilometers
LANL	Los Alamos National Laboratory
LCOE	levelized cost of energy
m	meters
MIA	minimum IFR instrument flight rule) altitude
MISO	Midcontinent Independent System Operator
MVA	minimum vectoring altitude
MWh	megawatt-hour
NCED	National Conservation Easement Database
NEXRAD	Next Generation Weather Radar
NGA	National Geospatial-Intelligence Agency
NLCD	National Land Cover Database
NMFS	National Marine Fisheries Service
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 Data Base
NYISO	New York Independent System Operator
ORNL	Oak Ridge National Laboratory
PALD	Protected Agricultural Lands Database
PV	photovoltaics
RAIMORA	risk of adverse impact on military operations and readiness areas
ReEDS	Regional Energy Deployment System
reV	Renewable Energy Potential model
SAM	Systems Advisor Model
SCE	Southern California Edison

SPP	Southwest Power Pool
TEPPC	Transmission Expansion Planning Policy Committee
USACE	U.S. Army Corps of Engineers
USBOR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USDOD	U.S. Department of Defense
USFS	U.S. Forest Service
USFWS	U.S. Fish & Wildlife Services
USGS	U.S. Geological Survey
WECC	Western Electricity Coordinating Council
WIND	Wind Integration National Dataset
yr	year

Executive Summary

Estimates of the potential of renewable energy are essential for understanding how we can decarbonize our electric grid and economy. They provide key data for policymakers, land managers, and energy modelers 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 uncertainty about developable land that are due to 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, the 2023 edition of this report, we present new estimates of the technical potential for land-based wind and 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. Additionally, we introduce new methodologies used to estimate wind capacity, wind energy losses, transmission cost and representation, updated technology cost and design, and scenarios of siting constraints designed to help bound the uncertainty of renewable potential.

Our results 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 the report.

Table ES-1. Developable Area, Capacity, and Multiyear Annual Mean Uncurtailed Generation Estimates for the CONUS. Solar capacity is DC and solar generation is AC.

Technology	Siting Scenario	Developable Area (km^2)	Capacity (GW)	Generation (TWh)
Land-Based Wind	Open Access	5,962,316	15,040	50,203
	Reference Access	1,923,113	11,120	38,037
	Limited Access	800,013	5,944	20,136
Solar PV	Open Access	6,178,337	265,668	476,015
	Reference Access	2,613,976	112,401	207,752
	Limited Access	1,342,439	57,724	109,045

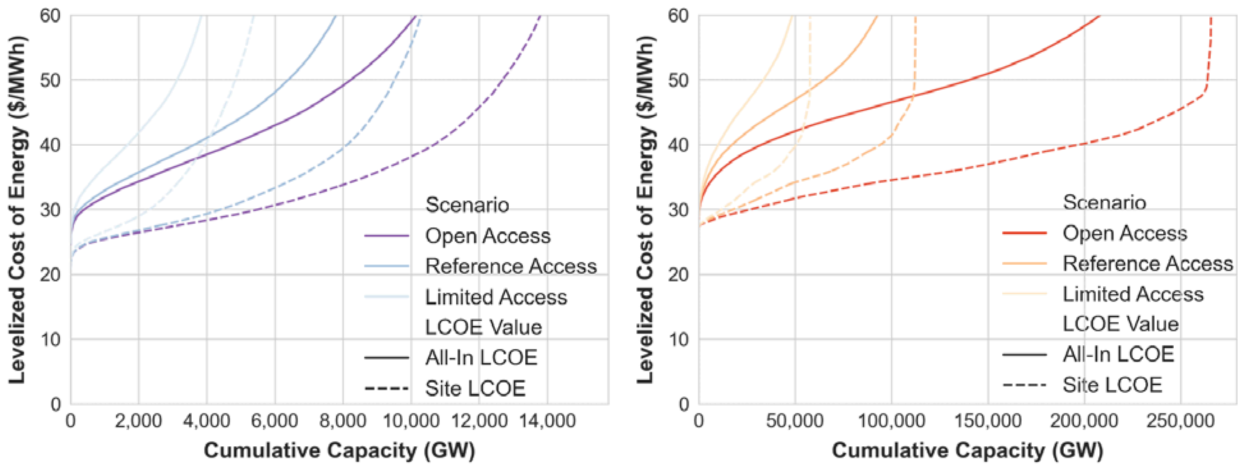

Figure ES-1. Levelized cost of energy ($/MWh) as a function of cumulative capacity (GW) for land-based wind (left) and solar PV (right)

Graphs are limited to resources under $60/MWh.

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1 Introduction

Estimates of the potential of renewable energy are essential for understanding how we can decarbonize our electric grid and economy. They provide key data for policymakers, land managers, and energy modelers 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 uncertainty about developable land that are due to 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 study, we present new estimates of the technical potential for land-based wind 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. Additionally, we introduce new methodologies used to estimate wind capacity, wind energy losses, transmission cost and representation, updated technology cost and design, and scenarios of siting constraints designed to help bound the uncertainty of renewable potential.

2 Methods and Modeling Framework

We use the Renewable Energy Potential (reV) model (version 0.7.3) to conduct our analysis (Maclaurin et al. 2019). Most of our modeling framework is the same as the one published by Maclaurin et al., but we make 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 ≈67,000 11.5-km x 11.5-km candidate solar and wind sites. The four primary components of data and assumptions we use to estimate resource potential are:

- Resources (wind speed and irradiance)
- 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 data set of half-hourly solar irradiance with ancillary meteorological information at a 4-km spatial resolution. It spans the CONUS for over 20 years (1998–2022). Land-based wind resource is represented using the 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 data sets, we sample the resource at hourly intervals, specifically at on-the-hour times. Because both the NSRDB and WIND Toolkit data sets provide instantaneous estimates of resources, we use the hour value as the index.

2.2 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. 2018). For this study, we use 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). Therefore, we leverage the 2023 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 2023).

For this study, we use the ATB technology and cost assumptions representative of the "Market Financial Case", a capital recovery period of 30 years, and costs from the year 2030. Solar PV assumptions are presented in Table 1 and wind assumptions are presented in Table 2.

Table 1. Solar PV Characteristics Used in Supply Curves

Solar PV Characteristic	ATB Moderate Case
PV array nameplate (MW)	1
PV array type	1-axis tracking
Tilt (degrees)	0
Losses (%)	10.4
Inverter loading ratio	1.34
Capacity density (MWdc/km^2)	43
Capital expenditures (2021$/kWac)	1,042
Fixed operational expenditures (2021$/kWac/yr)	18.4
Fixed charge rate	0.06778

Table 2. Wind Technology Characteristics Used in Supply Curves

Wind Turbine Characteristic	ATB Moderate Case
Turbine nameplate (MW)	6
Rotor-diameter (m)	170
Hub-height (m)	115
Losses (%)[a]	Endogenous
Capacity density (MW/km^2)[b]	Endogenous
Capital expenditures (2021$/kW)[c]	1,150
Fixed operational expenditures (2021$/kW)	27
Fixed charge rate	0.080373

[a] We use a static loss rate of 10.4%, and intra-power plant wake losses are determined endogenously and range from 0.05% to 25%.

[b] Capacity density is endogenous. We calculate two forms of capacity density based on the results. Included area capacity density has a median of 7 MW/km^2 and the convex hull capacity density has a median of 3 MW/km^2. See Lopez et al. (2023) for details about capacity density.

[c] The ATB assumes $1,150/kW for a 200-MW wind power plant. We apply an economies-of-scale cost curve in our siting optimization that has capital expenditures ranging from $1,029/kW to 2,360/kW depending on the number of turbines sited.

Solar PV losses are applied via fixed losses, which reduce 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 are applied by multiplying the solar generation profile by a factor of 0.896. SAM performs this calculation internally, and reV reports the result.

Wind generation losses are implemented via a transformation of the turbine power curve. Unlike haircut losses, this transformation decreases the power generated non-uniformly across the power curve wind speeds. reV offers several different power curve transformation options, all of which are described in detail in the reV documentations. For this study, we apply 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 1).

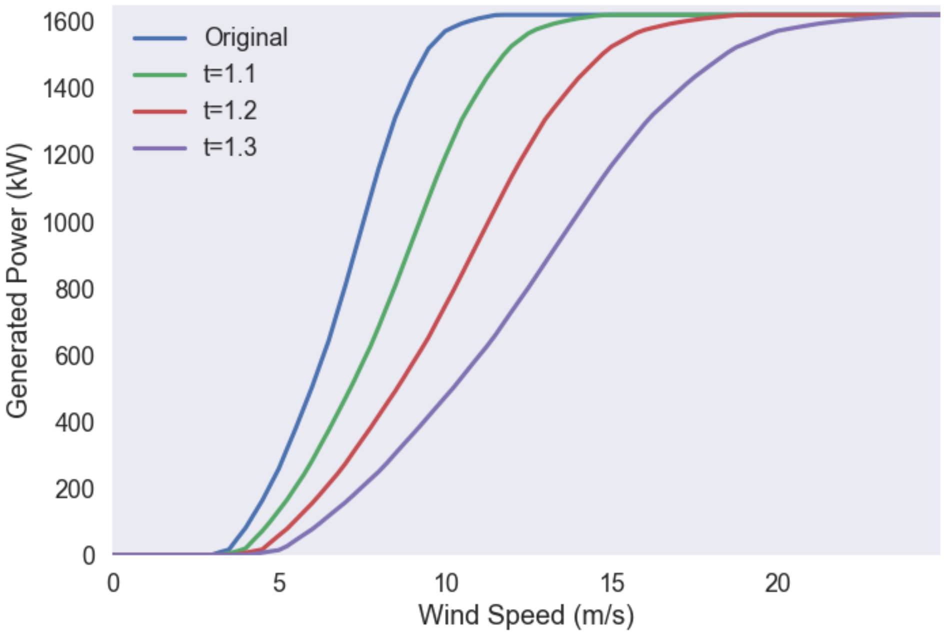

Figure 1. Power curve loss transformations of varying strengths.

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

Notably, the transformed power curve still reaches rated power at high wind speeds, which is not possible with simple haircut losses. Figure 2 illustrates this point by comparing the original power curve with both the transformed power curve and the power curve with haircut losses for a sample site with a 20% loss target. Note that the transformed power curve produces less power than the haircut loss power curve for wind speeds under ~9.5 m/s and does not reach rated power until ~13 m/s. This reduction in generation accounts for the 20% total annual losses at the site. The hourly generation profile is similarly affected, yielding less power than the haircut loss profile in some cases. However, the transformed power curve profile still reaches rated power at high wind speeds (Figure 3) which is a significant improvement over the haircut loss approach, especially for downstream modeling efforts.

