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Transforming ENERGY

Distributed Wind Energy Futures Study

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Purpose and Approach

Purpose:

Characterize the economic opportunities for distributed wind energy systems, from kilowatt to megawatt scale, in 2022 and 2035 under varied conditions to inform a potential role in a broader energy system transition to a zero-carbon economy.

Approach:

Apply state-of-the-art methods and parcel-level data in the National Renewable Energy Laboratory's (NREL's) Distributed Generation Market Demand (dGen™) modeling suite to estimate the "threshold capital expenditures (CapEx)" needed to make sites profitable; use benchmark system costs to quantify economic potential; and identify key regions of opportunity by land-use type, for specific wind turbine sizes and in disadvantaged communities.

Definitions and Terminology

- ***Behind-the-meter applications:*** On-site generation that directly offsets an end-user's consumption of retail electricity, ranging in size from kilowatts (kW) to megawatts (MW), and that serves primarily rural or suburban homes, farms, and manufacturing facilities.

- ***Front-of-the-meter applications:*** Interconnected to the distribution network and sells energy through a power purchase agreement or is owned by a local utility; may include multiple wind turbines greater than 100 kW in size; often, these turbines are 1 MW or larger in size.

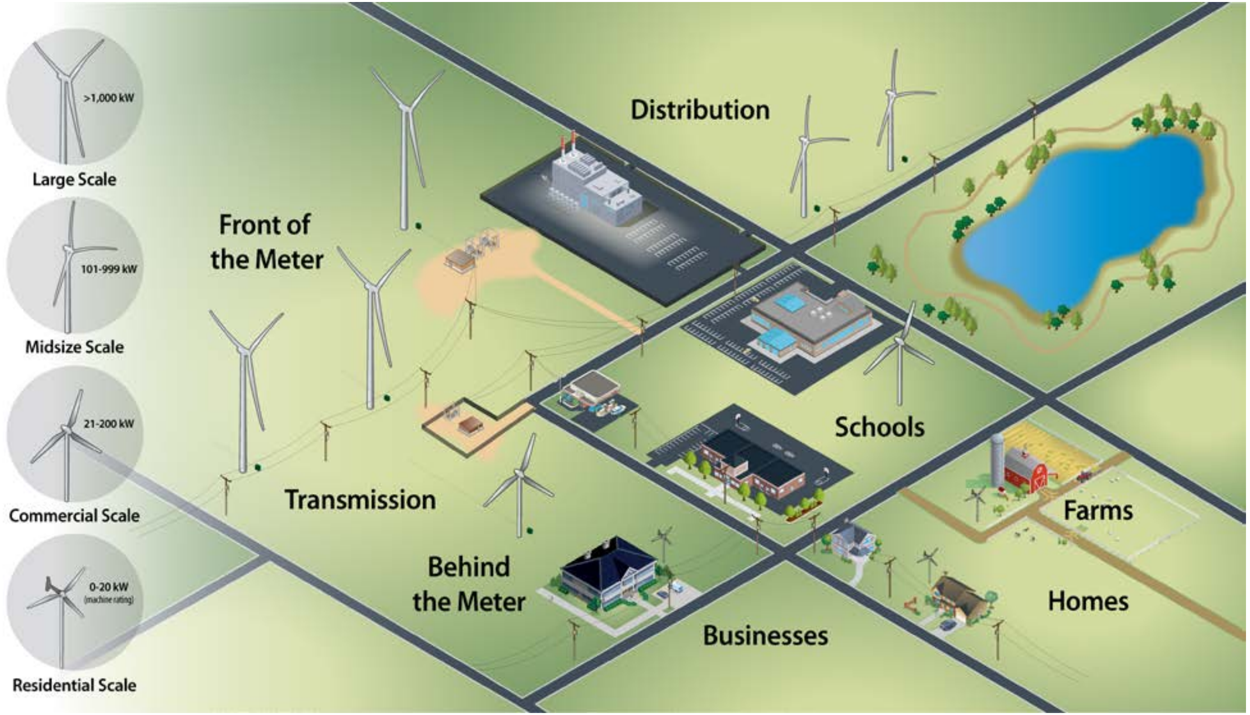
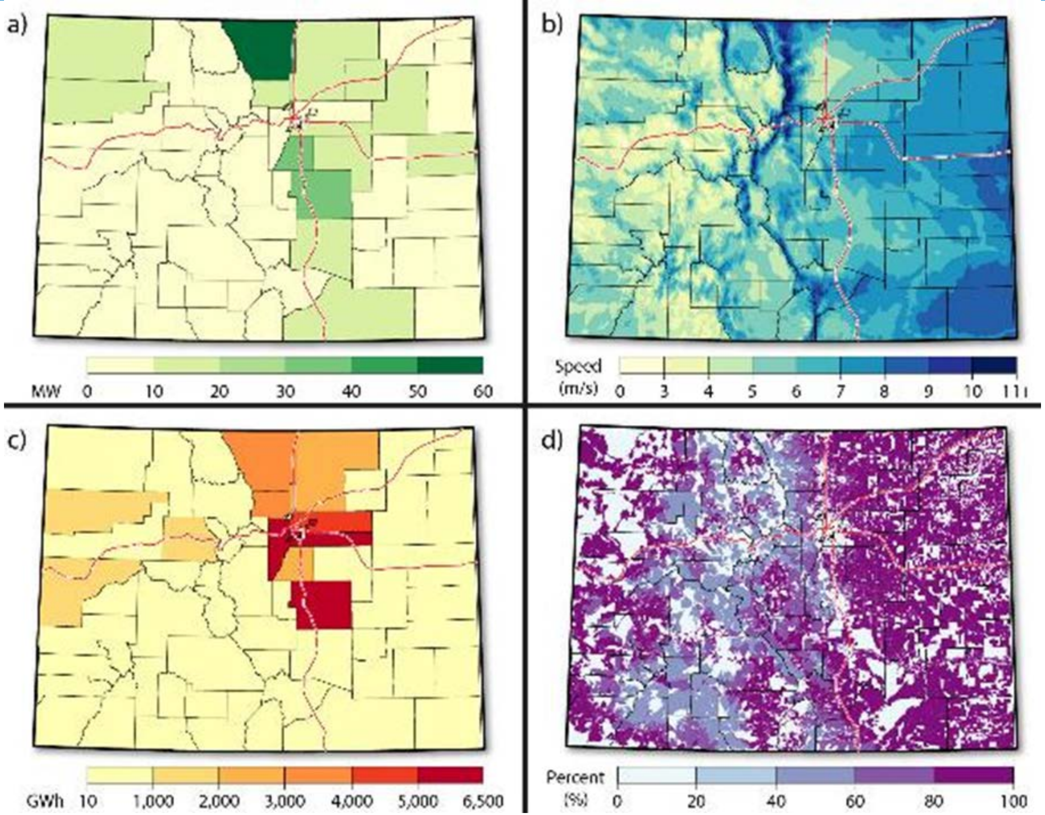


Illustration created by Al Hicks, NREL

Modeling Framework



Distributed wind energy statistics for Colorado: **(a) total economic potential, (b) average wind speed at 80-meter hub height, (c) annual electricity consumption, and (d) turbine siting availability.** (McCabe et al. 2018).

The dGen model forecasts adoption and operation of distributed energy resources (DERs) at high spatial fidelity for power system planning in the United States or other countries through 2050.

- Incorporates detailed spatial data to distinguish individual and regional adoption trends.
- Applies consumer decision-making based on cost-effectiveness of technology.
- Identifies drivers of adoption by analyzing multiple scenarios.
- Open-source tool available for download at:

https://github.com/NREL/dgen

Key Messages

- **The United States currently has the potential to profitably deploy nearly 1,400 gigawatts (GW) of distributed wind energy capacity.** This amount equates to more than half of the nation's current annual electricity consumption and is enough to provide millions of American households with clean power.

- **With favorable regulatory and policy direction, distributed wind energy could provide even more profitable power generation potential** in the coming decades.

- **Distributed wind technology can supply rural homes, businesses, and communities with local clean energy resources that foster an energy transition** and support the nation's low-carbon-emissions goals.

Data and Methodology

Parcel-Scale Analysis

Use of data at parcel* scale to identify location-specific land use, resource, and siting.

Assessment of each sampled parcel’s technical and economic viability:

- **By technology**: distributed wind and distributed solar
- **By application**: behind the meter and front of the meter.

*Parcel: taxable plot of land

Parcel data from: Homeland Infrastructure Foundation-Level Data (HIFLD) (2020).
https://gii.dhs.gov/hifld/content/hifld-data-catalog

Integrated Data and Tools

- **Use of parcel-level database (n = ~155 million parcels):** Assessing potential at the parcel level allows detailed consideration of land use, zoning, sector, and geography in urban and suburban settings.
- **reV resource processing:** The Renewable Energy Potential (reV) model is a spatiotemporal tool enabling bulk calculation of renewable energy capacity/generation. We also incorporate improved meteorological data from the Wind Integration National Dataset Toolkit and the National Solar Radiation Database.
- **Cambium:** An NREL data source that provides information on the marginal conditions of the power system across the United States through 2050.
- **PySAM library:** PySAM offers the full capabilities of NREL's System Advisor Model (SAM), including wind, solar photovoltaics (PV), and battery models; complex cashflow calculations; and retail tariff processing.

Workflow Summary

1. System location provides information on resource availability and informs technical parameters.

3. reV takes information on location, weather data, and technical configuration and produces wind and solar PV generation.

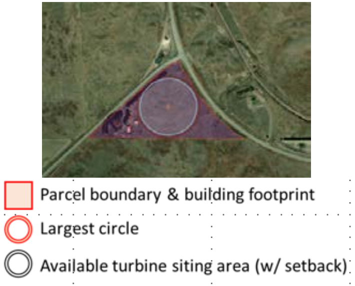
5. Optimize to identify threshold CapEx cost (capital cost at which system breaks even, or NPV > 0).

