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U.S. DEPARTMENT OF ENERGY

Wind Power Market-Value Enhancements through Larger Rotors and Taller Towers


Photo credit: LM Wind Power

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ENERGY TECHNOLOGIES AREA | ENERGY ANALYSIS AND ENVIRONMENTAL IMPACTS DIVISION

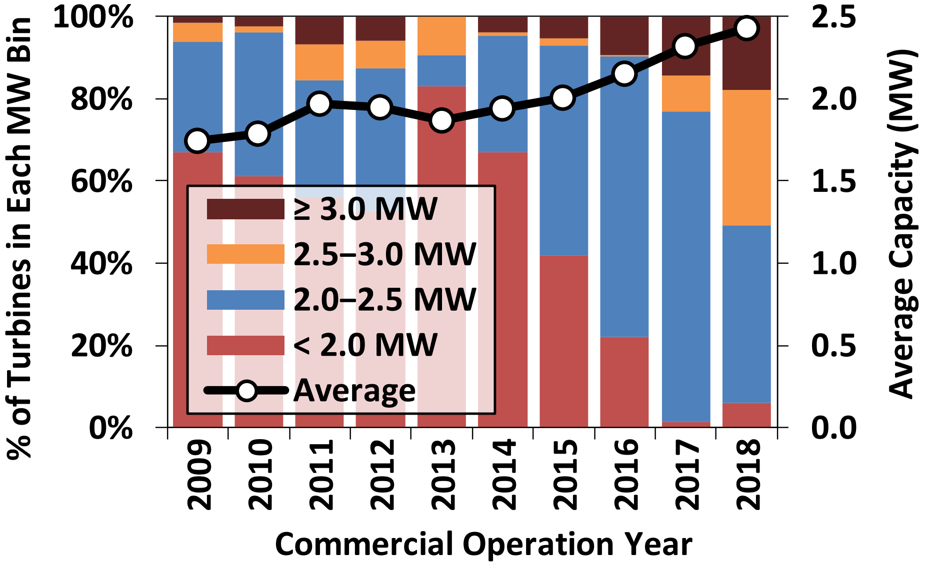
Presentation overview

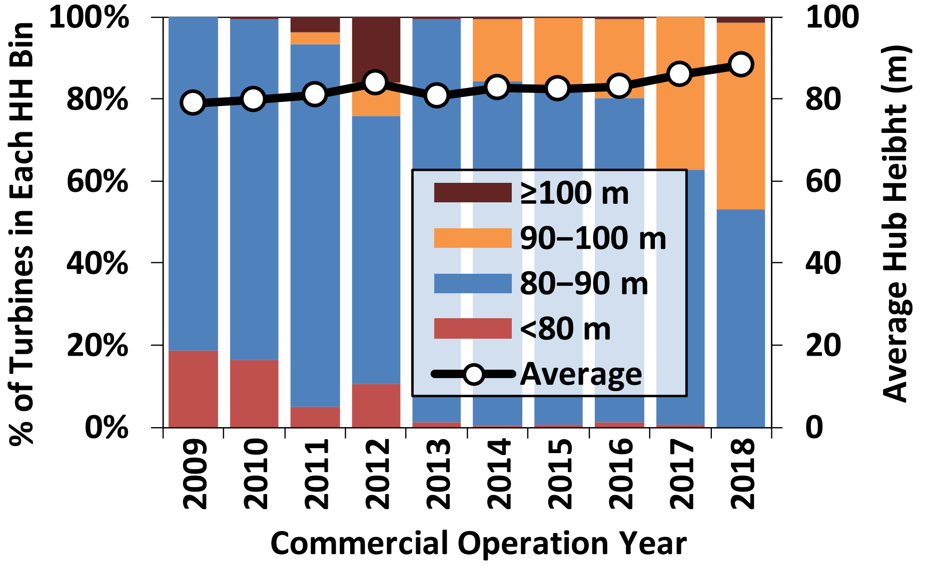
- Background and scope
- Data and methods for market value assessment
- Market value results using recent historical prices
- Possible additional benefits of taller, lower-specific-power turbines
- Summary and conclusions
- *Appendix:* market value results using forecasted prices

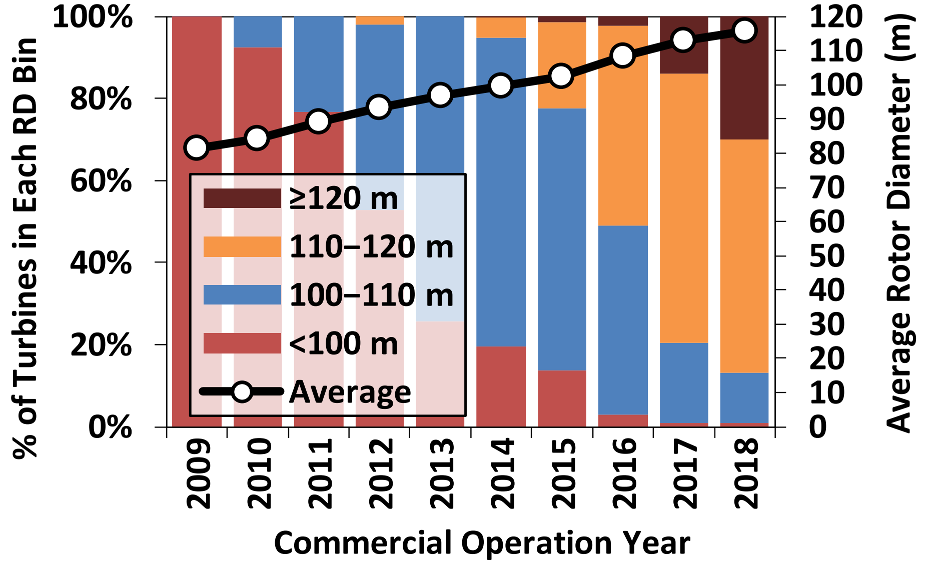
* This analysis focuses primarily on value enhancement. For analysis related to technology trends and the LCOE cost impacts of larger rotors see: Bolinger, M., E. Lantz, R. Wiser, B. Hoen, J. Rand, and R. Hammond. 2019 (submitted). "Opportunities for and Challenges to Further Reductions in the "Specific Power" Rating of Wind Turbines Installed in the United States." Submitted to *Wind Engineering* in September, 2019

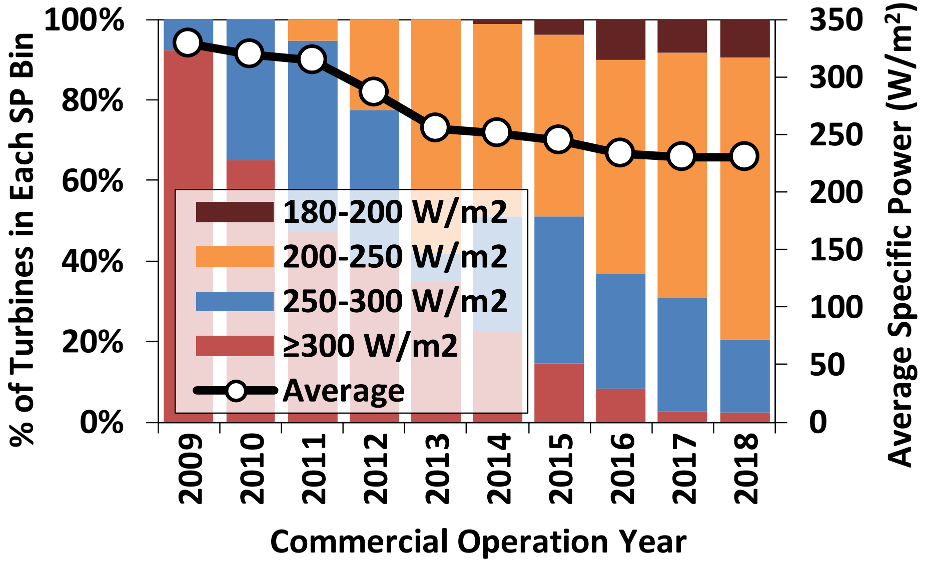
Background and Scope

A decade of turbine scaling in the US: larger rotors lead to lower specific power (SP); modest growth in hub heights (HH)







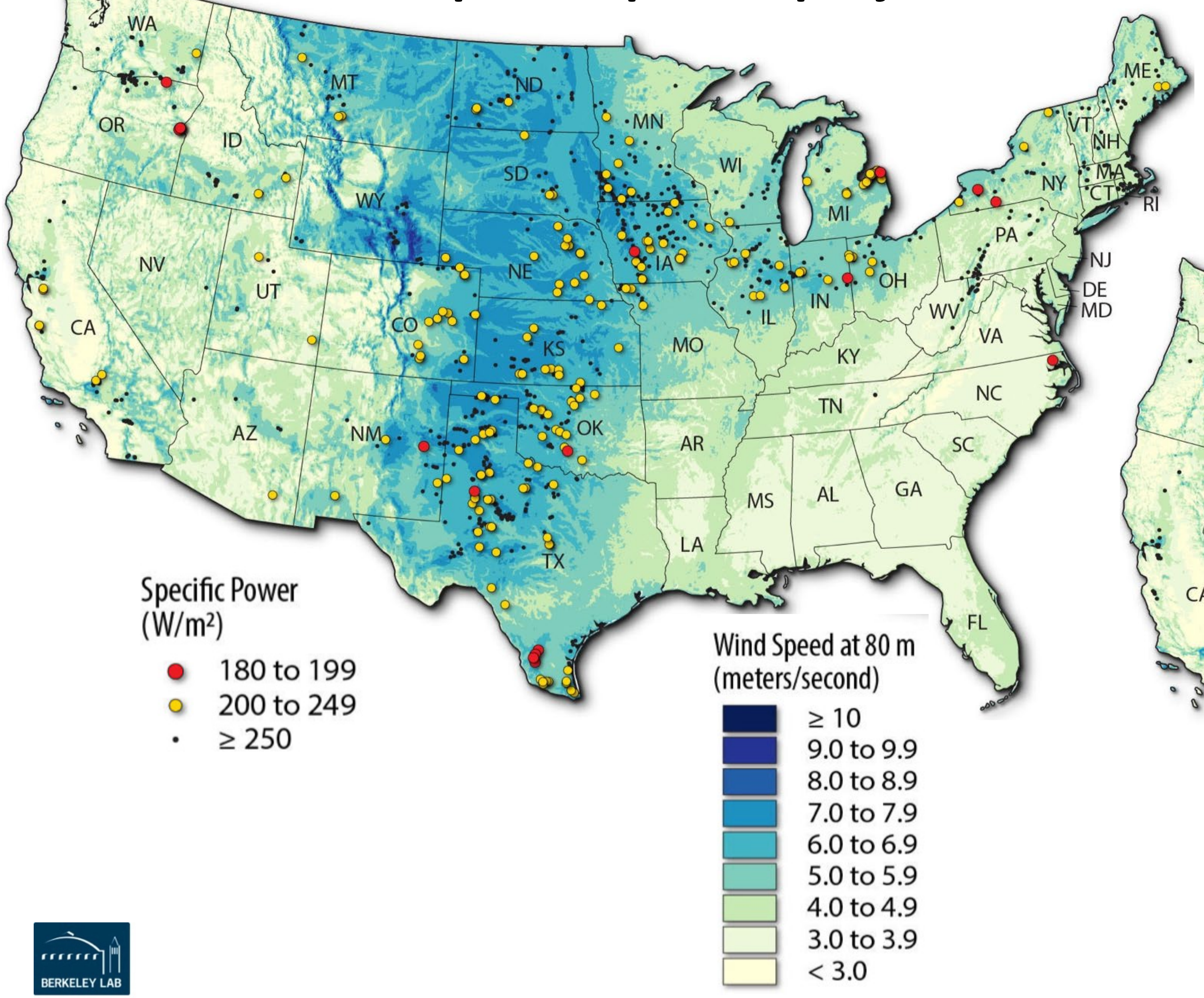


- The swept area of the rotor (m^2) has *doubled* since 2009, outpacing the 40% growth in capacity rating (W), resulting in a 30% reduction in specific power: from 329 W/m^2 to 230 W/m^2
- The average hub height has only grown by 12% since 2009: from 78.8 m to 88.1 m

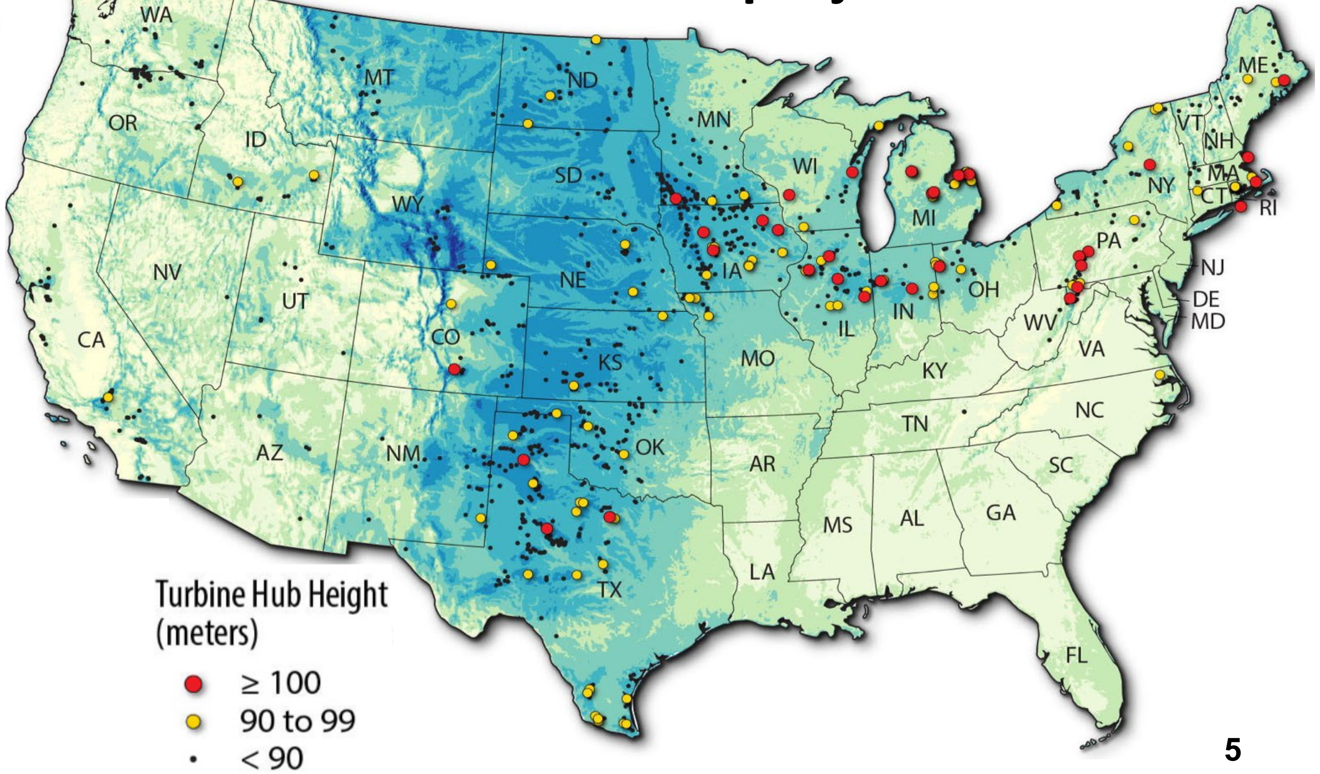
Deployment of taller towers and lower-specific-power turbines as of the end of 2018

- Low-specific-power turbines have been deployed at low- and high-wind-speed sites
- Tall towers concentrated in Great Lakes and Northeast regions (greater wind shear)