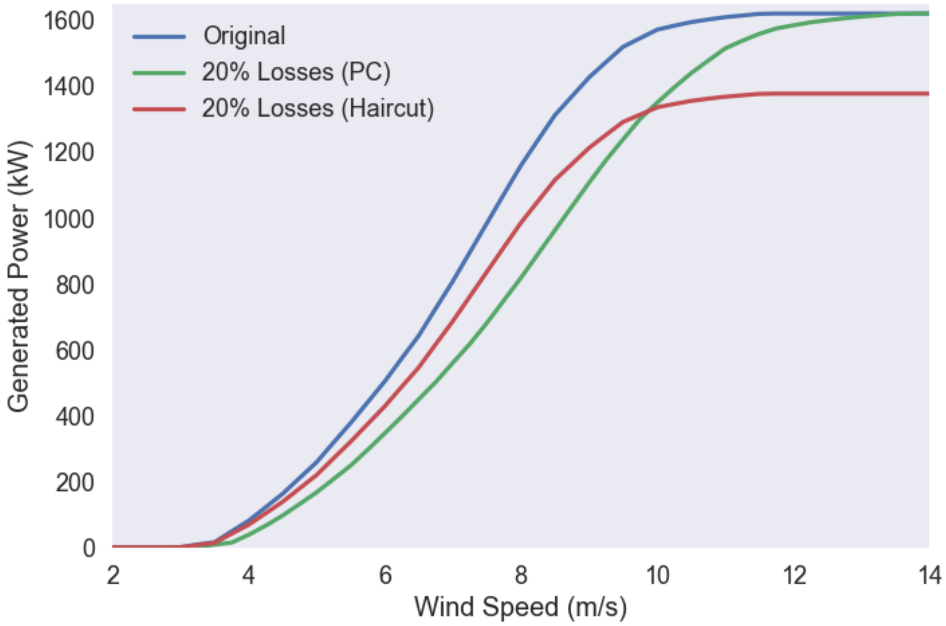

Figure 2. Example of power curve loss transformation.

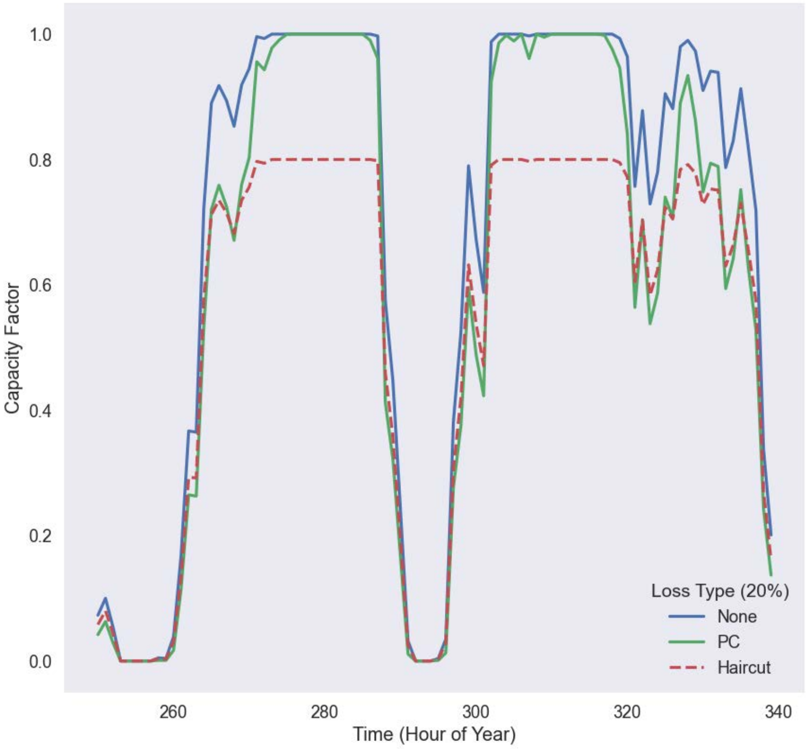

Figure 3. Sample generation output for various loss methods.

2.3 Siting Constraints and Considerations

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

To capture the uncertainty associated with siting criteria, we use a scenario-based approach introduced by Lopez et al. (2021). Specifically, we use three scenarios: Open Access, Reference Access, and Limited Access that 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 or excluding 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 apply solar PV and wind regulations from wind and solar ordinances databases (Lopez et al. 2023). These regulations are grouped and categorized by 50th and 90th percentiles. We apply the existing regulations as written in both the Reference and Limited scenarios. However, to capture possible restrictions based on the expansion of ordinances, we extrapolate them to the rest of the country. In the Reference scenario, we use the median of existing ordinances. In the Limited scenario, we use the 90th percentile of ordinances across the country.

The full suite of siting constraints by scenario is presented in Table 3 (page 8) for land-based wind and Table 4 (page 10) for solar PV.

To better capture the ability of wind turbines to be placed in complex environments, we use the spatial reduced order model methodology presented by Lopez et al. in 2023. The spatial reduced order model methodology uses an optimization routine to place individual turbines, considering the turbine configuration, the cost and losses associated with the wind farm, the wind resource at the site, and any restrictions 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 power that can be generated per unit area. However, the spatial reduced order model methodology calculates site-dependent capacity densities, which consider the cost of building and operating the wind farm and the amount of land available.

We updated our solar PV capacity density assumption to reflect recently published empirical deployment characteristics. Bolinger and Bolinger (2022) report a 0.24 $\mathrm{MW_{DC}}$/acre capacity density for a single-axis tracking panel. However, this only accounts for the array area and does not capture other PV system land use, such as service roads, inverters, fencing, etc. For the supply curves, we model total land-use requirements and thus need 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) as 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 obtain a density of 42.9 $\mathrm{MW_{DC}/km^2}$:

$$42.9\ \mathrm{MW_{DC}/km^2} = 0.24\ \mathrm{MW_{DC}/acre} * 247.105\ \mathrm{acres/km^2} * 6.3\ \mathrm{acres/MW_{AC}} / 8.7\ \mathrm{acres/MW_{AC}}$$

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

Table 3. Land-Based Wind Siting Constraints

"x" denotes where a layer is used to exclude land.

Category	Data Set	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 (9-km) and Next Generation Weather Radar (NEXRAD) radar setback (4-km)		x	x	Official-use-only communication with NORAD
Airspace/Defense	U.S. Department of Defense and NEXRAD radar line-of-sight exclusion			x	See Appendix A.5
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	x	x	x	(Department of Defense and ESRI2018)
Environmental	Bat Hibernacula		Priority 1, 2	Priority 1, 2, 3	(Diffendorfer et al., n.d.-a)
Environmental	Argonne National Laboratory and Bureau of Land Management (BLM) Wind Exclusions			x	(BLM, n.d.)
Environmental	National Land Cover Dataset Water, Woody/Herbaceous Wetlands	x	x	x	(U.S. Geological Survey 2021)
Environmental	Lesser Prairie Chicken core habitat			x	(Diffendorfer et al., n.d.-b)
Environmental	Greater Sage Grouse core habitat (BLM lands only)		x	x	(Diffendorfer et al., n.d.-b)
Environmental	Threatened and Endangered Species core habitat (BLM lands only)		x	x	(Diffendorfer et al., n.d.-c)
Environmental	United States Fish and 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	(BLM 2022)
Environmental	National Forest Service Inventoried Roadless Areas	x	x	x	(U.S. Forest Service, Geospatial Service and Technology Center 2001)

Category	Data Set	Open	Reference	Limited	Source
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 (USGS) Gap Analysis Project (GAP) 2022)
Infrastructure	Oil and gas well footprints (One well equals one 90-m x 90-m pixel.)	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] 2018)
Infrastructure	Transmission right-of-way	x	x	x	(Oak Ridge National Laboratory (ORNL) 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)
Infrastructure	Urbanized areas	x	x	x	(U.S. Census Bureau 2018)
Regulatory	Wind facility bans or moratoriums		x	x	(Lopez et al. 2022b)
Regulatory	Wind facility height limits (exceeding current turbine height assumption)		x	x	(Lopez et al. 2022b)
Regulatory	Oil and gas pipeline setback		220 m	400 m	(Lopez et al. 2022b)
Regulatory	Railroad setback		220 m	400 m	(Lopez et al. 2022b)
Regulatory	Road setback		220 m	400 m	(Lopez et al. 2022b)
Regulatory	Structure setback		400 m	1,000 m	(Lopez et al. 2022b)
Regulatory	Transmission setback		220 m	400 m	(Lopez et al. 2022b)
Regulatory	Water setback		220 m	400 m	(Lopez et al. 2022b)
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)

Table 4. Solar PV Siting Constraints

"x" denotes where a layer is used to exclude land.

Category	Data Set	Open	Reference	Limited	Source
Airspace/Defense	Intercontinental ballistic missile silo setback (3.7-km)		x	x	("ICBM Sites" 2019)
Environmental	National Land Cover Dataset Water, Woody/Herbaceous Wetlands	x	x	x	(U.S. Geological Survey 2021)
Environmental	Lesser Prairie Chicken core habitat			x	(Diffendorfer et al., n.d.-b)
Environmental	Greater Sage Grouse core habitat		x	x	(Diffendorfer et al., n.d.-b)
Environmental	Threatened and Endangered Species core habitat (federal lands only)		x	x	(Diffendorfer et al., n.d.-c)
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	x	x	x	(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)
Environmental	BLM Areas of Critical Environmental Concern	x	x	x	(BLM 2022)
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 (USGS) Gap Analysis Project (GAP) 2022)
Environmental	Big game migration corridors		x	x	(Kauffman et al. 2020; Kauffman, Lowrey, Beck, et al. 2022; Kauffman, Lowrey, Berg, et al. 2022)
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] 2018)

Category	Data Set	Open	Reference	Limited	Source
Infrastructure	Transmission right-of-way	x	x	x	(Oak Ridge National Laboratory (ORNL) 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)
Infrastructure	Urbanized areas				(U.S. Census Bureau 2018)
Regulatory	Solar existing bans or moratoriums		x	x	(Lopez et al. 2022a)
Regulatory	Oil and gas pipeline setback		30 m	76 m	(Lopez et al. 2022a)
Regulatory	Property line setback		15 m	46 m	(Lopez et al. 2022a)
Regulatory	Rail setback		30 m	76 m	(Lopez et al. 2022a)
Regulatory	Road setback		30 m	76 m	(Lopez et al. 2022a)
Regulatory	Building structure setback		61 m	152 m	(Lopez et al. 2022a)
Regulatory	Transmission setback		30 m	76 m	(Lopez et al. 2022a)
Regulatory	Water setback		30 m	76 m	(Lopez et al. 2022a)
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

2.4 Transmission Costs and Constraints

In this, the 2023 version of the supply curves, we made significant improvements to the methods and data used to estimate the transmission infrastructure required to connect new renewable energy projects to the electric grid.

Previously, Maclaurin et al. (2019) used the straight-line distance between a prospective site and existing electrical transmission to estimate the cost of a spur line and applied a single cost per MW-mile assumption. We introduce a least-cost-path methodology that considers the four components listed below. In addition, we introduce a new methodology for capturing network upgrade requirements as part of the total interconnection cost requirement.

- Siting constraints
- Regional component costs (hard costs)
- Land composition costs (soft costs)
- Point-of-interconnection (POI) costs
- Network upgrade costs.

We get our regional transmission costs from the Transmission Expansion Planning Policy Committee (TEPPC)[1], Southern California Edison (SCE)[2], the Midcontinent Independent System Operator (MISO)[3], 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), and NYISO (The New York Independent System Operator), do not have publicly available transmission costs. For those regions, we use the costs from another region, as shown in Table 5. Note that regional costs do not follow exact footprints of each independent service operator. We use regional component costs (Table 5) and land composition cost multipliers (Table 6 and Figure 4) to create 90-m x 90-m cost rasters for four voltage classes across the CONUS. These cost rasters reflect the cost to build transmission in each pixel for each line voltage rating.

