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RESEARCH ARTICLE

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National-scale impacts on wind energy production under curtailment scenarios to reduce bat fatalities

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Abstract

Wind energy often plays a major role in meeting renewable energy policy objectives; however, increased deployment can raise concerns regarding the impacts of wind plants on certain wildlife. Particularly, estimates suggest hundreds of thousands of bat fatalities occur annually at wind plants across North America, with potential implications for the viability of several bat species. One approach to reducing bat fatalities is shutting down (or curtailing) turbines when bats are most at risk, such as at night during relatively low wind speed periods throughout summer and early autumn. While curtailment has consistently been shown to reduce bat fatalities, the lost power production reduces revenues for wind plants. This study conducted simulations with a range of curtailment scenarios across the contiguous United States to examine sensitivities of annual energy production (AEP) loss and potential impacts on economic metrics for future wind energy deployment. We found that AEP reduction can vary across the country from less than 1% to more than 10% for different curtailment scenarios. From an estimated 2891 gigawatts (GW) of simulated economically viable wind capacity (measured by a positive net present value), we found the mid curtailment scenario (6.0 m/s wind speed cut-in from July 1 through October 31) reduced the quantity of economic wind capacity by 274 GW or 9.5%. Our results indicate that high levels of curtailment could substantially reduce the future footprint of financially viable wind energy. In this context, future work that illuminates cost-effective strategies to minimize curtailment while reducing bat fatalities would be of value.

KEYWORDS
annual energy production, bat fatalities, curtailment, wind energy

1 | INTRODUCTION

Future scenarios for decarbonizing the United States energy system frequently envision broad-scale deployment and geographic expansion of wind energy,[1–3] which could potentially impact certain wildlife populations.[4] Particularly, estimates of bat fatalities at operational wind plants are in the hundreds of thousands per year across the United States and Canada.[5] Mortality searches at wind plants have reported fatalities of at least

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22 of the 45 species that occur in the United States.[6] Several of these species, including the Indiana bat (*Myotis sodalis*), are federally listed as threatened or endangered under the Endangered Species Act (ESA), and additional species are undergoing species status assessments* for potential listing by the United States Fish and Wildlife Service (USFWS). One approach that has consistently resulted in significantly reducing bat fatalities is to curtail wind turbines.[7–9] Curtailment involves slowing or stopping the rotation of the turbine blades during periods of high risk for bat collisions (e.g., during low wind speed conditions).[7] Implementation can be voluntary or required by state permitting authorities or under the ESA. Curtailment to reduce bat-turbine collisions is an evolving practice predominantly founded on a relationship between low wind speed and high bat mortality during late summer and early autumn.[10]

From the perspective of the wind energy industry, these periods of curtailment are not only challenging for current operations due to lost revenue but can be even more problematic for new project development and financing. Research to date has not determined a predictive relationship between wind plant pre-construction bat activity and levels of post-construction bat mortality.[11] The uncertainty around potential lost revenue from curtailment can reduce the amount of debt a project can carry and can make securing financing more difficult.

Given the potential risks for bats and the anticipated expansion of wind energy, there is a growing need to understand the impacts of curtailment on future wind deployment at broad geographic scales and to evaluate the loss of annual energy production (AEP) in terms of profitability and financing uncertainties for new projects. Periods of lost energy production under curtailment can vary between regions due to the diurnal and seasonal trends of wind resource (i.e., the percentage of nighttime hours below the specified cut-in speed during months of curtailment). Additionally, site-specific wind resource quality and wind turbine specifications (e.g., rotor diameter, power curve, and nameplate capacity) are determining factors for the potential AEP and the estimated cost of wind energy.[12,13] The wide range of potential impacts that curtailment could have on wind energy facilities requires broad examination of the sensitivities across varying levels of curtailment as well as within and between regions where future wind deployment might occur. With this type of fleet-wide perspective, more informed industry and project specific considerations can be taken into account, enabling better decision-making regarding current curtailment practices as well as the need for future strategies to manage wind wildlife interactions.

This study quantified the magnitude of impact that varying levels of curtailment could have on hypothetical wind plants deployed across the contiguous United States (CONUS). The unique contribution of this work was to understand, at the national scale, the AEP loss from curtailment and to connect this AEP loss to wind energy financial metrics. Our findings should therefore be considered in relative terms to inform long-term energy planning and technology advancement needs and to illustrate how curtailment could potentially impact the viability of future wind energy deployment.

1.1 | Background

Bats face numerous threats that can result in population level declines, including White-nose Syndrome (WNS), habitat loss, reduced prey base, climate change, and wind energy development.[14–16] Hibernating, cave-roosting bats are most vulnerable to WNS, which has caused population declines in numerous North American species. Estimates suggest that populations of northern long-eared bats (*M. septentrionalis*), little brown bats (*M. lucifugus*), and tri-colored bats (*Perimyotis subflavus*) have declined by more than 90% since WNS was first reported in 2006.[17] Species status assessments for these three bat species are currently being conducted for ESA listing or up-listing from threatened to endangered.† Migratory tree-roosting species have not demonstrated vulnerability to WNS but are impacted by wind turbines and account for nearly 80% of bat fatalities at wind plants across the United States and Canada.[5] The three species most often reported at wind turbines are hoary bats (*Lasiurus cinereus*), eastern red bats (*Lasiurus borealis*), and silver-haired bats (*Lasionycteris noctivagans*).[5,6] In the United States, hoary bat fatalities account for 30.8% of estimated fatalities,[6] which could represent a population-level risk for the species.[18,19] These three unlisted species appear to be particularly at risk because of their low reproductive rate, broad geographic habitat ranges, and migratory routes that span across North America.[20,21] The combined habitat range of these species nearly covers the CONUS (Figure 1).‡§

1.1.1 | Curtailment approaches to reduce bat fatalities at wind facilities

Bat fatalities occur most often during late summer and early autumn when wind speed is relatively low.[22] This prompted experimental studies to compare normal operating conditions to various curtailment scenarios. Curtailment that only uses wind speed and time of year as criteria is commonly referred to as *blanket curtailment*. Blanket curtailment scenarios adjust the turbine cut-in speed, which is the wind speed at which the rotor begins to spin and the turbine generates electricity. Wind turbines with a cut-in speed of 3.5 m/s showed significant reductions in bat mortality by raising the cut-in speed to 5.0 and 6.5 m/s.[7] Although treatment cut-in speeds have varied across studies, 5.0 m/s has commonly been used.[7,8] Whitby et al.[8] conducted a meta-analysis of publicly available curtailment studies and estimated that raising the cut-in speed to 5.0 m/s reduces total bat fatalities by an average of 62% (with 95% confidence internal of 54–69%). The prescribed months of a given blanket curtailment strategy

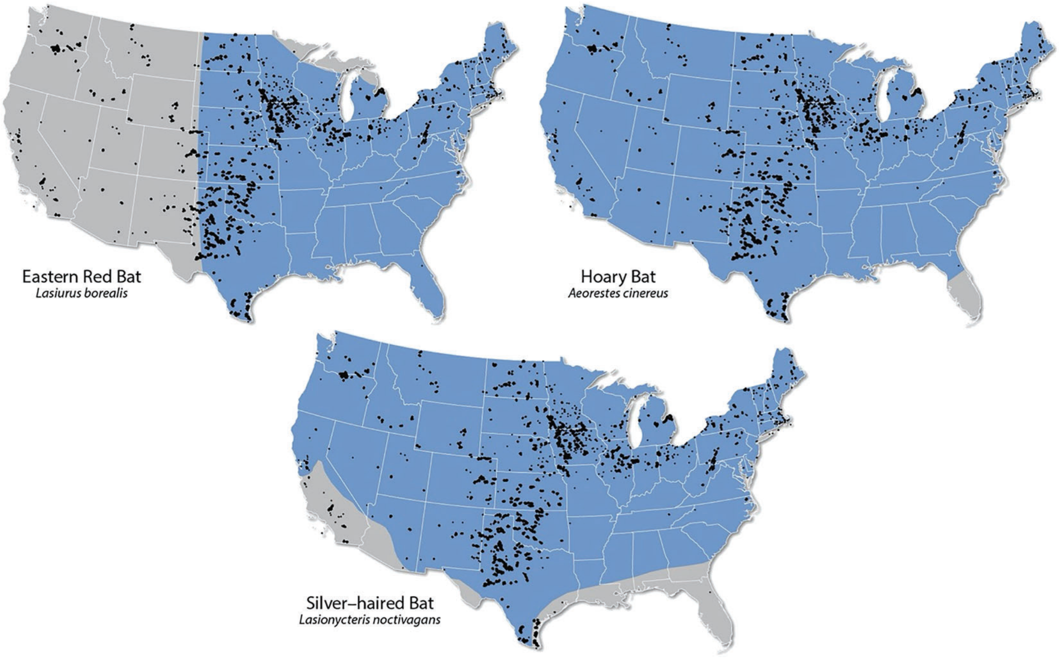

FIGURE 1 Species ranges for the hoary, eastern red, and silver-haired bats. Black dots show locations of existing wind facilities

can also vary across wind plants but mostly include late summer and early autumn. More extensive strategies, including those required by Habitat Conservation Plans (HCPs) for endangered species, can incorporate additional months in spring and summer.[¶]