Sample parcels → Size systems → Assess resource potential → Apply valuation framework → Calculate threshold capex

Post-processing:

- Technical and economic potential
- Spatial trends

Pre-processable

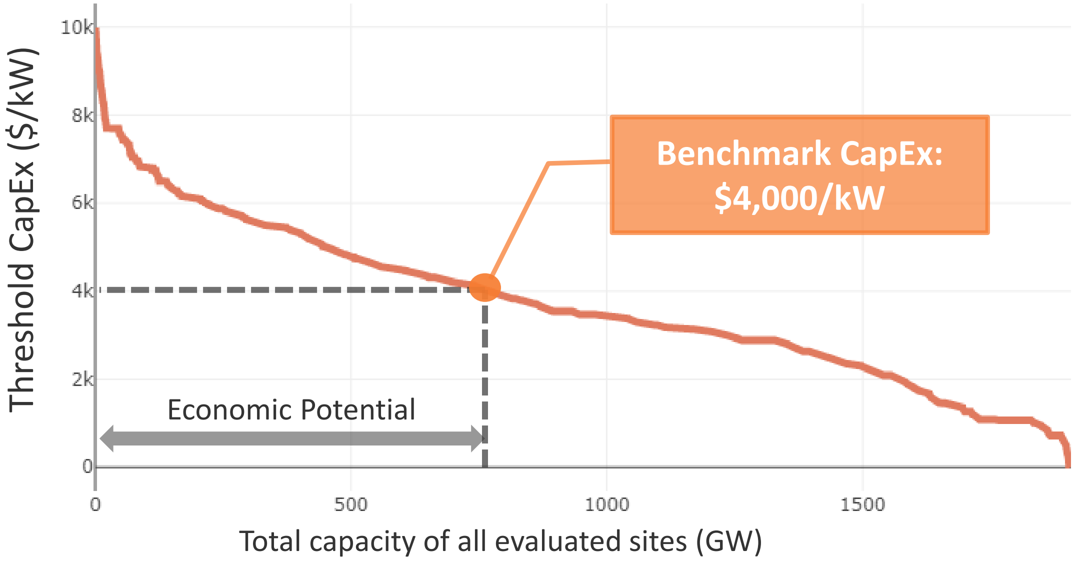


2. Based on information from the parcel, system is sized to its maximum technical capacity. Additional limits are (a) annual energy behind-the-meter load or (b) 10 MW, depending on the system configuration.

4. Depending on the application (front of the meter or behind the meter) and location, retail tariffs from Utility Rate Database or information from Cambium are used to estimate hourly annual revenues available to the system at that location.

Threshold CapEx Supply Curve

- The threshold CapEx supply curve can be used to determine the opportunity (in terms of capacity) given a specific manufacturer CapEx or project CapEx.
- The supply curve is unique for each scenario and reflects the specific economic considerations (incentives, compensation) evaluated under that scenario.
- The supply curve includes all turbine sizes and sectors.
- The total capacity (x-axis) is based on evaluating a sample of 1 million sites/parcel locations across the contiguous United States.



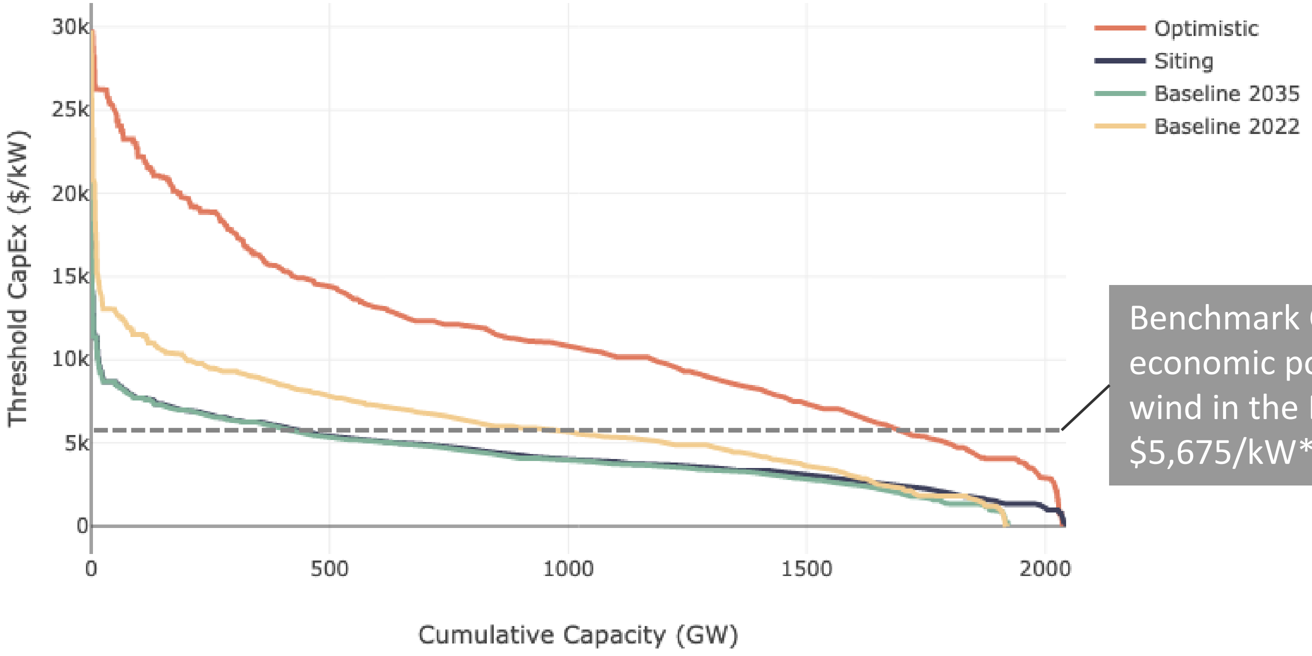
Results and Key Figures

Scenarios

N0.	Scenario Name	Sensitivity Parameters	Rationale
1.	Baseline 2022	2022 baseline costs and policies	Identify current (2022) opportunities (in terms of total capacity that has a positive NPV) with baseline assumptions
2.	Baseline 2035	2035 baseline cost projections, projected policies, projected DER value	Identify future (2035) opportunities with baseline assumptions
3.	Optimistic	2035 advanced cost projections, higher DER value, improved financing conditions, investment tax credit (ITC), siting	Impact of optimistic costs + high DER value + financing + ITC + relaxed siting
4.	Cost and Performance	Improvements in cost for all turbines, improvements in performance for large-size turbines	Impact of optimistic costs and performance (mainly applicable for mid-size and large turbines)
5.	Financing	Improved financing conditions	Impact of financing
6.	ITC	ITC at 30% for both wind and solar	Impact of ITC
7.	Value of DERs	A. Higher value of DERs B. Lower value of DERs	Impact of compensation mechanisms and wholesale market prices
8.	Siting	Decrease setback factor	Impact of relaxed siting considerations

Results at National Scale – Supply Curves for Selected Scenarios

Behind-the-meter opportunities for wind



Benchmark CapEx used to compare economic potential for behind-the-meter wind in the Baseline 2022 scenario: $5,675/kW*

*$5,675/kW is the value for residential wind turbines, whereas the supply curves are evaluated considering all turbine sizes and sectors.

Results at National Scale – Economic Potential by Scenario

Behind-the-meter opportunities for wind

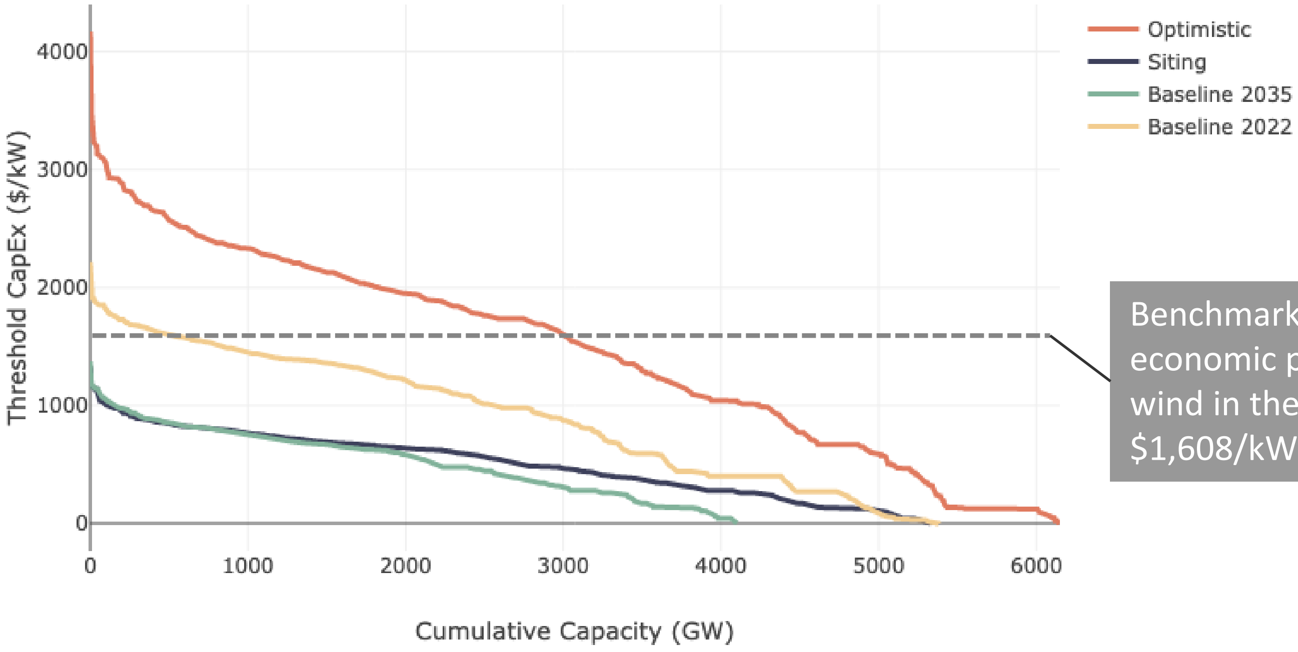
Scenario	Economic Potential in 2022 (GW)	Economic Potential in 2035 (GW)
	Behind the meter	Behind the meter
Baseline 2022	919	
Baseline 2035		773
Siting		803
Cost and Performance		773
DER Valuation		748
Financing		984
ITC		1,472
Optimistic		1,673

Behind-the-meter wind opportunities increase because of:

- Favorable policies like **extension of the ITC** and **net metering**
- **Improved financing** conditions.

