LCOE and Value Assessment of Larger Rotors and Taller Towers for Land-Based Wind

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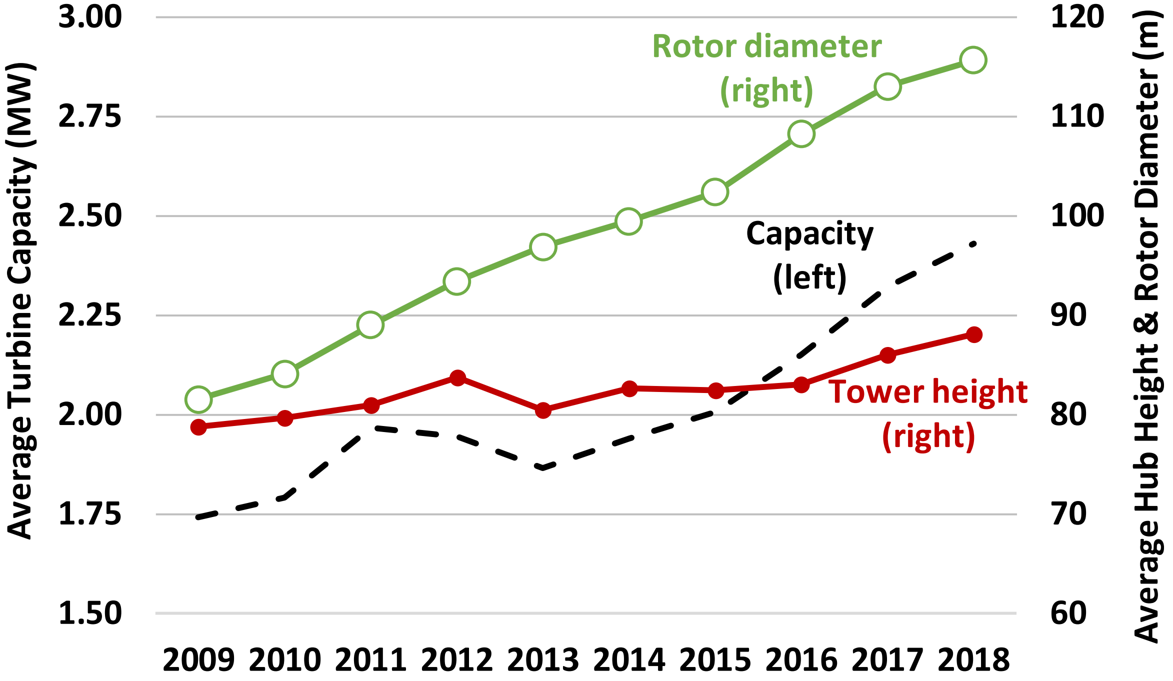
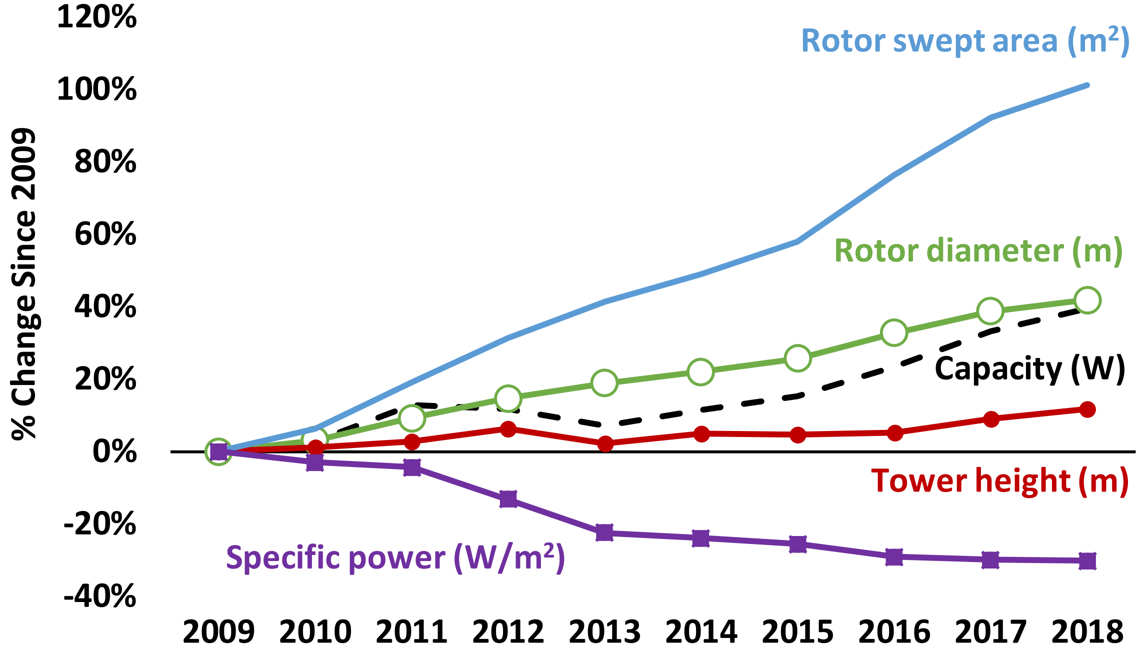
Presentation overview

- Historical scaling trends and impacts
- Geospatial LCOE analysis of future scaling scenarios
- Wholesale market value impacts (based on historical prices in 2018)
- Possible additional benefits of taller, lower-specific-power turbines
- Conclusions
- Q&A

Historical scaling trends and impacts

A decade of turbine scaling in the US: larger rotors outpaced greater turbine capacity, leading to lower "specific power"