Table 5. Regional Baseline Transmission Costs (2019$/mile)

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

Voltage	Prospective Site Capacity (MW)	TEPPC	SCE (CAISO, NYISO, ISONE, PJM)	MISO (SPP)	Southeast (ERCOT)
69	102	$984,000	$1,524,000	$1,255,000	$819,000
138	205	$1,180,000	$2,084,000	$1,446,000	$984,000
230	400	$1,570,000	$3,034,000	$1,695,000	$1,568,000
500	>1,500	$2,248,000	$4,777,000	$2,787,000	$4,056,000

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

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

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

Table 6. 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 then apply spatial constraints to the cost rasters, setting the cost to infinity in areas where development is prohibited. Spatial constraints for transmission siting were developed by SWCA Environmental Consultants. The siting constraints are grouped into four main categories representing the relative difficulty in siting transmission based on known environmental and cultural (archaeological and historical) resources. Maps of the transmission constraints are shown in Figure 2.

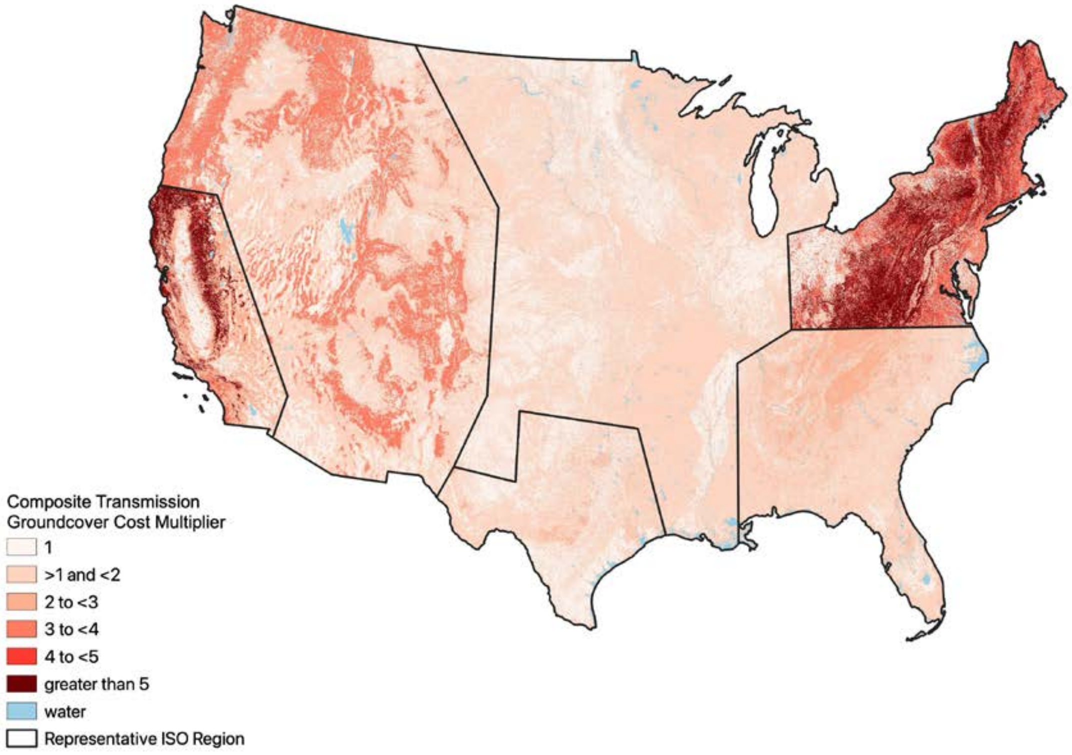
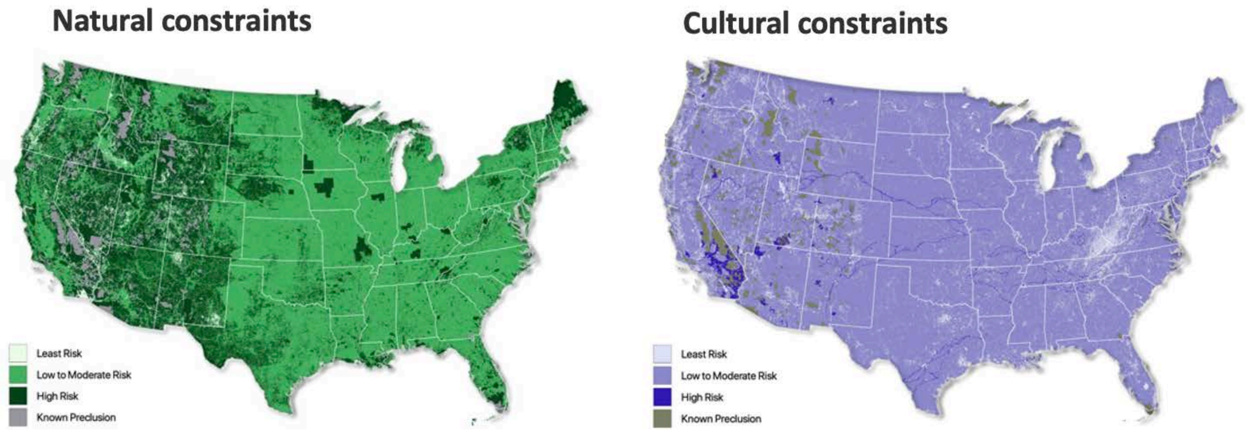


Figure 4. Regional transmission multipliers


Natural constraints

Cultural constraints

Figure 5. Transmission siting constraints: Natural constraints (left) and cultural constraints (right)

The cultural risk and constraint layer is created by combining seven sources (Table 7). Every layer is reclassified to represent the relative sensitivity for cultural resources, including estimates of both potential physical and visual effects. We detail the reclassification in Appendix A-4.

Table 7. Cultural Risk Model Input Data Sets

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
PAD-US	Conservation Biology Institute (CBI)
Transmission Line Data	Homeland Infrastructure Foundation-Level Data (HIFLD)
USA Historic Sites	ESRI

The environmental risk and constraint layer is created by combining the spatial layers documented in Table 8.

Table 8. Environmental Risk Model Input Data Sets

Acronyms are defined in the list of abbreviations and acronyms (page iv).

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 that are 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 that are 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” purposes and for those “unknown purposes”	Various	N/A	Conservation Easements
2	U.S. Army Corps of Engineers Land	USACE	USACE	Protected Areas Database of the United States, PAD-US (CBI Edition)

Risk Class	WECC Area Type	Designation Authority	Administering Agency	Data Layers
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/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, USDOD	BLM, USFWS, USBOR, BIA, USDOD	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-Unrestricted 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 United States, PAD-US (CBI Edition)
2	Urban Fringe Area	U.S. Census Bureau	N/A	Census Urban Areas Boundary

Risk Class	WECC Area Type	Designation Authority	Administering Agency	Data Layers
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	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, NOAA, NMFS	USFWS, NOAA, NMFS	Critical Habitat for Threatened and Endangered Species Composite Layer
3	Military Range/Installation	Statutory	USDOD	Protected Areas Database of the United States, PAD-US (CBI Edition)

Risk Class	WECC Area Type	Designation Authority	Administering Agency	Data Layers
3	National Conservation Area	Statutory	BLM	Protected Areas Database of the United States, PAD-US (CBI Edition)
3	National Monument	Presidential Proclamation	BLM	Protected Areas Database of the United States, PAD-US (CBI Edition)
3	National Recreation Area	Statutory	BLM, NPS, USFWS	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	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)
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

Risk Class	WECC Area Type	Designation Authority	Administering Agency	Data Layers
3	Wild and Scenic River, National Rivers and Wild and Scenic Riverways	Statutory	NPS, BLM, USFS	Wild and Scenic Rivers
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)

For each cost raster and each prospective solar or wind site (~67,000 11.5-km sites), we run 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. The list of possible connections is created by searching for substations within 300 miles, within the same state, limited to substations greater than 69 kV, and being equal to or greater than the spur-line voltage requirement. If the search returns no possible connections, the 300 mile constraint is relaxed. We then select the resulting line voltage and cost using the prospective site's voltage requirements that are based on the available capacity, as dictated by the siting constraints defined in Section 2.3. Substation upgrade costs (Table 9) are then added to the total line cost to represent a POI cost.

Table 9. Regional Substation Upgrade Costs (2019$)

Voltage	Prospective Site Capacity (MW)	TEPPC	SCE (CAISO, NYISO, ISONE, PJM)	MISO (SPP)	Southeast (ERCOT)
69	102	$1,352,000	$767,000	$1,100,000	$917,000
138	205	$2,198,000	$1,117,000	$1,600,000	$1,179,000
230	400	$5,500,000	$3,975,000	$2,200,000	$2,210,000
500	>1,500	$10,236,000	$9,665,000	$5,300,000	$8,340,000

To account for the broader infrastructure needs beyond the connecting electrical substation, we introduce 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 define 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). For these regions, the load centers are approximated as the largest population center in each region, and a few manual adjustments are made to them based on analyst's judgment of where the load center should be located for a region.[4]

For each connecting substation, we determine the shortest path along existing transmission lines to the nearest "load center." The shortest path may be to a neighboring balancing authority area but is restricted to within the same state. Network upgrade costs are estimated as 50% of the greenfield costs associated with each voltage class (Table 5, page 12).

A conceptual diagram of the transmission methodology and resulting topology is presented in Figure 3.

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[4] 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 6. Conceptual diagram of transmission routing

Source: Billy J. Roberts, National Renewable Energy Laboratory

3 Results

In this section, we present results from the study. We first show CONUS-wide results in Table 10 for each technology and siting regime. We then use maps and graphs to explore critical dimensions of the supply curve results. Finally, we present a state-level summary table of the results. For all results, we present solar capacity in DC and solar generation in AC.

Table 10. 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	5,962,316	15,040	50,203
Land-based Wind	Reference	1,923,113	11,120	38,037
Land-based Wind	Limited	800,013	5,944	20,136
Solar PV	Open	6,178,337	265,668	476,015
Solar PV	Reference	2,613,976	112,401	207,752
Solar PV	Limited	1,342,439	57,724	109,045

3.1 Capacity and Area

The developable area for wind (Figure 5) and solar (Figure 6) energy projects is determined by siting exclusions and varies depending on the specific siting regime. Assumptions about setbacks and developability on prime agricultural land are the primary drivers of available area for wind and solar respectively. Land-based wind capacity (Figure 7) is calculated using an optimization routine (described in Section 2.3, page 6), and solar PV capacity (Figure 8) is determined by multiplying the developable area by the assumed capacity density (43 MWdc/km^2).