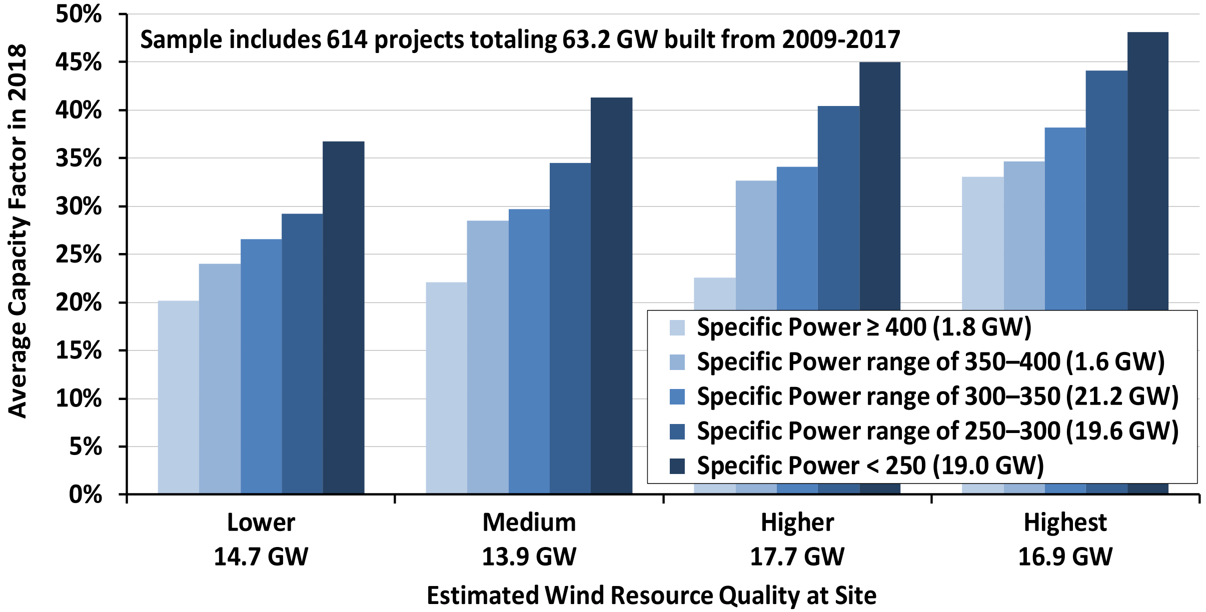
Low-specific-power projects

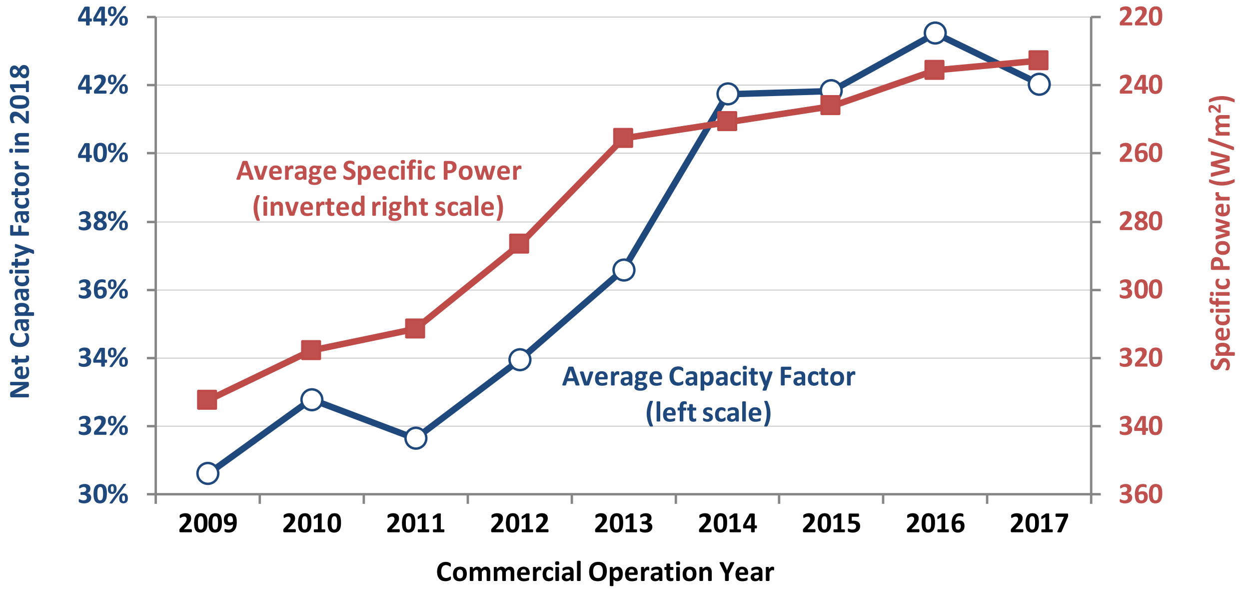


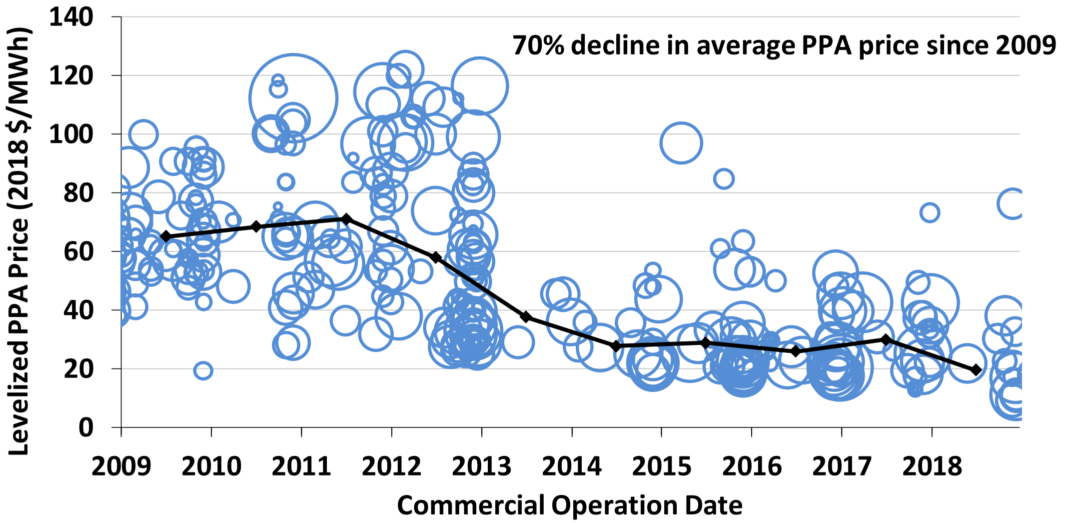
Tall-tower projects

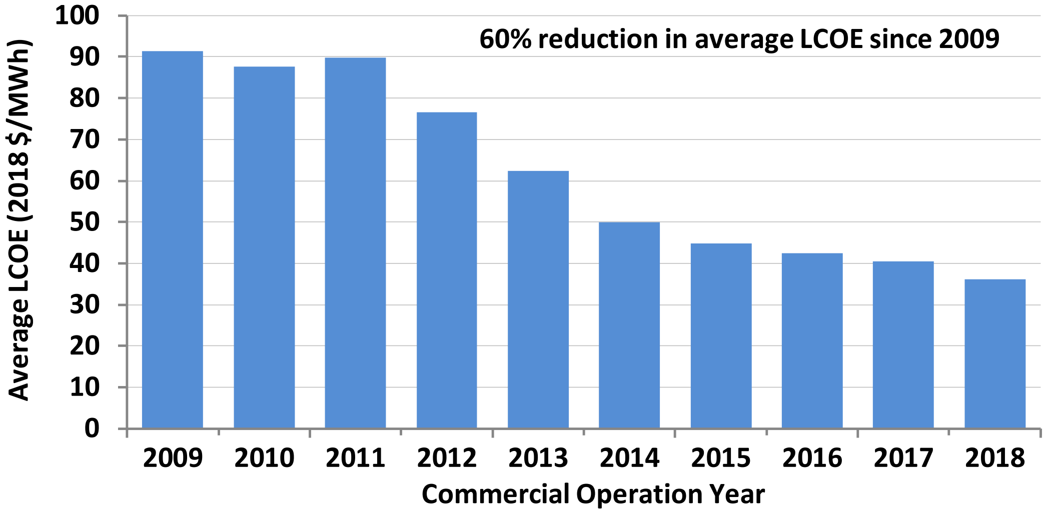


Lower specific power has enabled higher capacity factors, leading to lower PPA prices and LCOE







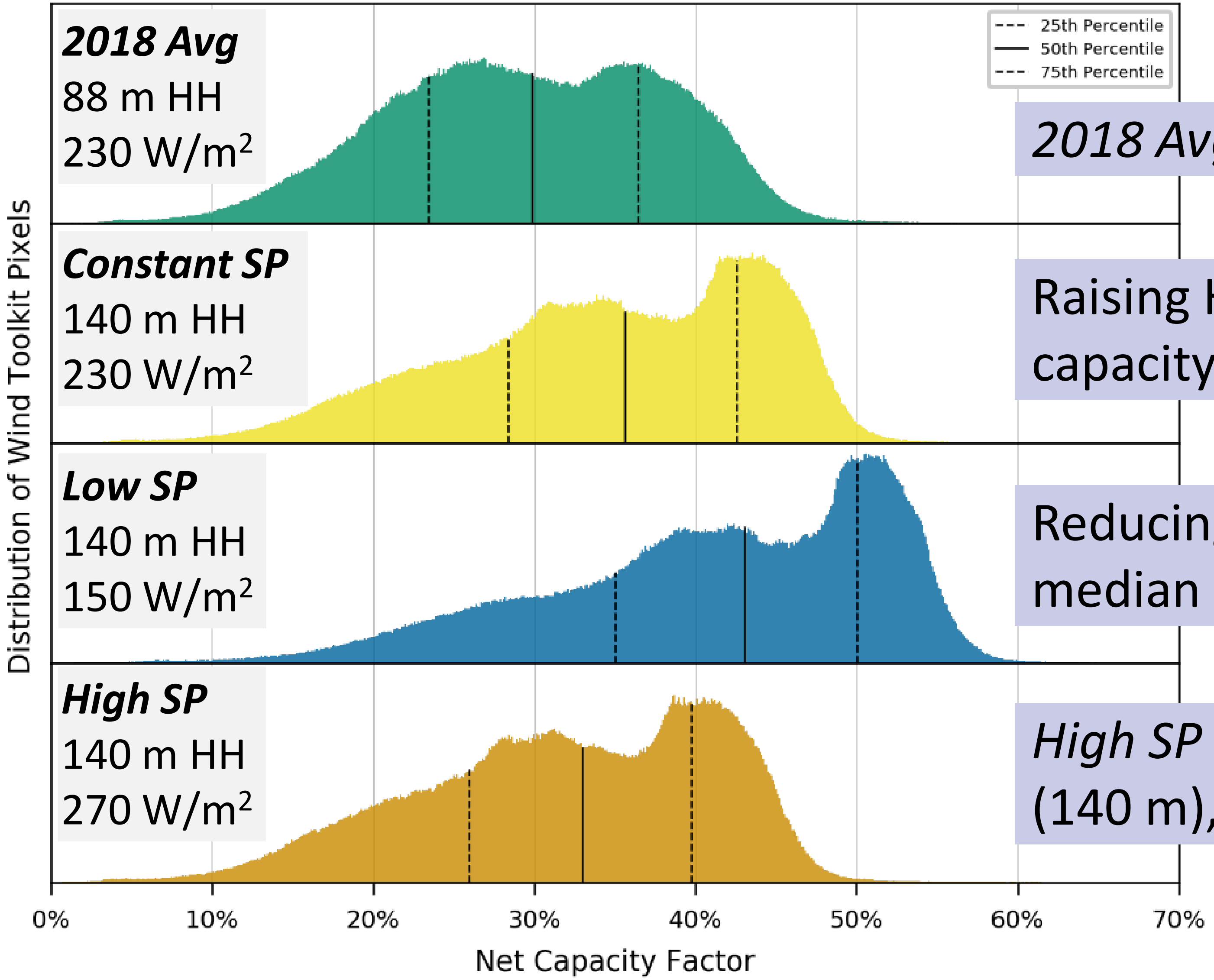


But will this trend towards taller, lower-SP turbines continue? We analyzed several different turbine configurations…

		2018 Avg	Constant SP	Low SP	High SP
Nameplate Capacity (MW)		2.43	5.0	5.0	5.0
Rotor Diameter (m)		116	166	206	153.5
Hub Height (m)		88	140	140	140
Specific Power (W/m^2)		230	230	150	270
CapEx Assumptions by Scenario (2018 $/kW)	Favor Low SP		1500	1500	1500
	Reference		1500	1620	1380
	Favor High SP		1500	1740	1260

The analysis presented on the next few slides relies on wind speed data from NREL's Wind Integration National Dataset (WIND) Toolkit (https://www.nrel.gov/grid/wind-toolkit.html), a national mesoscale wind-resource data set that includes meteorological data for more than 1.85 million locations in the contiguous United States (each pixel in the data set reflects a 2-km-by-2-km grid cell).

Impact of hub height (HH) and specific power (SP) on capacity factor (CF) across the US



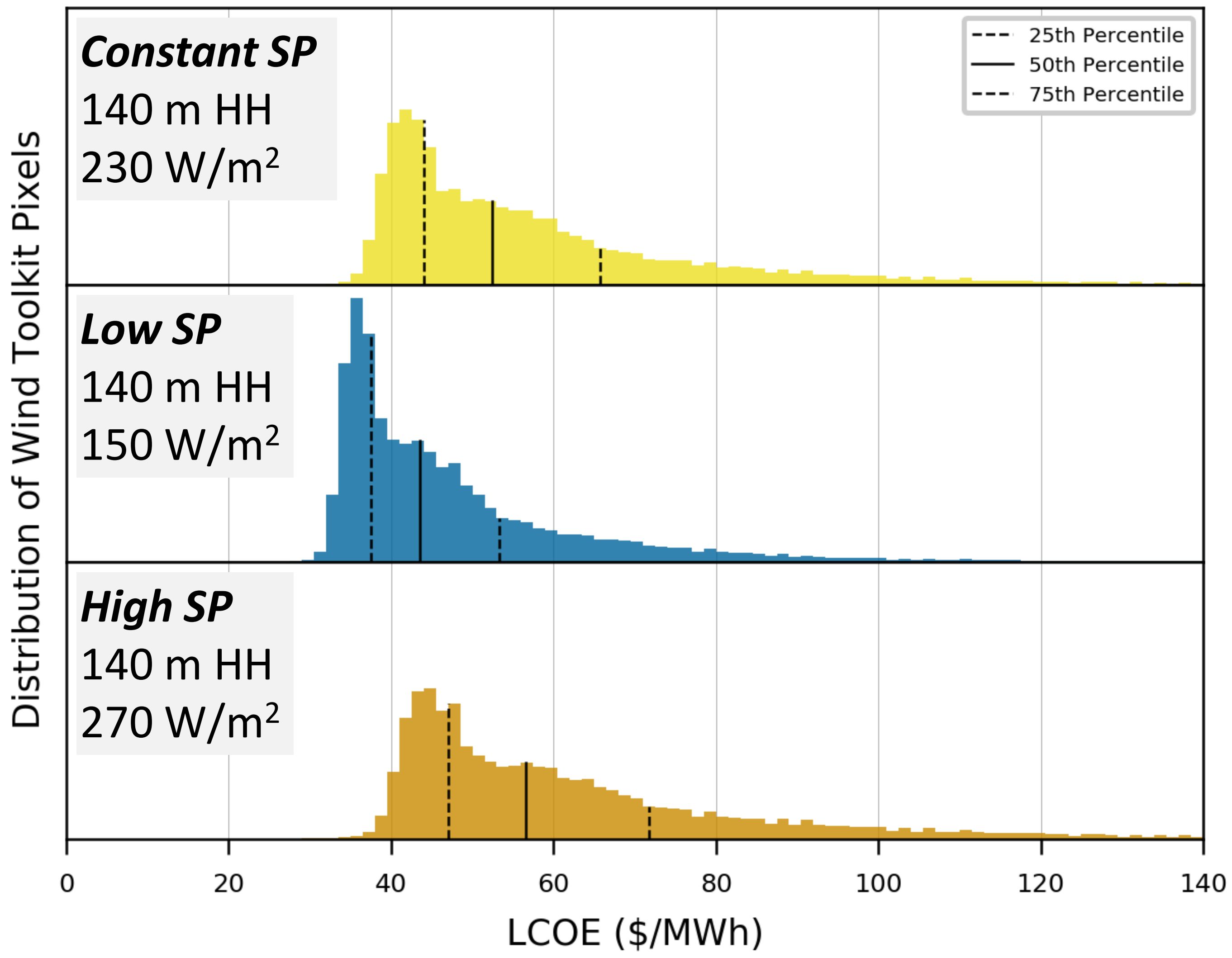
2018 Avg is the reference turbine

Raising HH from 88 m to 140 m boosts median capacity factor (CF) by 7 percentage points

Reducing SP from 230 W/m^2 to 150 W/m^2 boosts median CF by *another* 7 percentage points

High SP turbine benefits from higher hub height (140 m), but is hurt by higher SP (270 W/m^2)

If all three turbine configurations had the same CapEx, their LCOE distributions across the US would look like this…

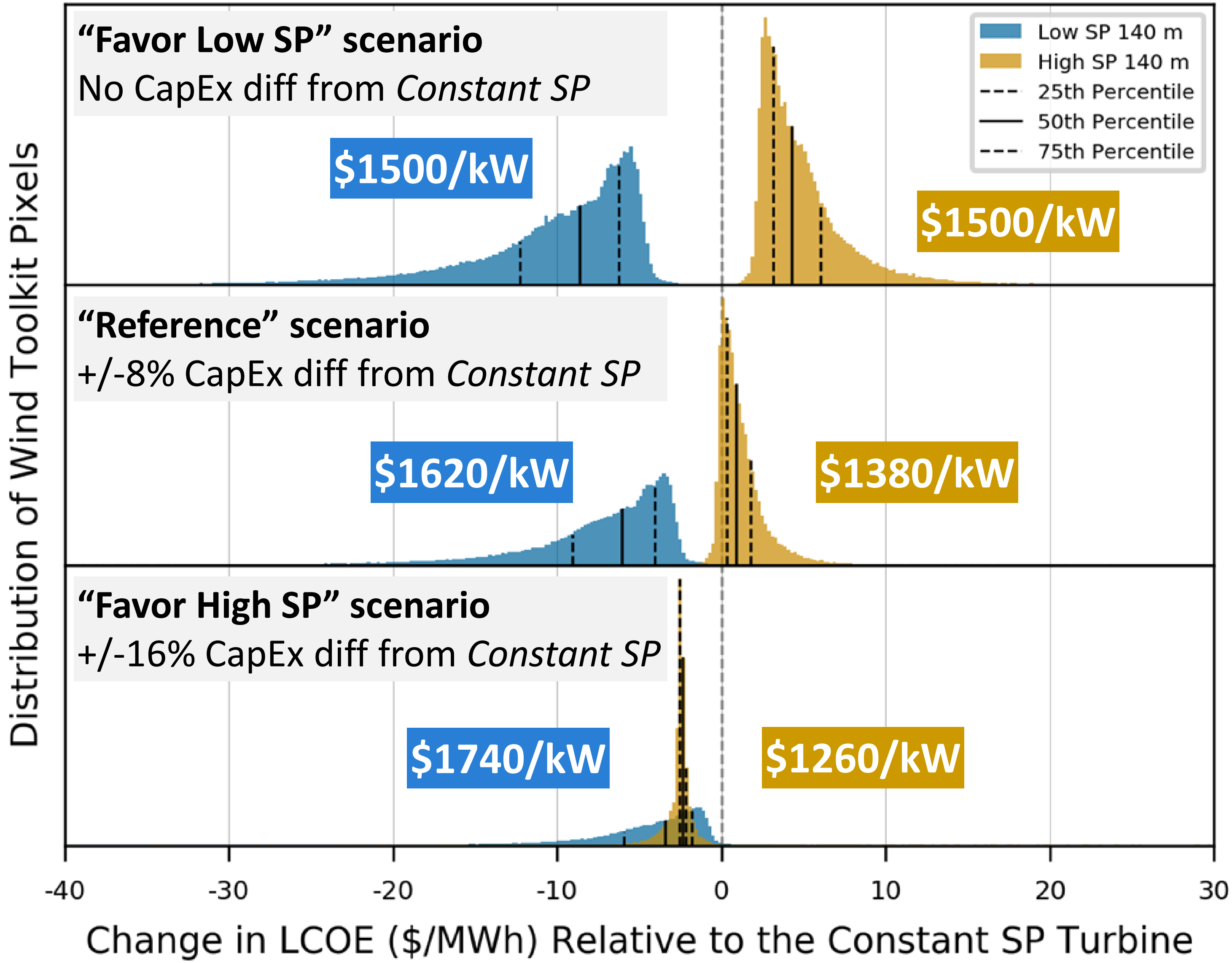


This is the "Favor Low SP" scenario, which assumes that all three turbines have a CapEx of $1500/kW

Given identical CapEx, their LCOE distributions are driven solely by the capacity factor differences shown on the previous slide (all else being equal)

Thus, no surprise that the *Low SP* turbine has the lowest median LCOE, followed by *Constant SP* and *High SP*

Even under less-favorable CapEx scenarios, *Low SP* fares well



In all three scenarios:

- The *Constant SP* turbine (the point of reference) has a CapEx of $1500/kW
- The *Low SP* turbine **always** has a lower LCOE than the *Constant SP* turbine

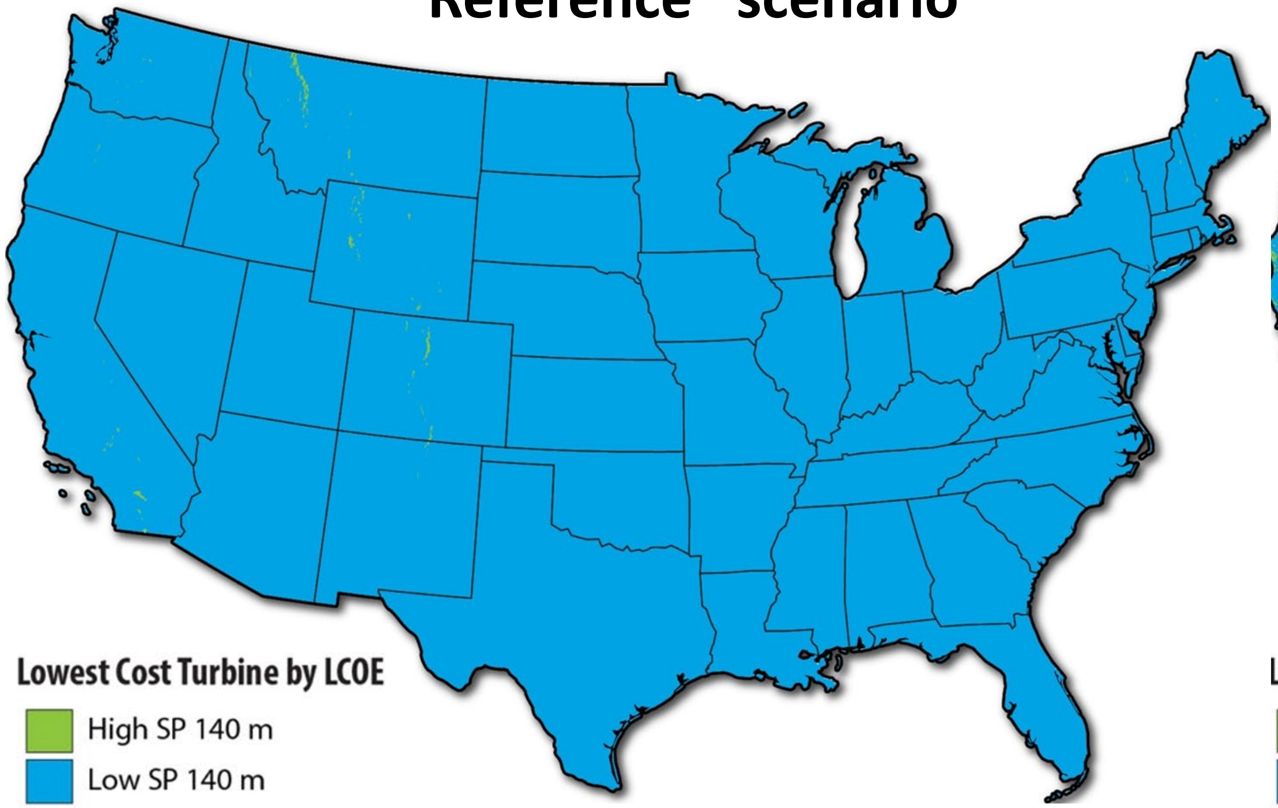
In the "Reference" scenario, the median LCOE for *Low SP* is $6/MWh less than for *Constant SP* ($7/MWh less than *High SP*)