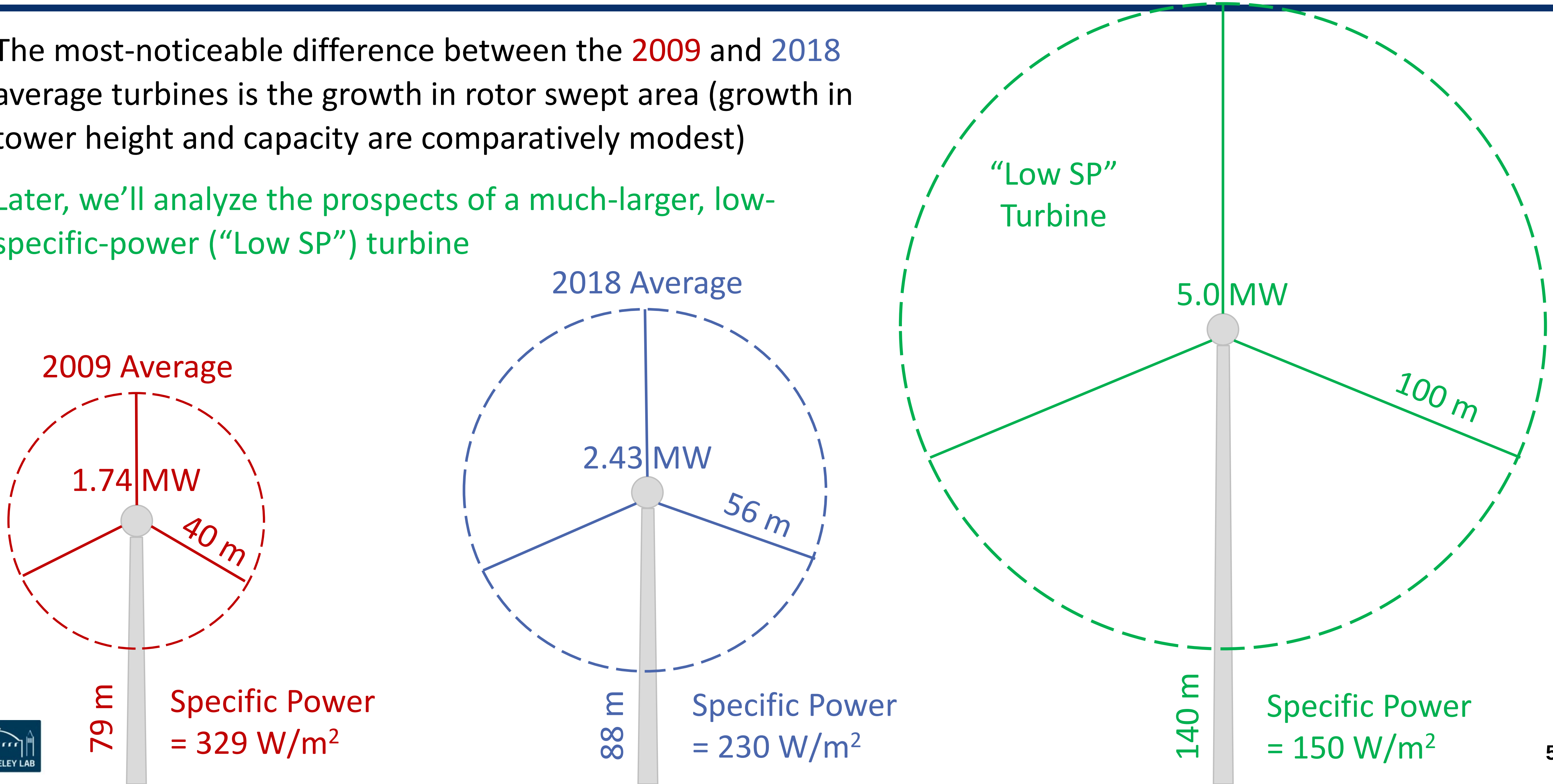




- The average tower or hub height has only grown by 12% since 2009: from 79 m to 88 m
- The swept area of the rotor (m^2) has *doubled* since 2009, outpacing the 40% growth in capacity rating (W), resulting in a 30% reduction in specific power (W/m^2): from 329 W/m^2 to 230 W/m^2

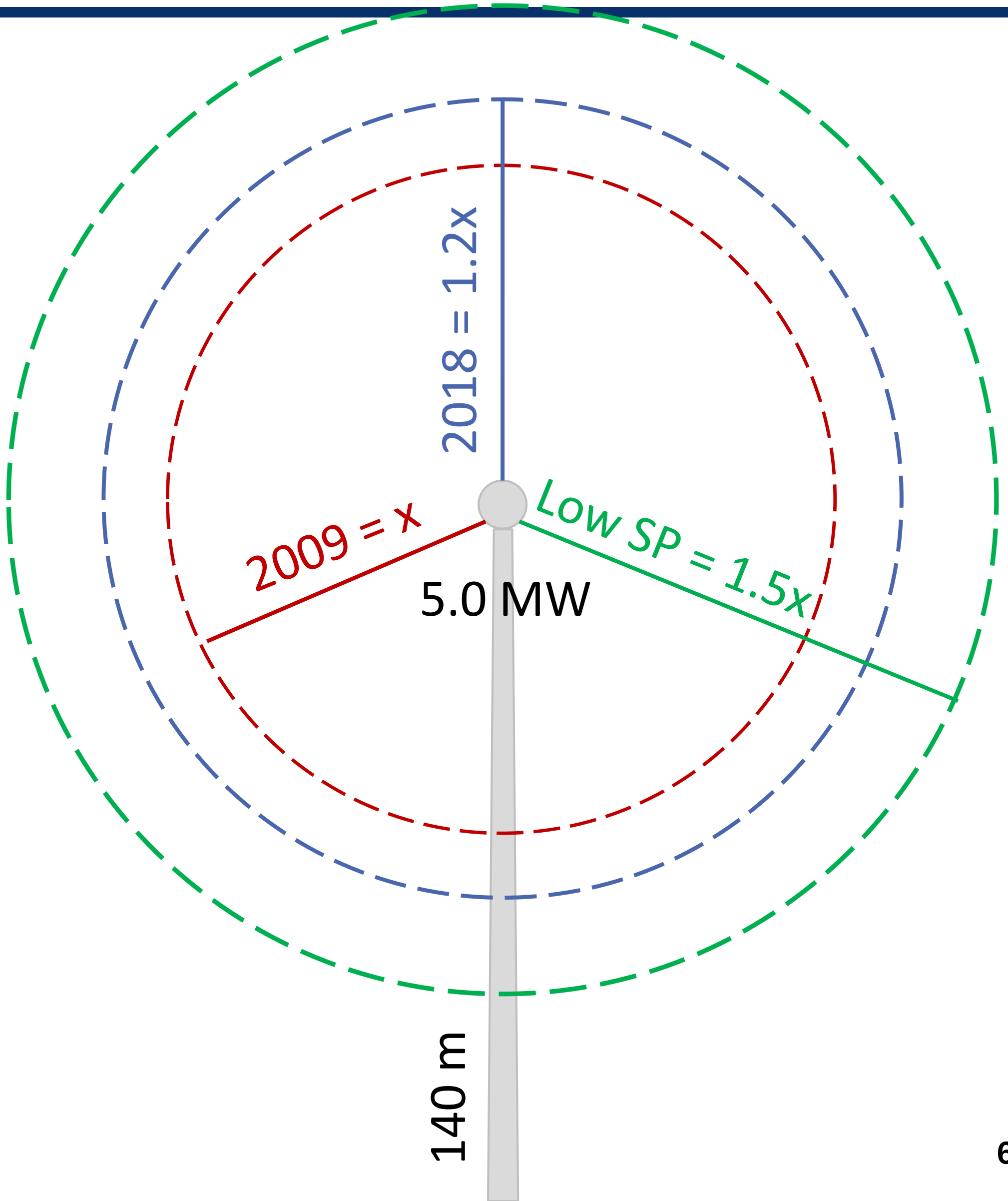
A visual representation of scaling

- The most-noticeable difference between the 2009 and 2018 average turbines is the growth in rotor swept area (growth in tower height and capacity are comparatively modest)
- Later, we'll analyze the prospects of a much-larger, low-specific-power ("Low SP") turbine



Focusing only on changes in specific power (W/m²), by holding capacity (and tower height) constant

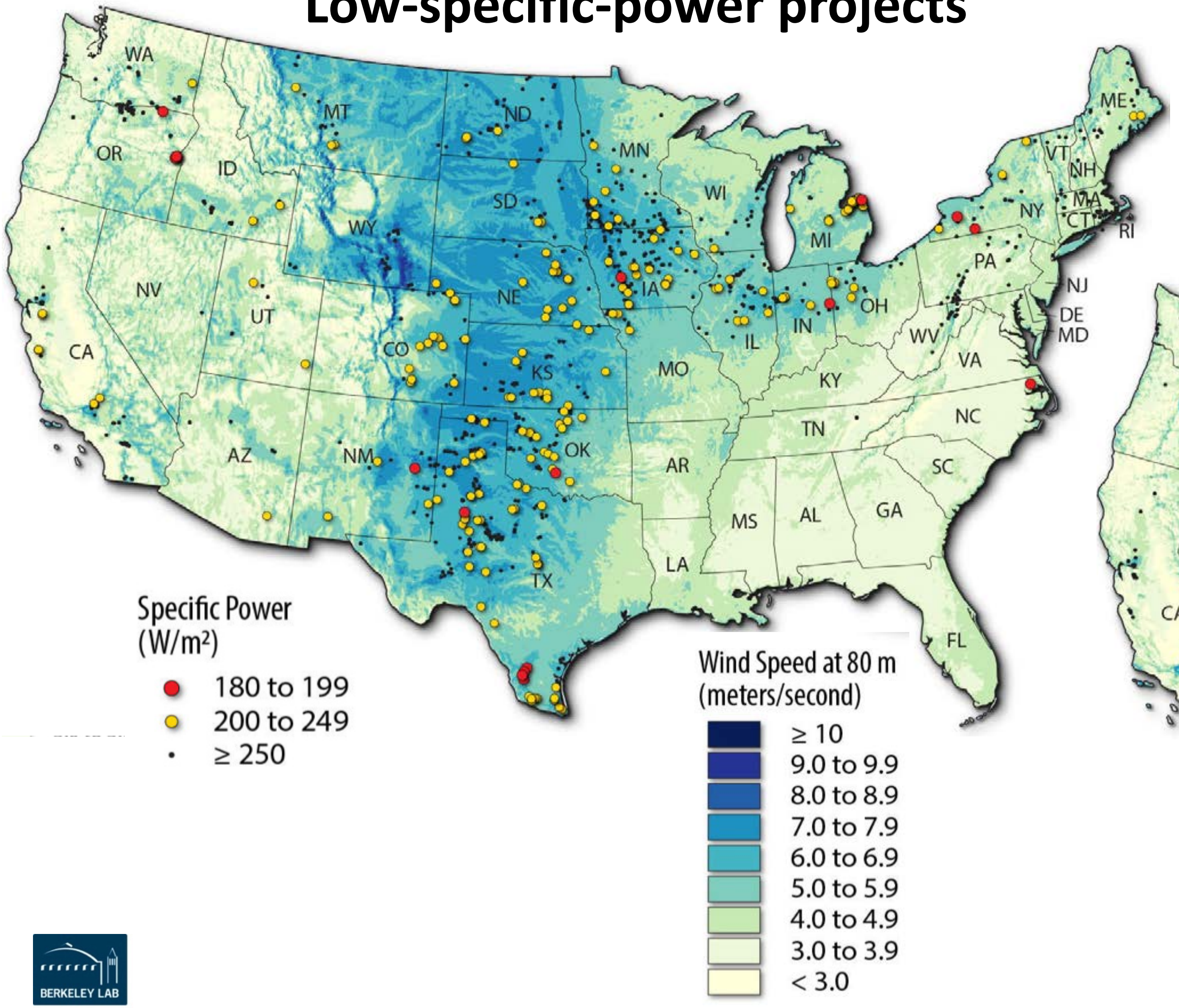
- For a given/fixed turbine capacity (e.g., 5 MW), the reduction in average specific power from 329 W/m² in 2009 to 230 W/m² in 2018 is equivalent to increasing blade length by 20%
- 20% longer blades expand the swept area of the rotor by 44% (πr^2)
- The 44% greater swept area captures more of the wind energy flowing by the turbine, causing the generator to run closer to (or at) full capacity more often—*leading to a higher capacity factor*
- Later, we'll analyze the impacts of reducing specific power to 150 W/m²—the equivalent of a 50% increase in blade length compared to 2009 (or a 25% increase compared to 2018), assuming a constant 5 MW capacity