Blanket curtailment likely overestimates periods of potential risk for bats and can thus result in turbines being curtailed when bats are not active. Other factors that can influence bat presence and activity patterns include differences in species composition, habitat, duration of nighttime hours, and weather conditions (e.g., rain, temperature, and wind regime).[23] From the perspective of a wind plant operator, overestimating bat activity increases the cost of curtailment and unnecessarily results in lost revenue. Because bat activity varies both throughout and among nights during these periods,[23] *smart curtailment* approaches aim to reduce the amount of time that wind plants are not producing electricity by using additional criteria associated with bat activity, such as localized weather conditions. Smart curtailment treatments have included additional variables, such as time of night[24] and temperature.[25] Additional factors that also might be important include precipitation or the abundance and availability of insects, as these might influence whether bats remain active and exert energy.[26] Detection of bat echolocation calls has recently been integrated into approaches to minimize periods of curtailment.[27,28] We clarify that smart curtailment can also refer to the use of bat detection technologies (e.g., acoustic devices), which is also called *sensor-based curtailment*. In this study, smart curtailment means applying additional thresholds for temperature and precipitation rate. We note that curtailment terms are not used consistently throughout the literature and across the wind energy industry.

Curtailment strategies are not implemented in the same way across wind plants, and voluntary actions to reduce fatalities for unlisted species are often not subject to any protocols or reporting requirements unless required by the state, which is uncommon. Threatened and endangered species protected under the ESA, like the Indiana bat, typically comprise a small proportion of fatalities.[5,6] Actions to mitigate[#] take of listed bat species can often be achieved through HPCs[||] and Incidental Take Permits[**] for individual fatalities at wind plants within the relevant species range. An HCP must include plans for minimizing impacts to sensitive species and thus will document the curtailment protocol to which the wind plant will adhere. These are negotiated on a case-by-case basis, and no two HCPs are exactly alike; however, a wind speed cut-in close to 5.0 m/s is often used for curtailment. A Technical Assistance Letter may also be sought to allow a wind plant to operate before an HCP is finalized and approved but requires adherence to strict conditions the USFWS considers meet standards for avoidance.[††] In the case of endangered bats, the USFWS prescribes avoidance by curtailing up to 6.9 m/s.[‡‡] Given the potential listing of several species that span the entire CONUS, technical assistance letters and HCPs might become more common.

1.1.2 | Implications of curtailment for future wind energy deployment

Depending on the specific curtailment implementation, site-specific studies reported lost annual revenue from 0.06% to 3.2%.[8,28,29] With the competitiveness of bulk power markets, including bat curtailment in wind project pre-construction financial analysis would generally be expected to reduce deployment viability. As both the wind resource and distributions of bat populations vary substantially across space and time, the effectiveness of a particular strategy to reduce bat mortality and minimize wind power production loss can also vary with space and time (e.g., across years or between wind plants). The ability to provide a holistic understanding of impacts of different curtailment regimes across broad geographic regions is critical to understanding where and what types of research and development investments and technology innovations could be most impactful. Moreover, with the expanding footprint of wind energy, understanding regional differences in potential risks to bats and impacts on energy production from curtailment can further inform how plants are designed and how technology is deployed across the country. With close to 8 TW of estimated wind energy technical potential across the CONUS,[12] the ranges of hoary and silver-haired bats alone coincide with nearly all of it (Figure 1). Both the competitiveness of the wind energy industry and the viability of vulnerable bat populations are at stake in meeting the country's increasingly ambitious clean energy goals.

2 | METHODS

We applied a range of nighttime curtailment scenarios based on previous studies that varied wind speed cut-in and curtailment months alone (referred to here as blanket curtailment) and in combination with temperature and precipitation rate thresholds (referred to here as smart curtailment). We simulated these blanket and smart curtailment strategies using gridded wind resource data across the CONUS while considering assumptions regarding land access constraints for new wind development (i.e., spatial exclusions).

2.1 | Modeling framework

This study employed the renewable energy potential (reV) model[30,31] developed by the National Renewable Energy Laboratory (NREL) to simulate the impact of curtailment across the CONUS. The reV model is integrated with NREL's System Advisor Model (SAM)[32] to estimate wind power production and to compute financial metrics at discrete locations across large geographic extents. We ran 7 years of hourly simulations at 2-km spatial resolution using NREL's Wind Toolkit (WTK) data set[33] to capture the spatial and temporal variability of wind resource (Figure 2). The WTK includes estimates of wind speed and temperature at multiple heights above ground level as well as surface precipitation rate. This enabled us to examine the impacts from blanket curtailment (considering wind speed alone) and smart curtailment (wind speed, temperature, and precipitation rate) at hourly time steps across different periods from spring through autumn.[§§]

2.2 | Curtailment scenarios

We evaluated 18 scenarios in total across combinations of three cut-in speeds and three timeframes for both blanket and smart curtailment. The cut-in speeds were 5.0, 6.0, and 6.9 m/s. The timeframes were July 15–October 15, July 1–October 31, and April 1–October 31. All scenarios

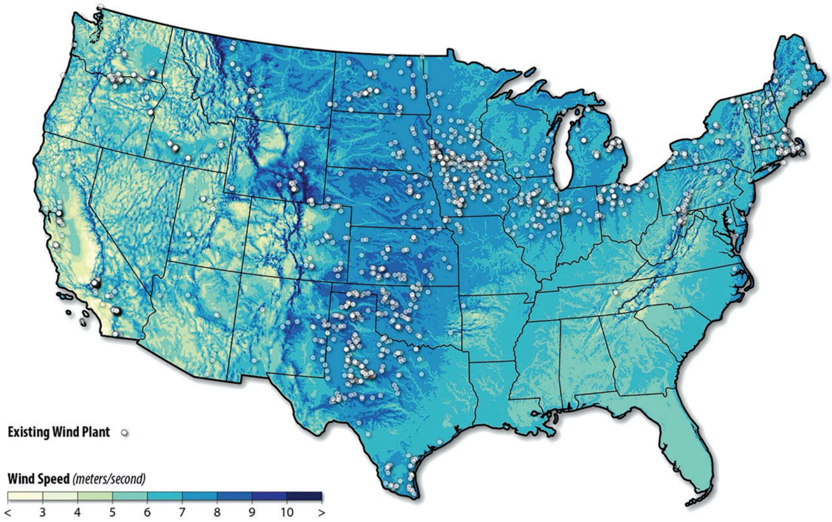

FIGURE 2 Wind speed average at 100-m height above ground level across the CONUS from the WTK. Wind speed average calculated from hourly data across 7 years (2007—2013). Locations of existing wind plants are shown for reference

included autumn migration, and the longest timeframe (April 1–October 31) included additional months for spring migration. Because bats are nocturnal, we curtailed from 30 minutes before civil dusk to 30 minutes after civil dawn. The lowest cut-in speed was 5.0 m/s, which is commonly used in HCPs for listed bat species. The highest curtailment cut-in speed was 6.9 m/s, which was based on the USFWS standards for take avoidance.[¶¶] Smart curtailment, in this case, assumed that bats are only active when the air temperature (at hub height) is above 10°C,[25] and as a proxy for rainy conditions, we assumed that greater than 1 mm per hour represents rain that would inhibit bat activity.