Results at National Scale – Supply Curves for Selected Scenarios

Front-of-the-meter opportunities for wind



Benchmark CapEx used to compare economic potential for front-of-the-meter wind in the Baseline 2022 scenario: $1,608/kW*

*$1,608/kW is the value for utility-scale wind turbines, whereas the supply curves are evaluated considering all turbine sizes and sectors.

Results at National Scale – Economic Potential by Scenario

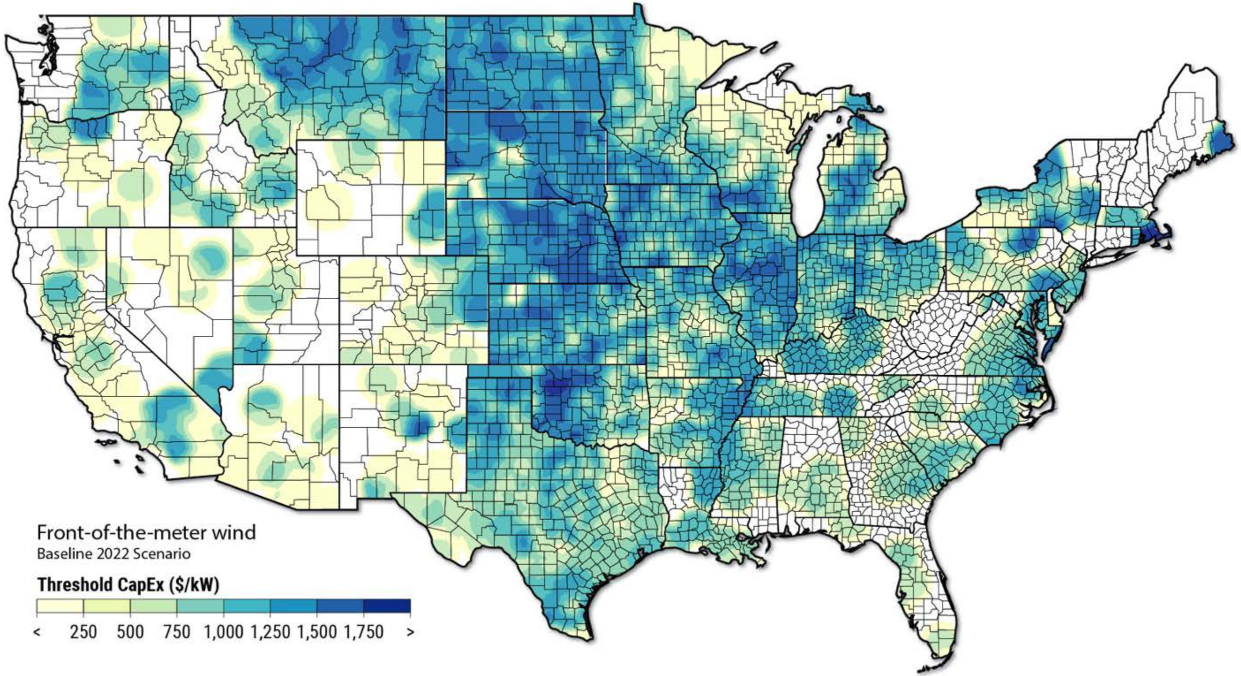
Front-of-the-meter opportunities for wind

Scenario	Economic Potential in 2022 (GW)	Economic Potential in 2035 (GW)
	Front of the meter	Front of the meter
Baseline 2022	474	
Baseline 2035		160
Siting		115
Cost and Performance		342
DER Valuation		256
Financing		513
ITC		2,152
Optimistic		4,264

- Improved siting alone mainly benefits relatively low-threshold CapEx sites, below $1,000/kW.
- With **improved economics** (ITC, financing) and **relaxed siting**, the potential benefit for front-of-the-meter systems is approximately an **order of magnitude larger** than the baseline value.

Baseline 2022 Scenario Results by Region

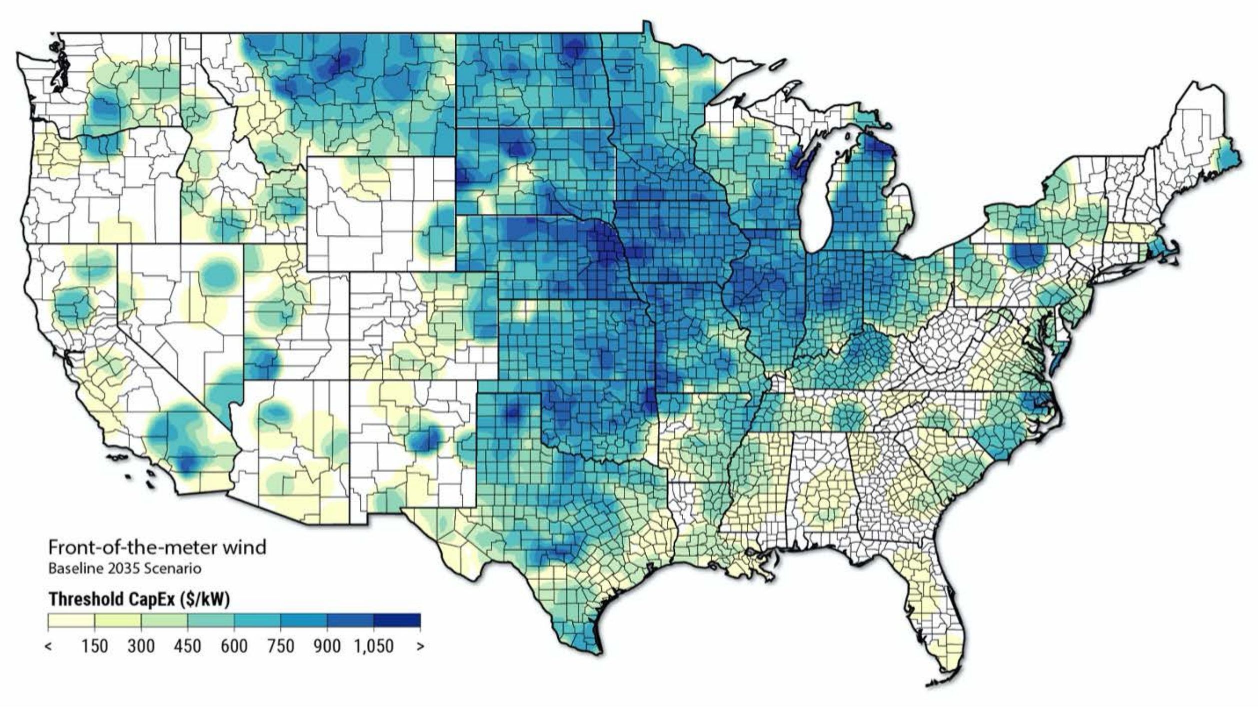
Front-of-the-meter opportunities for wind



- Areas of interest: **Great Plains**, **Midwest**, and **South Central**
- **Higher-quality wind resource** is the primary driver of economically viable front-of-the-meter applications
- Regions with **high-cost wholesale electricity** can also return high threshold CapEx values.

Baseline 2035 Scenario Results by Region

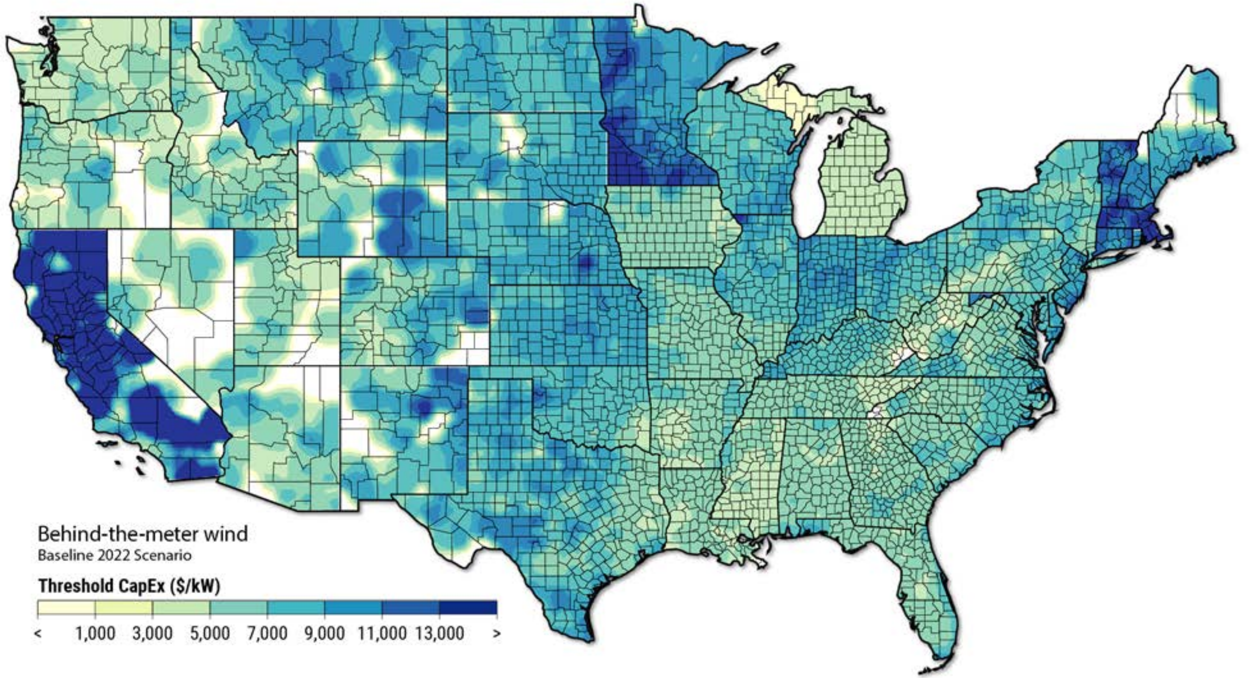
Front-of-the-meter opportunities for wind



- **Great Plains**, **Midwest**, and **South-Central** regions remain strong areas of economic viability
- **Sunsetting of wind energy policies (PTC and ITC)** and changes in modeled **wholesale power prices** result in differences between 2022 and 2035 results.