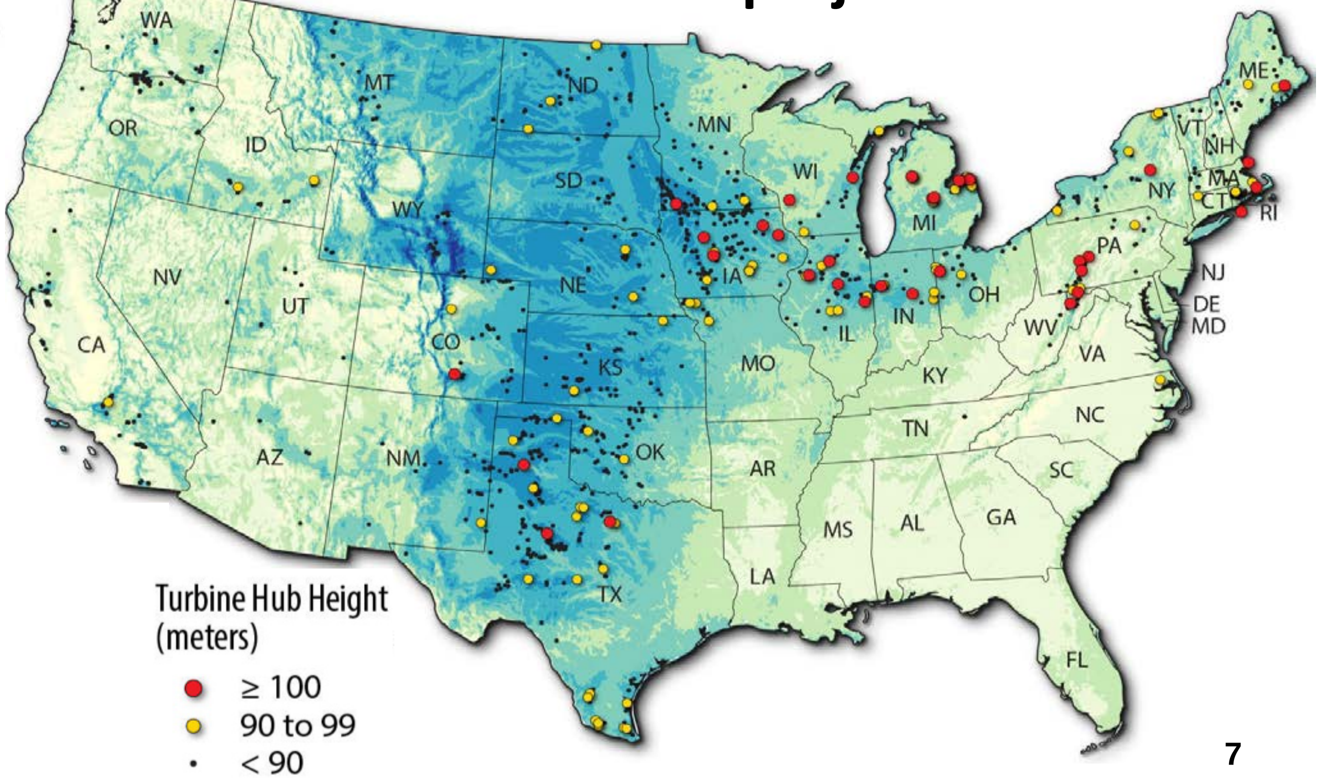
Deployment of taller towers and lower-specific-power turbines as of the end of 2018