2.3 | Technical potential assumptions

Within the reV model, we applied spatial exclusions from Lopez et al.[12] to represent siting constraints for wind deployment. Exclusion assumptions limit available land for deployment based on national-scale data including terrain, land use, and infrastructure. Specifically, we excluded urban areas, wetlands, steep terrain, legally or administratively protected lands, setbacks on buildings, roads, railroads, transmission lines, and radar stations and enacted county and state restrictions for wind development.[##] Based on non-excluded land for potential wind development, estimates of available capacity assumed a spatial capacity density of 3 MW/km^2, as is commonly applied in technical potential assessments in the United States.[12,30,34,35]

2.4 | Technology and cost assumptions

We modeled power output assuming contemporary turbine technologies selected according to the seven-year mean wind speed at each WTK location. Turbine assumptions (hub height, rotor diameter, nameplate rating, and power curve) aimed to represent the wide range of turbines that have recently been installed in the United States or will be available in the near future. We developed four turbine configurations based on the wind resource across the country, aiming to consider all regions including areas with little or no wind deployment currently (e.g., parts of the South and Southeast). The turbine configuration applied at each location was determined by the mean wind speed (Table 1) and did not consider site-specific turbulence or terrain features. Specific power ranged from 170 to 321 W/m^2 and net capacity factors (NCFs)[‖‖] assumed 20.8% total plant losses, which included electrical, environmental, turbine, availability, and wake losses. These plant losses represent a simplifying assumption for more detailed plant losses, which are difficult to capture in national-scale assessments. Therefore, our aim was to capture regional trends and illustrate the relative impacts of bat curtailment and differences between curtailment scenarios.

Capital costs in this study were broken down by turbine and balance of station (BOS) costs for a representative 100-MW wind plant. Turbine costs included the tower and the rotor and nacelle assembly, and BOS costs captured other wind plant investments from development through installation[36] (Table 1). We assumed fixed operations and maintenance (O&M) costs of \$44/kW per year. We applied regional multipliers to the BOS costs to represent differences in labor rates, materials and equipment costs, and seasonal working constraints[***] (Figure 3).

2.5 | Evaluations of financial metrics

This study examined the impact of curtailment on two financial metrics using NREL's SAM[32]: Net present value (NPV) and power purchase agreement (PPA) price. NPV is a common financial indicator of a wind plant's profitability and general economic feasibility, where positive NPV suggests

TABLE 1 Turbine configurations and cost assumptions based on long-term wind speed

	Mean wind speed			
Model parameter	**<7 m/s**	**7–8 m/s**	**8–9 m/s**	**>9 m/s**
Rotor diameter (m)	150	140	135	124
Rating (MW)	3.0	3.5	3.7	3.9
Specific power (W/m^2)	170	229	258	321
Hub height (m)	95	90	87.5	82
Max tip height (m)	170	160	155	144
specific power	170	229	258	321
Turbine cost (\$/kW)	852	804	787	785
Base BOS cost (\$/kW)	464	444	438	415

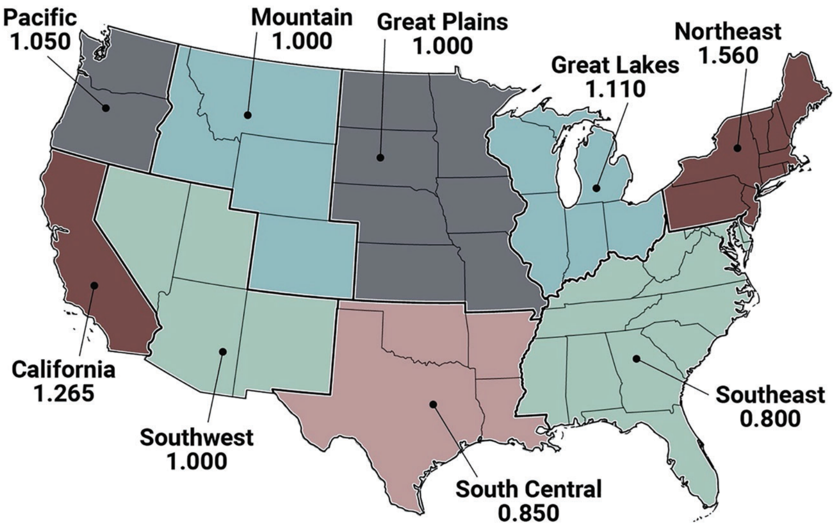

FIGURE 3 Regional BOS cost multipliers

financial viability and negative NPV indicates that a project would be economically infeasible.[37] NPV weighs the costs of a project against the estimated revenue to inform investment decisions. Although a positive NPV can be generally analogous to a profitable project, we note that a positive simulated NPV does not necessarily indicate that a specific project or site would in fact be profitable or would be likely to secure financing. Any site-specific evaluation would require more resolved and site-specific data to inform actual profitability and bankability. Rather, we are using positive NPV as a simple metric to represent economic feasibility, which does not consider PPA versus merchant sales during the project term, state wind energy production taxes, or the impacts of year-to-year wind resource variability on project cash flow. PPA price in this study represents the wholesale market price of electricity generated by a wind plant. The *PPA price offset* is the increase in estimated PPA price under curtailment—relative to no curtailment—that a project would need to secure during development to meet a target internal rate of return (IRR). Given the estimated cash flow of a project, the IRR is the rate at which the NPV would be zero.[37] PPA price is negotiated prior to construction and the agreement does not always cover the lifespan of a project, so the PPA price offset should be interpreted as the financial burden a wind project would have to overcome upfront under the curtailment scenarios. We applied a 20-year analysis period for the PPA, debt tenor, and discount rate, which is longer than many PPAs but aimed to align with the lifespan of typical projects.[38] A PPA can range from 10 to 25 years, and some plants sell into merchant markets after the first 10 years. PPA prices for wind energy vary highly between individual projects, are influenced by incentives (e.g., the production tax credit [PTC]), and differ across regional energy markets. We note that the required PPA price to make a project financially viable is highly site-specific and is driven by factors that could not be captured in a national-scale analysis, including land lease expenses, permitting costs and timeline, and transmission availability and costs, among others. Exploring the sensitives to these factors in further detail was beyond the scope of this study. To calculate the PPA price offset, we assumed a target IRR of 8% and applied the modified accelerated cost recovery system and bonus depreciation.[†††]

To represent regional market impacts on NPV, we modeled PPA prices for each independent system operator (ISO) or non-ISO region (Figure 4). We aimed to capture the regional differences between energy markets while also representing the undeveloped wind energy potential across these large areas. We estimated the capacity weighted NCF (based on non-excluded land area) and regionally adjusted capital costs to estimate a wholesale market price for each region. We then adjusted the regional market prices assuming a $20/MWh credit from the PTC.[‡‡‡] We made slight adjustments to the West, CAISO, PJM, and Southeast regions to calibrate with the national PPA price average from recent operational plants.[39§§§]

3 | RESULTS

Our results quantified the potential impact on wind energy deployment from low to high levels of curtailment at the regional and national scales. Given the broad geographic extent of this study, we aimed to evaluate the sensitivities of curtailment parameters (e.g., cut-in speed and curtailment timeframe) and connect the reduction in AEP to impacts on wind plant financial metrics. The following sections summarize our results first in terms of AEP reduction, then in terms of monthly loss of power production, and finally in terms of curtailment impacts on NPV and the PPA price offset.