The *High SP* turbine only beats *Constant SP*—and also starts to encroach upon *Low SP*—in the "Favor High SP" scenario

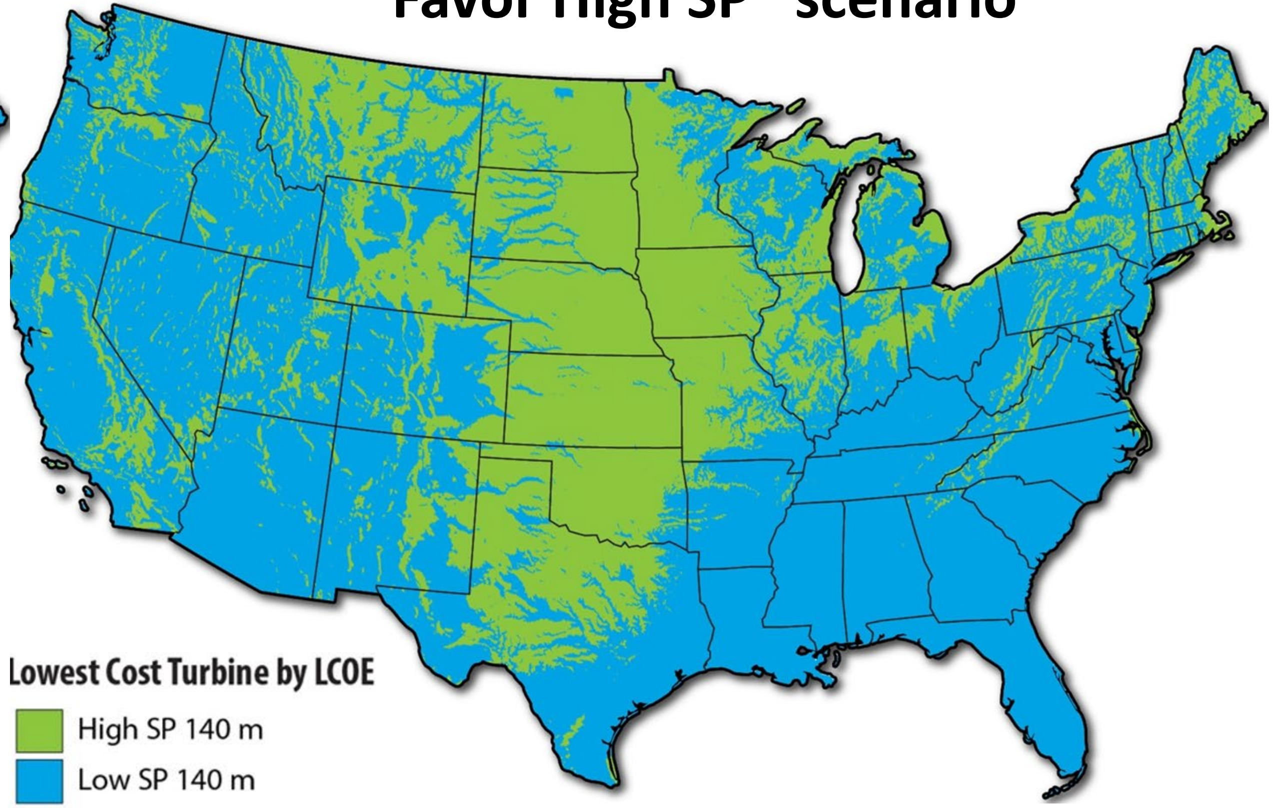
Conclusion: *Low SP* has a lot of CapEx headroom

Low SP dominates the "Reference" scenario; *High SP* only makes inroads in the "Favor High SP" scenario

"Reference" scenario

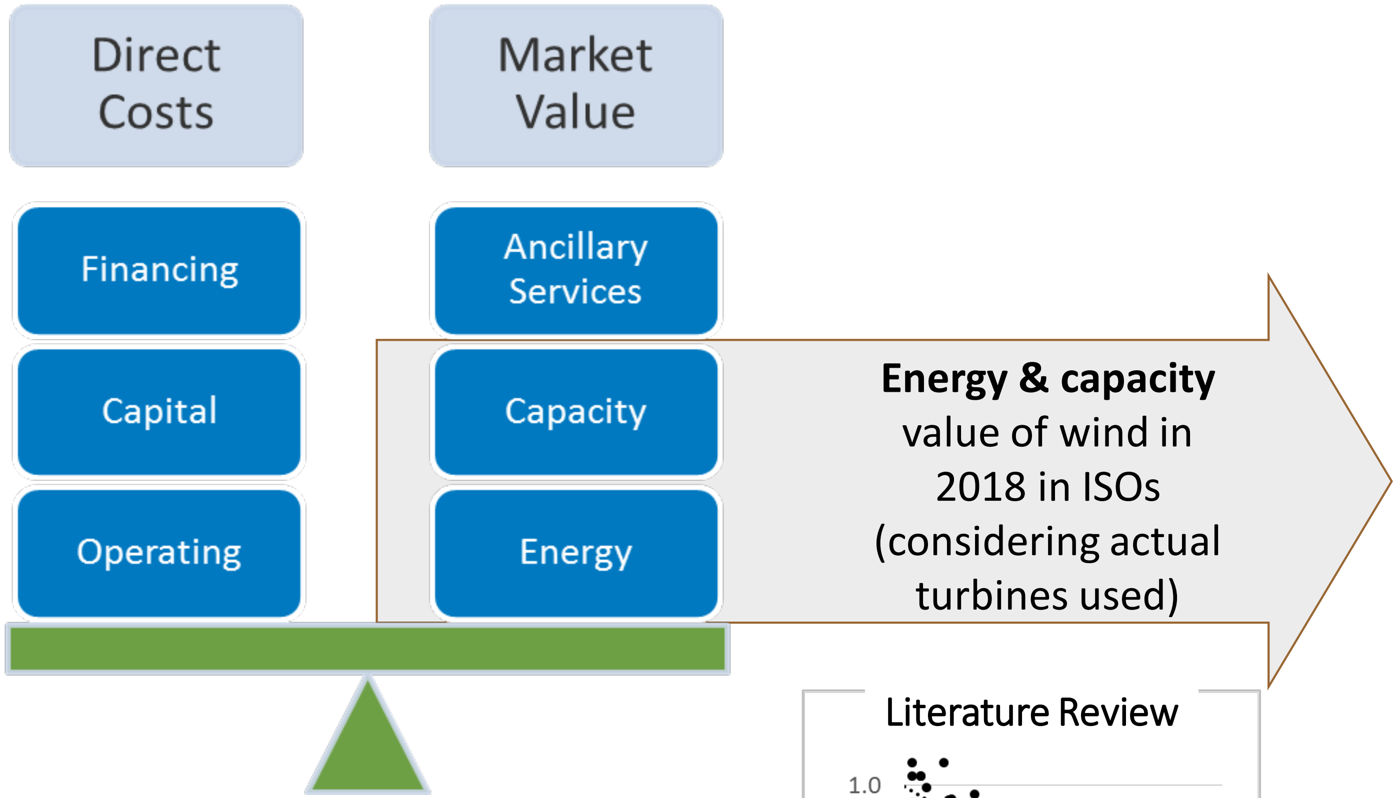


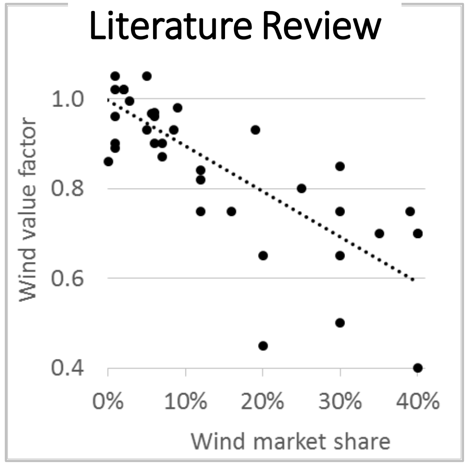
"Favor High SP" scenario



- *Constant SP* turbine never deploys in these two scenarios
- Given that *Low SP* already dominates in the "Reference" scenario, we do not need to map the more-favorable "Favor Low SP" scenario

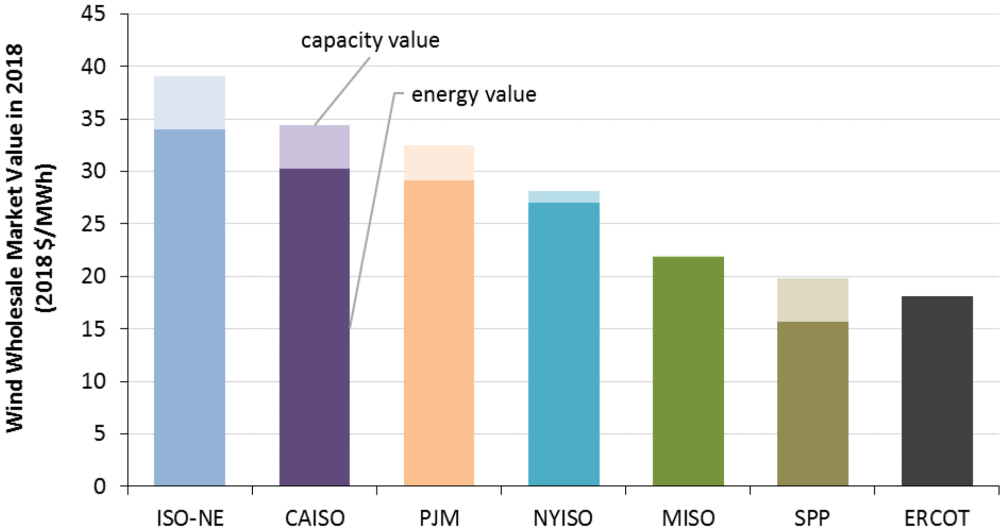
But also need to consider impact of turbine evolution on wholesale market value of wind: energy and capacity value

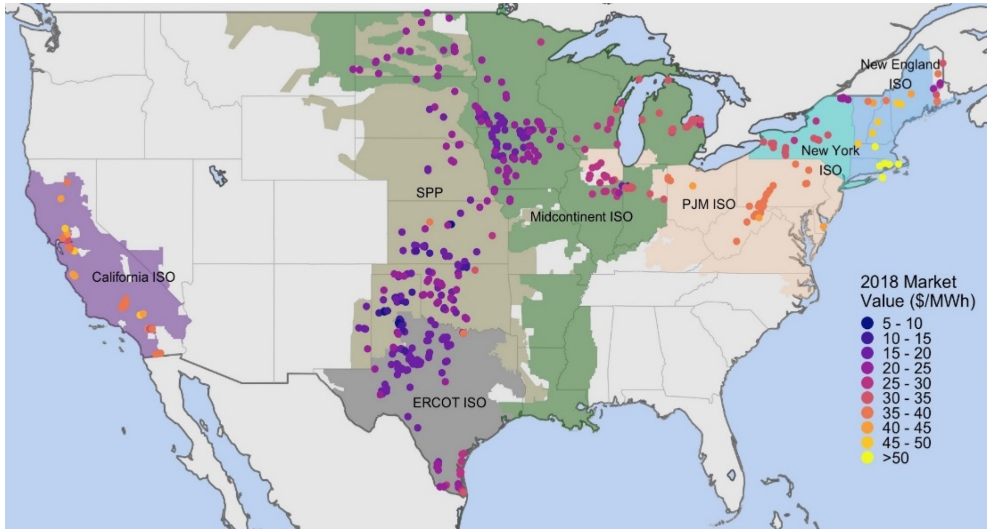




Wholesale market value of wind expected to decline over time as penetrations increase, all else equal

Hirth (2015)



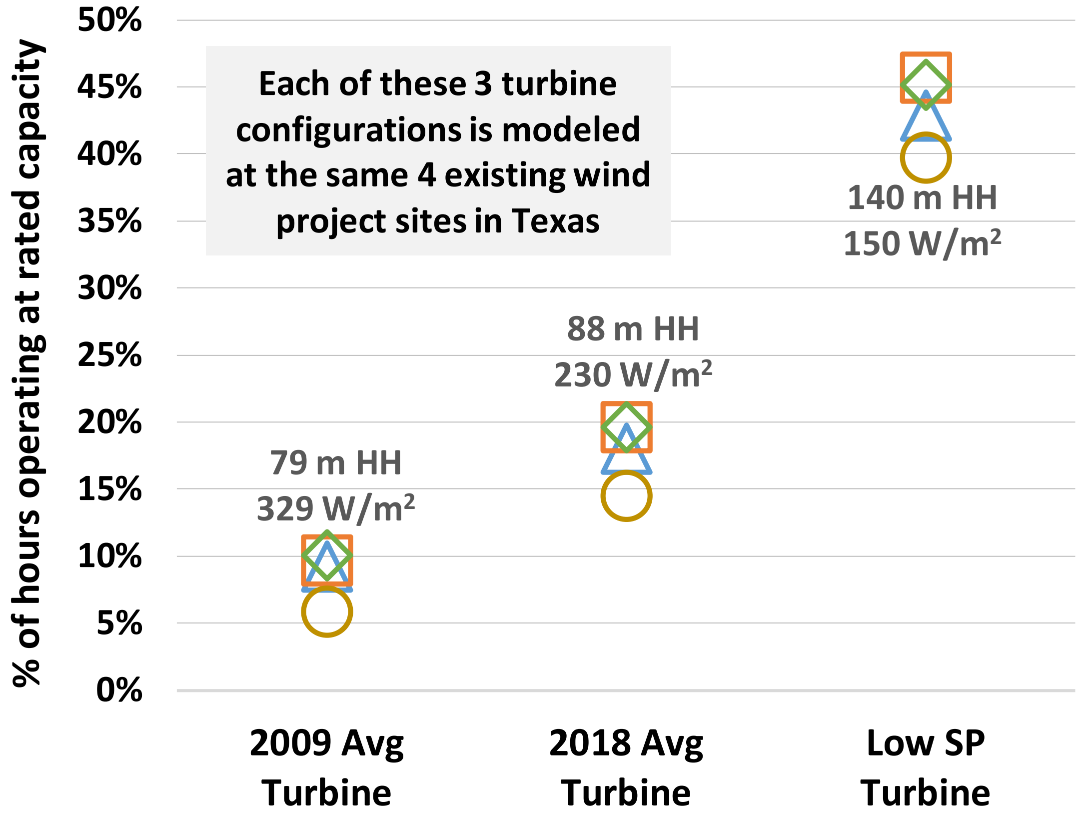


Wiser and Bolinger (2019)

How do taller, low-specific-power turbines impact market value?

Taller, low-specific-power turbines operate at rated capacity more often, and generate more power at lower wind speeds

- They boost generation during low-wind-speed hours more than during high-wind-speed hours (when they were likely already operating at rated capacity)
- Because low wind hours are often correlated with higher market prices (and vice versa), this shift in generation profile can enhance market value
- The higher capacity factors and lower variability in output can also lead to better utilization of transmission, lower forecast error, and more-favorable financing terms (all discussed later)



Findings from European studies on the market value of large rotors (and tall towers) suggests value enhancements

- At low wind penetration, most studies find little or no additional value to low-SP, high-HH machines, but above 5-15% penetration, low-SP and high-HH machines provide incremental market value that grows with penetration
- The European studies in the table below find that low-SP/high-HH turbines boost market value by 8% to 30% (~$3/MWh to $15/MWh), depending on the specific scenarios modeled
- Conceptually, this finding is a function of a relative increase in wind generation during periods of relatively lower wind speeds, which are, in some markets, partially correlated with periods of higher system needs and so higher prices especially when compared to periods of high wind speeds when wholesale prices are often suppressed due to wind

Report Citation	Wind Value Increase		Specific Power (W/m^2)		Hub Height (m)		Wind Penetration Analyzed
	%	$/MWh	Start	End	Start	End	
Dalla Riva et al. (2017)	8%	2.9	325	250	100	125	varies by country
	13%	4.8	325	175	100	150	
Hirth and Muller (2016)	15%	9	472	211	90	120	30%
	23%	14	472	100	90	120	
Hirth (2016)	12-14%	6.5	568	289	90	120	30%
May (2017)	14%	11	630	200	80	140	50% (all RE)
Johansson et al. (2017)	20%	11	200	100	100	100	40%
	30%	15	300	100	100	100	

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Scope of assessment presented in this slide deck

Analyze impacts of turbine evolution on grid-system wholesale market value

- Specific power and hub height variations
- Energy value and capacity value in organized wholesale power markets

Conduct assessment using past (and, in an appendix, possible future) wholesale prices

- Historical hourly wholesale energy prices and ISO-specific capacity rules and costs in 2018, at existing wind project locations in ISO regions
- *Appendix: forecasted hourly wholesale energy prices and capacity values in 2030 under varying scenarios, in four ISOs: ERCOT, SPP, NYISO, CAISO*

Also includes assessment of three other benefits of low-specific-power, tall turbines:

- Electric transmission expenditure, impacted by change in utilization
- Balancing / ancillary service costs, impacted by change in wind variability
- Cost of wind-plant financing, impacted by change in wind output variability

Data and Methods for Market Value Assessment

Multiple turbine variants analyzed to separately assess impact of specific power and hub height on market value

	2009 Average Turbine	2018 Average Turbine	2018 Average, Higher HH	2018 Average, Lower SP	Low-SP, High-HH	High-SP Turbine
Nameplate Capacity (MW)	1.74	**2.43**	2.43	2.43	**5.0**	5.0
Rotor Diameter (m)	82.1	**116.0**	116.0	143.6	**206.0**	153.6
Hub Height (m)	78.8	**88.1**	140.0	88.1	**140.0**	140.0
Specific Power (W/m^2)	329	**230**	230	150	**150**	270

- **Turbine power curves** are generated for each turbine using the NREL System Advisor Model (2018.11.11 r3)
  - Turbine power curve for each scenario was defined based on the characteristics listed above
- **Hourly wind output** is estimated with hourly wind speeds described on the following slides, under the simplifying assumptions of zero losses and that plants curtail output when wholesale prices are negative

Historical wind speed data used to conduct value analysis based on 2018 wholesale energy prices and capacity value

- **Public data do not broadly exist for plant-level hourly wind speeds**
  - Which are needed to assess energy and capacity value of varying turbine parameters
- We developed an **estimate of plant-level hourly wind speeds and capacity factors**
- Multiple approaches underwent extensive validation across inter-annual, seasonal, and diurnal time frames
  - Two top contenders were based on wind speeds from:
    1. ERA5 reanalysis
    2. MERRA+NREL WIND Tool Kit
- The ERA5-based approach was found to provide the most consistent agreement with observations across inter-annual, seasonal, and diurnal time frames
- Though we focus on 2018, we expect values to vary somewhat by year depending on pricing differences and resource profile differences – 2018 value enhancement provides an important benchmark however
- Details follow on the next slides