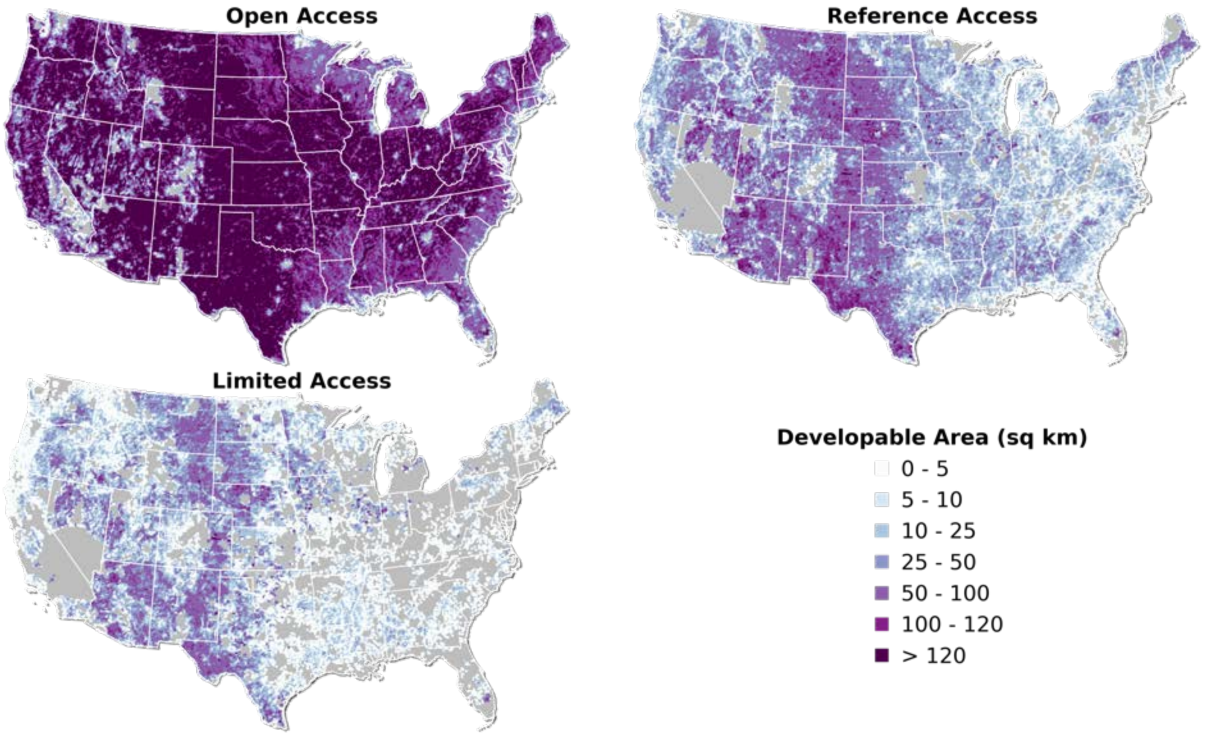

Figure 7. Developable area for land-based wind in Open, Reference, and Limited siting regimes

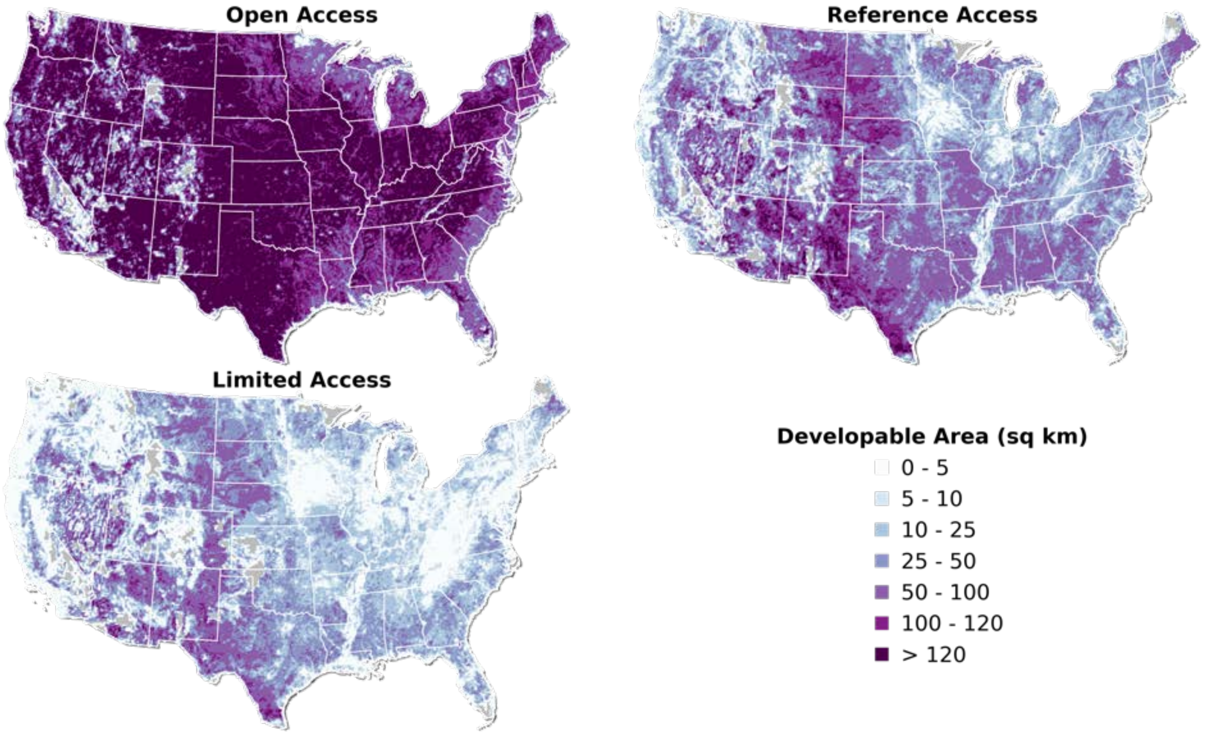

Figure 8. Developable area for solar PV in Open, Reference, and Limited siting regimes

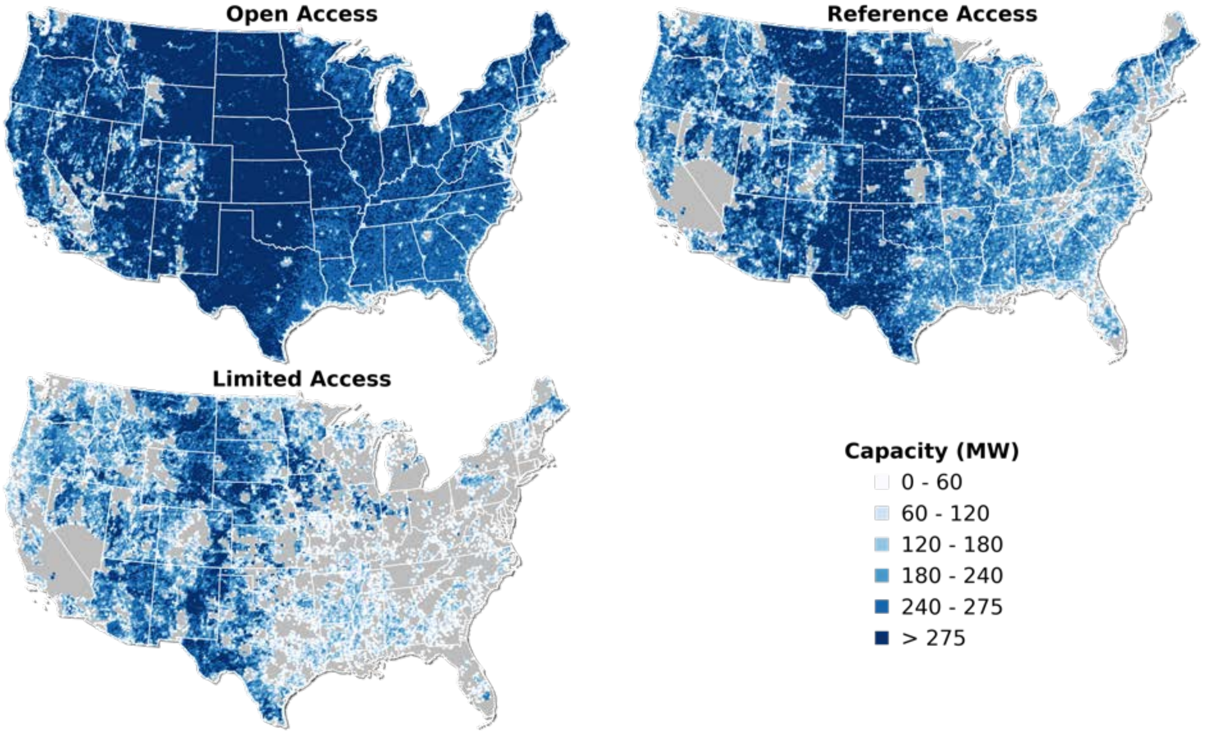

Figure 9. Available wind capacity in the three siting regimes

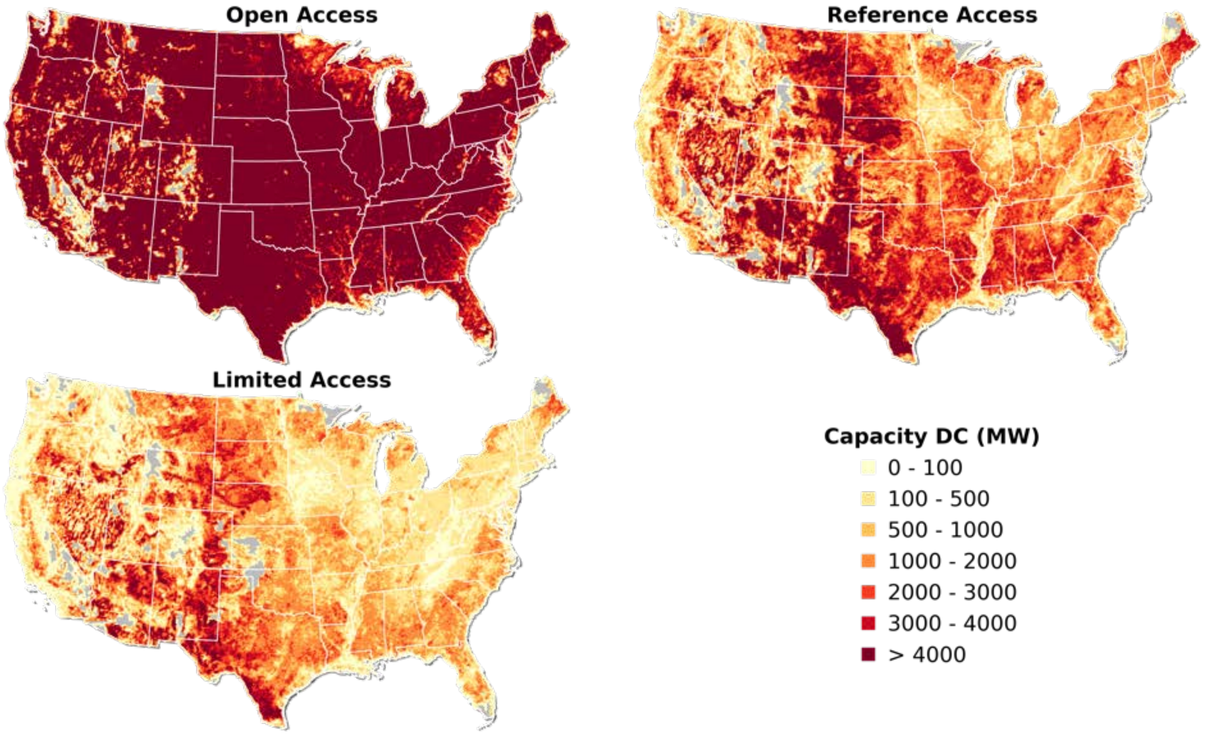

Figure 10. Available solar PV capacity (in DC) in the three siting regimes

3.2 Transmission Distance and Cost

Our transmission requirements are 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.). Figure 12 shows maps of these costs on a levelized basis, referred to as levelized cost of transmission (LCOT), for each of the three siting regimes. LCOT is like LCOE, but includes only costs related to transmission, including spur-transmission, substation upgrade, and reinforcement. Notable spatial trends include increased costs in the Northeast and Pacific regions that are driven by relative regional multipliers shown in Figure 4. Higher costs within state boundaries are driven by a combination of remoteness of resource relative to existing transmission as seen in southern Utah. In other cases, southern Georgia for example, network upgrade costs are the primary driver of relative differences between locations. These trends are present in both wind and solar PV LCOT maps. Figure 14 shows the cost of solar PV LCOT. The concentric circles are primarily caused by the modeling approach to network reinforcement costs. The closer a solar site is to a population center, the lower the cost to upgrade the grid.