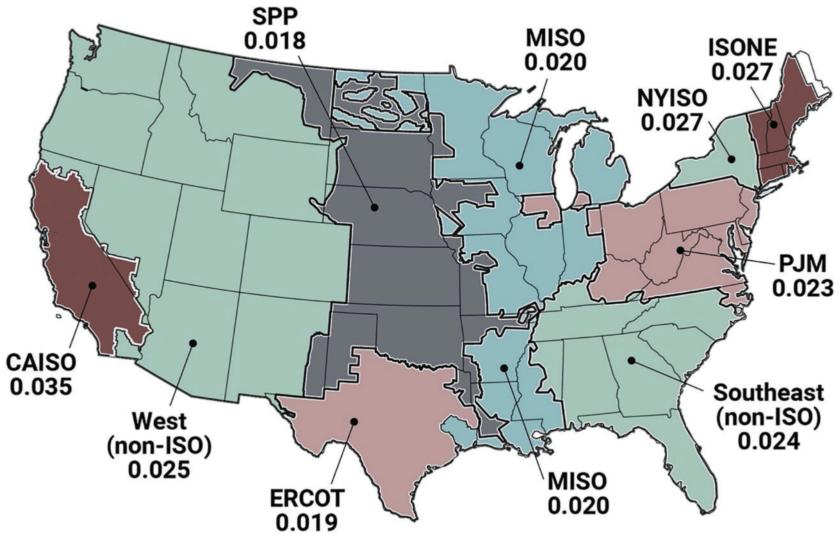

FIGURE 4 Estimated PPA price ($/kWh) by ISO or non-ISO region

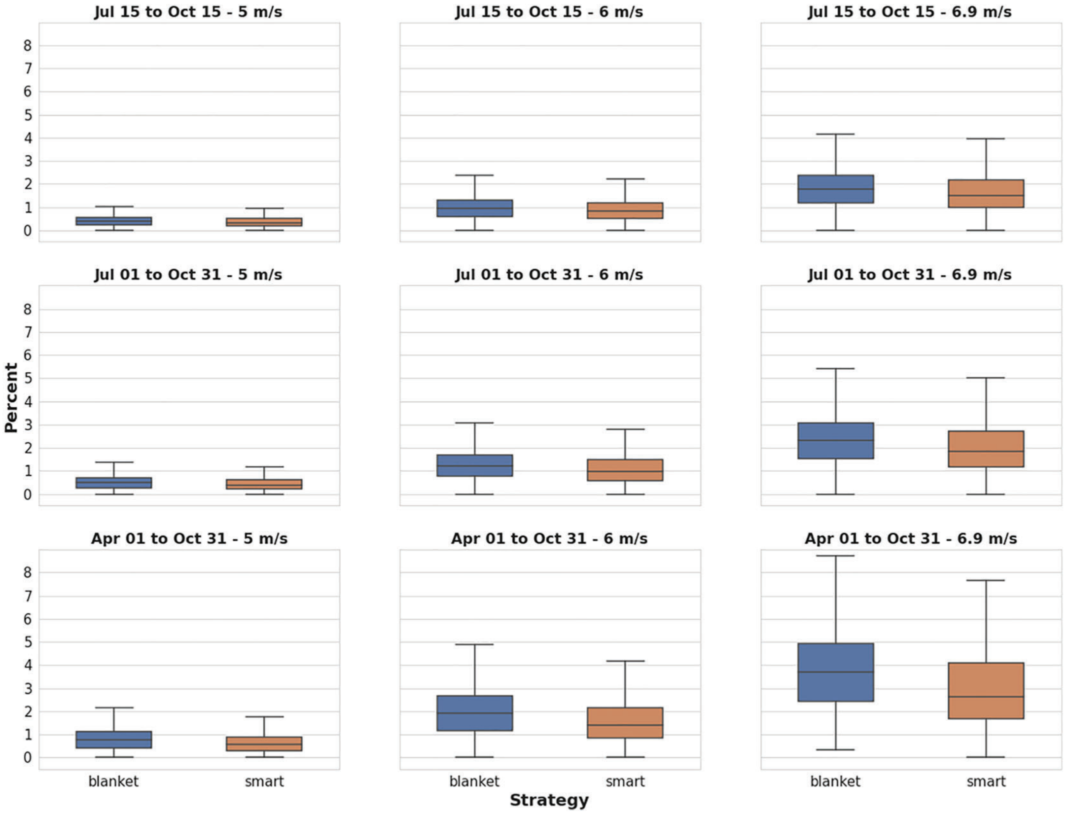

FIGURE 5 Percentage AEP reduction across all 18 scenarios at the national scale. Upper left is the low scenario (5 m/s from July 15 to October 15), the mid scenario (6 m/s from July 1 to October 31) is in the center, and lower right is the high scenario (6.9 m/s from April 1 to October 31)

3.1 | National-Scale AEP reduction

The 18 scenarios examined in this study demonstrate a wide range of AEP reduction driven principally by cut-in wind speed and timeframe of curtailment. Blanket versus smart curtailment had a smaller magnitude of impact that increased with higher levels of curtailment (Figure 5). A subset of the nine cut-in speed and timeframe combinations will be referred to subsequently as the low scenario (5.0 m/s from July 15 to October 15), the mid scenario (6.0 m/s from July 1 to October 31), and the high scenario (6.9 m/s from April 1 to October 31). Summarizing the relative impact between scenarios, the low scenario showed median AEP reduction of 0.5% and 0.4% for blanket and smart curtailment, respectively, while the median AEP reduction for the mid scenario was 1.3% and 1%, and for the high scenario was 3.8% and 2.7% for blanket and smart curtailment, respectively. The relative impact of cut-in speed on AEP was larger than that of time-frame across these scenarios (e.g., Figure 5 shows that reduction in AEP was greater across rows from 5.0 to 6.9 m/s than down columns with increasing curtailment timeframes).

3.2 | Regional AEP reduction

Our results illustrated the regional variability of AEP impact from curtailment and highlighted the relationship between wind speed distribution at a given location and AEP reduction (Figure 6). As would be expected, areas with high nighttime wind speeds—that are predominantly above the scenario cut-in speed—showed less impact from curtailment. For example, the interior of the country (Great Plains, Great Lakes, and South Central regions) has relatively high wind resource and showed less AEP reduction compared to the West Coast, Northeast, and Southeast.

Figure 7 shows the distributions of percentage AEP reduction regionally for the low, mid, and high scenarios. California and the Great Plains were on the high and low ends for the mid scenario with 1.8% and 0.7% median AEP reduction, respectively. Table 2 summarizes the percentage AEP reduction at reference locations across the summary regions. Results at these locations represent potential implications for areas with existing wind energy deployment. Similar to the national-scale results, the benefit of smart over blanket curtailment was relatively small for the low scenario and much greater for the high scenario. We found that smart compared to blanket curtailment avoided up to 0.06% AEP loss under the low scenario (from 0.24% to 0.18% AEP reduction at the Northeast location), while under the high scenario smart versus blanket curtailment avoided up to 1.46% AEP loss (from 4.02% to 2.56% AEP reduction at the Southwest location). The cost of smart versus blanket curtailment was not considered in this study; however, these results suggest the value of smart curtailment could be greater under higher levels of curtailment (increased cut-in speed and/or longer timeframe).

The benefit of smart over blanket curtailment in terms of AEP was higher in regions with relatively lower nighttime temperatures and more nighttime precipitation during the summer and autumn. The distributions of AEP reduction relative to available capacity in the Northwest,