- 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



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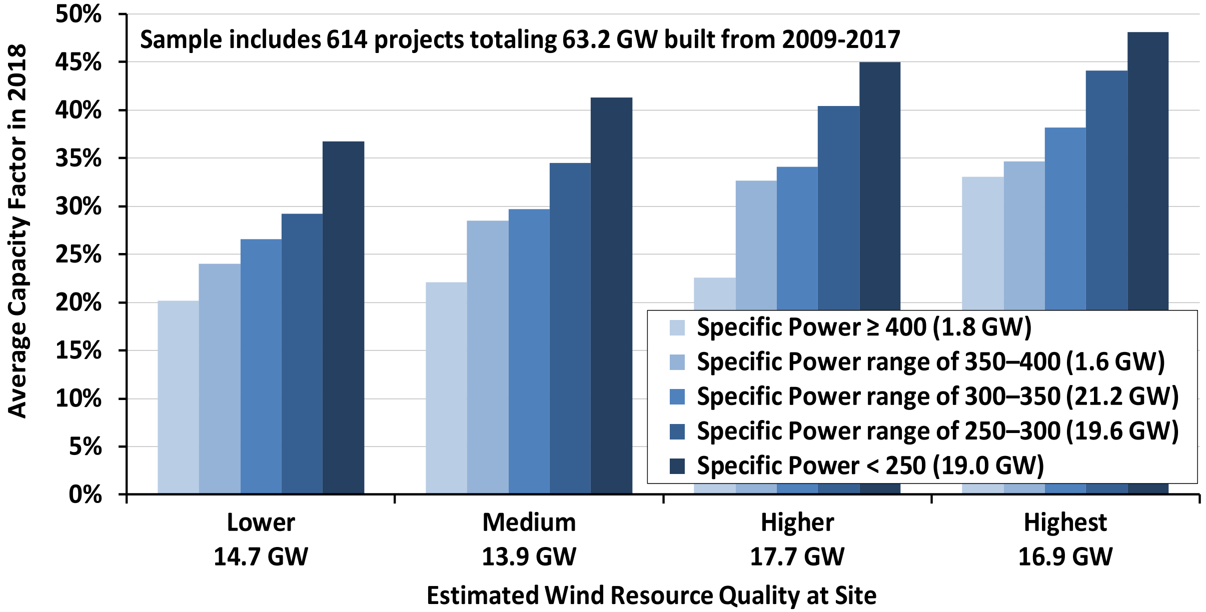
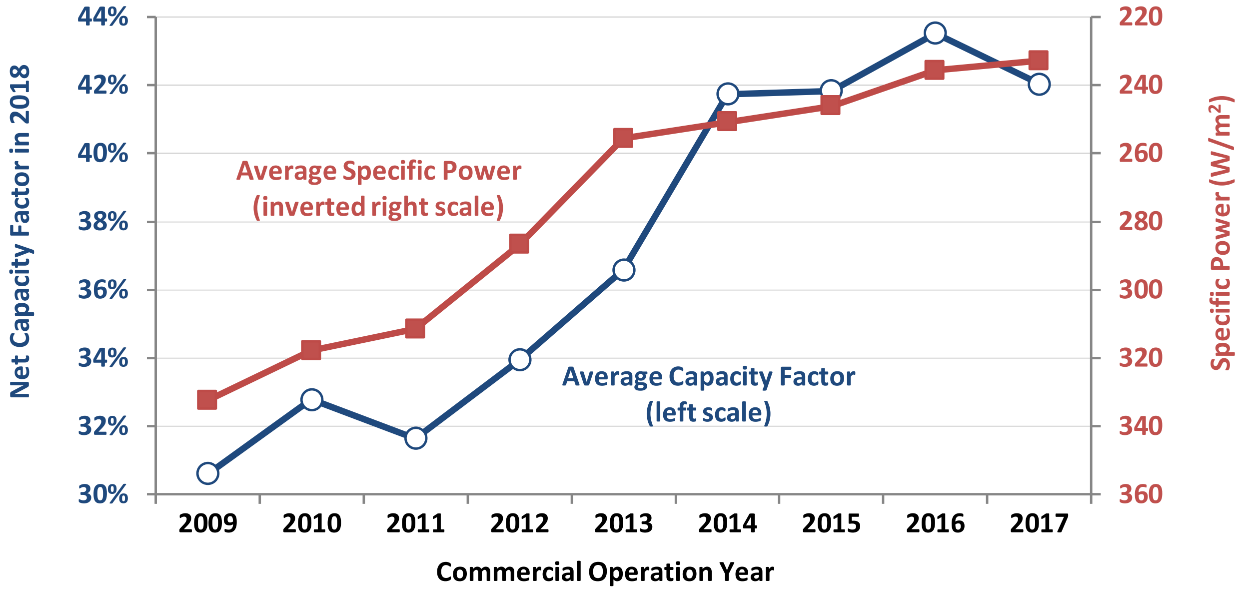
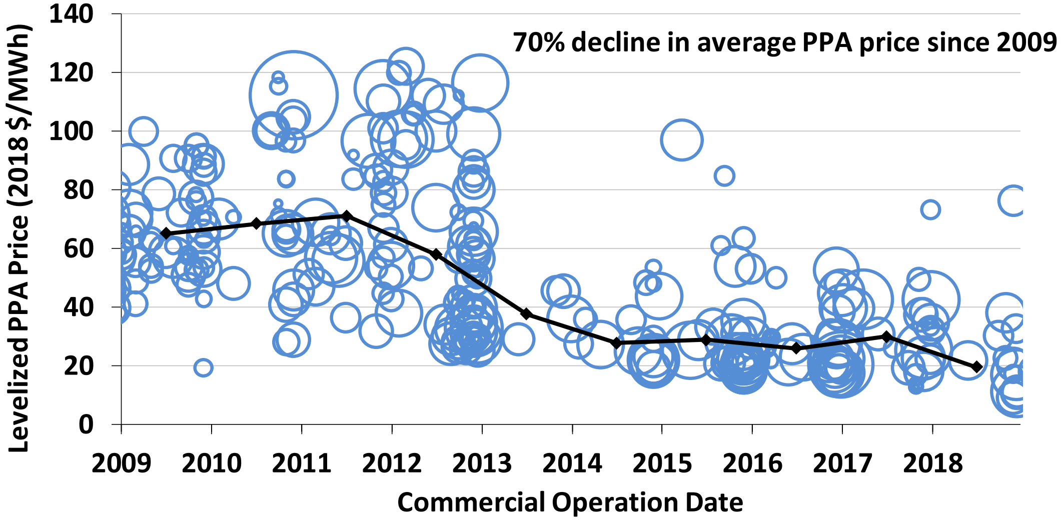
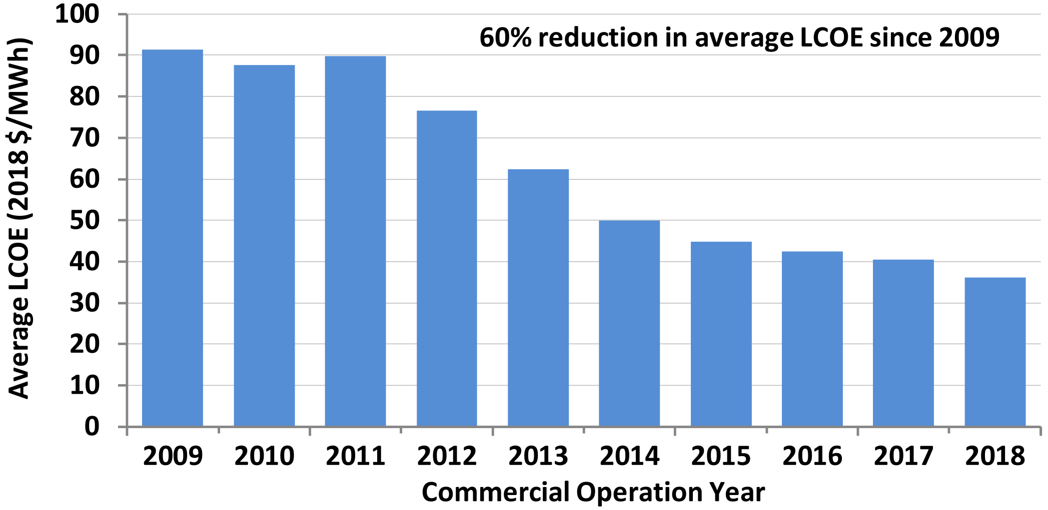
Lower specific power has driven capacity factors higher, enabling lower PPA prices and LCOE









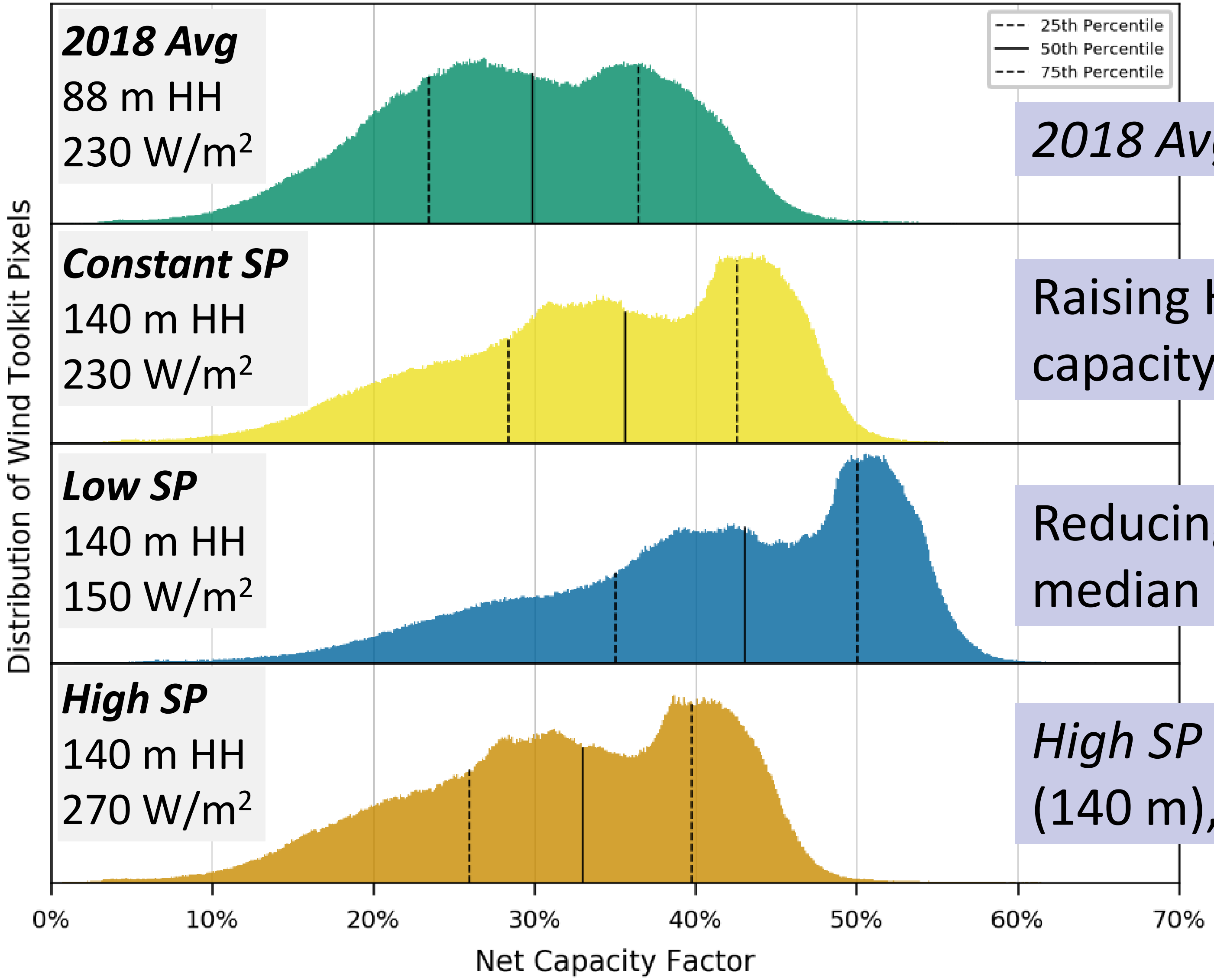
Geospatial LCOE analysis of future scaling scenarios