Historical wind speed data used to conduct value analysis based on 2018 wholesale energy prices and capacity value

- **The basic approach**:
  - Start with site-level hourly wind speeds (i.e., from ERA5) and determine plant-level generation using the power curve of the dominant turbine type actually in use at the pre-existing wind project site
  - Adjust this hourly generation estimate to be consistent with available recorded generation
    - But first, account for plant-level curtailment in recorded generation records
    - Available generation records include EIA monthly plant-level generation and hourly ISO-level generation
    - An iterative process was used to ensure that each plant generation estimate matched the monthly totals while the sum of plants over an ISO matched the hourly records
  - Back-calculate wind speed based on adjusted generation estimate and turbine power curve
  - Scale new, back-calculated wind speed estimates to different hub-heights based on wind sheer found within ERA5 for particular hour and location
  - Apply final, back-calculated wind speed estimates to the multiple turbine variants shown earlier to determine hourly generation (and value) under each scenario, rolled up to annual 2018 value estimate
  - Limitation: this approach focuses on existing wind sites, and does not account for wake or other losses→ testing indicated that ignoring losses has a marginal effect on overall temporal patterns in generation

Historical wind speed data used to conduct value analysis based on 2018 wholesale energy prices and capacity value

ERA5-based hourly generation estimates

Split plants by ISO (and non-ISOs) and adjust for curtailment

(1) Split plants based on EIA860 designations
(2) Deflate generation estimates based on hourly plant-level curtailment estimates
   - Bias correction process requires post-curtailment estimates

Iterative process to bias correct based on recorded plant-level monthly and hourly ISO generation

Bias correction for ISO plants

Back-out wind speeds at each plant, and run new tech power curves

(1) Inflate bias-corrected generation estimates based on plant-level curtailment estimates
(2) Run these generation estimates backward through plant-specific power curves to find new hourly wind speed estimates
(3) Use these new bias-corrected wind speeds with the various wind turbine scenario assumptions to develop new hourly generation profiles

Line up final generation estimates with nodal prices

- Assume curtailment below $0/MWh *(this threshold was chosen as to represent a post-PTC world)*

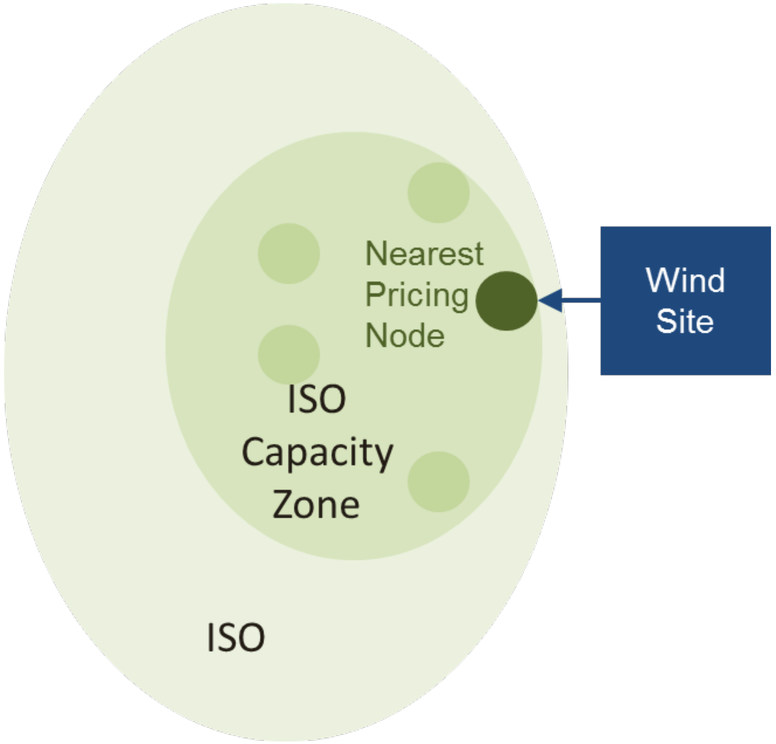
Add capacity value estimates

Final estimates of value by scenario

A visual representation of the basic approach

Energy and capacity value assessments for 2018 rely on wholesale market prices and capacity rules in each ISO

- Grid-system market value is inclusive of hourly energy value and, outside of ERCOT (which is an energy-only market), capacity value; our analysis focuses on 2018
- Value is based on associating wind project sites to the nearest wholesale pricing point among the 60,000+ nodes across the county, with nodes mapped to ISOs and ISO capacity zones
- Energy value is estimated based on hourly wind output and hourly nodal real-time energy prices (LMPs), under the assumption that plants curtail when prices are negative
- Capacity value is based on capacity credit rules for each ISO, and capacity prices or costs appropriate for each location
- Total value is presented as energy value plus capacity value, divided by pre-curtailment annual wind generation



Additional details on the data and methods

- Analysis is conducted on a marginal 'price taker' basis, in effect assuming that modeled turbines are deployed on the margin and do not affect wholesale prices differently from those observed historically
  - This will tend to over-state impacts from what would otherwise be anticipated
- Analysis allows modeled wind turbines to be deployed at any existing site in the U.S., regardless of the IEC class of the site and the turbines' appropriateness for the site
  - In reality, the lowest-SP turbines would not be expected to deploy in the highest-wind sites
- Analysis to estimate capacity value is based on market rules, capacity credit, and capacity costs consistent with historical practice and rules in each ISO
  - Note that rules in CAISO do not enable turbine design variations to impact capacity value, and ERCOT has no capacity requirement (and, therefore, no capacity value)
- Analysis is focused on 2018 value, and restricted to actual wind project sites in ISO regions

Market Value Results Using 2018 Historical Prices

Notes on presentation of results

- Focus is primarily on comparing summed energy + capacity value in 2018 of the low-specific-power, tall-tower turbine vs. the 2018 average turbine, at existing wind project sites in ISO regions
- Results are presented as *both* a percentage (%) change *and* an absolute ($/MWh) change in market value of low-SP / high-HH turbine vs. the 2018 average turbine
- Some slides disentangle impacts associated with energy value and capacity value
- Final slides highlight a subset of results for all turbine variants, including hub height and specific power variations, for both energy value and capacity value

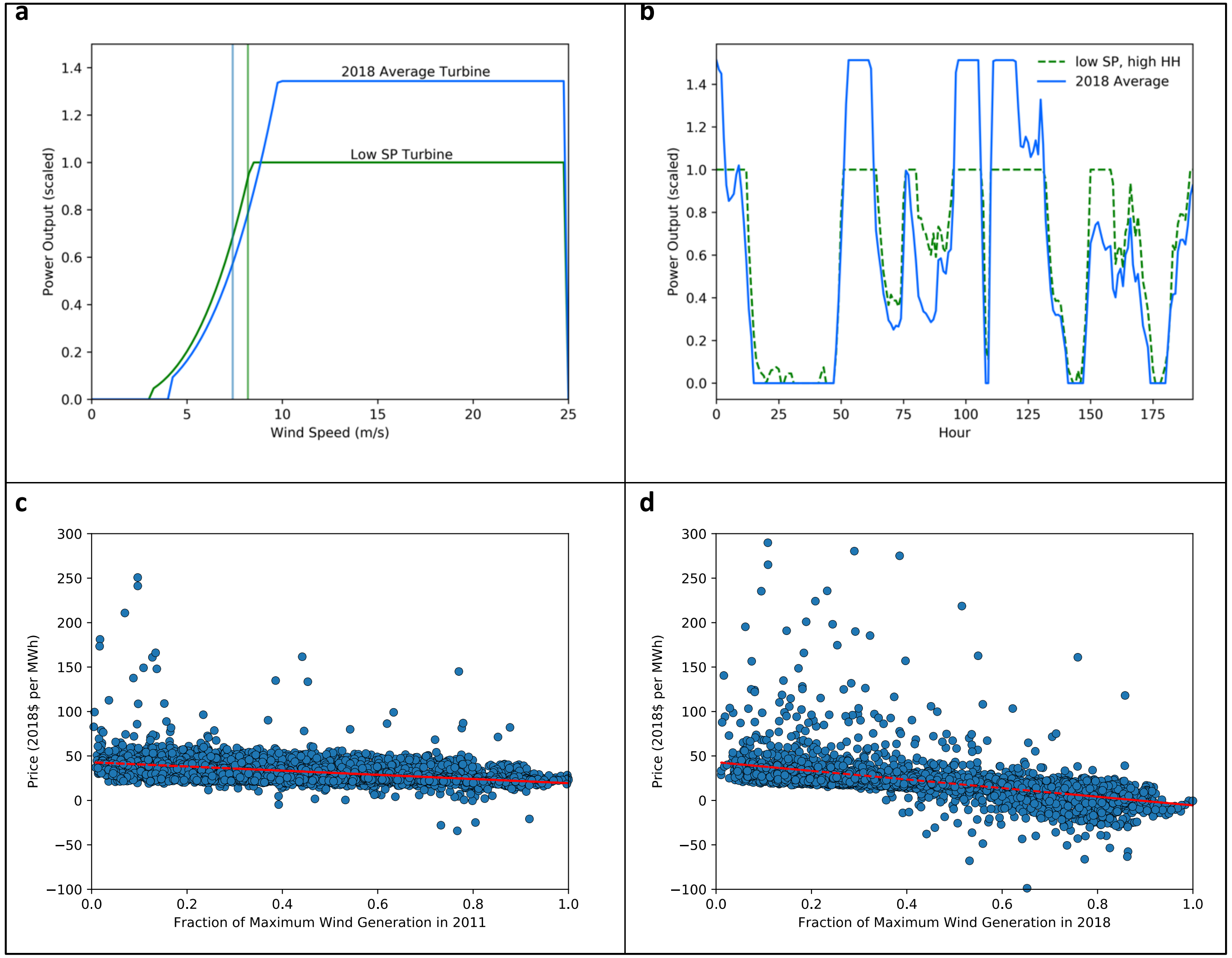
Intuition through example #1: why lower-specific-power and taller turbines can boost wholesale market value

Consider a single wind plant in SPP

Figure a: Scaled power curves for avg. 2018 and low-SP, high-HH turbines, along with avg. wind speed at both tower heights. Low specific-power, tall-tower turbines operate at rated power more of the time & generate relatively more power at lower speeds.

Figure b: Low specific-power, tall turbines feature higher capacity factors, and have less variability of output. For the same total energy generated, such turbines shift output away from the windiest hours towards other hours.

Figure c,d: As wind penetration increases, windiest hours see greatest wholesale price declines. Figures illustrate this effect at a single price node in SPP, where prices are plotted against the relative level of regional wind generation in 2011 (a, low wind penetration) and 2018 (b, high wind penetration). Shows how low-SP / high-HH turbines can shift generation away from the windiest hours, increasing the average wholesale price received for energy generation.



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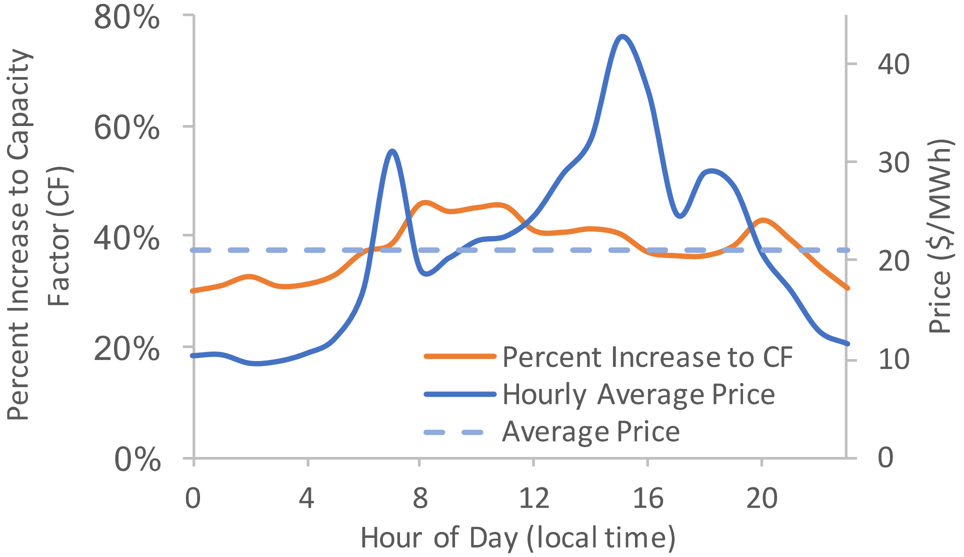
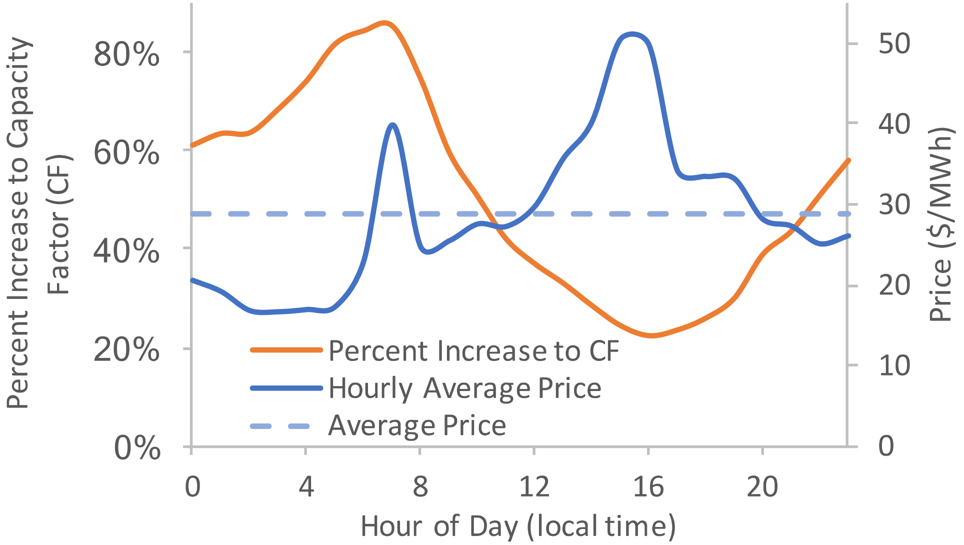
Intuition through example #2: value increase driven by the correlation of generation enhancement with high-priced hours

- Top panel:
  - This plant is located in west Texas
  - This plant shows one of the largest value boosts from the low-SP/high-HH turbine (vs 2018 Average)
  - The generation increase is larger during the middle of the day, when prices are generally higher than average
- Bottom panel:
  - This plant is located in south Texas
  - This plant shows almost no increase in value from the low-SP/high-HH turbine (versus 2018 Average)
  - The generation boost occurs during the early morning, and is not correlated with high prices





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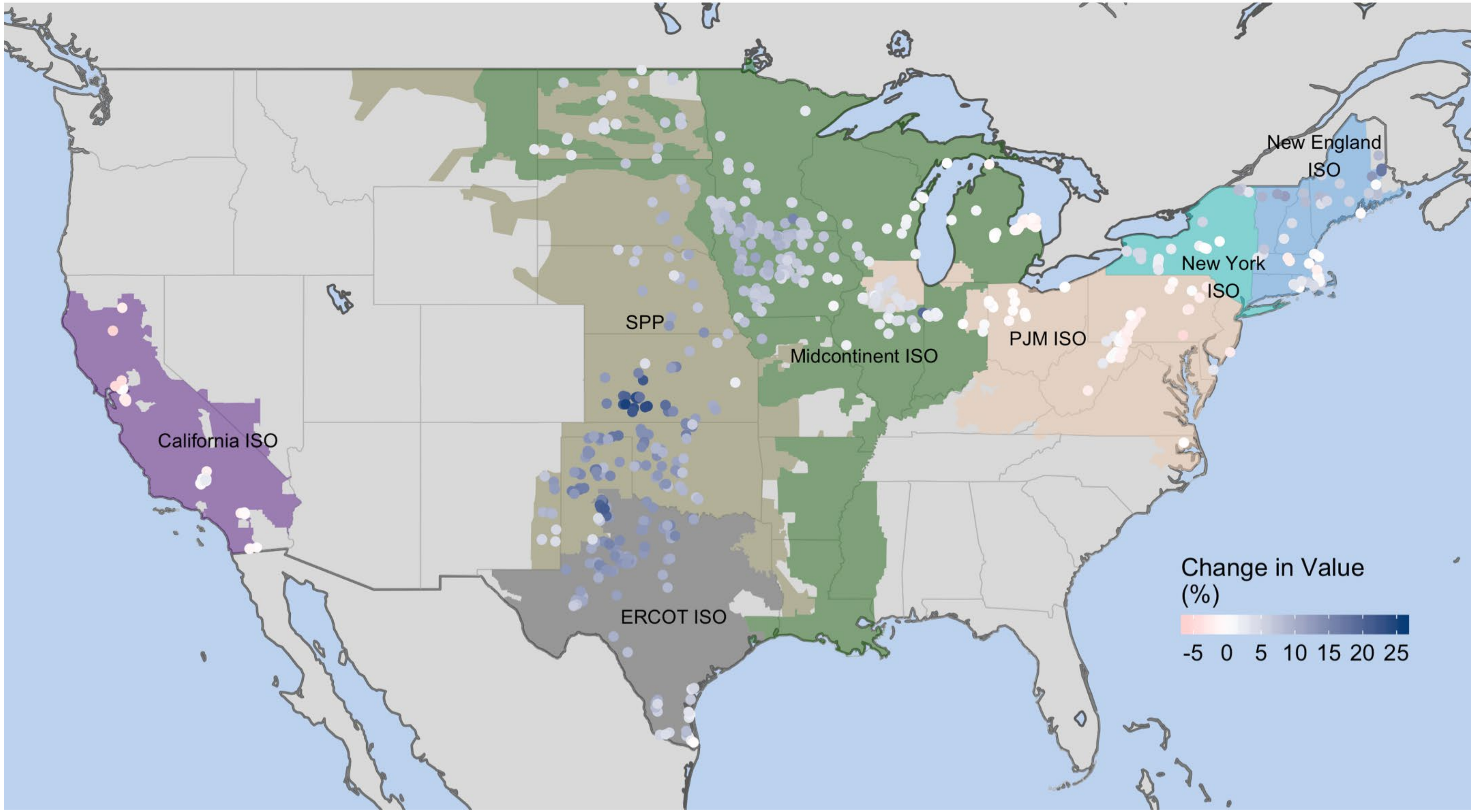
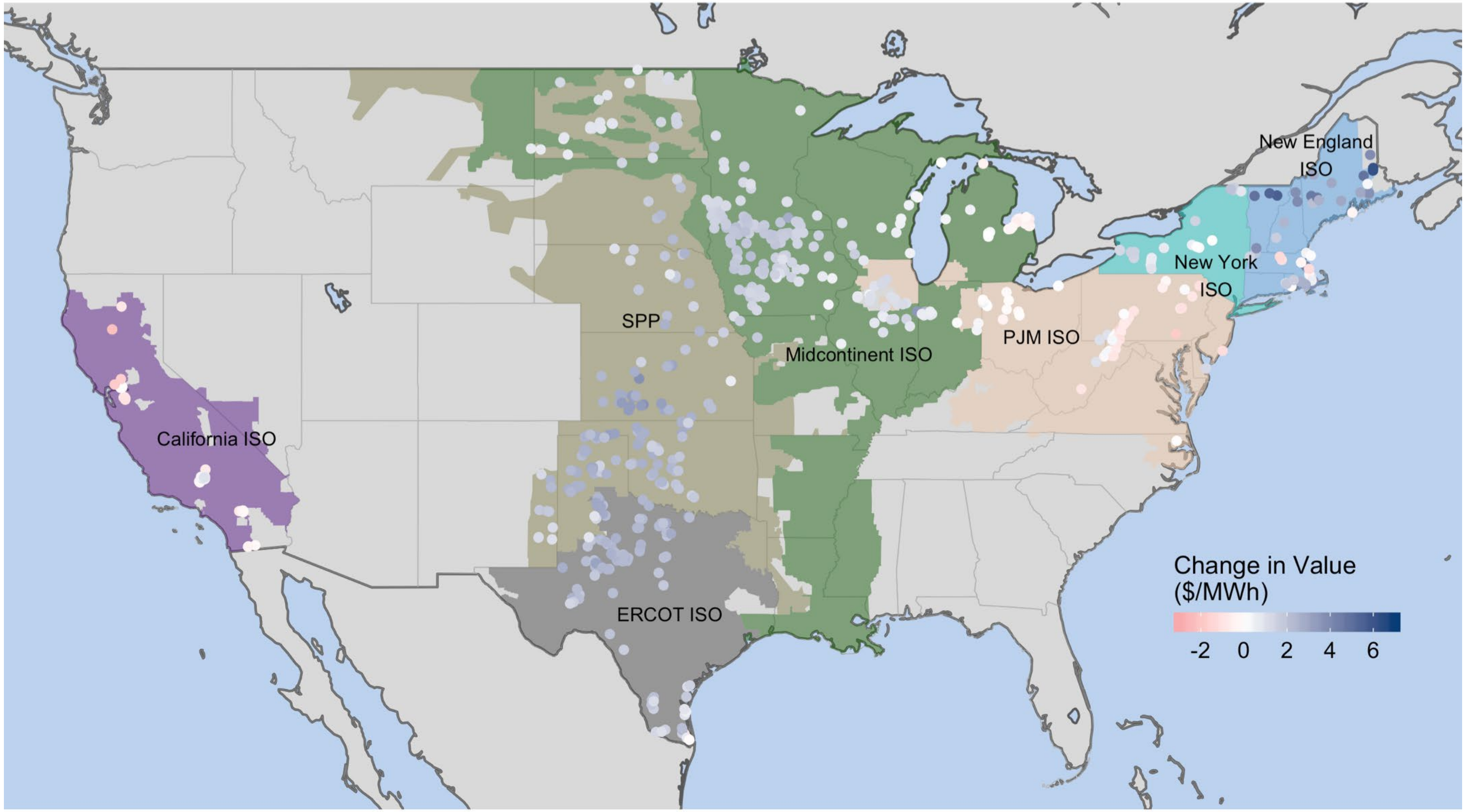
Percentage change in 2018 summed energy and capacity value of low-SP / high-HH turbine versus 2018 average turbine