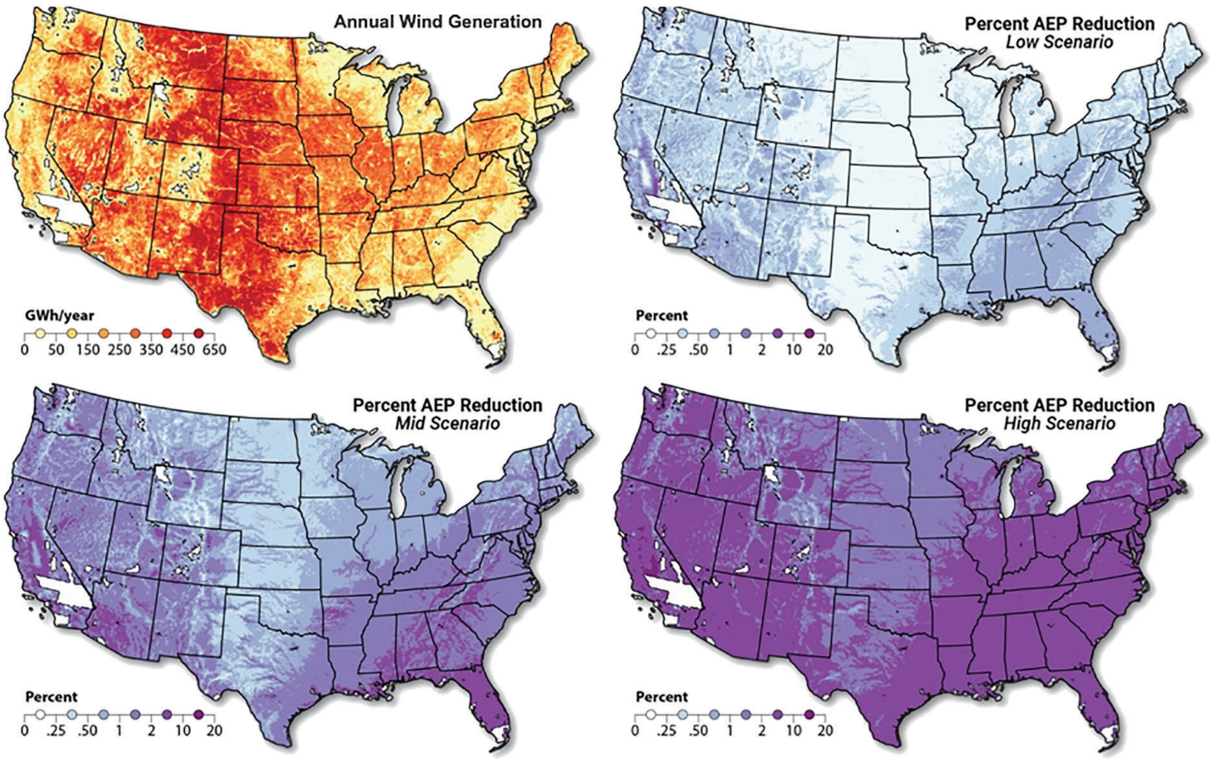

FIGURE 6 Percentage AEP reduction across the CONUS under low, mid, and high blanket curtailment scenarios. The white extents indicate excluded areas

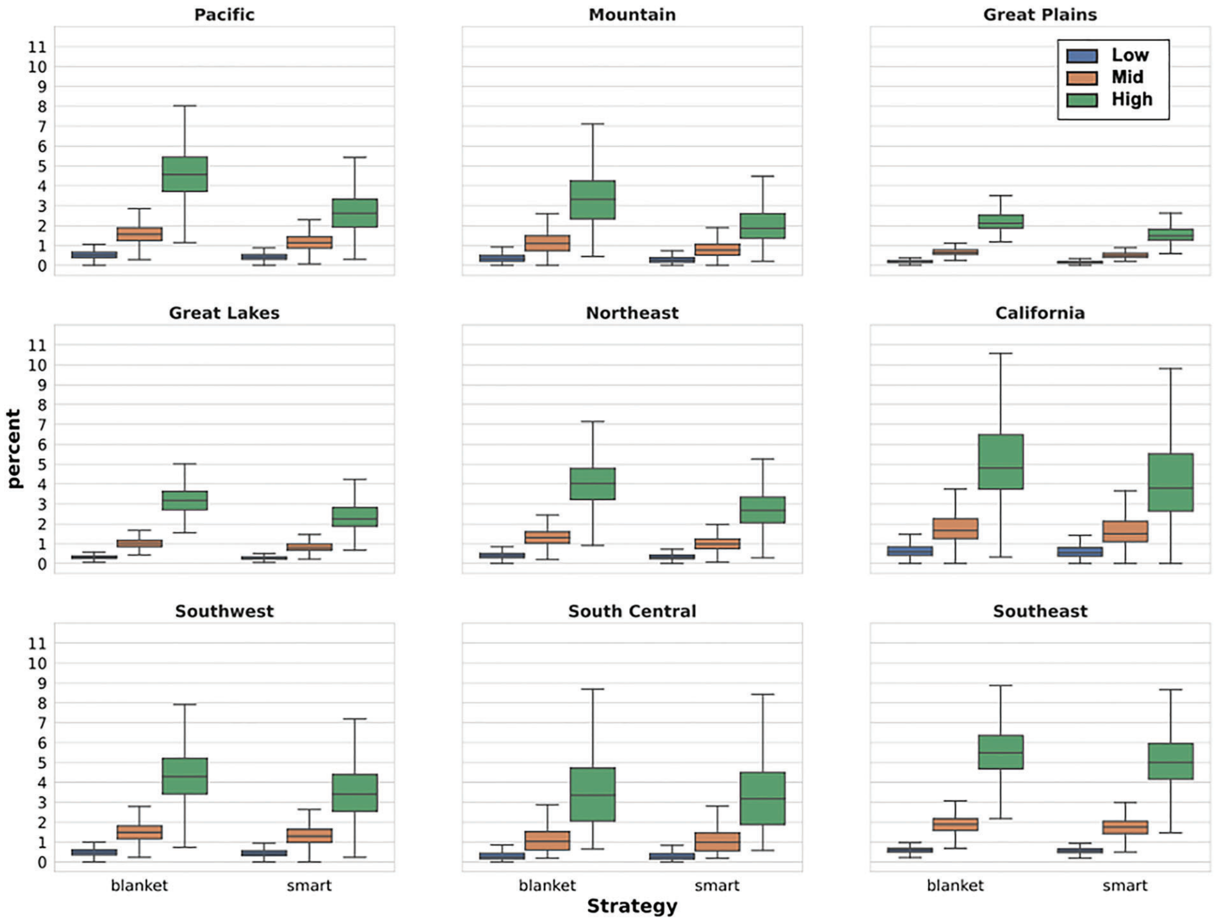

FIGURE 7 Regional percentage AEP reduction for low, mid, and high curtailment scenarios

TABLE 2 Percentage AEP reduction at regional reference locations

Reference location	Mean annual wind speed (m/s)	Net capacity factor (%)	% AEP reduction Blanket—low	Smart—low	Blanket—high	Smart—high
Pacific: North-Central OR	6.68	37	0.24	0.24	2.47	2.00
Mountain: Southeast WY	9.48	39	0.10	0.08	1.31	0.79
Great Plains: North Central IA	7.84	44	0.14	0.12	1.83	1.33
Great Lakes: Northwest OH	6.90	42	0.39	0.36	3.44	2.64
Northeast: Southwest PA	7.26	39	0.24	0.18	2.39	1.55
California: Central Valley	7.00	38	0.17	0.16	2.25	1.89
Southwest: Eastern AZ	6.32	33	0.40	0.36	4.02	2.56
South Central: Northern TX	8.13	42	0.07	0.07	1.41	1.35
Southeast: Eastern TN	6.68	35	0.45	0.42	4.13	3.70

Note: Mean annual wind speed (m/s) based on 7-year WTK mean. Net capacity factors are without bat curtailment and include standard plant losses described in Section 2.4.

Mountain, and Northeast regions suggest potential benefit from smart curtailment (Figure 8). For example, the median AEP reduction for the Pacific region shifted down from 4.5% to 2.6% under the smart mid versus the blanket mid scenario, while in the South Central region, the two distributions coincided closely.