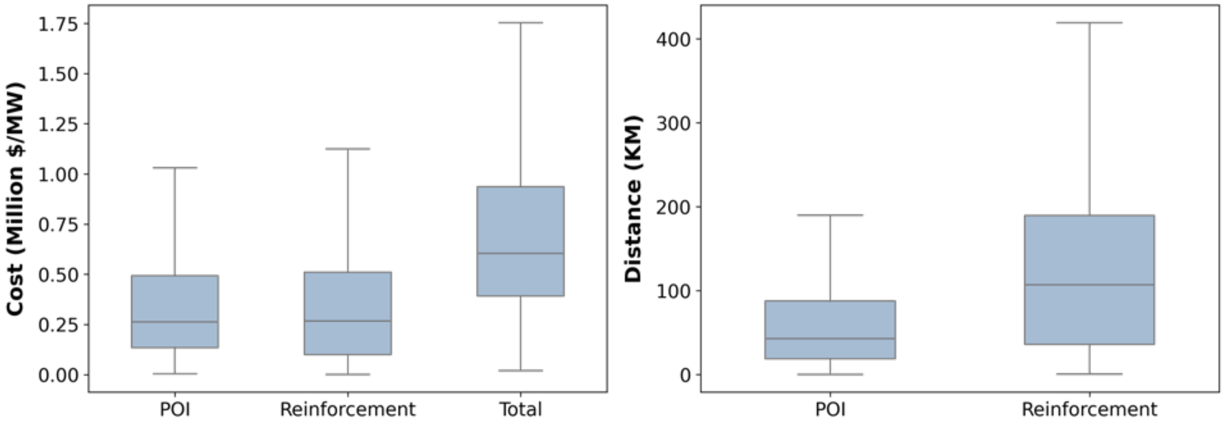

Figure 11. Transmission cost and distance distributions for the wind Reference siting regime

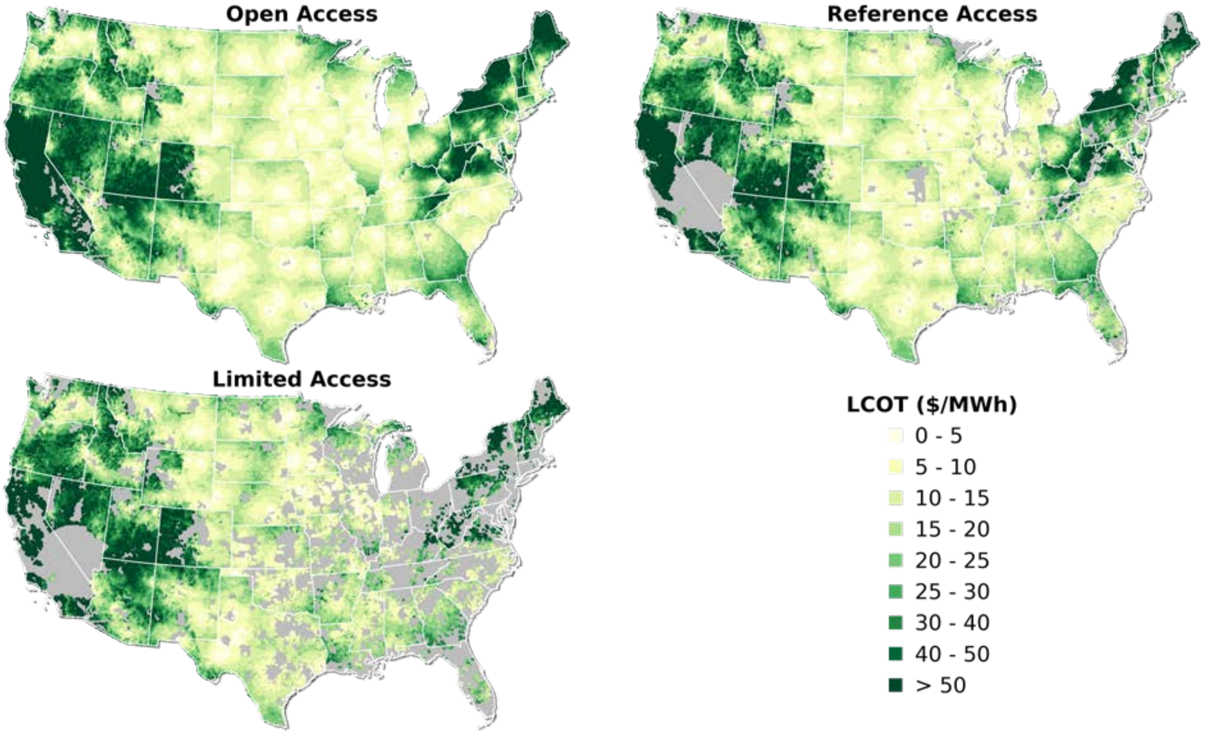

Figure 12. Levelized cost of transmission for the three wind siting regimes

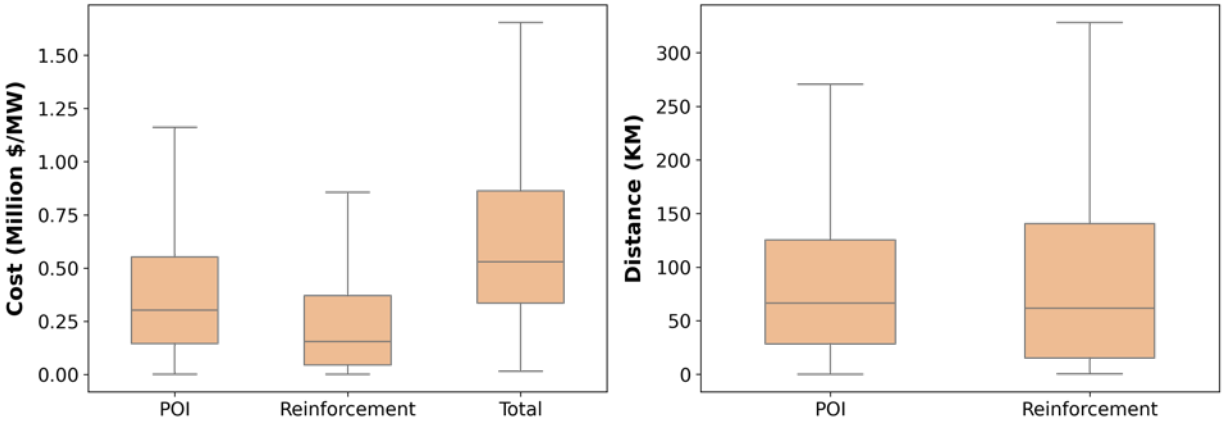

Figure 13. Transmission cost and distance distributions for the PV Reference siting regime

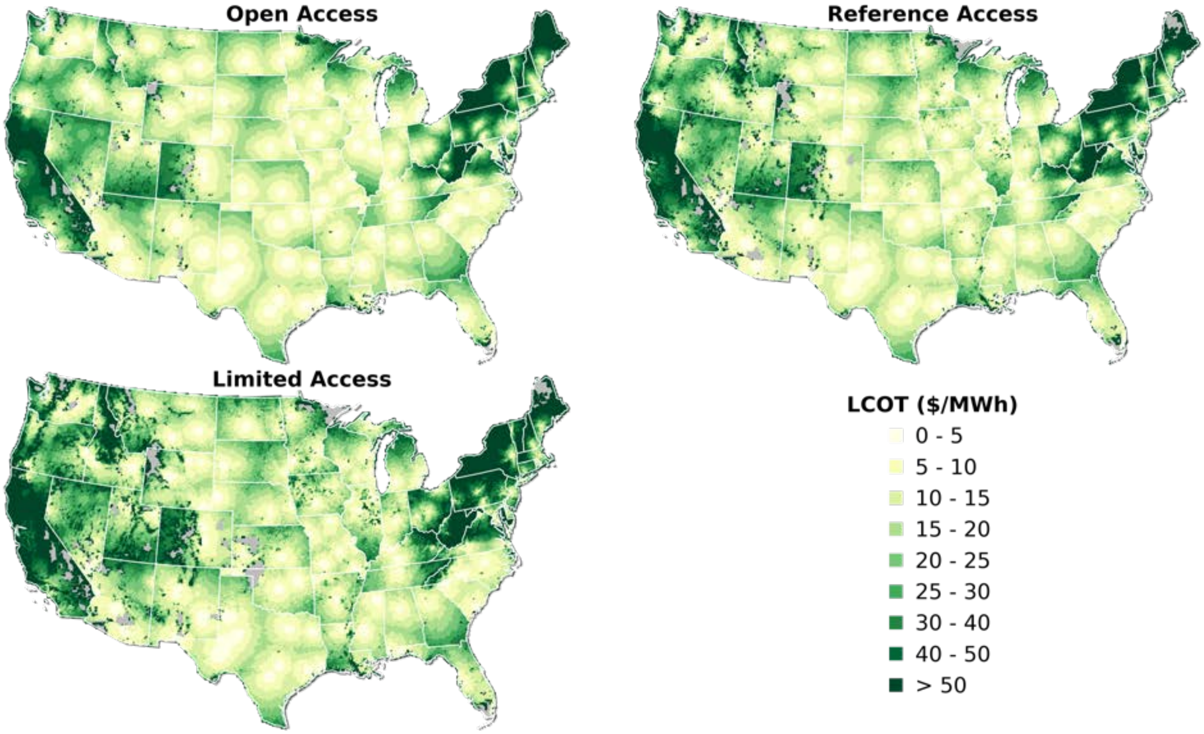

Figure 14. Levelized cost of transmission for the three PV siting regimes

3.3 Supply Curves

Supply curves represent the quantity and cost of renewable resources. In Figure 13 through Figure 18, we partition the supply curves into “all-in” and “site” levelized cost of energy (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 e.g., 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 graphs to show just resources under $70/MWh to preserve resolution at lower cost resources.