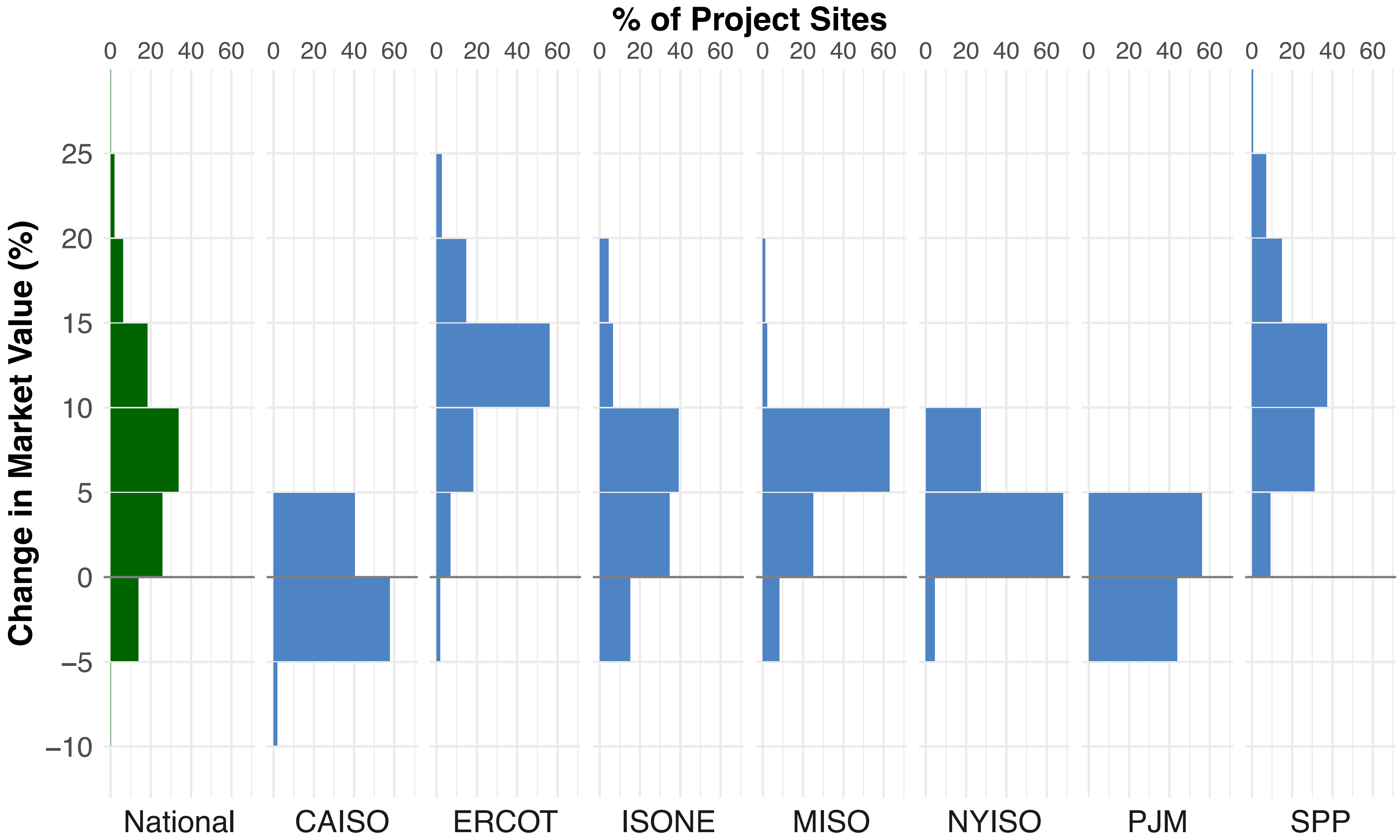
- Percentage value enhancement from low-SP / high-HH turbine is greatest in regions with highest wind penetration levels, and/or w/ transmission constraints
- Value is enhanced most in SPP and ERCOT, in general
- Significant enhancement is also found in MISO
- ISO-NE enhancement highly location dependent→ much higher where transmission constraints are greatest
- Relatively little value enhancement for most sites in CAISO, PJM, NYISO

Absolute change in 2018 summed energy and capacity value ($/MWh) of low-SP / high-HH versus 2018 average turbine



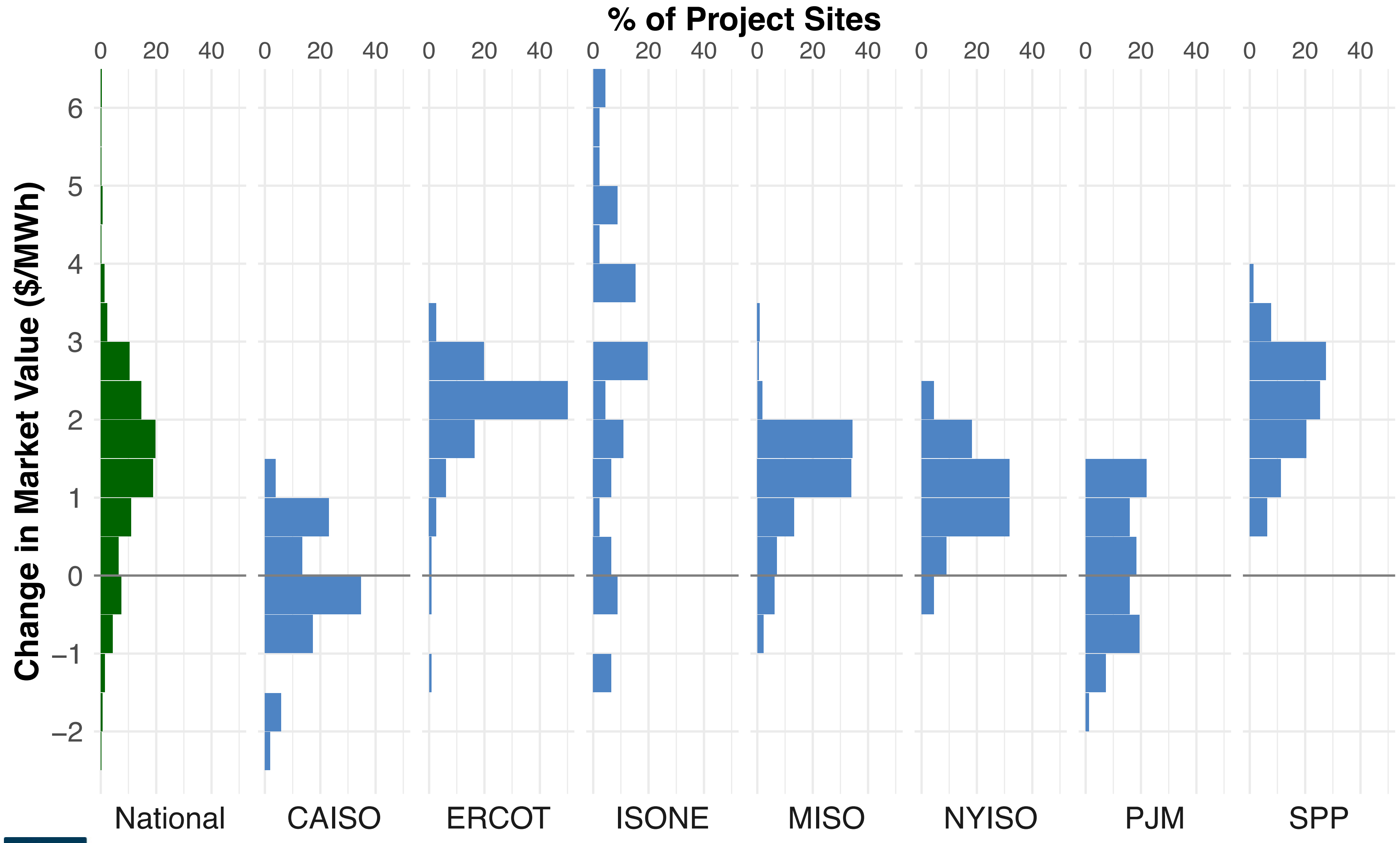
- Absolute ($/MWh) value enhancement is impacted by percentage increases and base wholesale power prices
- Value enhancement greatest in the north of ISO-NE
  - High percentage enhancement, and high base wholesale prices
- Outside of ISO-NE, absolute value is enhanced most in the high-penetration wind regions of SPP and ERCOT, and to a lesser extent MISO
- Less absolute enhancement is seen in CAISO, PJM, NYISO

Percentage change in 2018 summed energy and capacity value of low-SP / high-HH turbine versus 2018 average turbine



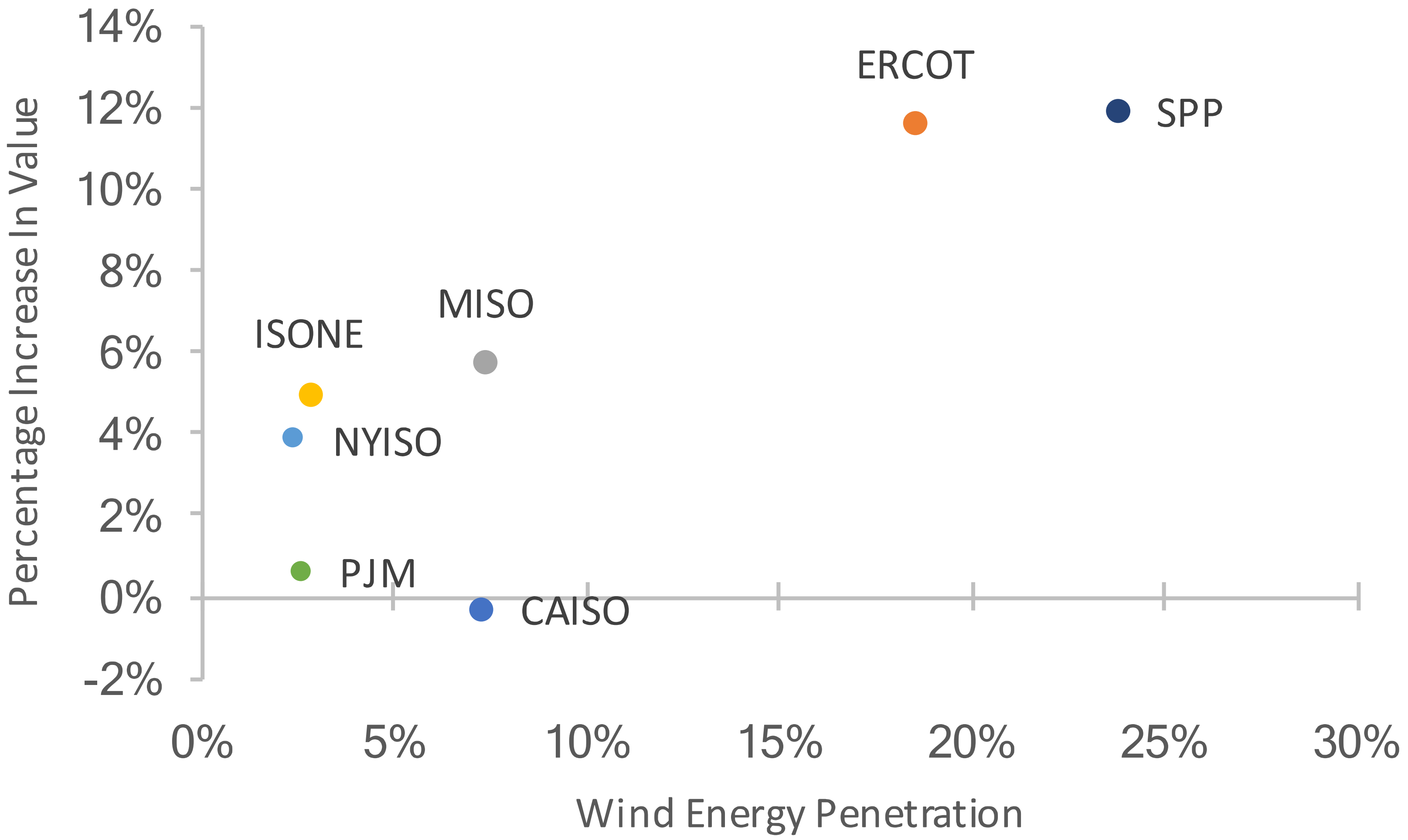
- Nationally, there is a normal distribution of percentage change in market value centered between a 5% to 10% increase in value
- ERCOT and SPP are centered on a 10% to 15% increase
- CAISO and PJM are centered on a 0% change
- Other regions are in between these two groupings
- Project-level results are distributed widely around these central values

Absolute change in 2018 summed energy and capacity value ($/MWh) of low-SP / high-HH turbine versus 2018 average turbine



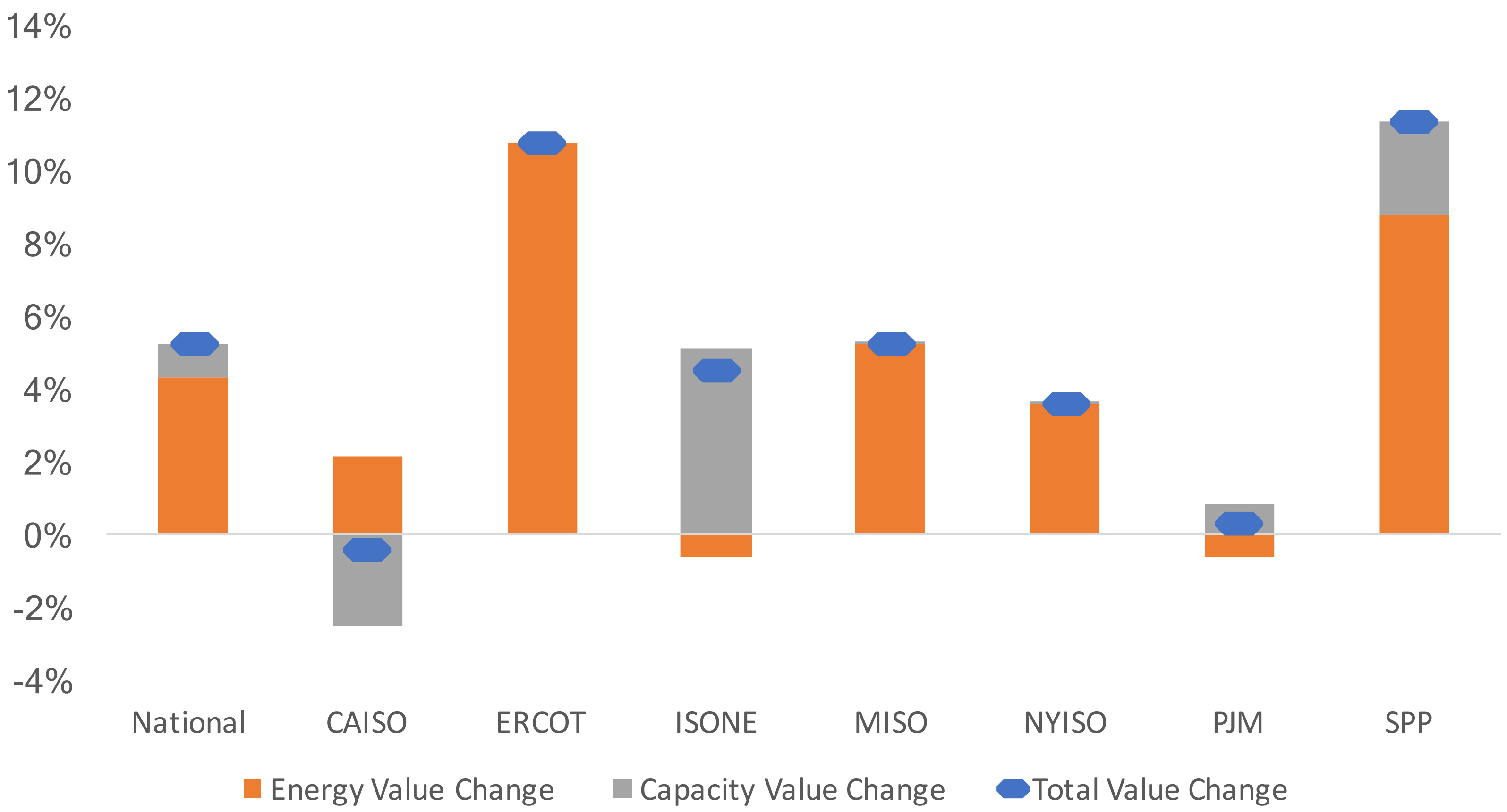
- Nationally, there is a normal distribution of absolute change in market value centered between a $1/MWh to $2/MWh increase in value
- ERCOT and SPP are centered on a $2/MWh to $3/MWh increase
- ISO-NE absolute change varies across an exceptionally large range of values based on location→ due to transmission constraints
- CAISO and PJM are centered on no change in market value

Average percentage change in value from low-SP / high-HH turbine is somewhat correlated with wind penetration levels