Baseline 2022 Scenario Results by Region

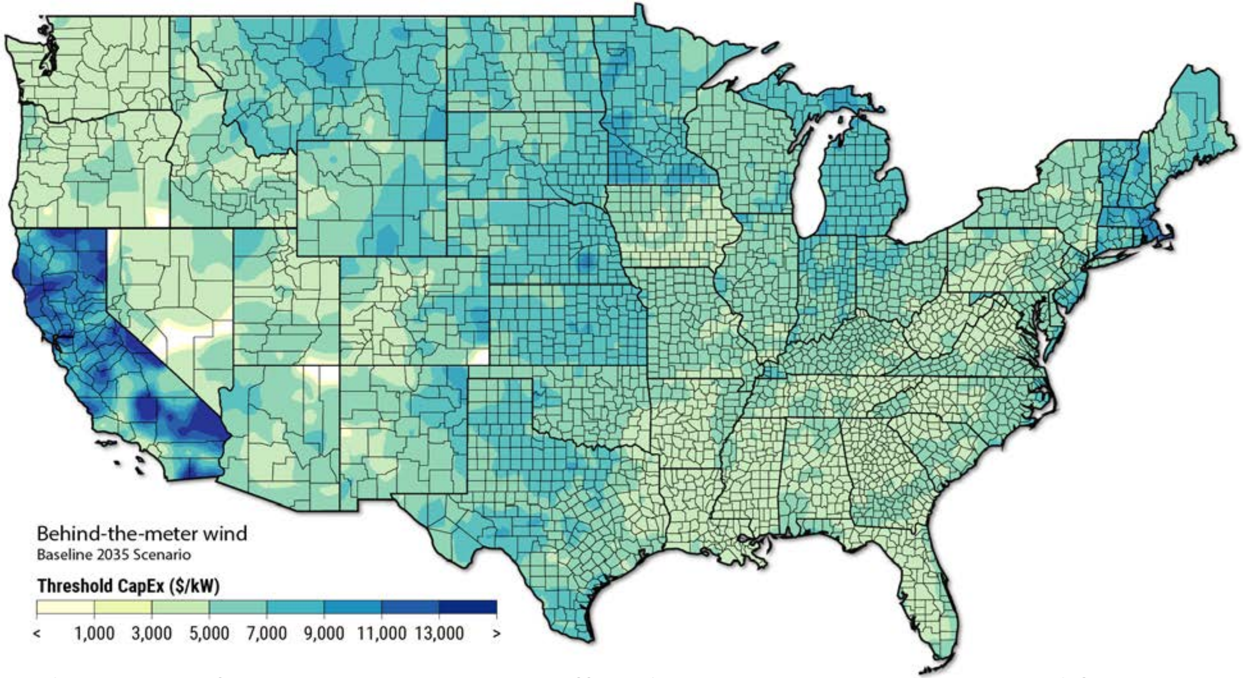
Behind-the-meter opportunities for wind



- Areas of interest: **California**, **Minnesota**, and **Northeast** region
- A combination of **good resource, high retail electricity prices, and favorable policies contribute to profitable behind-the-meter applications**.

Baseline 2035 Scenario Results by Region

Behind-the-meter opportunities for wind



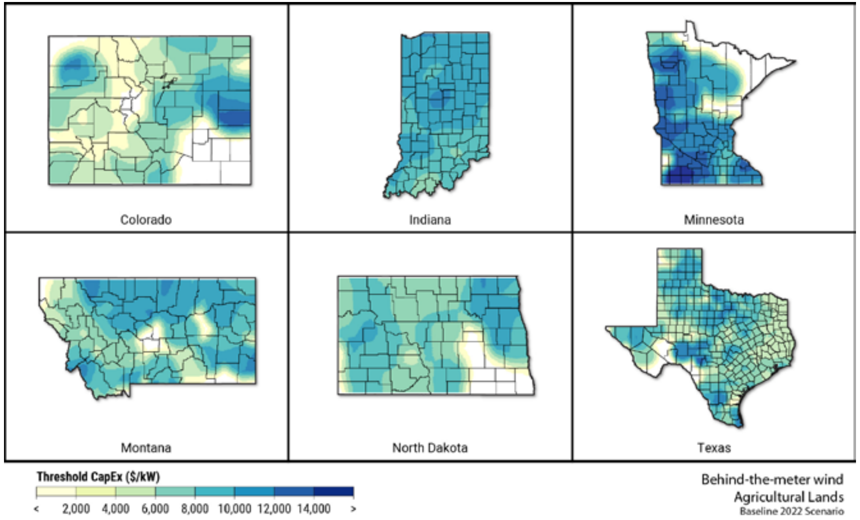
- Spatial patterns of opportunity are more diffuse between 2022 and 2035—**California** remains an especially strong area of economic viability.
- **Sunsetting of the federal production and investment tax credits** and **expiration of net-metering** policies result in lower threshold CapEx values in 2035.

Agriculture Land-Use Opportunities

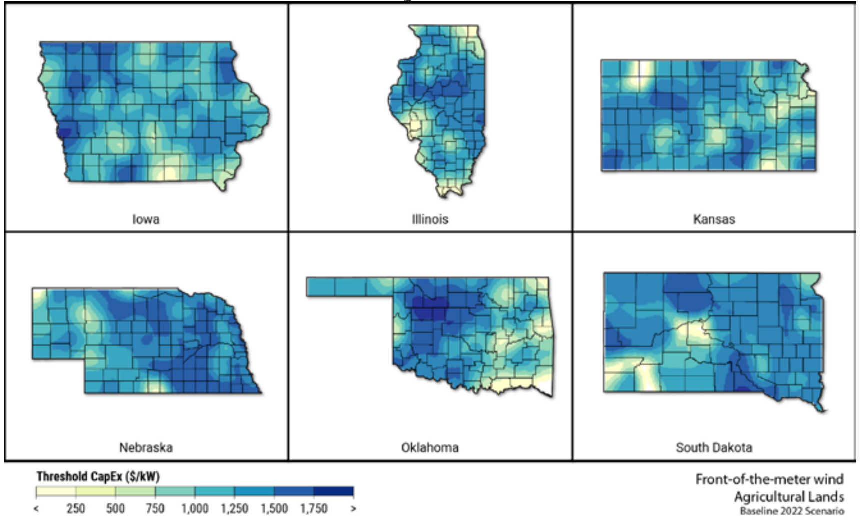
The top six states contain **hundreds of gigawatts of economic potential** for behind-the-meter and front-of-the-meter applications.

Behind-the-meter systems are constrained by local load and are **most correlated with the combination of electricity consumption, electricity rates, and windy land; resource quality and higher cost pricing nodes drive front-of-the-meter agriculture land outcomes**.

Behind the meter



Front of the meter

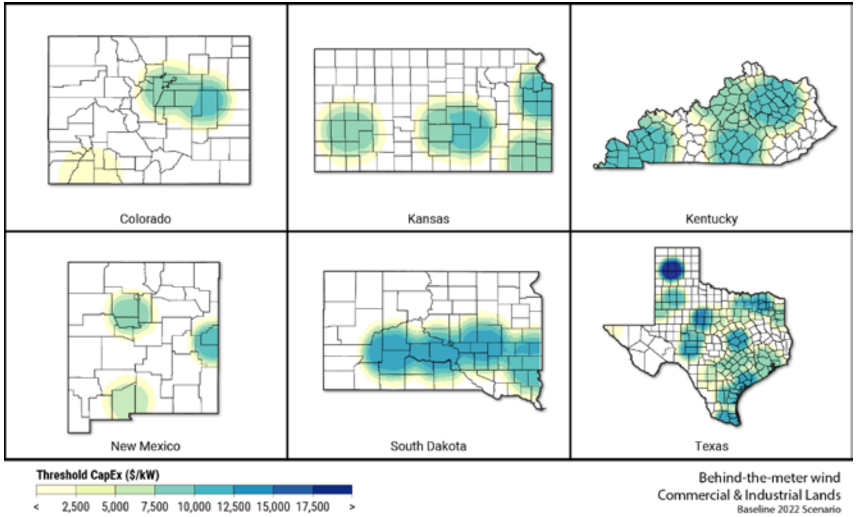


Commercial and Industrial Sector Opportunities

Commercial and industrial lands offer compelling near- and long-term distributed wind energy potential, particularly for behind-the-meter applications, albeit in relatively less area compared to agricultural lands.

The top six behind-the-meter states each offer more than **900 MW of potential** in the applicable localities.