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



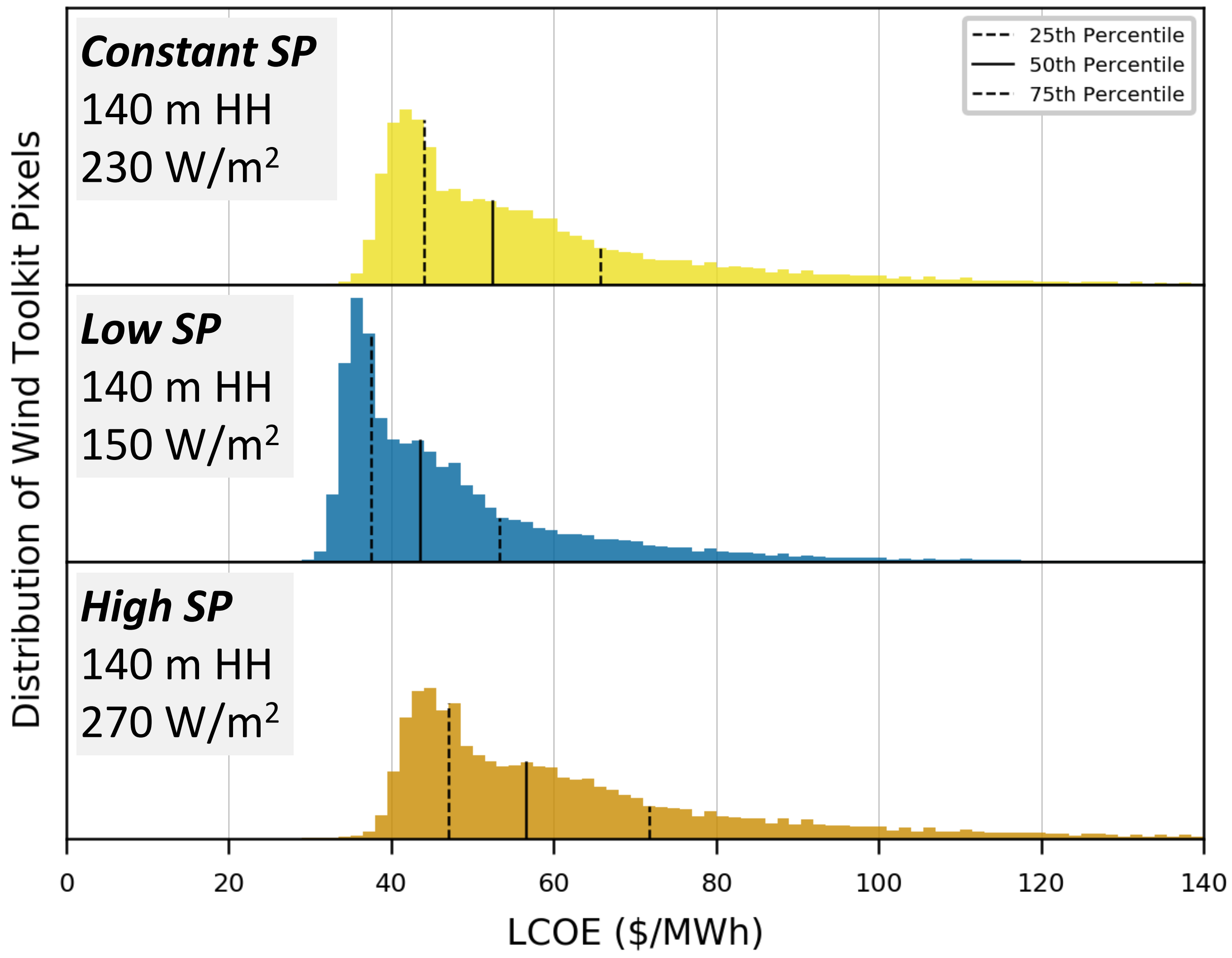
2018 Avg is the reference turbine

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…

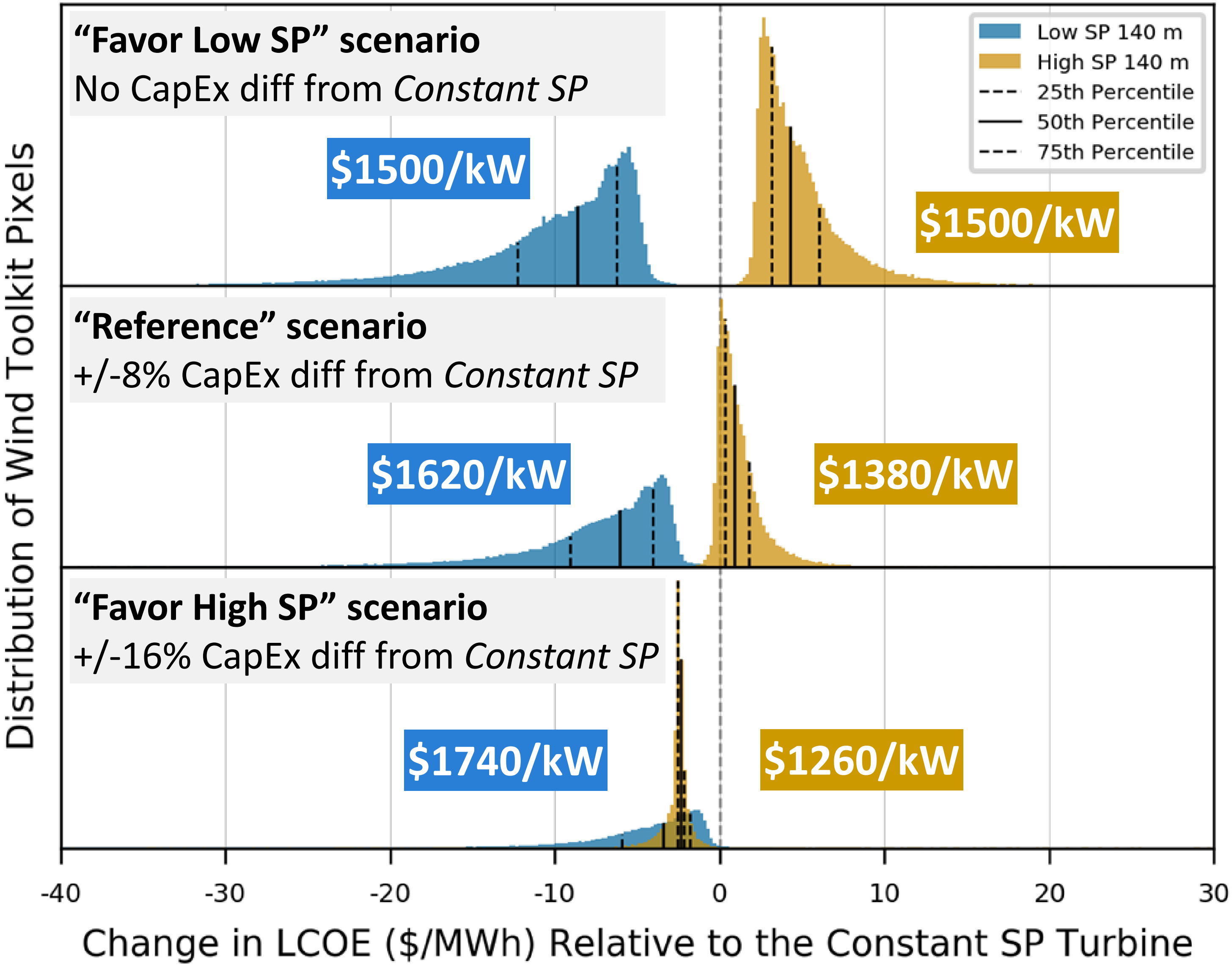


This is the "Favor Low SP" scenario, which assumes that all three turbines have a CapEx of $1500/kW