Note: The same is not true for absolute $/MWh value enhancement, because that metric is also highly impacted by general wholesale price variations from one ISO to the next (e.g., ISO-NE has relatively high overall wholesale prices compared to other regions)

Average percentage change in value from low-SP / high-HH turbine is driven more by energy value than capacity value



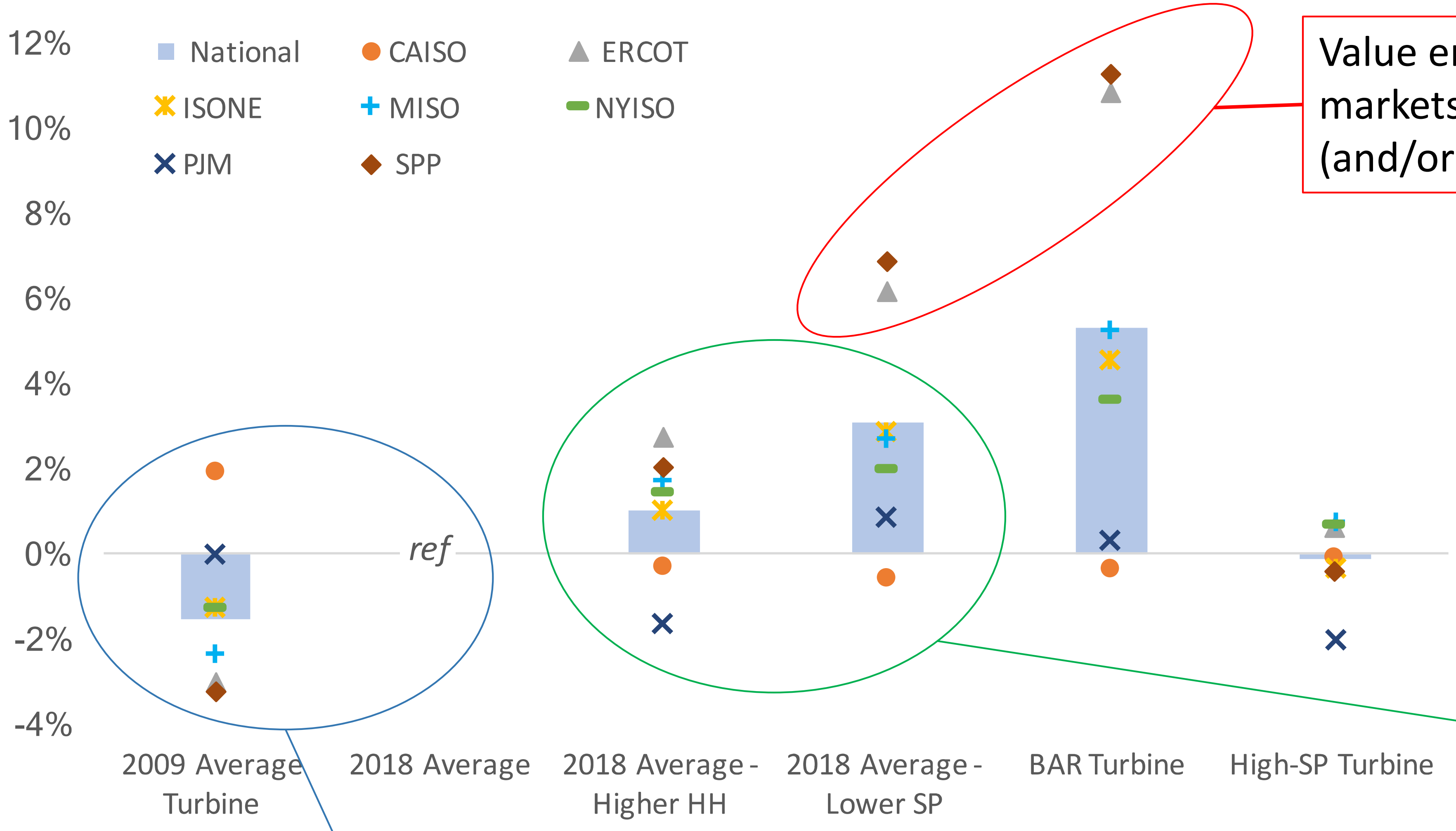
- The change in value from low-SP / high-HH turbines is due to both energy value and capacity value→ energy value dominates
- Low wind penetration in ISONE and PJM lead to small decreases in energy value, although the capacity value increase is large in ISONE
- There is no capacity requirement in ERCOT due to its energy-only market design
- In CAISO, the capacity credit is not currently calculated based on each turbine's generation profile → and so capacity value effect is negative as total MWh increases but absolute $ credit is unchanged
- In other markets, the relative size of the change in capacity value depends on rules around the determination of wind's capacity credit, and the price or cost of capacity

Average difference in energy and capacity value between each turbine & the 2018 average turbine *(national summary)*

	2009 Average Turbine	2018 Average	2018 Average, Higher HH	2018 Average, Lower SP	Low-SP, High-HH	High-SP Turbine
Energy Value ($/MWh)	-0.38	*ref*	0.30	0.62	1.15	0.07
Capacity Value ($/MWh)	-0.03	*ref*	-0.03	0.20	0.25	-0.10
Total Value ($/MWh)	-0.41	*ref*	0.27	0.82	1.40	-0.04
Total Value (% difference)	-1.6%	*ref*	1.0%	3.1%	5.3%	-0.1%

- As expected, the low-SP / high-HH turbine produces the greatest increase to value; the 2009 average turbine produces less value than the 2018 average turbine
  - Industry has already made progress boosting market value with low-SP machines, but more progress can be made with even lower SP and higher HH
- Value increase from low-SP / high-HH is due to both increased HH and decreasing SP, but SP effect is 2-3x greater than HH effect
- Value increase is due to both energy value and capacity value, but energy value dominates
- High-SP turbine at 140m HH provides marginal energy value improvement, largely negated by decline in capacity value
  - Small decrease in capacity value seen with higher HH occurs because there is an increase in total MWh generated, but the capacity credit does not increase as much as total generation (so, on a per MWh basis, capacity value declines)
  - This effect is most clear in CAISO, where the capacity credit of wind is not currently calculated based on each turbine's generation profile, and thus stays constant between scenarios, but is then spread across a greater number of generation hours as HH increases

Average percentage difference in summed energy and capacity value between each turbine and the *2018 Average* turbine



Value enhancement is greatest in markets with high wind penetrations (and/or with transmission constraints)

A reduction in specific power from 230 W/m^2 to 150 W/m^2 has a greater impact than raising hub height from 88m to 140m

Industry has already made progress boosting market value via turbine design, but more progress is possible

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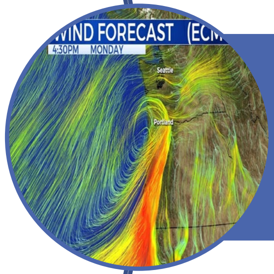
Possible Additional Benefits of Turbines with Low Specific Power and Tall Towers

We explore three *additional* possible benefits, beyond those related to direct-LCOE and market value presented earlier

Transmission expenditures



Balancing / ancillary service costs

Cost of wind-plant financing

Transmission expenditures are expected to be lower for the low-SP / high-HH turbine relative to the 2018 average turbine

- Lower specific power & taller turbines result in higher capacity factors, thereby increasing the utilization of transmission lines and reducing the $/MWh-wind cost of transmission
- Three types of transmission expenditures can be associated with wind power plants that might benefit from low specific power, tall wind turbines
    1. **Spur-line costs:** Transmission between the wind plant and the substation
    2. **Interconnection costs:** The cost (after the spur line) of interconnecting a plant to the bulk transmission network, including any substation upgrades as well as any transmission network upgrade costs that are specifically assigned to wind plant owners
    3. **Bulk network expansion:** Broader network expansion costs that are driven, in part, by the presence of wind development, often in remote areas
- Note that costs associated with the first two transmission needs (spur lines and interconnection costs) are generally borne by wind plant owners; the third category of bulk network expansion is sometimes socialized, not paid directly by the wind plant owner

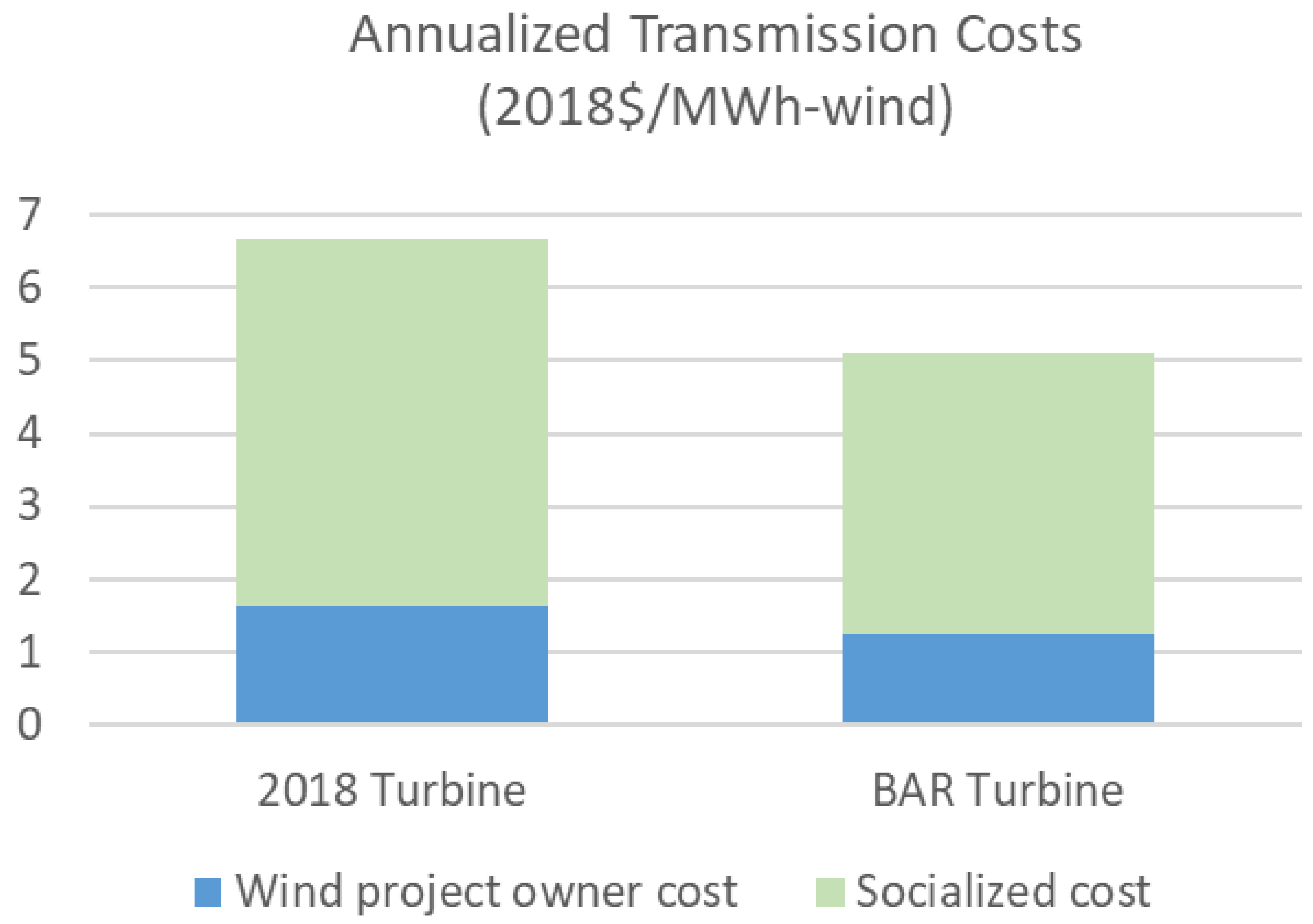
Estimating the benefits of increased transmission utilization from low specific power, tall tower wind turbines

- Spur line costs: assumed spur line distance of 10 miles from previous development experience in the U.S., and spur line costs of ~$4,000/MW-mile from NREL ReEDS = $40/kW upfront cost, financed over 30 years at 3.5% real weighted average cost of capital (WACC)
- Interconnection costs: previous LBNL work analyzing wind-plant interconnection costs in PJM and MISO, and data from EIA, suggest that costs have averaged ~$70/kW-yr historically, financed over 30 years at 3.5% real WACC
- Additional bulk network expansion: previous LBNL work suggests that these costs average ~$5/MWh, or ~$390/kW-yr; these are assumed to be socialized and amortized over 60 years by a utility investor at a 4.4% real WACC
- From previous analysis by NREL & LBNL, average capacity factor for turbines similar to those installed in 2018 = 42%, low-SP / high-HH turbines = 55%, resulting in different $/MWh-wind cost of transmission due to capacity utilization differences
- Note: We only consider transmission capital costs, and therefore conservatively assume differential utilization does not impact transmission operating costs; additionally, we do not consider any benefits from transmission reduction due to low-SP / high-HH turbines being located closer to load

Source: https://emp.lbl.gov/publications/improving-estimates-transmission

Transmission cost-reduction benefit equals ~$1.6/MWh for the low-SP / high-HH turbine, relative to the 2018 average turbine

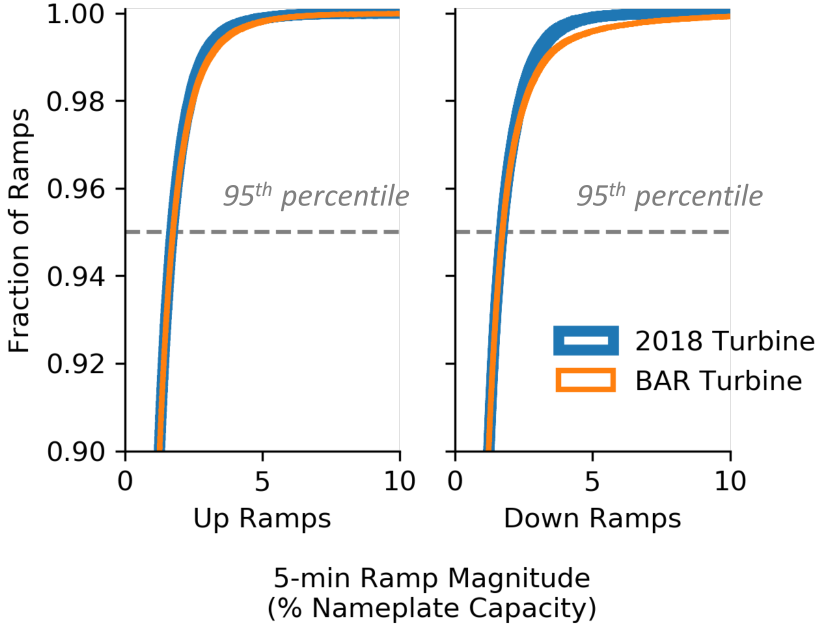
- Low-SP / high-HH turbine saves ~$1.6/MWh of total costs on average
- ~25% ($0.4/MWh) of this accrues to the wind project owner, due to lower spur line and interconnection costs
- ~75% ($1.2/MWh) is a socialized benefit, due to lower network expansion costs



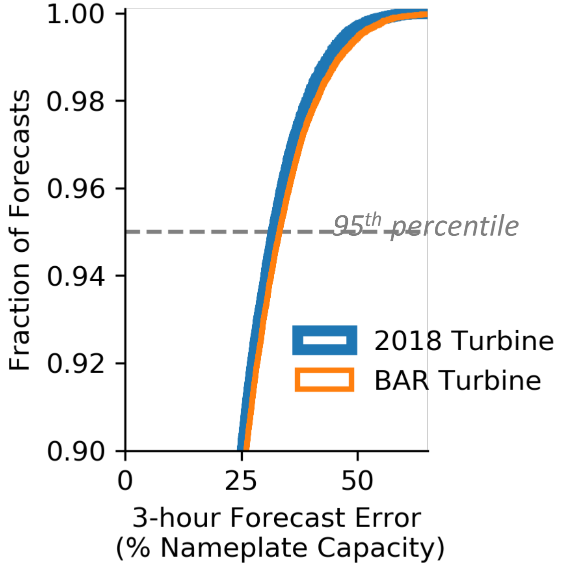
Short-term variability and forecast errors of low-SP / high-HH turbines are slightly higher than 2018 average turbines

- System operators use reserves to maintain balance between supply and demand
- Short-term variability and uncertainty of wind can increase required reserves, increasing costs
- Balancing reserves depend on the largest ramps or forecast errors (often at the 95th percentile) from the aggregate variability and uncertainty of all turbines
- Largest ramps and forecast errors occur when wind is in the steep part of the power curve, rather that at rated capacity; the steeper power curve of the low-SP / high-HH turbines can lead to slightly greater reserve requirements

- In ERCOT, regulation reserves depend on sub-hourly ramps
- 95th percentile of aggregate ramps nearly identical



- In ERCOT, non-spinning reserves depend on 3-hour forecast errors
- 95th percentile of aggregate forecast errors (based on persistence) are *slightly* higher for low-SP / high-HH turbines



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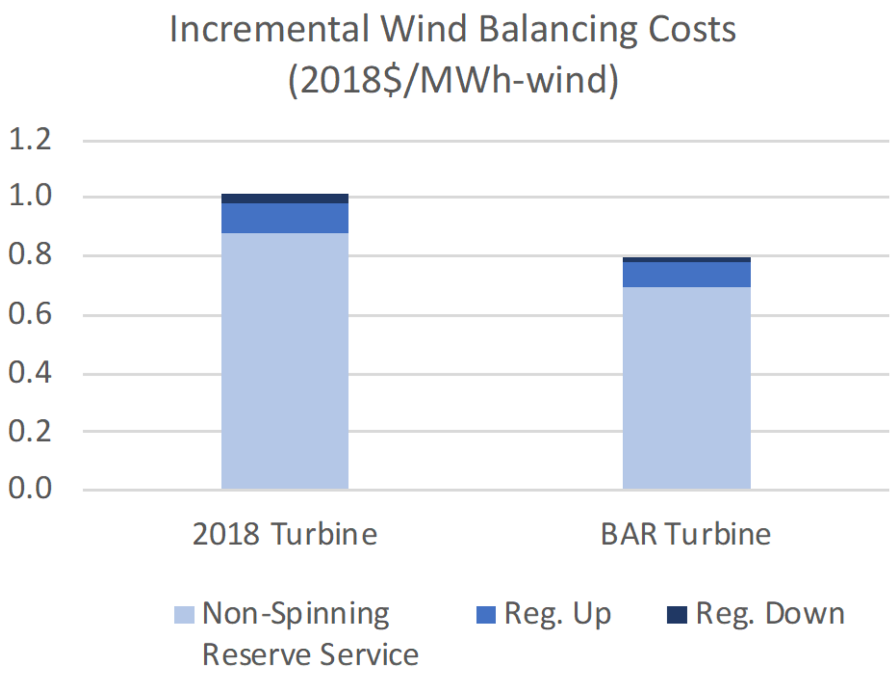
Balancing cost-reduction benefit equals ~$0.2/MWh for the low-SP / high-HH turbine, relative to 2018 average turbine