Behind the meter



Front of the meter

State	80th Percentile Threshold CapEx 2022 ($/kW)	Technical Potential (GW)
Nebraska	1,488	0.9
Texas	1,394	4.7
Illinois	1,364	14.0
South Dakota	1,327	0.7
New Mexico	1,121	1.0
Indiana	1,081	2.8
Utah	840	3.1
North Dakota	840	0.4
Colorado	706	1.6
Michigan	628	0.7

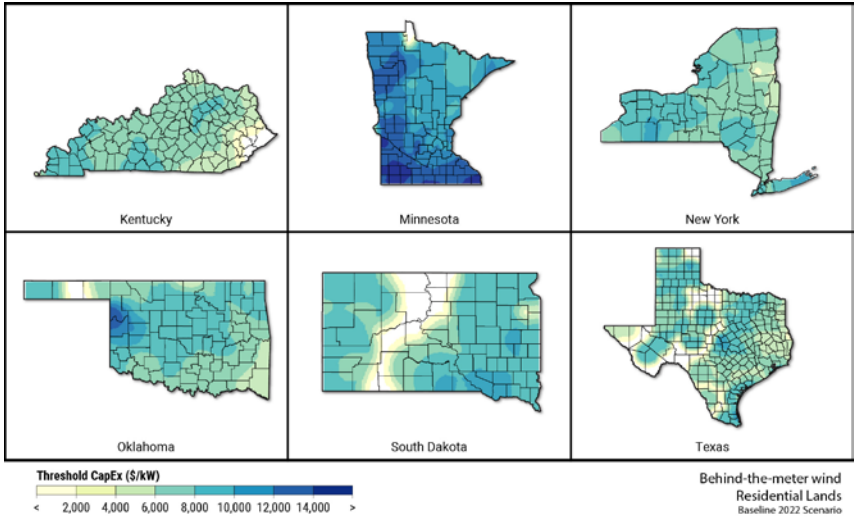
**Front of the meter not economic under our modeling assumptions*

Residential Sector Opportunities

Economic potential on residential lands is driven by total area with favorable conditions; however, the pockets of **high retail rates in California and New England** make for very attractive complements to these six states where behind-the-meter economic potential is largest.

Residential distributed wind opportunities (especially for behind-the-meter applications) exist in suburban locales—limited land area that constrains siting ability results in opportunities outside of metropolitan and urban regions.

Behind the meter



Front of the meter

State	80th Percentile Threshold CapEx 2022 ($/kW)	Technical Potential (GW)
North Dakota	1,586	6.4
New York	1,441	28.8
Missouri	1,308	2.1
Michigan	1,140	2.2
Maryland	1,131	0.7
Arkansas	1,090	9.9
California	1,014	9.6
Texas	782	16.2
Nevada	636	1.6
Colorado	617	18.1

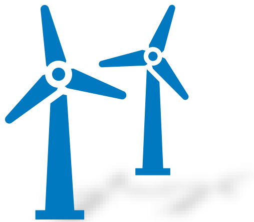
**Front of the meter not economic under our modeling assumptions*

Energy Equity

Energy Equity

*Disadvantaged Communities (DACs)**

Census areas with a high risk for **environmental hazards** and/or areas that include high proportions of **low-income** households.



Distributed wind has the potential to ***alleviate energy burden*** with ***lower electricity costs*** and bolster ***electricity reliability*** in DACs.

*Our definition of DACs is based on Energy Justice (EJ) Indexes from the Environmental Projection Agency's EJ Screen and Brownfield Sites (by census block group) and NREL's REPLICA data set (by census tract). We acknowledge that these definitions are dynamic and evolving at the present time, and our results may not be directly comparable to similar studies that rely on different definitions.

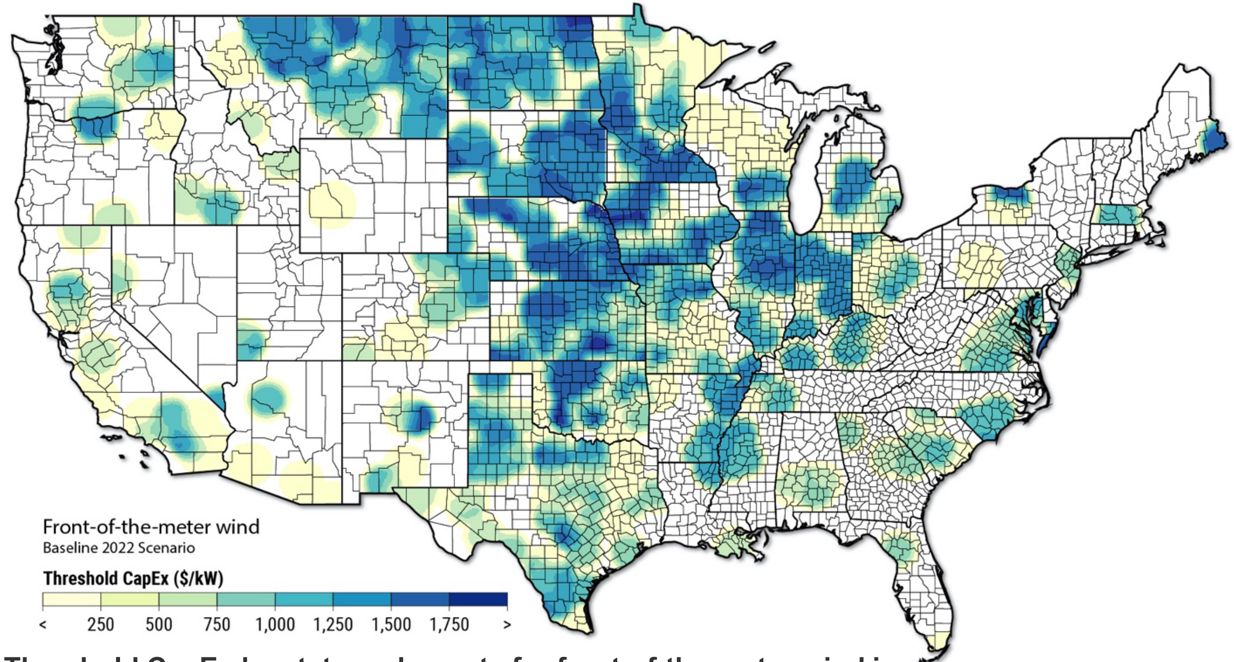
Energy Equity

Opportunities in Disadvantaged Communities

Front of the Meter

States With the Largest Economic Potential:

Oklahoma
Illinois
Kansas
New Mexico
Nebraska
Montana



Threshold CapEx by state and county for front-of-the-meter wind in disadvantaged communities; Baseline 2022 scenario

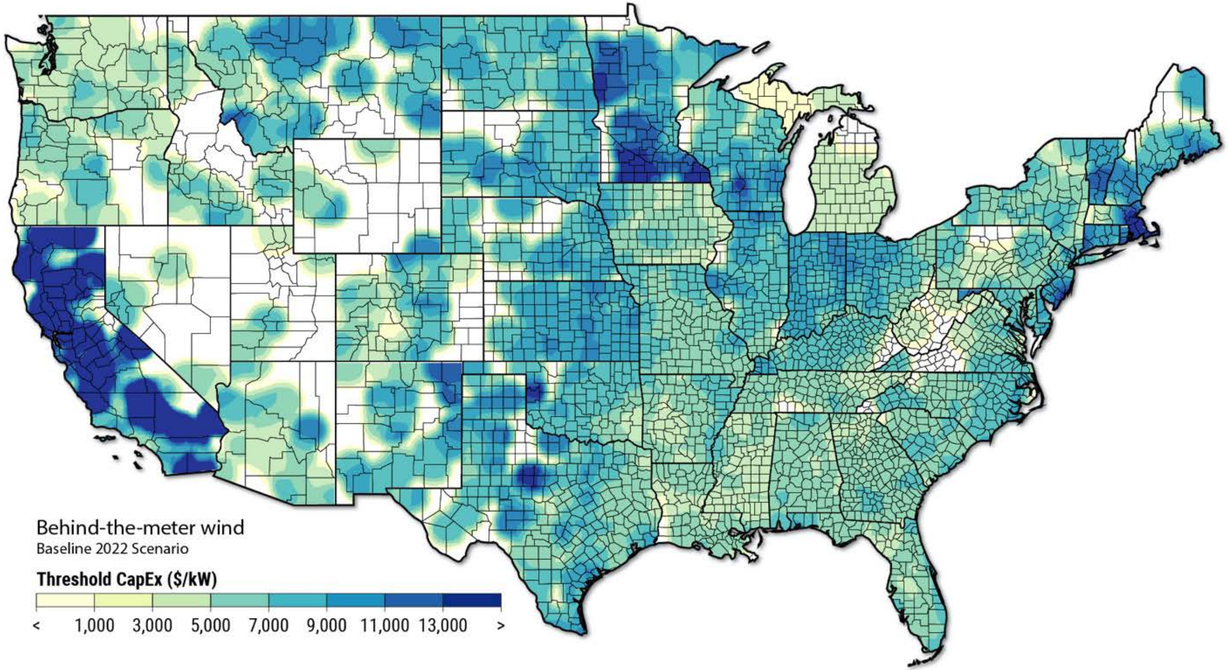
Energy Equity

Opportunities in Disadvantaged Communities

Behind the Meter

States With the Largest Economic Potential:

Texas
Montana
New Mexico
California
South Dakota
Kansas



Threshold CapEx by state and county for behind-the-meter wind in disadvantaged communities; Baseline 2022 scenario

Key Conclusions

- The economics of distributed wind energy are strong, but increasing competitiveness with other distributed energy resources, especially solar PV, is also important to foster customer uptake and use.
- Policy matters; extending the ITC at 30% had a bigger effect on economic potential than all other (single) variables modeled for both front-of-the-meter and behind-the-meter systems.
- Today's economic potential is higher for behind-the-meter applications, at 919 GW, with 474 GW for front-of-the-meter applications in the Baseline 2022 scenario; with future policy support and more relaxed siting conditions, the economic potential of front-of-the-meter applications could eventually double that of behind-the-meter applications.
- Economic potential for front-of-the-meter and behind-the-meter distributed wind applications in the Baseline 2022 scenario is deepest in the Midwest and heartland, but behind-the-meter systems also see meaningful pockets in windy regions and localities with particularly high retail rates, such as California and parts of New England.
- Agricultural lands make up 70% of the total 2022 economic potential for behind-the-meter wind and 97% of the total 2022 economic potential for front-of-the-meter wind.
- Kansas, Colorado, Texas, South Dakota, New Mexico, and Kentucky each have more than 900 MW of behind-the-meter economic potential in 2022 on commercial and industrial lands.
- Behind-the-meter economic potential in 2022 on residential lands is largest in New York, Minnesota, Kentucky, Texas, Oklahoma, and South Dakota.
- All distributed wind turbine size classes are observed to have gigawatts of economic potential, supporting the continued development of technologies serving the multiple facets of the distributed wind sector.