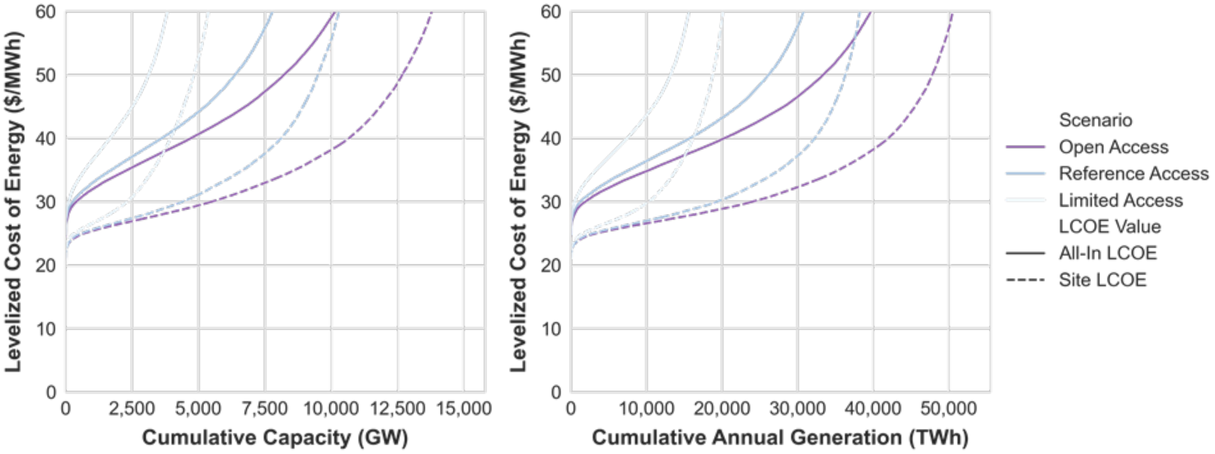

Figure 15. LCOE for wind supply curves as a function of cumulative capacity (left) and energy (right)

The figures show both the all-in LCOE and the site LCOE for all siting regimes.
Values above $60/MWh are not shown.

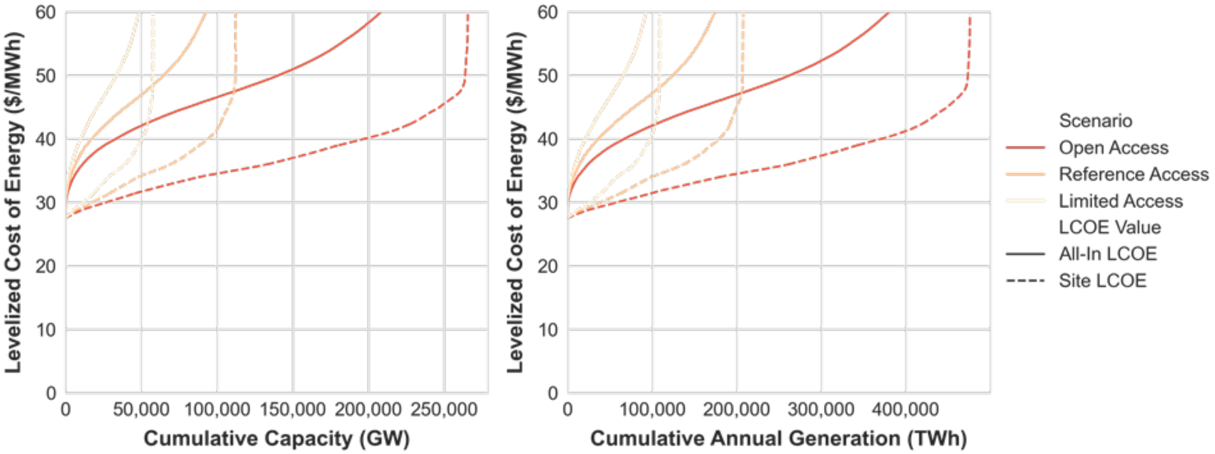

Figure 16. LCOE for PV supply curves as a function of cumulative capacity (left) and energy (right)

The figures show both the all-in LCOE and the site LCOE for all siting regimes.
Values above $60/MWh are not shown.