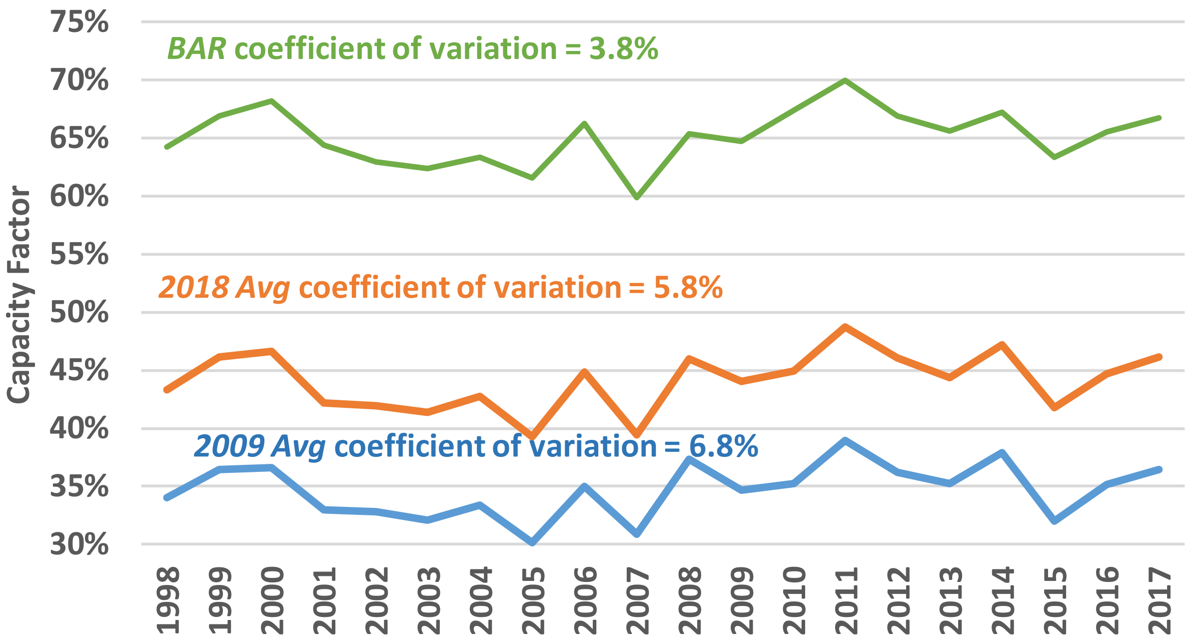
- Balancing cost reduction of low-SP / high-HH turbines is due to only slightly greater balancing reserve requirements being spread over much more energy (higher capacity factor)
- This cost reduction, described more below, is socialized
- Non-Spinning Reserve Service:
  - The price for non-spinning reserves in ERCOT was $9.2/MWh in 2018
  - With current turbines, ERCOT increases non-spin reserves by ~40 MW per GW of wind at a cost of $0.88/MWh-wind with a capacity factor of 42%
  - Slightly greater forecast errors for low-SP / high-HH turbines (3.6% greater) increases the incremental reserve requirement to ~42 MW per GW of wind, which costs only $0.7/MWh-wind with capacity factor of 55%



- Regulation Reserves:
  - The average price for regulation up and down in ERCOT was $14.0/MWh and $5.2/MWh, respectively, in 2018
  - With current turbines, ERCOT increases regulation up by ~3 MW and regulation down by ~2 MW per GW of wind
  - Incremental regulation requirements would be nearly identical with low-SP / high-HH turbines
  - With the higher capacity factor for low-SP / high-HH turbines, regulation costs go from $0.13/MWh-wind with current turbines to $0.10/MWh-wind with low-SP / high-HH turbines

The low-SP / high-HH turbine should have less-variable annual energy production (AEP), enabling better financing terms

- The graph shows capacity factors by calendar year at a site in Texas for the *2009 Average* (329 W/m^2, 79m HH), *2018 Average* (230 W/m^2, 88m HH), and *low-SP / high-HH turbine* (150 W/m^2, 140m HH) turbines
- With lower specific power, the average capacity factor increases while the coefficient of variation (i.e., the standard deviation of capacity factor divided by the average capacity factor over the same period) declines
- If recognized by lenders through a corresponding reduction in the required debt service coverage ratio (DSCR), the low-SP / high-HH turbine's lower coefficient of variation would allow for greater debt leverage (i.e., more low-cost debt, less higher-cost equity), leading to a lower LCOE



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Moving from less AEP uncertainty to a lower DSCR

- Inter-annual variation (IAV) in the wind resource is only part of the total AEP uncertainty that lenders consider
  - There is also uncertainty in wind speed measurement, wind flow modeling, plant losses, etc.
  - If we assume that all other (non-IAV) uncertainties have a combined standard deviation of 6.5% regardless of turbine type, then total AEP uncertainty (added in quadrature) comes to 8.7% for the *2018 Average* turbine and 7.5% for the *low-SP / high-HH* turbine
- Assuming a normal distribution and 1-tailed z-values, along with the total AEP uncertainties noted in the previous bullet, the P99 capacity factor of the *2018 Average* turbine is 35.5% (compared to P50 of 44.5%), while the P99 capacity factor of the *low-SP / high-HH* turbine is 54.0% (compared to a P50 of 65.4%)
- Given these P50 and P99 capacity factors, a typical DSCR of 1.0 at P99 equates to a P50 DSCR of 1.253 for the *2018 Average* turbine and 1.211 for the *low-SP / high-HH* turbine

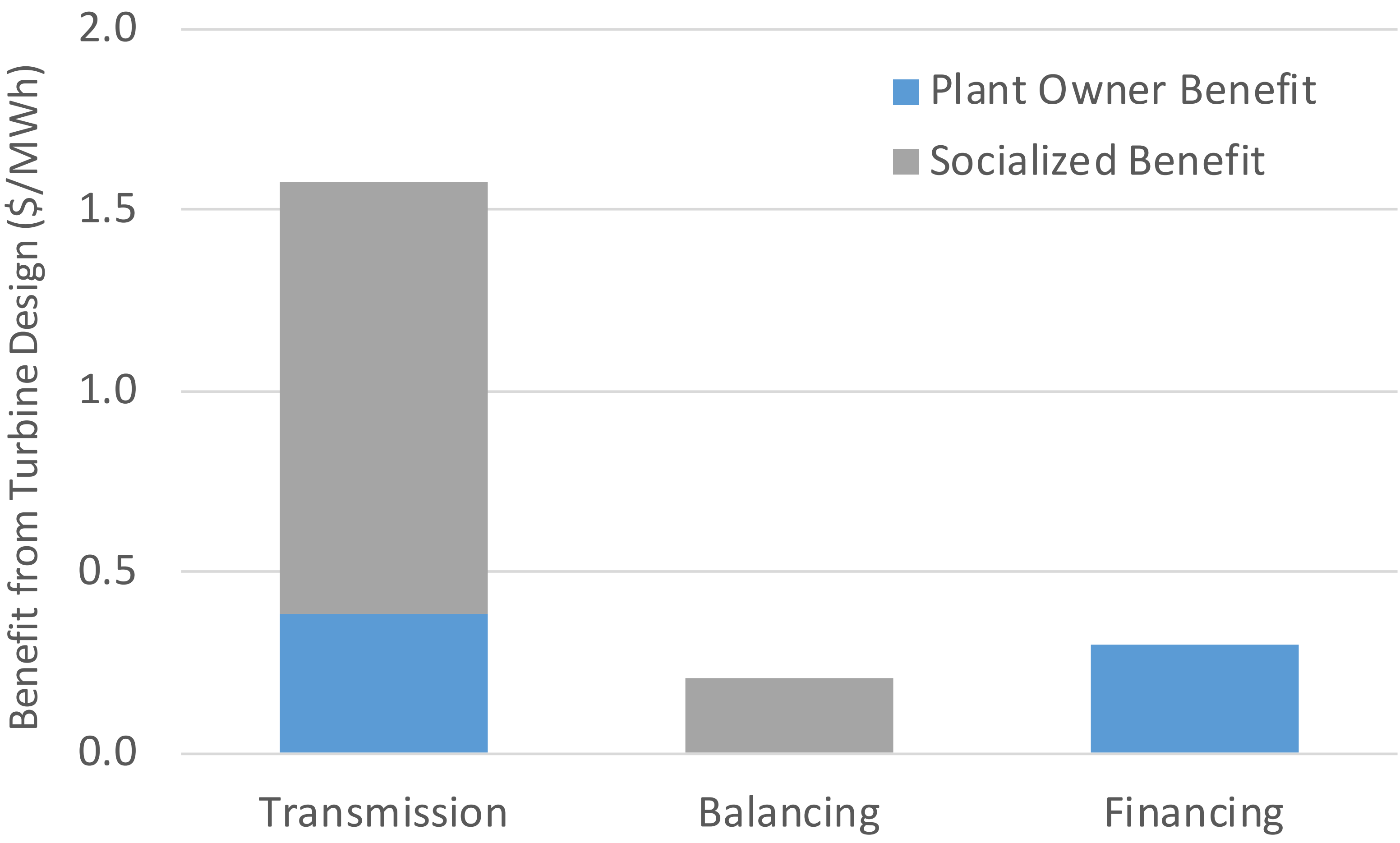
Moving from a lower DSCR to a lower LCOE

- A lower DSCR allows a project to support more debt (i.e., less coverage is required to service a given amount of debt, meaning that more debt can be serviced)
- Because debt is typically cheaper than equity, more debt (and less equity) in the capital stack typically reduces the weighted average cost of capital (WACC)
- All else equal, a lower WACC leads to a lower LCOE
- With the PTC available, the DSCRs calculated on the previous slide would allow leverage to increase from 32.0% (for the *2018 Average* turbine) to 32.6% (for the *low-SP / high-HH* turbine), reducing LCOE from \$16.87/MWh to \$16.76/MWh (levelized over 30 years in 2018 dollars)—***a reduction of \$0.11/MWh***
- Without the PTC, leverage would increase from 76.9% (*2018 Average* turbine) to 78.4% (*low-SP / high-HH* turbine), reducing LCOE from \$24.72/MWh to \$24.43/MWh (levelized over 30 years in 2018 dollars)—***a reduction of \$0.30/MWh***

Other key modeling assumptions include \$1400/kW CapEx, \$40/kW-year OpEx, 45% capacity factor, 30-year debt interest rate of 4.0%, 10% sponsor IRR

Supplemental factors sum to a ~$2/MWh benefit of the low-SP / high-HH turbine relative to the 2018 average turbine

- Financing benefits and some of the transmission benefits accrue to wind project owners: $0.7/MWh
- Other benefits accrue to the overall electricity system: $1.4/MWh
- These benefits add to the energy and capacity value impacts analyzed earlier



Summary and Conclusions

Summary and Conclusions

- Significant turbine scaling has already provided LCOE and value benefits, and further benefits are possible through a continuation of this trend
- Previous analysis suggests sizable direct LCOE benefits from further move towards low specific power turbines; analysis presented here focused on several *additional* benefits
- Regions with high levels of wind penetration and/or transmission constraints show an increase in market value from the low-SP / high-HH turbine (versus the 2018 average turbine): ~11% on average in 2018, corresponding to ~$2-3/MWh
  - Lower values in regions with low wind penetrations: $1-2/MWh median value boost in 2018 across all sites
  - Specific power is a stronger lever for value enhancement than is hub height, among turbines analyzed
  - Value boost is mostly due to higher energy value; capacity value is a smaller driver
  - As shown in appendix, modeling provides clues as to how energy and capacity value might evolve
- Other possible benefits: higher transmission utilization (from higher capacity factor) can save ~$1.6/MWh; improved financing terms (from less-variable AEP and lower DSCR) might save another ~$0.3/MWh; lower balancing costs might add another ~$0.2/MWh

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Appendix: Market Value Results Using Forecasted Prices

Assessing possible future impacts uses LCG models of wholesale prices, leveraging 2018 EERE SPO-funded work

Four Regions: Modeled with LCG UPLAN and Gen-X Models

ERCOT | SPP | CAISO | NYISO

Low VRE in 2030

- **Low VRE** future with wind and solar shares frozen at 2016 levels

High VRE in 2030

- **Balanced VRE** (20% Wind, 20% Solar)
- **High Wind** (30% Wind and at least 10% Solar)
- **High Solar** (30% Solar and at least 10% Wind)

Impacts on wholesale electricity prices

Impacts on 'market value' of wind and solar

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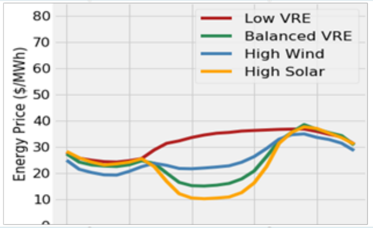
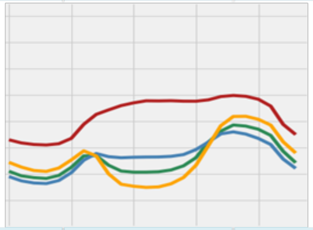
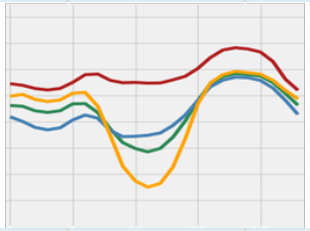
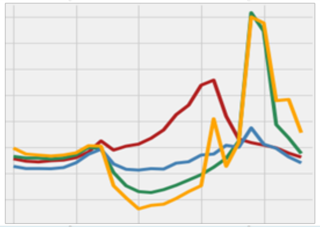
Additional modeling details…

- Modeling intended to focus on possible trends in pricing profiles and related implications, more so than absolute values
- Capacity expansion and production simulation, with plant-level operational detail
- Capacity balance ensured through economic retirement decisions and additions; sufficient revenue via prices to just ensure resource adequacy
- Basic energy and ancillary service (AS) designs remain largely as they are today, with price caps, ORDC in ERCOT, and co-optimization of energy and AS
- Residual revenue to ensure resource adequacy recovered in top-100 net load hours, with wind's capacity credit determined by generation in those hours
- Little storage growth assumed, meaning that resulting price volatility may be greater than one would really expect
- Intra-ISO transmission was expanded to keep congestion-related curtailment below 3% of annual VRE energy. The modeling focused on ISO wide average prices, meaning that nodal price volatility is likely higher than what is captured with the regional prices

For more details, see: https://emp.lbl.gov/publications/impacts-high-variable-renewable

LBNL/LCG's previous analysis of wholesale price effects of VRE in 2030 is used in our assessment of turbine design

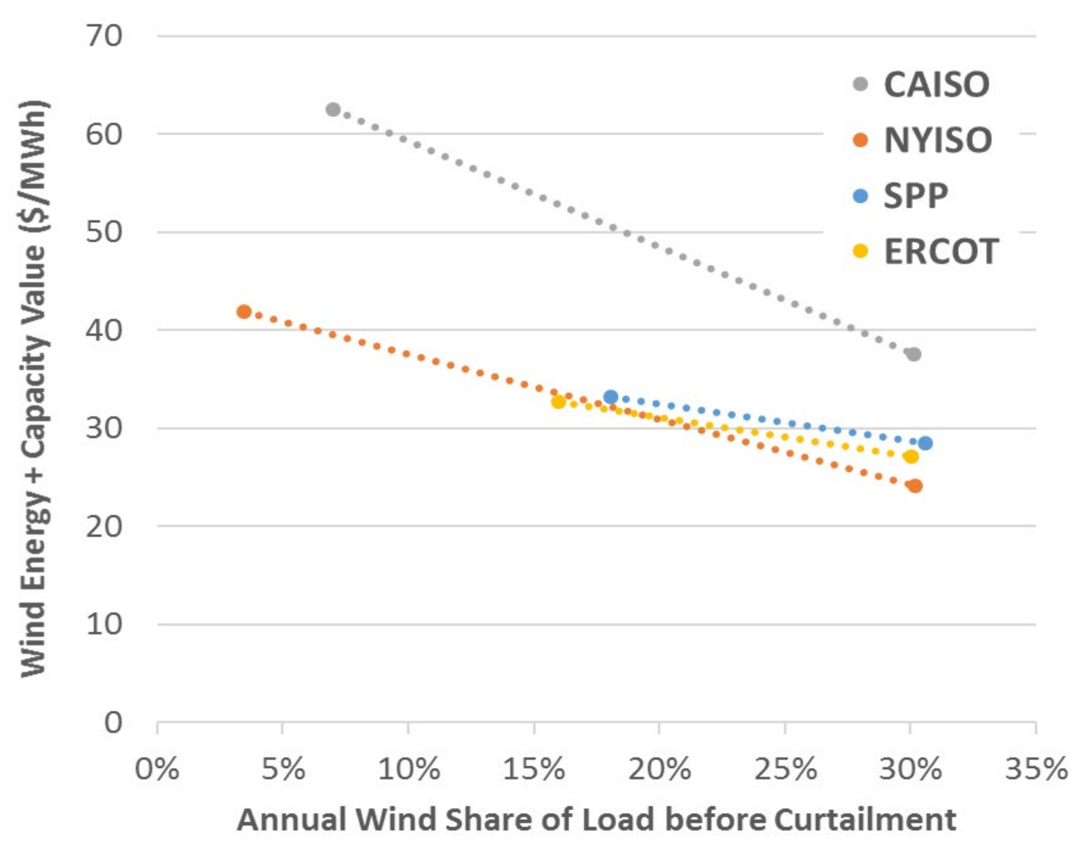
Impacts in 2030 relative to baseline with 2016 wind & solar shares	**Southwest Power Pool** 2016: 18% wind & 0% solar			**NYISO (New York)** 2016: 3% wind & 1% solar			**CAISO (California)** 2016: 7% wind & 14% solar			**ERCOT (Texas)** 2016: 16% wind & 1% solar		
	Wind	Balanced	Solar	Wind	Balanced	Solar	Wind	Balanced	Solar	Wind	Balanced	Solar
Lower Average Prices [$/MWh]	-19%	-21%	-27%	-37%	-38%	-39%	-25%	-23%	-27%	-25%	-17%	-15%
More Hours <$5/MWh In baseline: 0% of all hours	6%	8%	13%	2%	7%	11%	6%	7%	11%	6%	11%	19%
Changes in Diurnal Price Profile red baseline shows 2016 wind & solar shares												
More Price Variability	1.8x	2.1x	2.5x	2.1x	2.3x	2.5x	3.0x	2.9x	3.4x	1x	4.7x	6.6x
Higher AS Prices Regulation Down	5x	6x	9x	2x	2x	3x	3x	3x	3x	2x	3x	4x
Change in Timing of Top Net-Load Hours	Shift from 4pm to 7pm			Shift from 3pm to 5-7pm			No further shift 7pm			Shift from 3pm to 6-8pm		

LCG results from 2018 LBNL report are used in our value analysis

LBNL/LCG research found that wind's impact on wholesale prices leads to a decline in market value with penetration

Wind market value in 2030 is 14-42% lower in *High Wind* than in *Low VRE* scenarios (considering energy + capacity)

Carbon prices boost value in CAISO



Assumptions about turbines varied by region. Most importantly, turbines were assumed to be roughly similar to those existing in today's fleet. In the west, a 3 MW Vestas V-90 was used, which has a high specific power of 472 W/m^2. In the other regions, a mix of composite turbines were used, but were based on existing turbine characteristics. Turbine height was assumed to be 100 meters (or 80 m in ERCOT). Wind speed was based on data from the Eastern and Western Wind data sets (and ERCOT-specific modeling).