Thank You

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Distributed Wind Cost Projections

Current Distributed Wind Techno-Economic Summary

Parameter	Residential Turbine	Commercial Turbine	Mid-Size Turbine	Large-Size Turbine
Representative Machine Rating (kW)	20	100	650	1,500
Rotor Diameter (m)	12.4	27.6	70	107
Hub Height (m)	30	40	60	80
Specific Power (W/m^2)	166	167	169	167
Max Cp	0.4	0.5	0.5	0.5
Max Tip Speed (m/s)	95	75	70	82
Max Tip Speed Ratio	9.7	8	8	8
Balance of System CapEx ($/kW)	$3,100	$1,770	$869	$951
Turbine CapEx ($/kW)	$2,575	$2,535	$1,897	$1,288
Operations & Maintenance ($/kW-year)	$35	$35	$35	$35
Losses	11.5%	11.5%	11.5%	11.5%

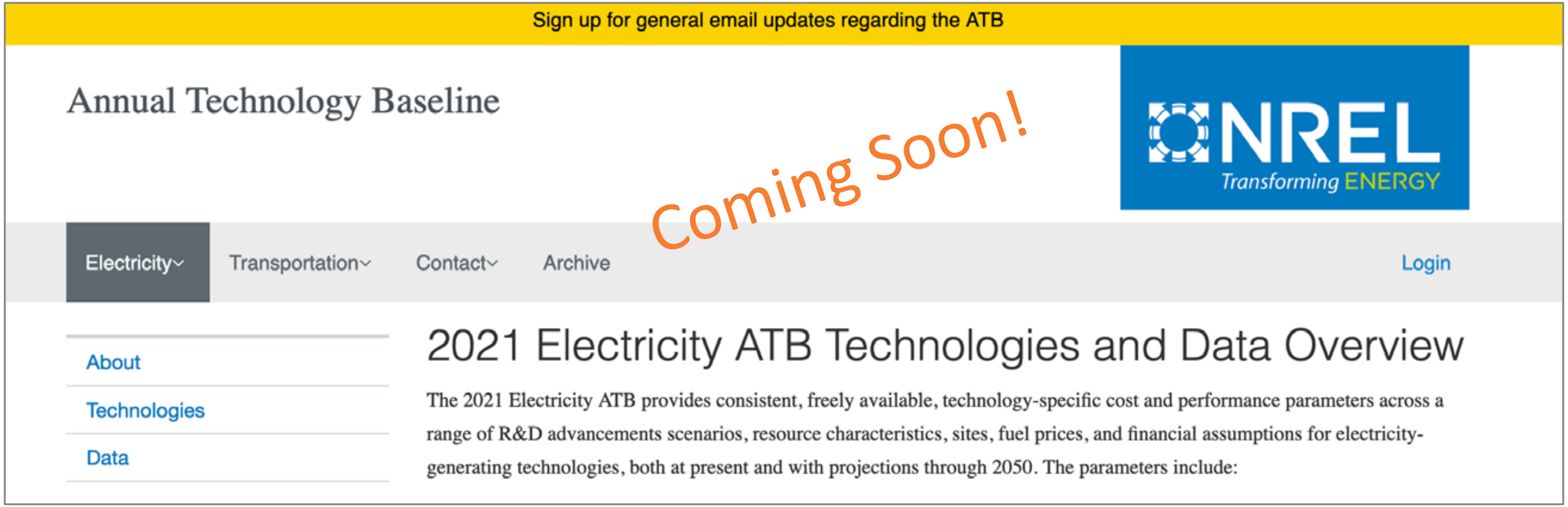
- Performance parameters were used as inputs in the dWind model.
- CapEx and operational expenditure (OpEx) estimates merely serve as a reference of where distributed wind energy stands today. They were not used as inputs in the dWind model.

CapEx and OpEx Forecasting Methodology

Scenario	Description	Rationale
Reference	Up to 45% reduction in capital cost by 2030 and 70% reduction by 2050; 4% reduction in O&M cost by 2030 and 10% reduction by 2050	Derived from land-based wind median learning rate, projected global growth rates, short-term cost estimates, and the Wind Vision study cost reduction assumptions[1]
High Deployment	Up to 52% reduction in capital cost by 2030 and 71% reduction by 2050; 4% reduction in O&M cost by 2030 and 10% reduction by 2050	
Breakthrough	Up to 70% reduction in capital cost by 2030 and 75% reduction by 2050; 4% reduction in O&M cost by 2030 and 10% reduction by 2050	

[1] U.S. Department of Energy. 2015. *Wind Vision: A New Era for Wind Power in the United States*. DOE/GO-102015-4557. https://www.energy.gov/sites/default/files/2015/03/f20/wv_full_report.pdf.

Distributed Wind Being Added to Annual Technology Baseline in 2022!



https://atb.nrel.gov/electricity/2021/index

Understanding Cost Projections

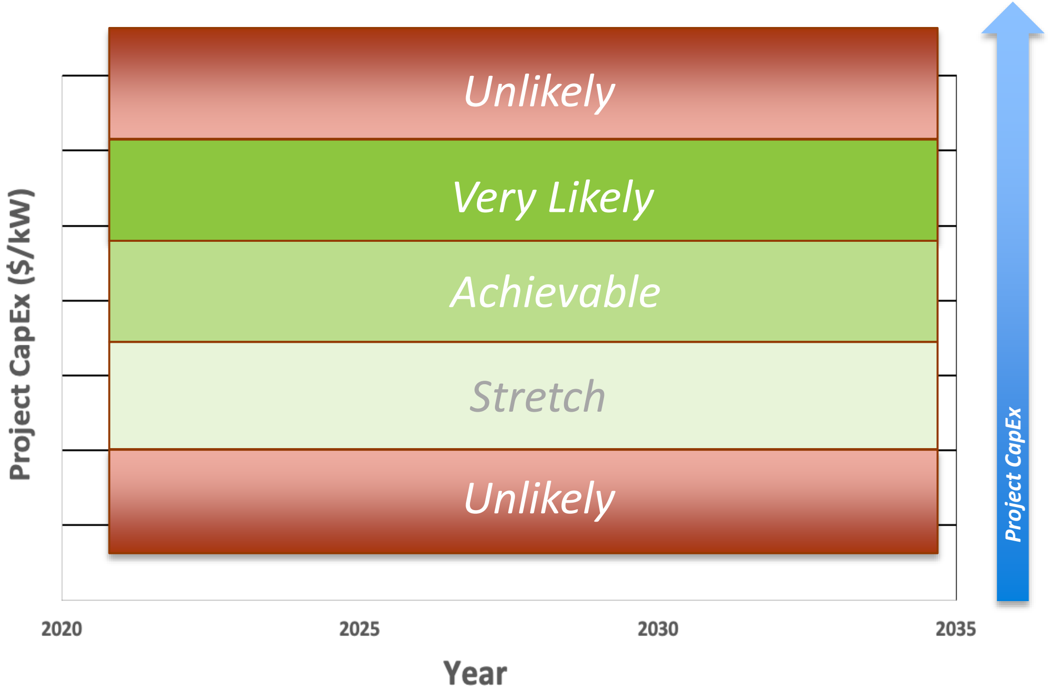
Cost projections are split into "zones" of likelihood:

- **Unlikely**: Would require (positive or negative) disruption of the distributed wind industry to reach these cost levels.

- **Very Likely**: Business-as-usual.

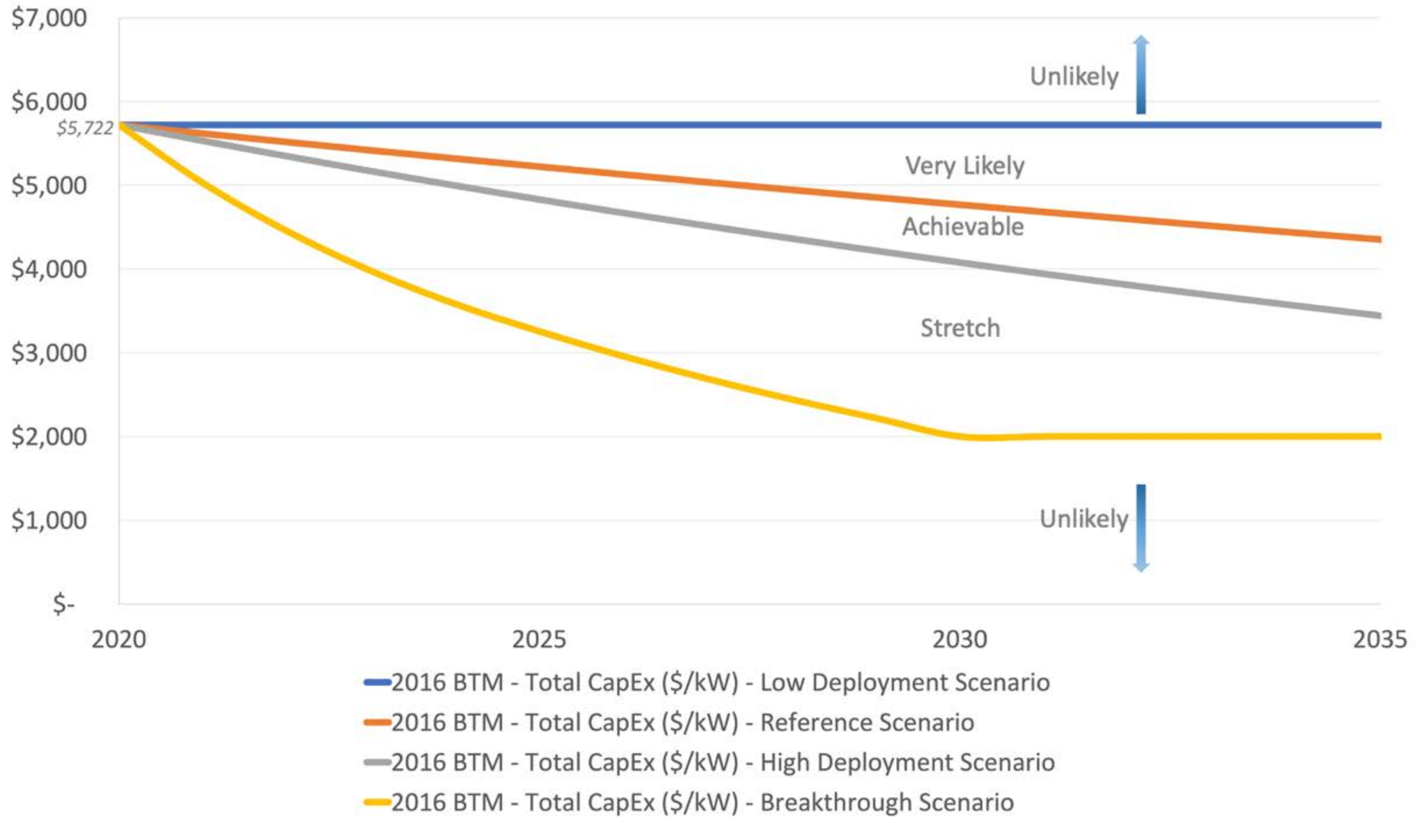
- **Achievable**: Ramping up of turbine manufacturing (and demand), relaxed siting constraints, ITC for distributed wind, better/standardized financing options, cheaper turbine erection technologies, and material-light foundation technologies, better zoning, permitting, interconnection, and incentives (ZPII) practices.