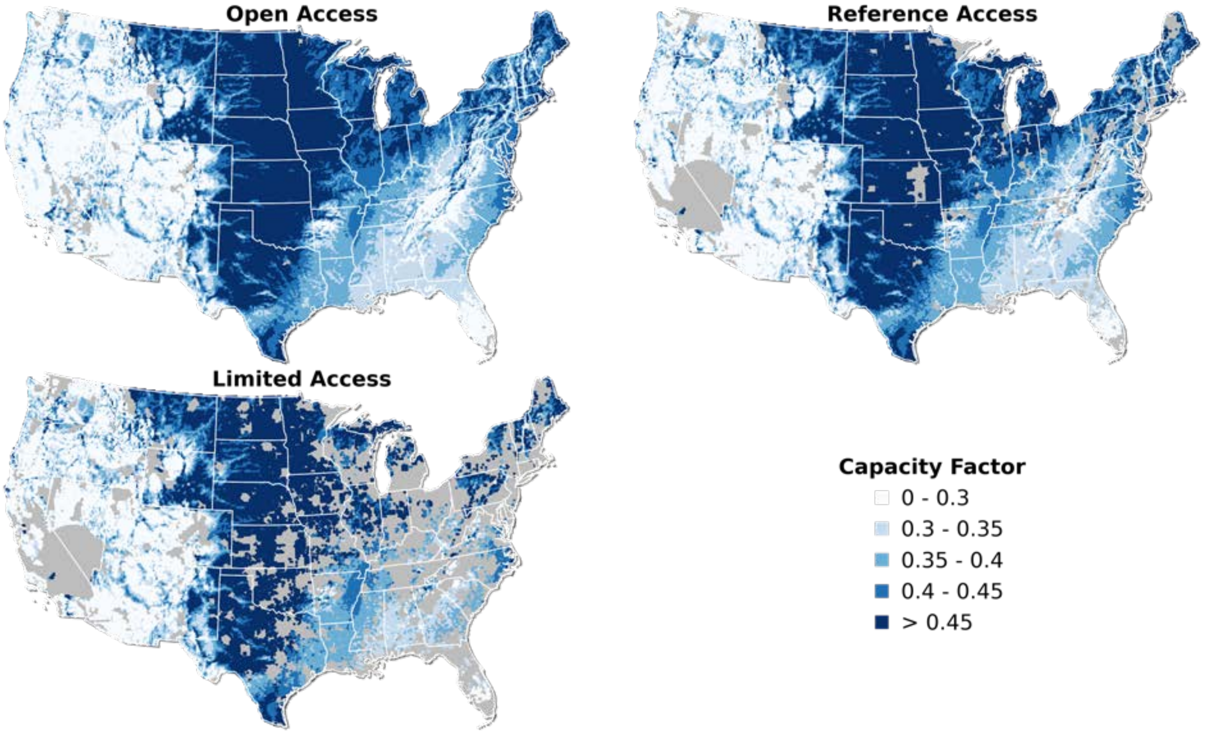

Figure 17. Wind capacity factor maps for the three siting regimes

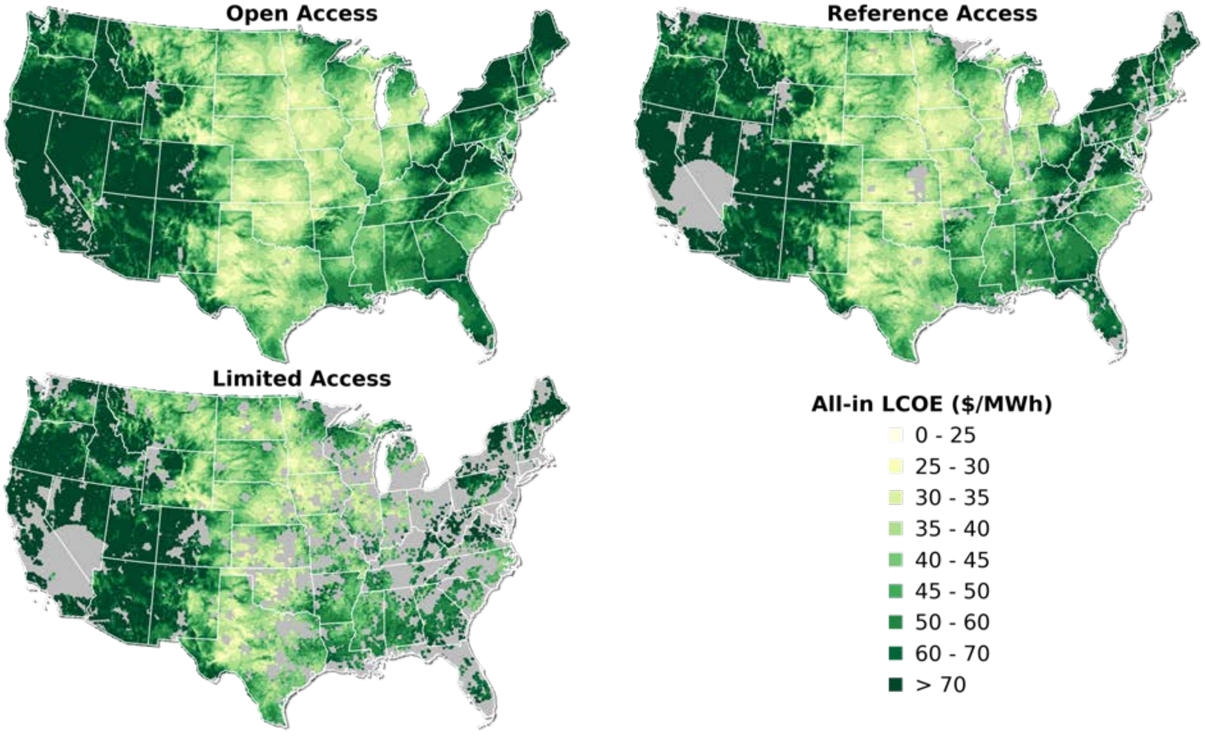

Figure 18. Wind all-in LCOE values for the three siting regimes

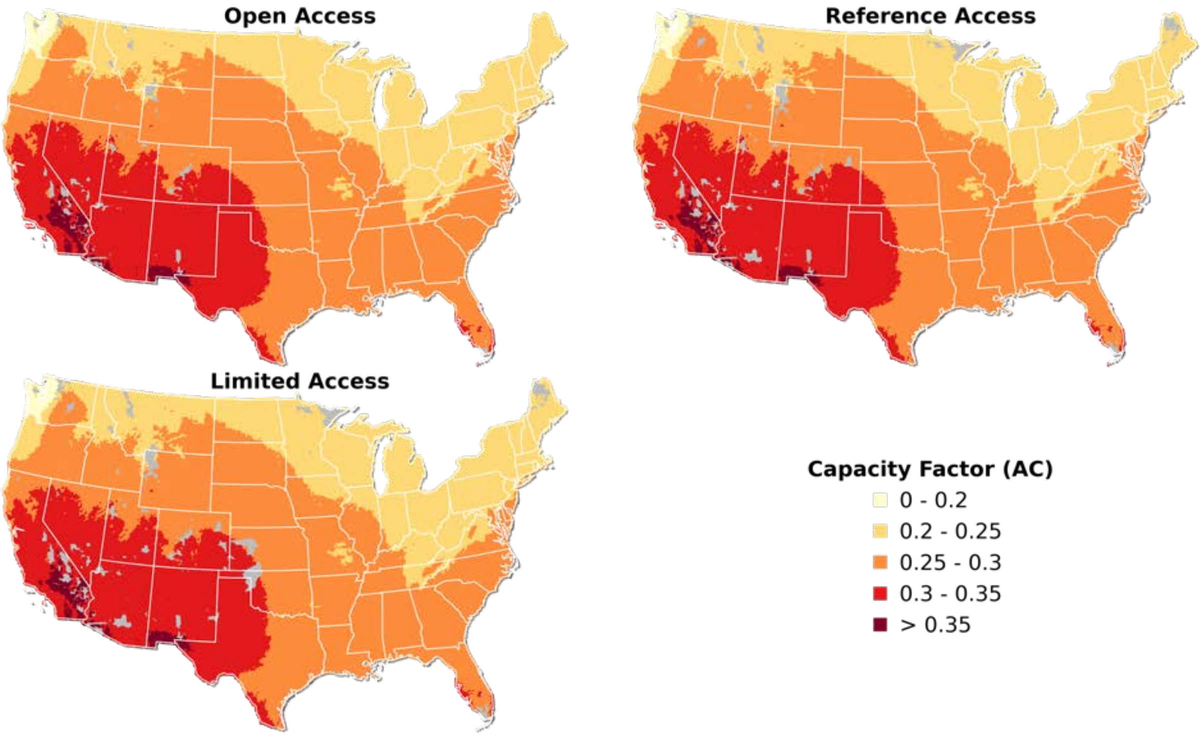

Figure 19. Solar PV capacity factor maps for the three siting regimes

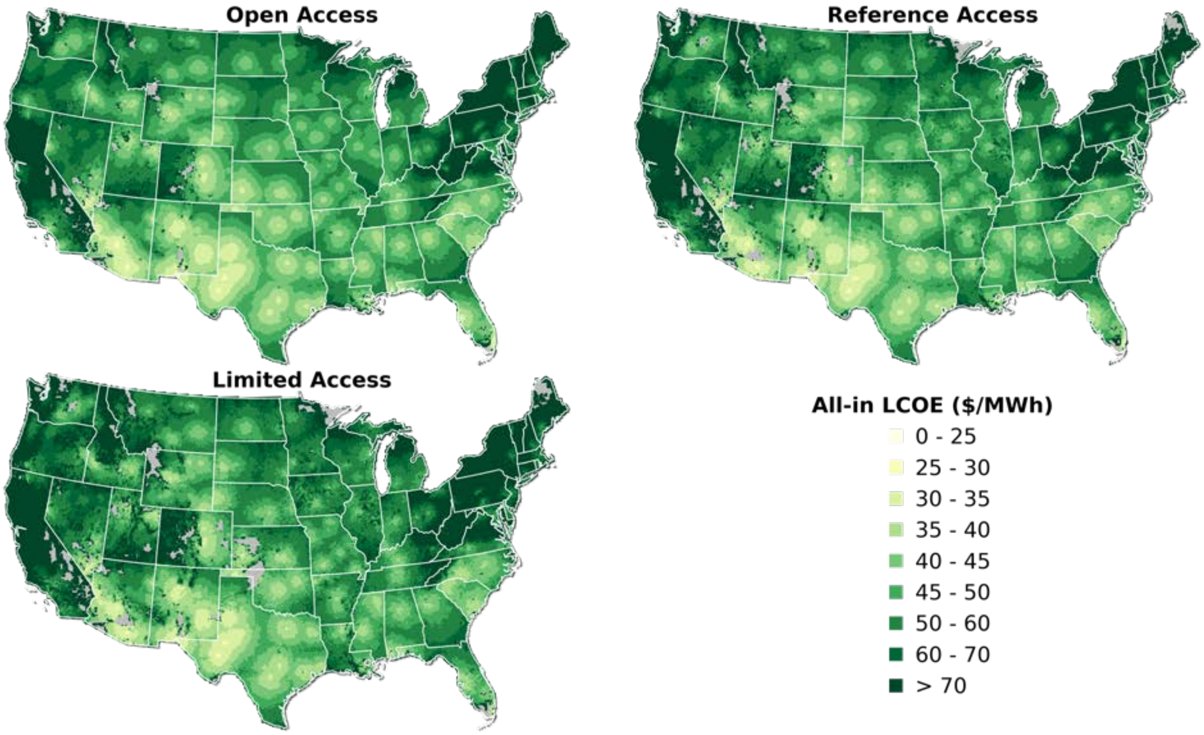

Figure 20. Solar PV all-in LCOE values for the three siting regimes

3.4 State-Level Results

Table 11 and Table 12 present state-level developable area, capacity, and generation for the wind and PV Reference siting regimes.

Table 11. 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	106,291	26,596	5,219	257,964	184,632	57,066	721	522	164
Arizona	229,173	129,300	83,753	539,172	474,252	411,012	1,245	1,093	954
Arkansas	109,008	25,704	5,153	268,878	187,488	78,024	875	615	264
California	217,460	37,743	10,107	605,040	306,234	136,464	1,237	659	304
Colorado	186,503	81,857	35,936	471,474	402,468	264,072	1,323	1,159	780
Connecticut	6,366	251	6	20,580	5,448	156	77	21	1
D.C.	0	0	0	0	0	0	0	0	0
Delaware	2,333	144	0	9,246	4,086	0	36	16	0
Florida	62,813	6,211	1,882	210,000	78,636	13,752	553	209	35
Georgia	101,723	18,575	2,244	271,566	190,236	35,724	784	557	106
Idaho	163,054	59,557	18,999	413,154	333,018	216,750	997	826	532
Illinois	125,224	21,592	8,449	293,376	182,928	65,682	1,137	714	262
Indiana	79,723	8,728	3,547	187,446	102,138	28,392	709	391	113
Iowa	135,037	33,739	15,584	315,174	257,574	124,350	1,357	1,120	550
Kansas	202,462	57,845	12,753	471,618	331,026	141,162	2,079	1,458	633
Kentucky	94,523	11,589	542	210,546	144,438	12,336	664	462	39
Louisiana	60,598	15,574	2,750	182,586	136,398	39,906	572	433	130
Maine	61,297	14,740	5,008	173,904	94,488	46,752	666	360	185
Maryland	13,858	729	49	45,726	15,462	654	162	57	3
Massachusetts	9,422	514	48	33,534	8,640	810	129	34	3
Michigan	91,181	13,403	3,308	296,976	178,182	33,270	1,183	721	139
Minnesota	139,830	39,538	21,835	423,648	321,930	204,882	1,770	1,362	875
Mississippi	91,076	22,168	3,942	237,978	182,862	54,996	727	567	177

State	Developable Area (km^2)			Capacity (MW)			Generation (TWh)		
	Open	Reference	Limited	Open	Reference	Limited	Open	Reference	Limited
Missouri	160,826	32,768	3,858	375,492	289,086	46,896	1,453	1,129	182
Montana	314,624	169,197	79,951	791,148	699,078	544,152	2,756	2,477	1,967
Nebraska	187,083	83,892	47,780	442,224	393,510	282,504	1,918	1,713	1,231
Nevada	200,966	62,185	33,200	515,298	240,252	199,122	1,181	532	433
New Hampshire	17,901	3,621	537	48,330	30,186	9,186	169	113	37
New Jersey	5,444	255	17	26,076	5,802	300	94	21	1
New Mexico	267,405	159,028	82,117	629,202	582,216	461,628	1,913	1,787	1,425
New York	84,741	13,767	2,030	234,036	146,886	20,946	843	552	82
North Carolina	87,263	9,619	1,350	235,860	124,932	19,638	732	397	66
North Dakota	159,373	54,473	23,224	397,158	322,758	204,774	1,699	1,389	888
Ohio	87,195	9,044	720	205,764	134,238	6,426	736	485	24
Oklahoma	164,380	45,698	10,154	393,186	329,130	98,412	1,675	1,416	432
Oregon	201,985	64,352	26,322	487,878	393,516	276,114	1,194	972	692
Pennsylvania	94,112	11,366	2,607	226,260	107,970	33,714	784	401	136
Rhode Island	1,059	65	6	4,200	1,710	0	17	7	0
South Carolina	50,535	8,173	1,098	147,156	92,892	14,922	429	272	43
South Dakota	179,663	85,605	38,430	437,346	400,188	287,472	1,806	1,654	1,188
Tennessee	85,383	9,790	1,042	205,332	105,468	14,892	606	335	51
Texas	603,564	242,876	103,723	1,426,314	1,226,190	669,600	5,500	4,777	2,607
Utah	146,195	68,723	33,259	393,282	304,908	240,552	897	701	554
Vermont	20,416	3,589	411	49,476	32,538	7,152	169	118	29
Virginia	83,987	8,947	654	200,436	110,142	14,910	605	343	47
Washington	119,267	37,491	13,023	306,996	236,994	140,466	772	614	385
West Virginia	52,658	6,150	306	124,446	71,550	7,176	376	218	24
Wisconsin	95,936	16,993	2,978	286,056	206,016	38,550	1,113	808	154
Wyoming	202,037	90,656	53,487	507,924	410,100	339,030	1,747	1,446	1,210

Table 12. State-Level Summary of PV Reference Siting Regime Results

State	Developable Area (km^2)			Capacity (MW)			Generation (TWh)		
	Open	Reference	Limited	Open	Reference	Limited	Open	Reference	Limited
Alabama	110,829	58,928	22,879	3,556,451	1,890,975	734,168	8,216	4,374	1,704
Arizona	233,847	139,770	92,272	7,504,039	4,485,143	2,960,982	22,203	13,304	8,806
Arkansas	111,166	43,999	18,016	3,567,253	1,411,908	578,114	8,166	3,205	1,315
California	234,071	64,643	30,098	7,511,248	2,074,355	965,835	20,662	5,815	2,725
Colorado	189,243	90,413	50,218	6,072,715	2,901,326	1,611,465	16,015	7,740	4,318
Connecticut	9,892	2,763	464	317,437	88,654	14,876	659	184	31
D.C.	106	10	1	3,394	314	21	8	1	0
Delaware	3,064	655	293	98,336	21,010	9,415	221	47	21
Florida	76,223	33,926	16,770	2,445,953	1,088,680	538,134	6,160	2,724	1,349
Georgia	112,049	53,581	24,145	3,595,592	1,719,392	774,815	8,564	4,096	1,861
Idaho	164,109	48,337	26,303	5,266,194	1,551,114	844,043	12,072	3,668	2,027
Illinois	133,155	21,186	8,974	4,272,886	679,855	287,971	9,441	1,510	640
Indiana	85,268	18,694	6,808	2,736,221	599,880	218,474	5,891	1,292	470
Iowa	137,438	17,606	5,111	4,410,311	564,982	163,998	9,716	1,246	362
Kansas	204,839	60,737	24,280	6,573,201	1,949,010	779,141	16,463	4,890	1,931
Kentucky	97,955	26,911	6,386	3,143,335	863,571	204,921	6,764	1,873	448
Louisiana	64,937	29,441	15,473	2,083,784	944,739	496,515	4,901	2,191	1,151
Maine	61,315	23,959	10,736	1,967,582	768,830	344,504	3,857	1,523	680
Maryland	18,222	4,032	1,235	584,729	129,371	39,616	1,273	282	87
Massachusetts	15,107	4,482	870	484,773	143,820	27,934	998	297	58
Michigan	98,706	40,738	16,767	3,167,427	1,307,278	538,041	6,447	2,635	1,082
Minnesota	143,712	34,364	18,921	4,611,658	1,102,719	607,155	9,713	2,302	1,266
Mississippi	93,229	49,448	21,676	2,991,691	1,586,769	695,578	6,964	3,677	1,613
Missouri	165,854	73,501	27,402	5,322,177	2,358,621	879,303	12,018	5,309	1,983
Montana	314,209	153,639	80,134	10,082,812	4,930,216	2,571,479	21,675	10,711	5,591
Nebraska	188,064	99,109	58,140	6,034,887	3,180,366	1,865,690	14,537	7,708	4,524