Analysis presented in this deck applies **turbine design variants** noted earlier to assess **change in value** under *Low VRE* and *High VRE* scenarios

Wind speed data was constructed to be consistent with the wind speed data used in the LCG modeling

- Wind speed data and corresponding generation estimates were used to conduct value analysis based on modeled future wholesale energy prices and capacity value
- Wind speeds used to determine generation profiles in the LCG modeling were based on wind speeds from year 2006 contained in the Eastern and Western wind datasets from NREL (precursors to NREL's WIND Toolkit) and also from wind resources modeled by AWS for ERCOT
- We have the underlying wind speed data from the Eastern and Western data sets, but from ERCOT we only have generation data
    - For ERCOT, we need to back-out wind speeds from the available site-level hourly generation data
        - We ran generation estimates through inverse, site-specific power curves to develop wind speed estimates
        - Limitations: AWS included loss estimates and used 1 of 3 generalized power curves determined by wind class
            - We are not able to run the exact inverse process consistent with AWS due to data availability limitations
            - Our inverse wind speed estimate will be slightly biased as we do not account for wake losses in the inversion process; we are able to account for constant losses
            - Additional small errors are caused by the fact that the power curves we use (corresponding to actual turbines at each existing site) will be somewhat different than the composite power curves that AWS used
        - ERCOT data Citation: "Simulation of Wind Generation Patterns for the ERCOT Service Area," AWS Truepower, 2012

Key details and caveats about the future scenarios

- We focus on two of the future pricing scenarios: *High Wind* penetration and *Low VRE* penetration
- Four regions are covered: CAISO, SPP, ERCOT, and NYISO
- Regional transmission is built to minimize curtailment
- In comparison to the 2018 analysis, this future analysis is based on *ISO-zonal* price series, after significant transmission has been added to the system, as opposed to *local nodal* price series from 2018
  - Resulting price volatility will be lower
  - This may be somewhat counteracted by the choice to include relatively low levels of storage
  - Thus, it is important to compare the results between low VRE and High Wind scenarios as well as simply looking at the High Wind scenario results
- Modeling is intended to focus on possible trends in pricing profiles and related implications, more-so than absolute values

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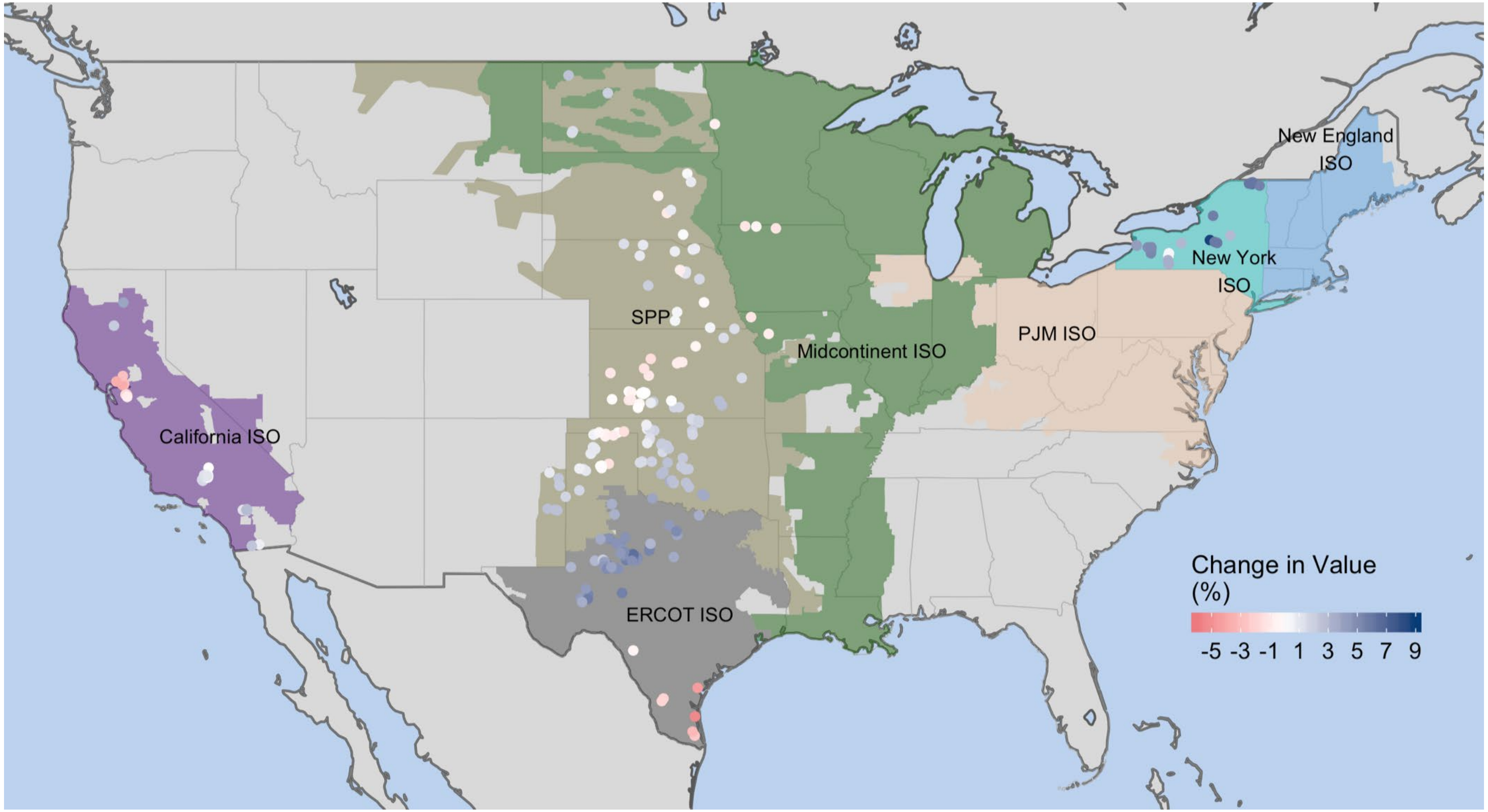
Average difference in energy and capacity value between each turbine & the 2018 average turbine *(national summary)*

	2009 Average Turbine	2018 Average	2018 Average, Higher HH	2018 Average, Lower SP	Low-SP, High-HH	High-SP Turbine
High Wind Value ($/MWh)	-0.30	*ref*	-0.24	0.55	0.45	-0.46
Low VRE Value ($/MWh)	-0.22	*ref*	-0.37	0.52	0.33	-0.60
High Wind Value (% difference)	-0.97	*ref*	-0.58	1.83	1.78	-1.32
Low VRE Value (% difference)	-0.53	*ref*	-0.89	1.32	0.94	-1.46

- Low-SP / high-HH turbine does show a larger value boost in the *High Wind* scenario compared to the *Low VRE* scenario
  - Wind penetration increases the value of the low-SP / high-HH turbine, consistent with 2018 results shown earlier
- Decrease in capacity value seen with higher hub heights occurs because there is an increase in total MWh generated, but the capacity credit does not increase as much as total generation (so, on a per MWh basis, capacity value declines)

2030 High Wind: Percentage change in summed energy and capacity value of low-SP / high-HH turbine vs. 2018 avg turbine

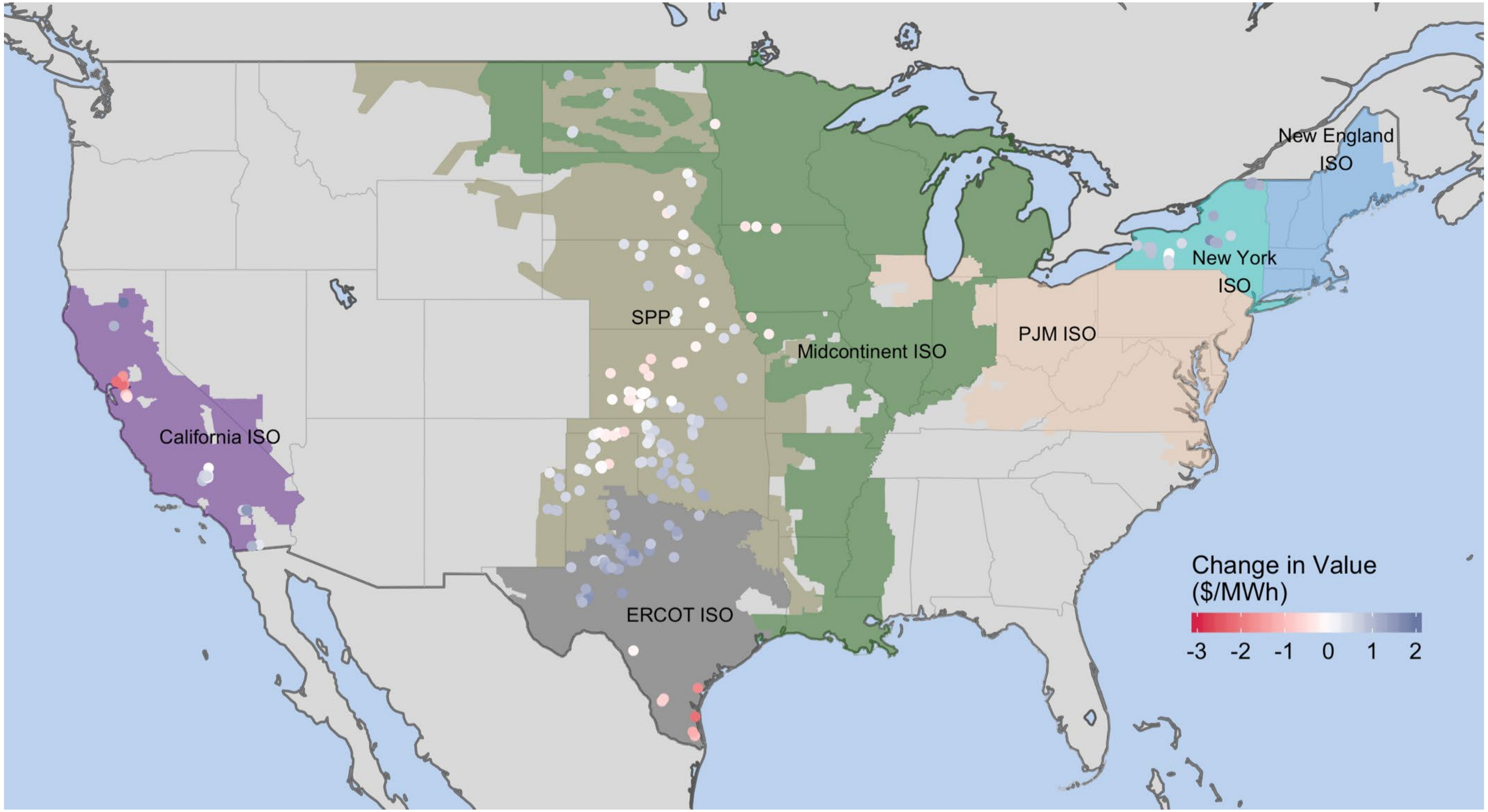


NYISO and ERCOT have the largest and most consistent increases in value with low-SP / high-HH turbines in the 2030 High Wind scenario

The change in value in CAISO and SPP varies by site, with some areas in each ISO showing increases and others showing decreases in value

Additionally, ERCOT shows value reductions in the south

2030 High Wind: Absolute change in summed energy and capacity value of low-SP / high-HH turbine vs. 2018 avg turbine



On an absolute scale, the increase in value from low-SP / high-HH turbines is more-similar across the ISOs

Regional variation within CAISO, SPP, and ERCOT is still noticeable

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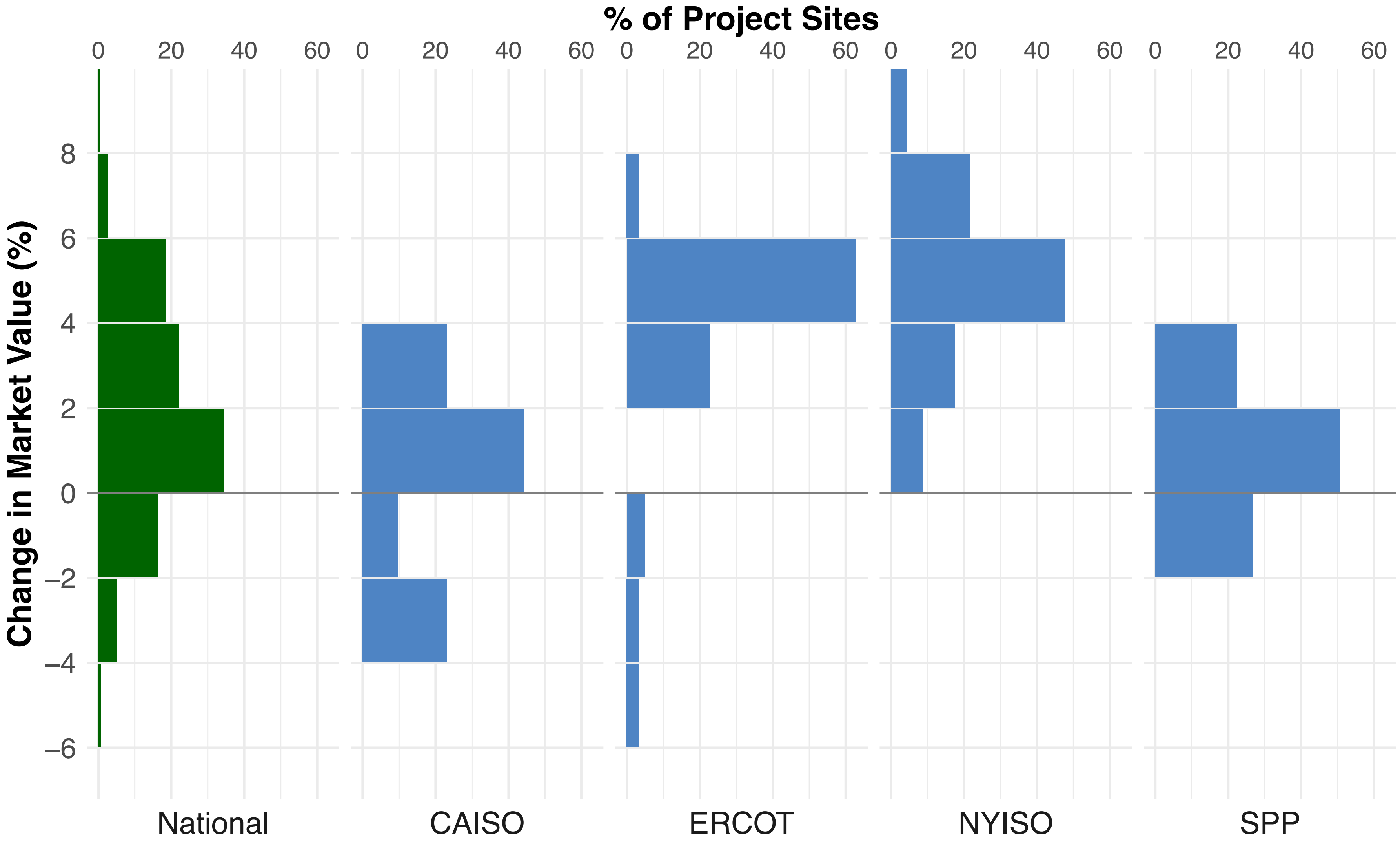
2030 High Wind: Percentage change in summed energy and capacity value of low-SP / high-HH turbine vs. 2018 avg turbine

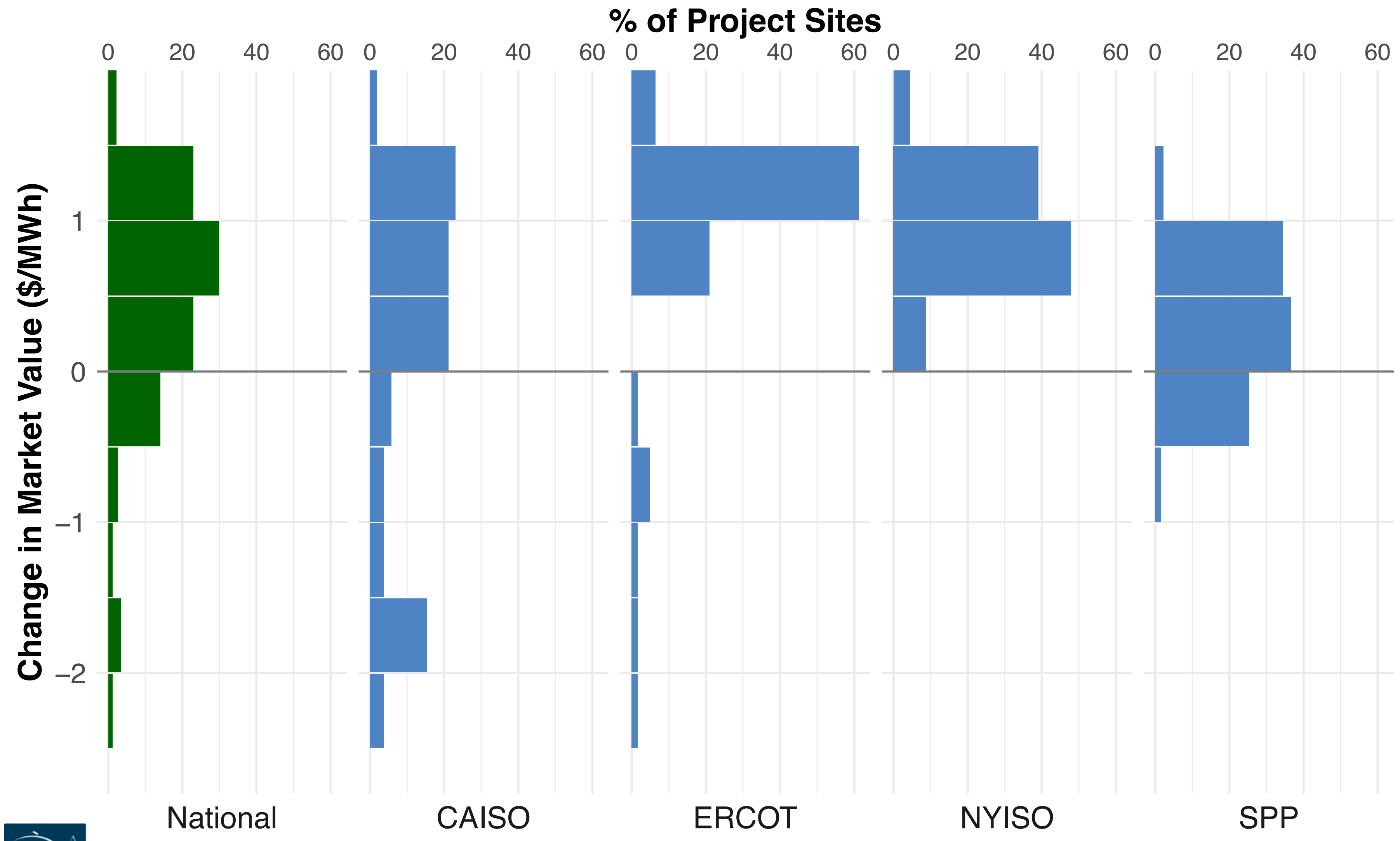


NYISO shows the highest relative value increase from the low-SP / high-HH turbine in the 2030 High Wind scenario

Although SPP and NYISO have similar estimated average wholesale energy prices across their entire regions, the areas in NYISO that contain the wind plants (West and Central) have average energy prices that are roughly 55% and 69% of the regional average prices

Thus, the relative difference in value is higher in New York, although the absolute value is more similar (see next slide)

2030 High Wind: Absolute change in summed energy and capacity value of low-SP / high-HH turbine vs. 2018 avg turbine



Most of the value changes of the low-SP / high-HH turbine are found to be between $0/MWh to $1.5/MWh, in each ISO

CAISO, SPP, and ERCOT have some plants that lose value, although most plants even in those regions see value increases from low-SP / high-HH turbines

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Conclusions from forward-looking assessment of energy and capacity value of low-SP / high-HH turbines

- Forward-looking modeling provides some clues as to how low-SP / high-HH value might evolve in the future
- However, the model of 2030 prices was quick to build transmission, possibly leading to relatively low valuations of the low-SP / high-HH turbine relative to the 2018 average turbine
  - Allocations between energy value and capacity value may also help explain the discrepancies between these findings, the 2018 results presented earlier, and the results of the European literature
- Nonetheless, the 2030 percentage value enhancement from the low-SP / high-HH turbine relative to the 2018 average turbine is roughly double under a *High Wind* scenario compared to a *Low VRE* scenario
  - Indicating that the value of the low-SP / high-HH turbine will, in general, increase with wind penetration
- To better understand the results presented here, and why they differ from the 2018 analysis and the European literature, additional modeling would be needed