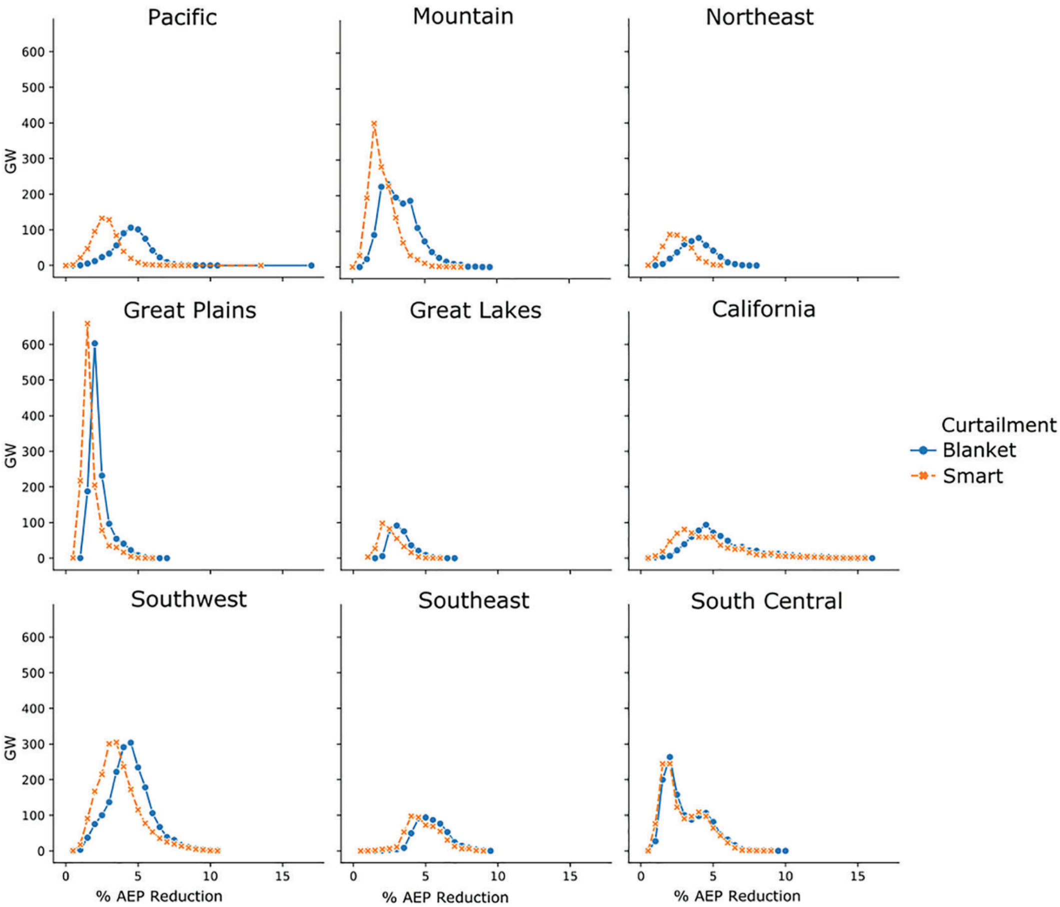

FIGURE 8 Regional distributions of percentage AEP reduction under mid smart and blanket scenarios by available capacity after removing land area from spatial exclusions (see Lopez et al.[12] for exclusion assumptions)

3.3 | Monthly impacts on energy production

When the percentage of lost power production was considered on a monthly basis, curtailment clearly had a larger percentage impact relative to AEP. Maximum loss in monthly power production ranged from 0.5% for the smart low scenario at the South Central reference location to 16.6% for the blanket high scenario at the Southeast reference location (Figure 9). Seasonal trends in wind resource play an important role on the impacts of curtailment on monthly power production. For example, the Southwest location showed a large seasonal drop in NCFs without curtailment (Figure 10 left column) in the late summer and early autumn, corresponding to substantial loss of power production during these months (as high as 14.5%). The South Central location demonstrated less seasonal variability in NCFs and thus less and more stable loss of power production across months of curtailment compared to the other locations shown. The Southeast location had the most pronounced seasonal decrease in NCFs and the greatest power production loss during months of curtailment (as high as 16.6%, as mentioned above). The Pacific and Southwest reference locations showed pronounced difference in the spring and autumn between blanket and smart curtailment when temperatures are typically colder and/or there is more rain. The Southeast location also showed benefit from smart over blanket curtailment in the mid and high scenarios, likely due to increased precipitation.

3.4 | Curtailment impacts on financial metrics

These results connected, at a high level, the relationship between lost energy production and the impacts on wind plant development (e.g., financing and PPAs) and operations (e.g., revenues and financial solvency). The impact of curtailment on the wind industry is more relevant in terms of financial metrics than AEP reduction. The competitiveness of bulk power markets means that negotiations of a PPA can pivot on fractions of a cent, with the 2015–2018 national average PPA price around \$0.025/kWh.[39] Figure 10 shows how much higher the PPA price would have to be for a project under development to achieve a target IRR of 8% under the three curtailment scenarios, illustrating the upfront financial

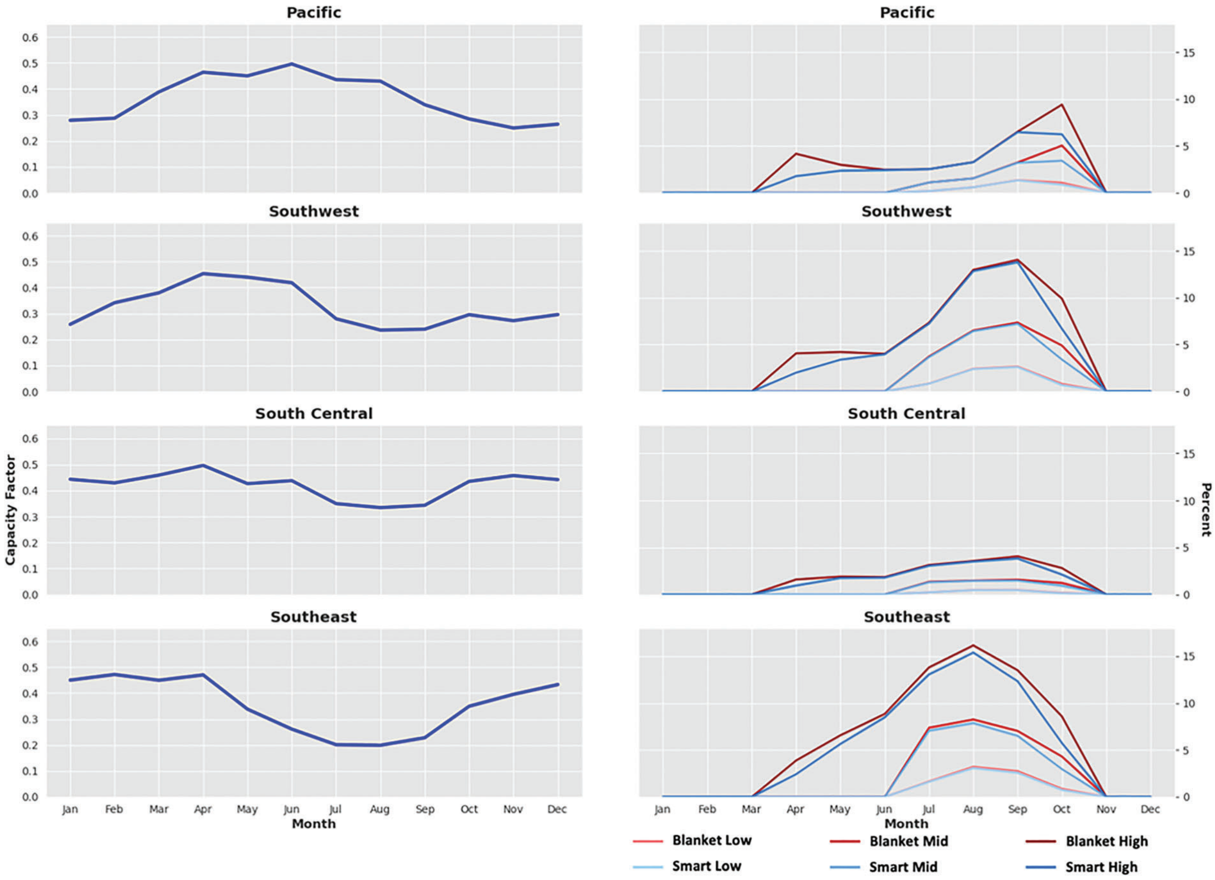

FIGURE 9 Net capacity factors without curtailment (left column) and monthly percentage energy production loss under curtailment (right column) at a subset of reference locations. Net capacity factor is the percentage of nameplate capacity generated on average during each month. The side-by-side comparison illustrates the relative monthly energy production without curtailment and the percentage of that production potentially lost under curtailment scenarios. Monthly profiles calculated using the 2012 WTK wind resource

burden. Similar to regional trends in AEP reduction, the PPA price offset was higher in areas with lower wind resource. The maps in Figure 10 reflect the spatial patterns of wind resource (Figure 2) but also account for regional differences in BOS costs, as described in Table 1. The impact across the CONUS showed the low smart scenario required less than a 2% PPA price offset to meet the target IRR. The mid smart scenario showed between 2% and 4% offset for most of the Southeast as well as parts of the South Central, the Southwest, and California. The high smart scenario illustrated how large areas would require a 4% or higher PPA price to meet the target IRR.