State	Developable Area (km^2)			Capacity (MW)			Generation (TWh)		
	Open	Reference	Limited	Open	Reference	Limited	Open	Reference	Limited
Nevada	201,971	104,505	65,826	6,481,153	3,353,530	2,112,311	17,778	9,284	5,848
New Hampshire	18,884	6,083	1,236	605,964	195,189	39,653	1,207	390	79
New Jersey	10,907	2,722	728	349,994	87,339	23,347	748	187	51
New Mexico	269,079	189,542	117,811	8,634,612	6,082,309	3,780,506	25,278	17,878	11,144
New York	93,227	29,322	8,676	2,991,619	940,921	278,393	5,820	1,824	539
North Carolina	96,980	26,393	11,814	3,112,058	846,954	379,100	7,188	1,964	883
North Dakota	159,098	60,396	33,948	5,105,376	1,938,089	1,089,387	10,930	4,186	2,350
Ohio	97,235	20,488	5,069	3,120,223	657,466	162,674	6,437	1,344	334
Oklahoma	166,754	76,092	33,076	5,351,047	2,441,744	1,061,399	13,482	6,162	2,680
Oregon	204,327	62,915	29,813	6,556,775	2,018,930	956,700	14,929	4,787	2,313
Pennsylvania	104,636	27,313	6,237	3,357,708	876,452	200,128	6,607	1,716	390
Rhode Island	1,841	669	150	59,075	21,467	4,817	125	45	10
South Carolina	55,346	27,695	12,254	1,776,020	888,720	393,222	4,214	2,103	932
South Dakota	180,186	94,658	54,185	5,782,076	3,037,544	1,738,777	13,212	6,993	3,999
Tennessee	92,326	32,434	9,870	2,962,701	1,040,777	316,728	6,583	2,318	709
Texas	621,215	369,705	224,910	19,934,492	11,863,654	7,217,273	53,311	31,889	19,532
Utah	147,800	71,516	42,225	4,742,835	2,294,920	1,354,996	12,785	6,235	3,692
Vermont	20,981	5,195	1,071	673,267	166,690	34,356	1,294	319	66
Virginia	89,069	30,041	10,476	2,858,172	963,990	336,182	6,253	2,123	745
Washington	123,288	27,529	10,499	3,956,261	883,405	336,894	8,070	1,828	718
West Virginia	53,759	7,894	1,282	1,725,093	253,302	41,138	3,474	511	83
Wisconsin	100,135	36,208	13,599	3,213,297	1,161,913	436,399	6,762	2,429	910
Wyoming	202,687	109,790	63,313	6,504,139	3,523,107	2,031,701	15,925	8,631	4,996

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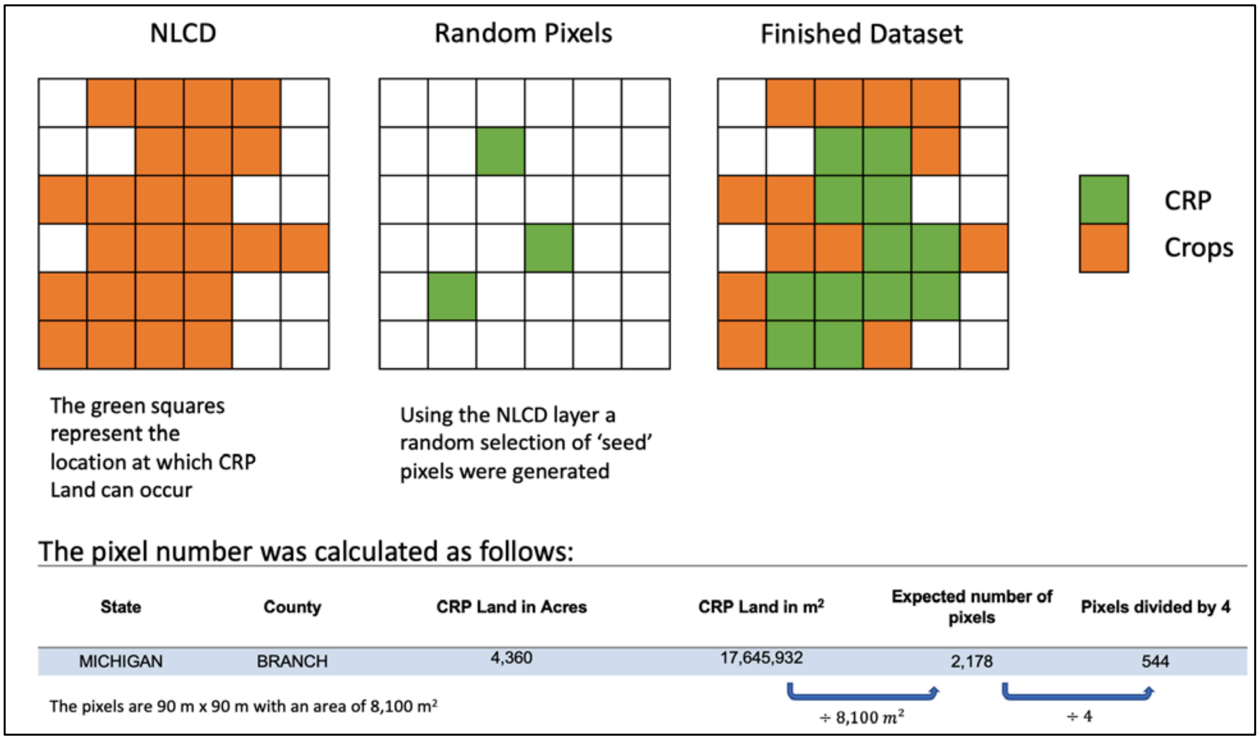
Appendix A.

A.1 Conservation Reserve Program Lands

Conservation reserve program or CRP is a land conservation program administered by the Farm Service Agency (reference below). This program allows agricultural land to be used to demarcate sensitive ecological land for *conservation* rather than agricultural use. While 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) which is needed for PV (photovoltaic) development as it is unavailable to build on. Therefore, a method for downscaling county level data to a reV compliant format was created. The intention of this was to capture the rough magnitude of lands that should be excluded from solar PV development on a per county basis.

The CRP land was generated only in croplands as identified by the 2016 NLCD (National Land Cover Dataset). It is assumed that the land set aside for CRP efforts are a small percentage of a land owner's land and therefore efforts were made to create many smaller areas rather than few large areas. Each county was assigned several random seeds that were proportional to the target CRP area (see figure xx). The equation used was the total CRP land in m^2 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 incapsulate a 4 x 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

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 information, which does not constitute a comprehensive list:

- Digital-Terminal Procedures Publication (d-TPP)/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 (MVA) and Minimum IFR [instrument flight rule] Altitude (MIA) Charts
- VFR Raster Charts (Multiple charts exist and are typically accessed by flight expected in an area or region)
- Gross Weight Adjustment Areas (Emergency Fuel Dump)
- NAS Airspace Classes (Classes A-G and special airspace requirements).

Classifying airspace height limits for the United States with site-specific precision is not feasible for this assessment. However, there still is 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 use 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 use to create runway buffers and which intersect with the wind supply curve:

- **77.9 B.1:** Number of runways >3,200 feet long: 7,202
  100 to 1 for a horizontal distance of 20,000 feet from nearest point of nearest runway
- **77.9 B.2:** Number of runways <3,200 feet 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 takeoff area of each heliport.

A.3 Big Game

We use 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 are grouped by herd and type (e.g., “winter range,” “route,” “stopover,” “corridor,” and “annual range”). We leave all data types unmodified except for the route type. This data type was originally represented as lines, but we apply a 300-m buffer to account for movement uncertainties, based on discussion with a subject matter expert, Hall Sawyer of Western EcoSystem Technologies.

We do not exclude big game migration or seasonal range data, but rather, we apply a reduced capacity density of 16 MW/km^2 (as opposed to the standard 32 MW/km^2) in all areas where big game migration data are present. Doing so enables utility-scale PV development in big game habitat but allows for array designs/plant layouts that maintain connectivity between key habitats.

A.4 Transmission Cultural Risk Model Details

Digital Elevation Models: To derive slope, we use 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 over 30% grade are assigned to Level 1, and slopes less than 30 degrees are assigned to Level 2. Significant resources that have been listed in the NRHP or are associated with otherwise protected areas (e.g., national monuments) are identified as more sensitive Levels 3 or 4 using NRHP and PAD-US data.

National Land Cover Database: The National Land Cover Database (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 due to surface modifications are assigned to Level 1. Where other information is present to suggest significant historical buildings, structures, objects, or landscapes are present, these are identified through the NRHP and associated data sets.

National Register of Historic Places: The NRHP geospatial data sets contains 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 due to sensitivity in disclosing site locations to the public. Still, the data set 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 that are 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 while others may be affected by visual impacts at much greater distances. The 0.5-mile buffer is chosen as a compromise, to indicate that impacts may be likely within that area. Polygons are also present in the NRHP geospatial data, but a review of that data set indicates those polygons are unreliable. For the actual footprints of NRHP locations where physical impacts are of primary concern, the USA Historic Sites data are used (discussed below).

Protected Areas Database of the United States: This data set 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 data set, 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 data set. These buffers are assigned to Level 1, with the assumption that these areas are generally compatible with additional transmission line developments.

USA Historic Sites: This data set is similar to PAD-US at certain locations, but it contains polygons representing historic sites that are not depicted in PAD-US. The data set 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 are assigned to Level 4 given their accurate location and their designation specifically as historically significant sites. Though this data set contains accurate boundaries of land of historical significance, it does not contain all NRHP site locations, and it compliments both the NRHP and the PAD-US data sets.

In summary, cultural risk Level 1 areas can be summarized as those that are 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 that are specifically identified as wilderness areas or those that are historically significant in PAD-US and USA Historic Sites.

A.5 Radar Line-of-Sight (LOS)

Department of Defense and NEXRAD radar station locations are provided by the North American Aerospace Defense Command (NORAD). These locations are 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 use the Open-Source software, QGIS, and the Visibility Analysis plugin 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).