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

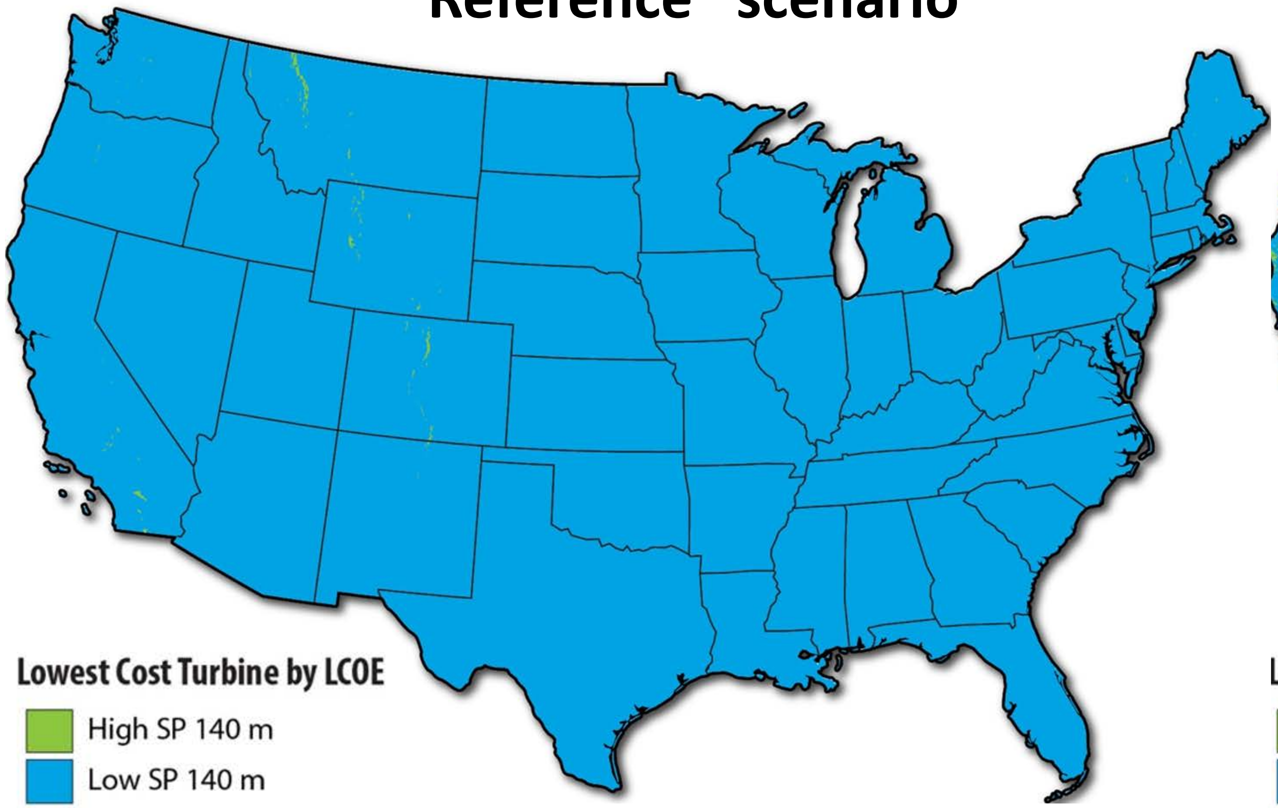
In the "Reference" scenario, the median LCOE for *Low SP* is $6/MWh less than for *Constant SP* ($7/MWh less than *High SP*)

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

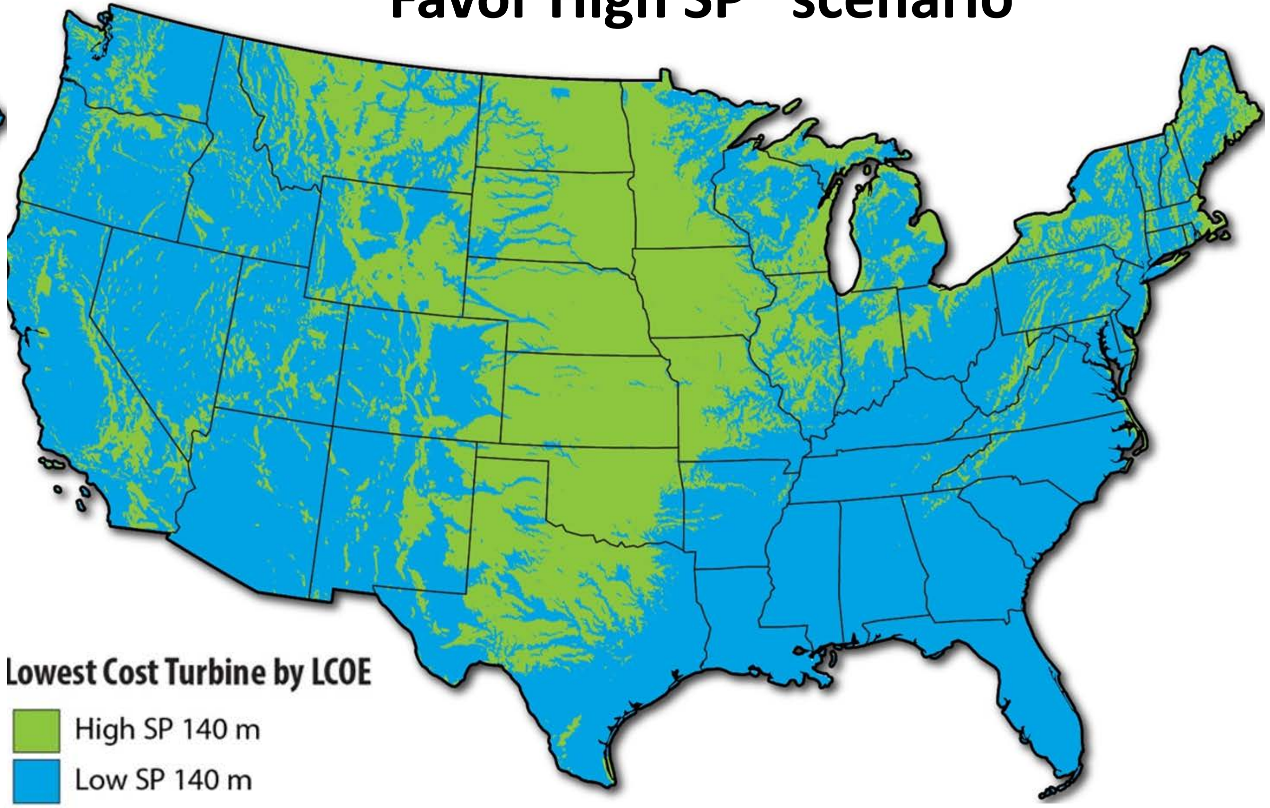
Conclusion: *Low SP* has a lot of CapEx headroom