We examined the amount of potential capacity that would change from positive to negative NPV under bat curtailment scenarios, as a surrogate for relative economic feasibility. We remind the reader that we used positive versus negative NPV to bound the magnitude of financial impact at the national scale; a project-level analysis would include site-specific development factors that could substantially change the NPV. Without curtailment, we estimated 2891 GW of economically feasible potential capacity. From that potential capacity, we found that 84 GW (2.9%) under the low smart scenario, 274 GW (9.5%) under the mid smart scenario, and 753 GW (26%) under the high smart scenario would no longer be economically feasible (Figure 11). Increased curtailment removed potential capacity in areas that were marginally feasible without curtailment and constrained the potential for future deployment to where wind has historically been most economically viable.

4 | DISCUSSION AND CONCLUSIONS

This study examined the relative differences in AEP reduction over the range of curtailment scenarios at 1.5 million wind resource locations across the CONUS. This spatial fidelity provides insight into the potential impacts of curtailment from a regional context and for areas that do not yet have operational wind plants (e.g., much of the Southeast United States). Our modeling approach represented regional differences in wind plant costs as well as differences between regional wholesale wind energy markets, represented as levelized PPA prices. There are several specific limitations in this study that should be considered while evaluating the results. The costs of wind energy are expected to continue to decrease in the

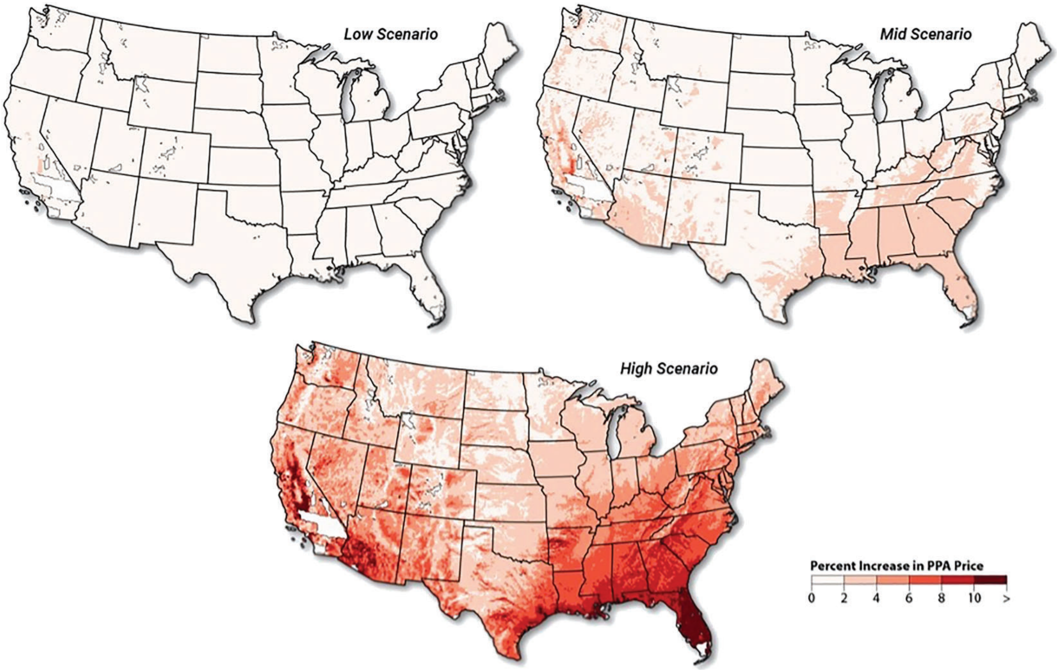

FIGURE 10 PPA price offset for a wind project with target IRR of 8% under low, mid, and high smart curtailment scenarios. The white extents indicate excluded areas

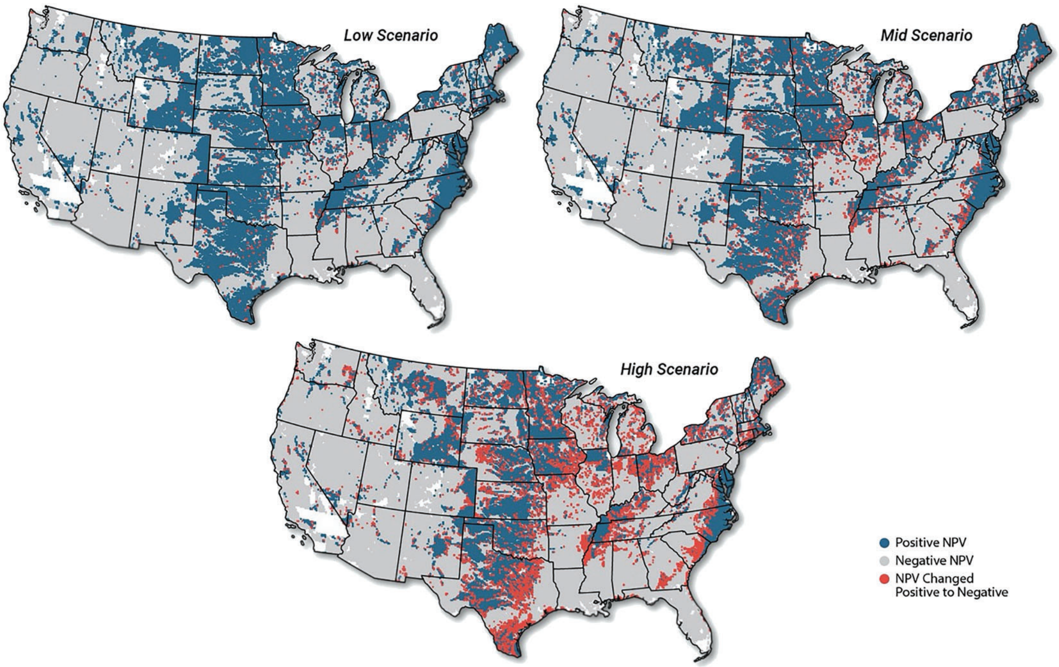

FIGURE 11 Positive and negative NPV and areas that flipped from positive to negative under smart curtailment scenarios. The combined blue and red areas show where NPV was positive without curtailment. The white extents indicate excluded areas

coming decades[40]; however, a detailed examination of future cost projections was outside the scope of this study. Wind plant financial modeling is highly complex and site-specific, and our modeling approach did not aim to examine the impacts of curtailment in terms of project-specific profitability or return on investment, which are influenced by development and construction costs, land lease, site characteristics, transmission costs, among many other factors.[41] Furthermore, the legal and contractual implications of curtailment are project-specific and beyond the scope of this analysis. We included the PTC in our financial modeling; elimination of or changes to the PTC would substantially change the results.

The national scale of this analysis required simplifying our assumptions in estimating wind plant energy production and computing financial metrics. Nonetheless, the relative impact of curtailment on the metrics we presented aimed to bound and inform the magnitude of the issue when considered within a regional context. While our assumptions regarding financial parameters are not representative for all locations and across different developers and plant operators, the differences we observed in NPV and PPA price offset likely captured the trends and relative impact of curtailment on the viability of new wind deployment but should not be construed as indicative of performance at any specific point in space or time. Examination of the sensitivities driven by cost assumptions and financial parameters (e.g., sensitivities to capital costs and O&M) was beyond the scope of this study and is an area for future research. Furthermore, uncertainty in cost reduction trajectories and future energy market projections are important to consider in evaluating the results of this study.

One of our key findings with respect to power production was that cut-in speed had a larger impact on AEP than the months of curtailment, suggesting that a longer timeframe of curtailment might have less financial impact on the wind industry than higher cut-in speeds. However, further research is needed to quantify these tradeoffs in terms of risk reduction for bats. Smart curtailment, as modeled here, showed the most benefit in regions with relatively lower nighttime temperatures and/or more precipitation during curtailment periods, for example, the Pacific, Mountain, and Northeast regions. Specific locations showed smart curtailment to reduce AEP loss by up to 40% over blanket curtailment for the high scenario (from 3.4% to 2.6% AEP loss). Additional research is needed to contextualize the value of smart versus blanket curtailment for both bats and wind plants. Noting that we examined smart curtailment specifically based on temperature and precipitation, research demonstrating the efficacy of sensor-based curtailment and bat deterrent technologies across broad geographies is needed to inform future national-scale assessments.