- **Stretch**: *(In addition to pathways identified for the Achievable bucket)* **Very** significant ramping up of turbine manufacturing, countrywide adoption of a single set of standardized ZPII practices.



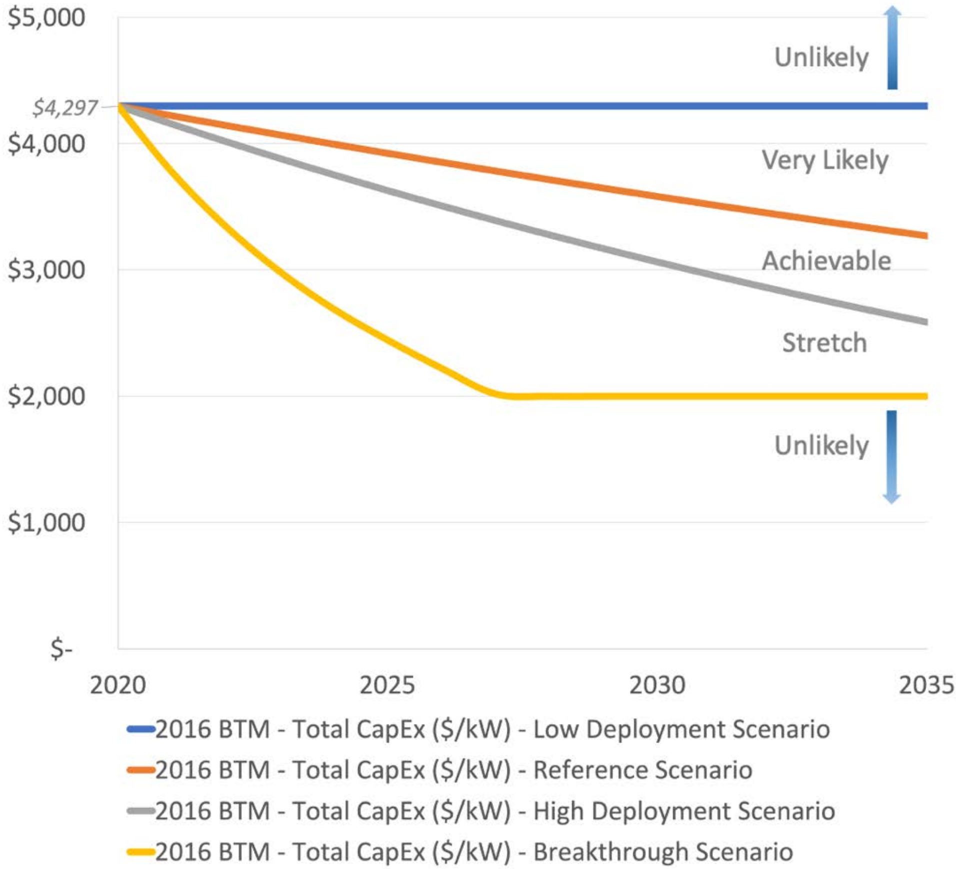
Residential-Scale Distributed Wind Project CapEx Projections (2020–2035)

- Each curve represents median expected CapEx within each of the four scenarios.
- Lower ceiling of $2,000 to prevent CapEx of projects dropping below CapEx of large-scale projects.



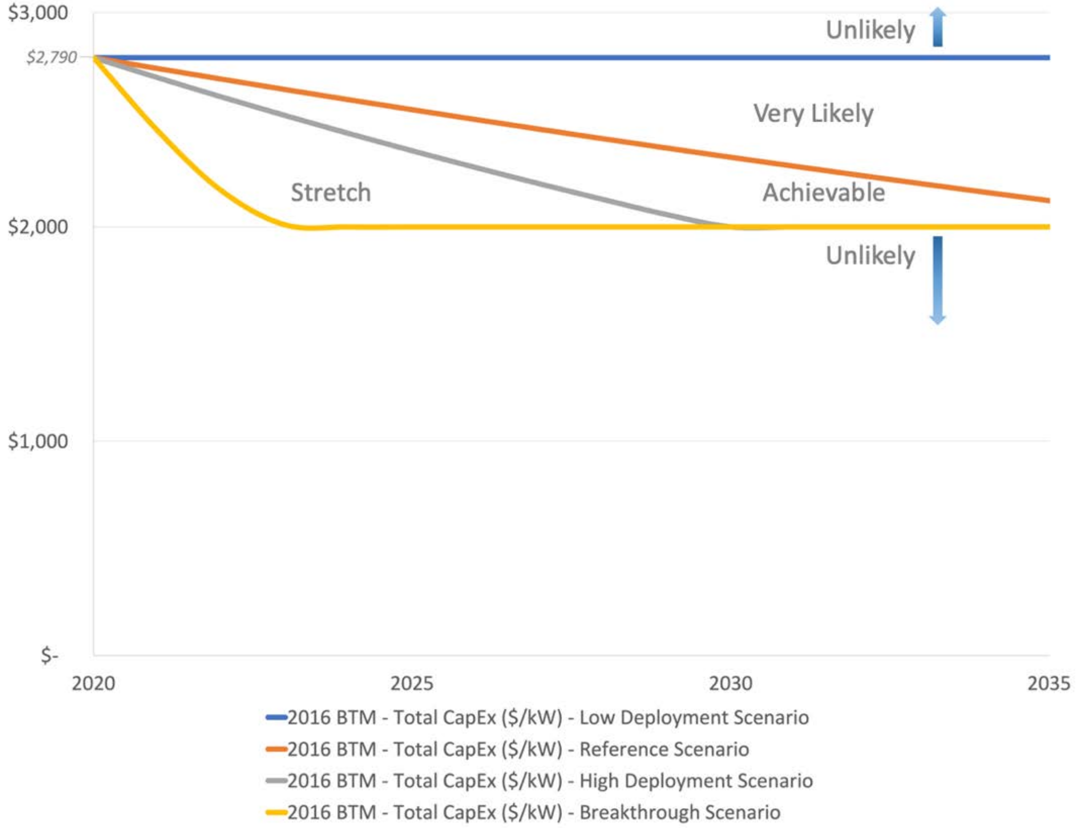
Note: *These projections are for single-turbine distributed wind projects. "BTM" represents behind the meter.*

Commercial-Scale Distributed Wind Project CapEx Projections (2020–2035)



Note: *These projections are for single-turbine distributed wind projects. "BTM" represents behind the meter.*

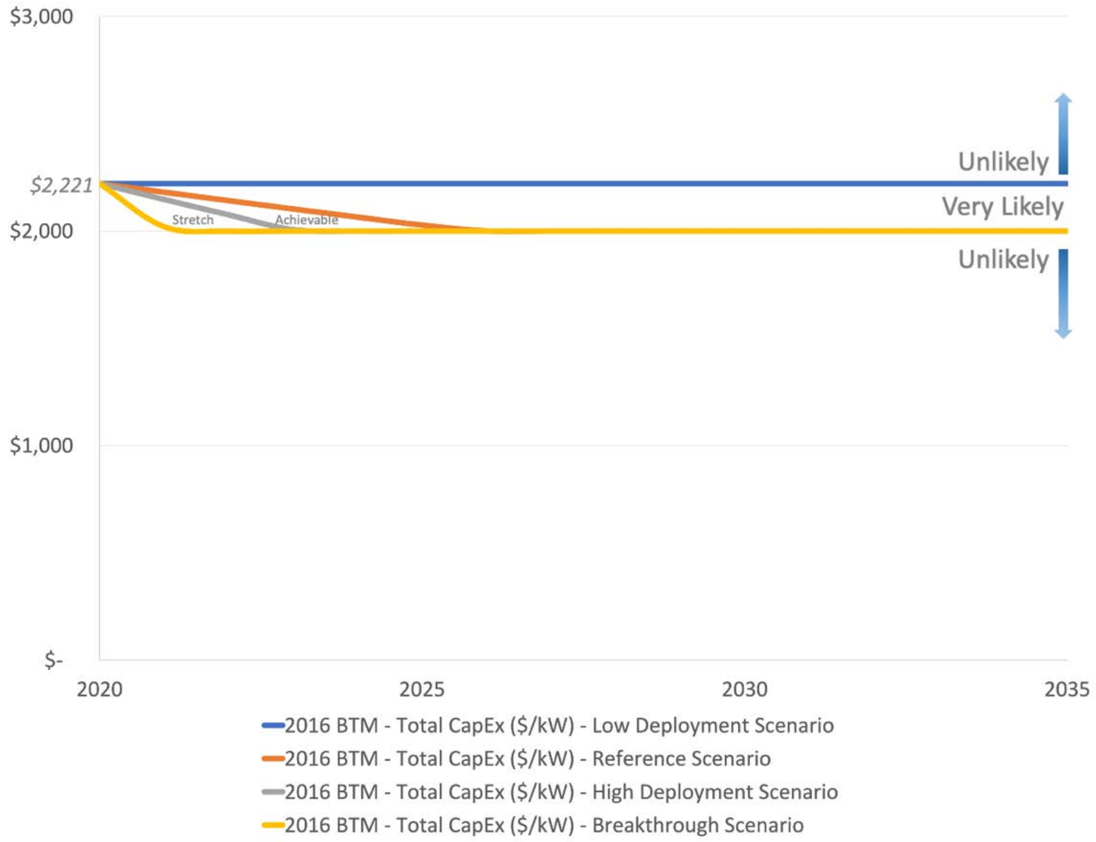
Midsize-Scale Distributed Wind Project CapEx Projections (2020–2035)



Note: *These projections are for single-turbine distributed wind projects. "BTM" represents behind the meter.*

Large-Scale Distributed Wind Project CapEx Projections (2020–2035)

- For large turbines, we relied on the low wind cost trajectory detailed in the 2015 Wind Vision study.
- Given this LCOE trajectory, we then reverse-engineered the required CapEx, OpEx, and capacity factors.