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

"Reference" scenario



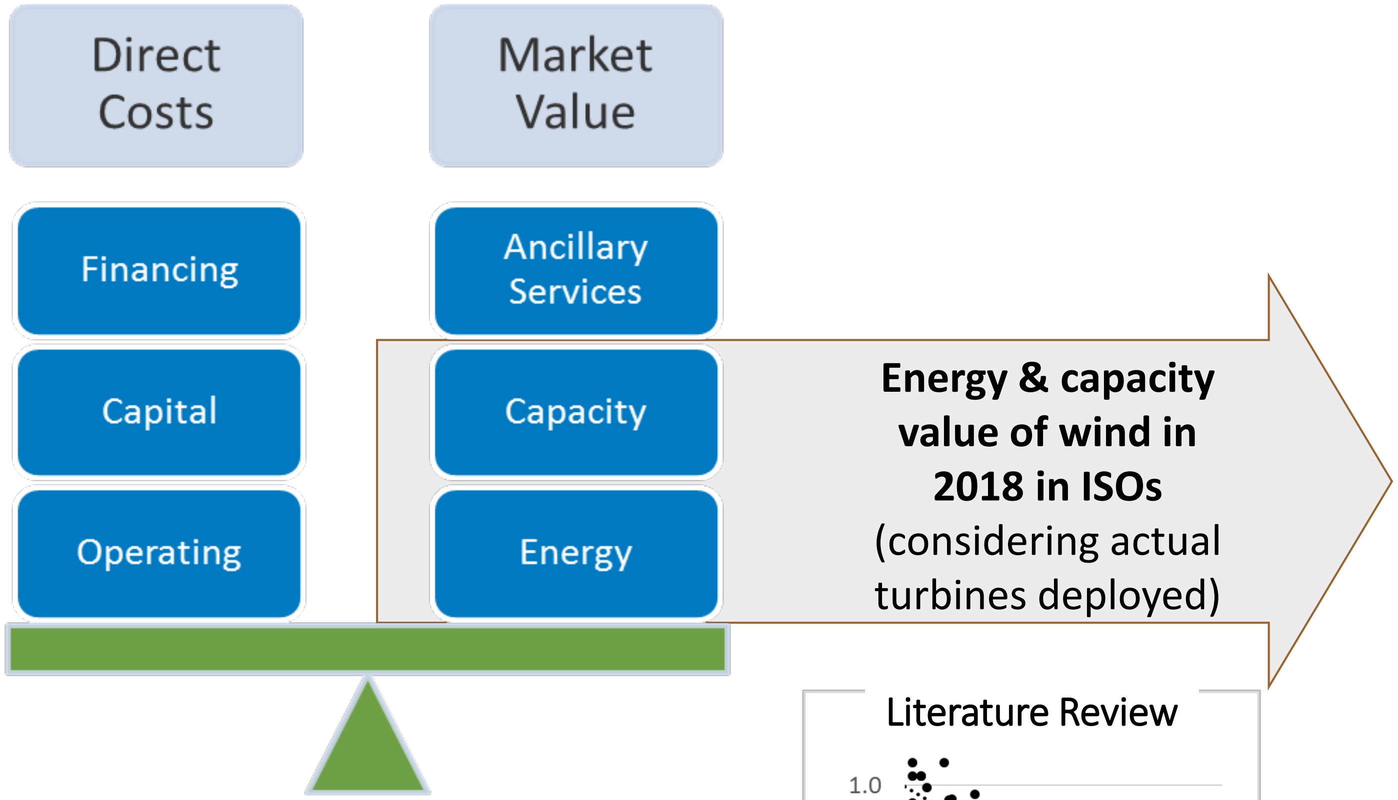
"Favor High SP" scenario

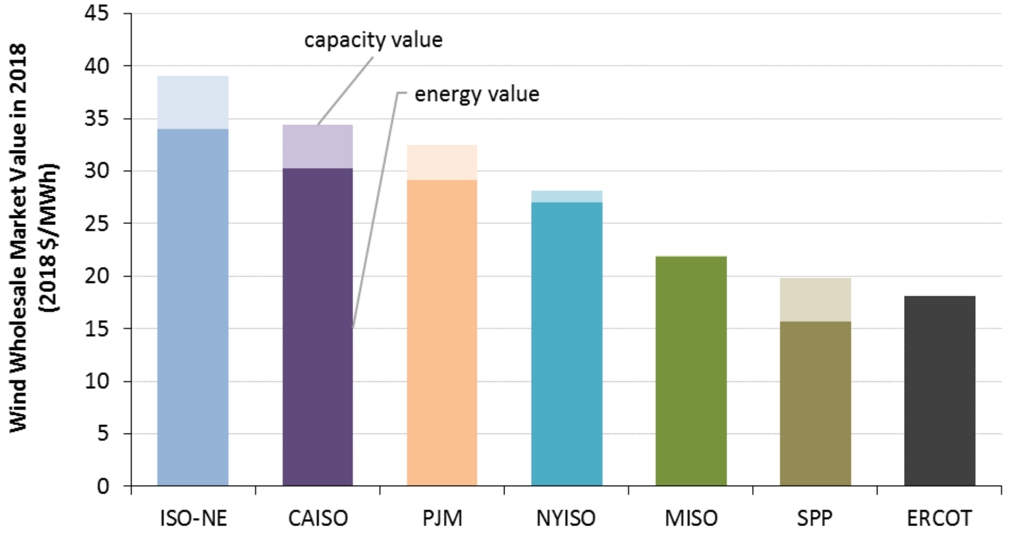


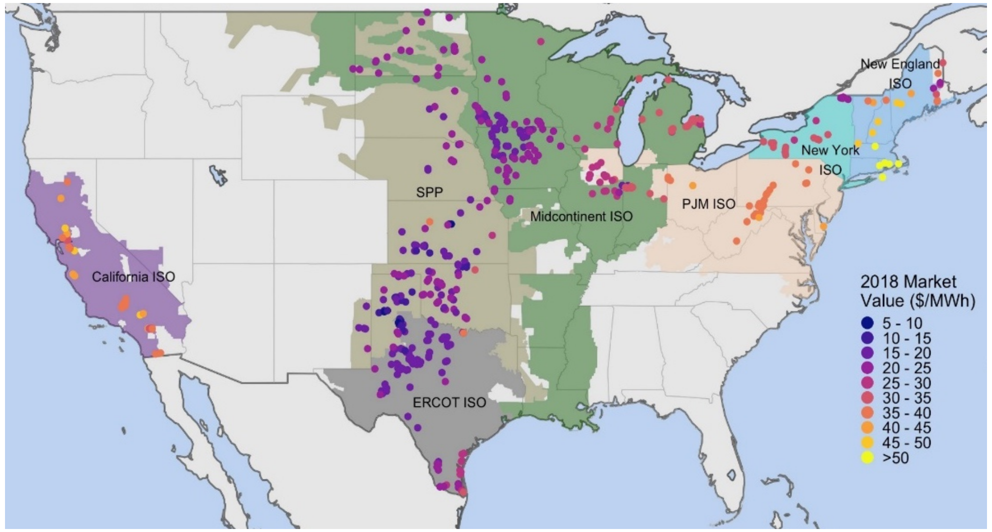
- *Constant SP* turbine never deploys in these two scenarios
- Given that *Low SP* already dominates in the "Reference" scenario, we do not need to map the more-favorable "Favor Low SP" scenario

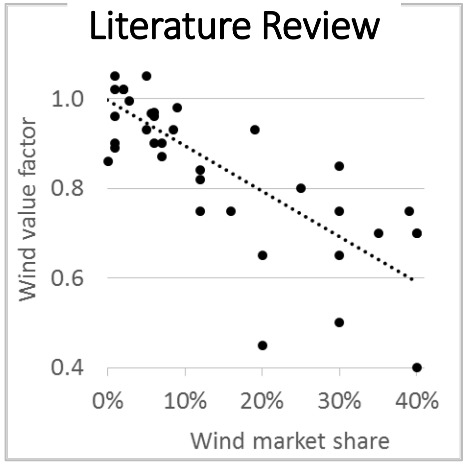
Wholesale market value impacts (based on historical prices in 2018)

In addition to LCOE, we also need to consider the impact of turbine design on the wholesale market value of wind









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

Hirth (2015)

Wiser and Bolinger (2019)