For the low and mid smart scenarios, we found AEP reduction to be below 3% at nearly all locations, which coincides with previous site-based research at existing wind plants.[7,8] The high smart scenario showed substantially higher AEP reduction with large regional differences reaching as high as 9.8% in California. In the Southeast region, 42.7% of the available capacity with positive NPV under no curtailment changed to negative NPV under the high smart scenario, suggesting financial infeasibility for wind projects. However, the AEP reduction among this financially infeasible capacity in the Southeast ranged from 1.9% to 6.9% (median of 4.3%). Across the CONUS, the range of AEP reduction for financially infeasible capacity under high smart curtailment was 0.5% to 6.9% (median of 2.3%). This wide range suggests that the percentage AEP reduction alone might not be a good indicator for the financial impact of curtailment on wind energy projects. Regional differences across energy markets and capital and O&M costs further complicate using AEP reduction to characterize the potential impact on new wind development.

Our results suggest that high levels of curtailment (both blanket and smart) could substantially reduce the future footprint of financially viable wind energy. Our modeling approach considered spatial exclusions including setbacks from infrastructure (e.g., from buildings, roads, and radar stations), urban areas, steep terrain, and protected areas.[12] Consideration of additional siting and operational constraints could further reduce the geographic footprint of viable wind energy deployment. These encompass a broad range of considerations including social acceptance (e.g., turbine noise, shadow flicker, and viewshed),[42] transmission constraints and costs (e.g., available transmission capacity and transmission congestion),[43] airspace concerns (e.g., radar line-of-sight and civilian and military airspace),[44] and wildlife other than bats (e.g., sage-grouse and eagles).[45,46]

Curtailment periods could be shorter than one hour (the temporal resolution used in this study), and wind plants could respond at the minute-level to changes in wind speed. This study did not examine whether using finer temporal resolution wind resource data (e.g., 5 minute) would change our results. Wind turbine power curves have a roughly cubic relationship, below rated power, between wind speed and power output and are typically very steep between 5 and 6.9 m/s. This suggests our results might underestimate the losses in AEP, especially at locations with high sub-hourly wind speed variation. Examining the sensitivities of AEP loss driven by the temporal resolution of wind resource data and the shape of turbine power curves could help to further understand these relationships.

The diurnal and seasonal patterns of wind resource and how they align with electricity demand are also important to consider in regional contexts.[47] Furthermore, the value of energy production is not constant from dusk to dawn, with higher electricity consumption in the evening hours than during the rest of the night.[¶¶¶] Examining these relationships between energy markets and the timing of nighttime curtailment (e.g., considering time of day pricing) is critical in future work to further inform the financial impacts of curtailment with important nuance. For example, wind energy can provide important value to the grid by complementing solar generation profiles to reduce the combined variability and increase reliability[48]; curtailment of wind energy production during evening hours in the summer months could reduce the benefits of this complementarity.

Continuous bat activity is unlikely when blanket or smart curtailment criteria are met, and therefore, there is a large opportunity for bat detection technology to reduce the time of curtailment required to minimize risk to bats.[28] However, the costs and efficacy of detection technologies remain open questions. In this study, we assumed that when scenario criteria were met, bats would be continuously active—which likely overestimated the necessary amount of curtailment—yet developers, plant operators, and regulators currently have limited recourse beyond that assumption in designing a curtailment approach.

The reduction in annual and monthly energy production varied substantially across cut-in speeds and timeframes of curtailment. This wide range of impact on wind energy production merits further field studies to better quantify how much risk of bat fatalities can be reduced with increasing curtailment intensity. Although general patterns of bat activity and risk are known (i.e., bat activity and risk tend to increase in late summer and early autumn under low wind speed conditions),[5,6,8,10] there remains a high degree of variability in mortality among nights. Additional data relating bat activity to weather conditions or insect availability may provide more insight into when bats are at risk to better inform curtailment scenarios. Moreover, a better understanding of the connection between bat activity and fatalities at operational wind plants will be necessary to prescribe curtailment regimes that are feasible for the wind industry while sufficiently reducing the impact on bat populations. For example, Peterson et al.[49] found that the subset of bat activity measured only when wind turbines were operational, or exposed activity, explained 80% of the variation in carcass-based estimates of fatality rates. The authors noted that measuring the exposed bat activity provides a quantitative basis for designing, evaluating, and adaptively managing curtailment strategies.

It is possible for additional bat species, including those with relatively large geographic ranges (e.g., the little brown bat or hoary bat), to be listed as threatened or endangered under the ESA within the decade. Given the results presented, additional investigation into cost-effective minimization strategies is warranted. Smart curtailment strategies based on modeled or sensor-based detection of bat activity, or other strategies that do not require changes to turbine operations, such as deterrent technologies,[50] might provide more feasible solutions to maximize AEP while minimizing wind turbine-related bat mortality.

A holistic understanding of impacts under different curtailment regimes across broad geographic regions is critical to understanding where and what types of research and development investments and technology innovations would provide the most benefit. The confluence of all these factors with wildlife impacts (not only on bats) will be an important focus for future research, particularly in modeling the evolution of the future power system with broad scale deployment of wind energy.

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PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available from the Wind Toolkit at https://www.nrel.gov/grid/wind-toolkit.html and the National Wind Energy Supply Curves at https://www.nrel.gov/gis/wind-supply-curves.html.

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ENDNOTES

[*] https://www.fws.gov/southeast/endangered-species-act/species-status-assessments/

[†] https://www.fws.gov/northeast/virginiafield/pdf/news_releases/20201125%20Bat%20SSA%201-page%20update.pdf.

[‡] Species range data from the International Union for Conservation of Nature (IUCN): https://www.iucn.org.

[§] Hoen, B.D., Diffendorfer, J.E., Rand, J.T., Kramer, L.A., Garrity, C.P., and Hunt, H.E., 2018, United States Wind Turbine Database (ver. 3.2, October 14, 2020): U.S. Geological Survey, American Wind Energy Association, and Lawrence Berkeley National Laboratory data release, https://doi.org/10.5066/F7TX3DN0.

[¶] Habitat conservation plans for the federally endangered Indiana bat (*Myotis sodalis*) https://www.fws.gov/midwest/endangered/permits/hcp/r3hcps.html.

[#] The United States Fish and Wildlife Service defines mitigation as measures taken to “avoid, minimize, and compensate” for impacts. https://www.federalregister.gov/documents/2016/11/21/2016-27751/us-fish-and-wildlife-service-mitigation-policy.

[||] https://www.fws.gov/endangered/what-we-do/hcp-overview.html.

[**] https://www.fws.gov/endangered/permits/index.html.

[††] The United States Fish and Wildlife Service defines avoidance as “avoiding the impact altogether by not taking a certain action or parts of an action.” https://www.federalregister.gov/documents/2016/11/21/2016-27751/us-fish-and-wildlife-service-mitigation-policy.

[‡‡] https://issues.nawindpower.com/article/going-bat-wildlife-wind-energys-conservation-effort.

[§§] Hoen, B.D., Diffendorfer, J.E., Rand, J.T., Kramer, L.A., Garrity, C.P., and Hunt, H.E., 2018, United States Wind Turbine Database (ver. 3.2, October 14, 2020): U.S. Geological Survey, American Wind Energy Association, and Lawrence Berkeley National Laboratory data release, https://doi.org/10.5066/F7TX3DN0.

[¶¶] https://issues.nawindpower.com/article/going-bat-wildlife-wind-energys-conservation-effort

[##] Reference Access Scenario: https://www.nrel.gov/gis/renewable-energy-supply-curves.html

[‖‖] Capacity factor is the percentage of total installed capacity produced during a time period (e.g., during an hour or on average across a year). Net capacity factor considers turbine and wind plant energy generation losses. Average annual net capacity factors typically range from 25% to 40% for wind energy facilities.

[***] Regional BOS cost multipliers derived from empirical construction cost data provided by industry partners.

[†††] https://sam.nrel.gov/financial-models/utility-scale-ppa.html

[‡‡‡] At the end of 2020, the PTC was extended, and the credit changed to $18/MWh. https://www.eia.gov/todayinenergy/detail.php?id=46576

[§§§] The national PPA price average was based on executed PPA's in 2015, 2016, and 2017.

[¶¶¶] US Electricity Information Administration's Hourly Electricity Monitor
https://www.eia.gov/todayinenergy/detail.php?id = 43295

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