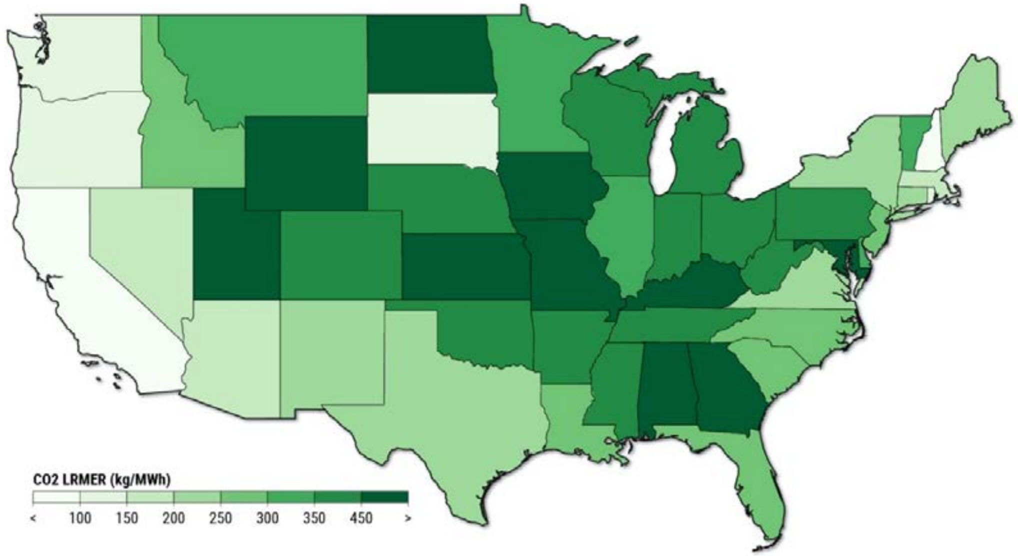


Note: *These projections are for single-turbine distributed wind projects. "BTM" represents behind the meter.*

Distributed Wind Grid Emissions Impacts

Cambium Long-Run Marginal Emission Rate

- Primary output metric: **avoided CO_2 emissions in kg**
  - A measure of the estimated potential reduction in CO_2 emissions that could be achieved by installing a distributed wind or solar system in a given location
- Key input: **long-run marginal emission rate (LRMER) in kg/MWh**
  - The emission rate of the generation that a marginal change in load would be served by
  - Taken from the NREL Cambium model (Midcase scenario).

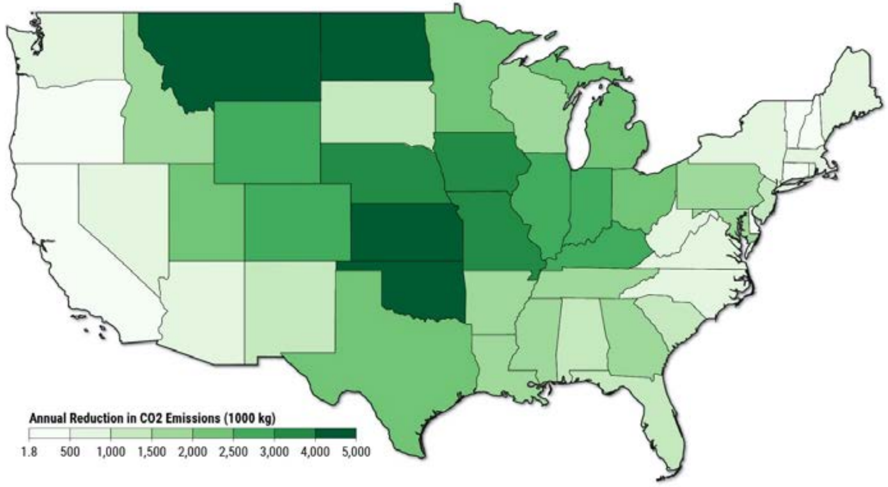


Cambium Impacts – Front-of-the-meter Applications

- Figure shows highest (95th percentile) instance of avoided CO_2 emissions estimates (kg) by state for front-of-the-meter wind applications
- Locations with highest emissions offset potential coincide with regions of good wind resource
  - Close correlation with LRMER input data as well
- Elevated emissions offset potential in:
  - **Montana**
  - **North Dakota**
  - **Kansas**.

Note: Magnitude of emissions offsets much higher than behind-the-meter applications due to larger average system size for front-of-the-meter applications.

Grid Impacts: Annual Reduction in Emissions (kg CO_2/year)



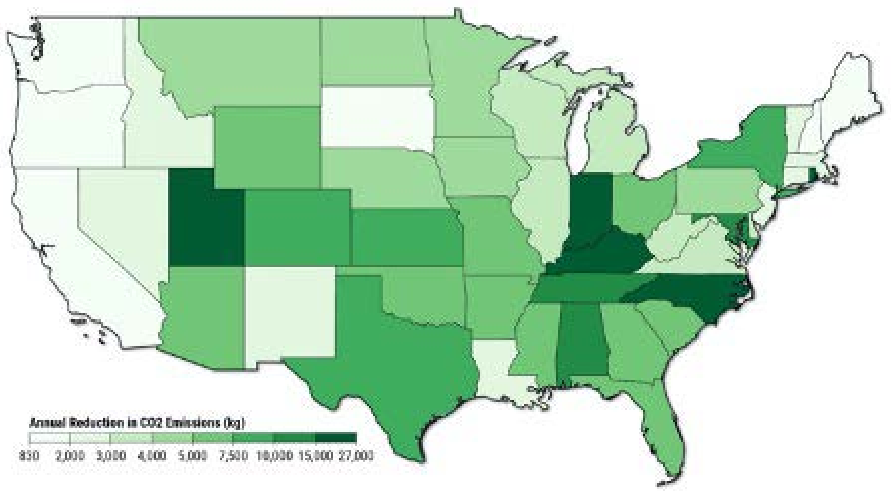
Modeled impacts for front-of-the-meter wind generation on avoided carbon emissions in 2035. These results are not simulated and are exogenously determined by Cambium.

Cambium Impacts – Behind-the-meter Applications

- Figure shows highest (95th percentile) instance of avoided CO_2 emissions estimates (kg) by state for behind-the-meter wind applications
- More nuanced trends in emissions offset potential, though close relationship with LRMER input data still evident
- Elevated emissions offset potential in:
    - **Kentucky**
    - **North Carolina**
    - **Indiana**.

Note: Magnitude of emissions offsets relatively small compared to front-of-the-meter applications due to smaller average system size for behind-the-meter applications.

Grid Impacts: Annual Reduction in Emissions (kg CO_2/year)



Modeled impacts for front-of-the-meter wind generation on avoided carbon emissions in 2035. These results are not simulated and are exogenously determined by Cambium.

Distributed Wind Opportunities in Disadvantaged Communities

Energy Equity

Opportunities in Disadvantaged Communities

Front of the Meter

43% of all suitable parcels

State	Economic Potential 2022 (GW)	80th Percentile Threshold CapEx ($/kW)	Technical Potential (GW)	Average Energy Burden for DACs in Each State (% Income)
Oklahoma	58.5	1,688	78.8	18
Illinois	16.9	1,621	86.1	15
Kansas	15.4	1,612	73.1	20
New Mexico	14.9	1,086	28.4	16
Nebraska	8.6	1,721	36.0	19
Montana	7.7	1,511	57.0	21
New York	4.8	1,342	6.2	14
South Dakota	4.5	1,613	40.5	18
Missouri	4.2	1,544	71.8	20
Iowa	3.4	1,744	18.2	16

States with the largest economic potential for front-of-the-meter applications in disadvantaged communities (Baseline 2022 scenario)

Energy Equity

Opportunities in Disadvantaged Communities

Behind the Meter

47% of all suitable parcels

State	Economic Potential 2022 (GW)	80th Percentile Threshold CapEx ($/kW)	Technical Potential (GW)	Average Energy Burden for DACs in Each State (% Income)
Texas	61.3	7,444	96.4	15
Montana	45.1	9,313	46.6	21
New Mexico	33.5	8,274	108.6	16
California	26.0	21,301	43.1	9
South Dakota	21.3	8,058	21.4	18
Kansas	15.9	9,201	16.0	20
Illinois	13.9	7,656	15.1	15
Kentucky	13.7	7,323	22.8	18
North Dakota	12.8	8,130	22.9	17
New York	12.0	6,719	30.0	14

States with the largest economic potential for behind-the-meter applications in disadvantaged communities (Baseline 2022 scenario)