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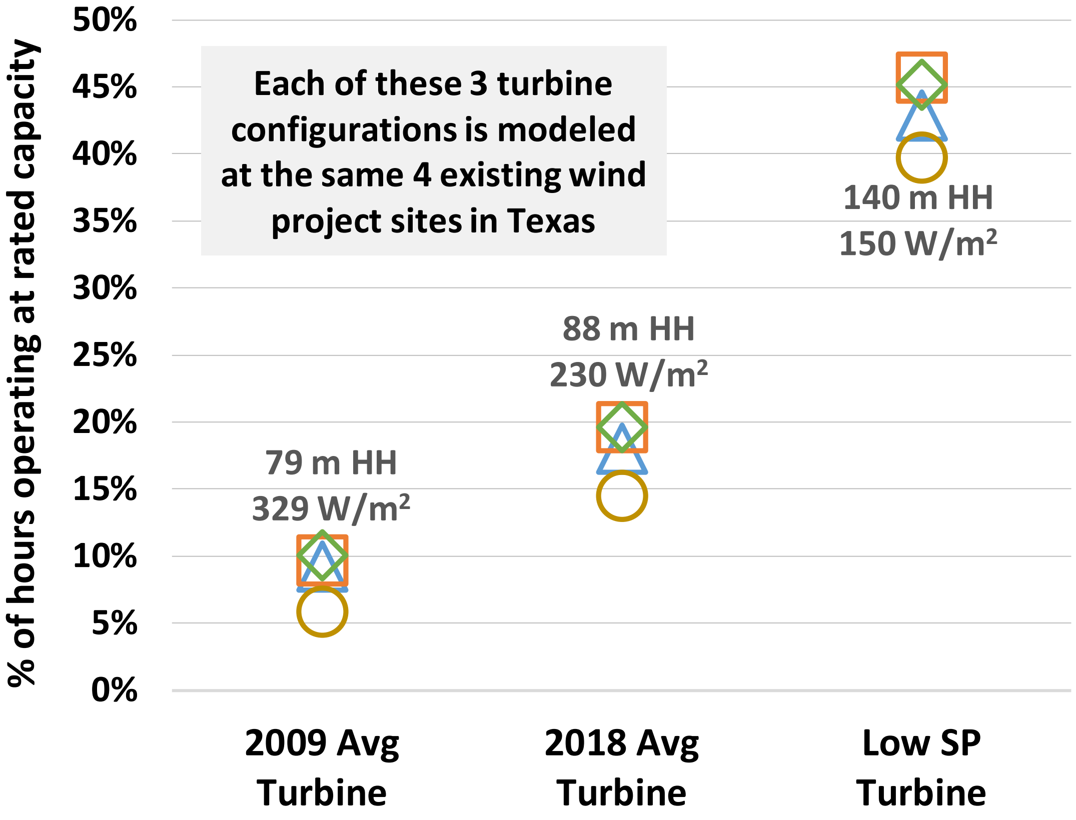
How do taller, low-specific-power turbines impact market value?

Taller, low-SP turbines operate at rated capacity more often, and generate relatively more power at lower wind speeds (when prices tend to be higher)

- 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)



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Scope of value assessment

- We focus on **energy value** and **capacity value** in organized wholesale power markets
- We base our assessment on **historical hourly wholesale prices and wind speeds** at existing wind project locations within all seven ISO regions
  - ➢ We use hourly wholesale energy prices and ISO-specific capacity rules and costs from 2018
  - ➢ We developed refined estimates of plant-level hourly wind speeds and capacity factors
  - ➢ *Details of how we estimated wind speeds, assigned project locations to pricing nodes, and developed estimates of capacity credit are beyond the scope of this presentation*
- We analyze the same *2018 Average* and *Low SP* turbine configurations as described earlier in the LCOE analysis (along with the *2009 Average* turbine)

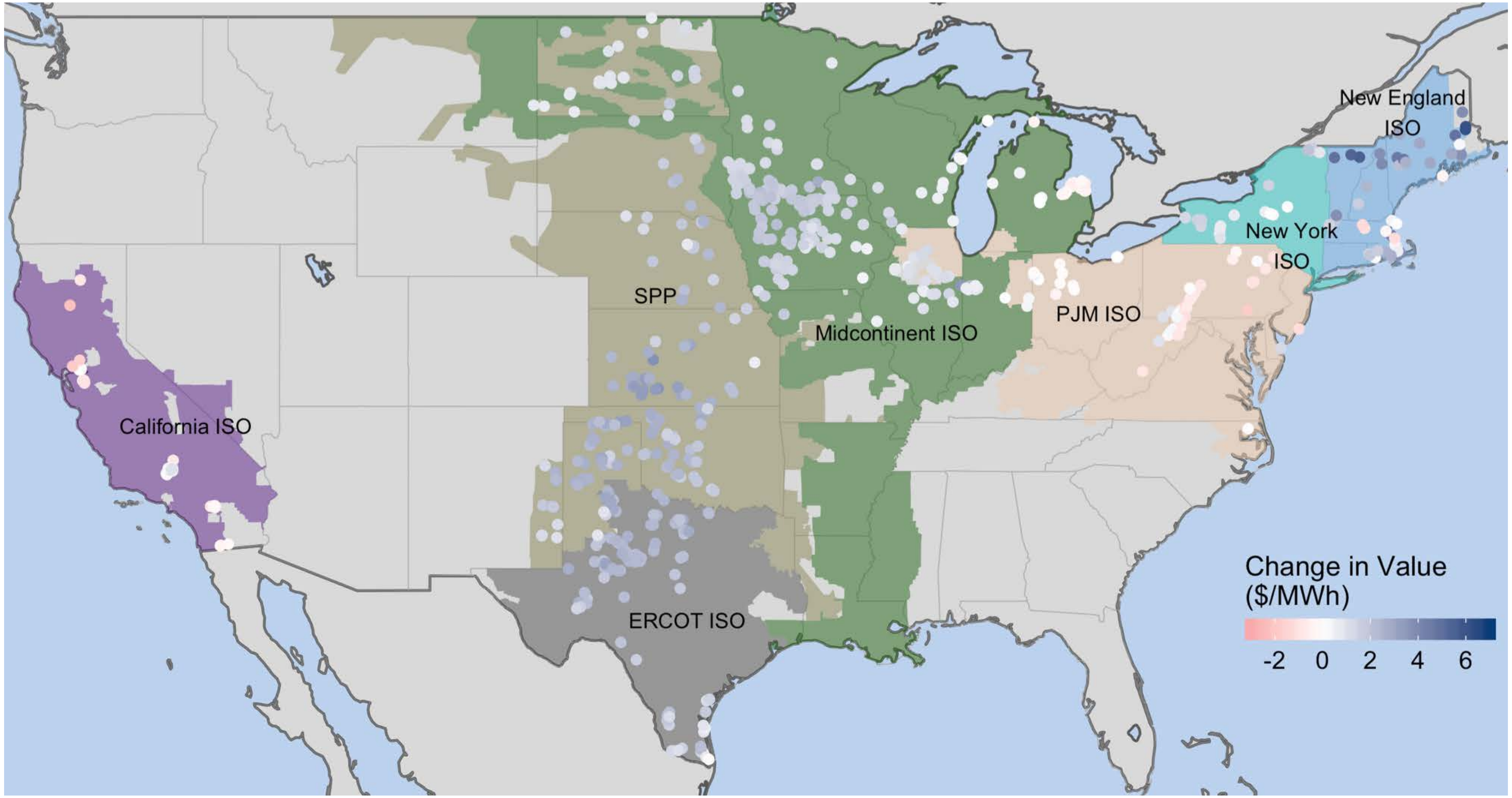
Note: Historical impacts are not necessarily indicative of future impacts, as wholesale pricing patterns can shift and greater wind penetration can erode market value

Average nationwide results

Turbine Specs	2009 Avg	2018 Avg	Low SP
Nameplate Capacity (MW)	1.74	2.43	5.0
Rotor Diameter (m)	82.1	116.0	206.0
Hub Height (m)	78.8	88.1	140.0
Specific Power (W/m^2)	329	230	150
Relative Market Value (vs. 2018 Avg turbine)			
Energy Value ($/MWh)	-0.38	*Reference Turbine*	1.15
Capacity Value ($/MWh)	-0.03		0.25
Total Value ($/MWh)	-0.41		1.40
Total Value (% difference)	*-1.6%*		*5.3%*

- We've already enhanced value since 2009 (by +$0.41/MWh), but more gain is possible
- *Low SP* value boost is due to both energy value and capacity value, but energy value dominates
- *Low SP* value boost comes from both higher HH and lower SP, but SP effect is 2-3x greater than HH effect (a function of the relative change in HH and SP)

Plant-level ABSOLUTE change in value (energy + capacity) when moving from *2018 Avg* to *Low SP* turbine



- Value boost is greatest in regions with highest wind penetration levels (ERCOT and SPP), and/or with transmission constraints (ISO-NE)
- ISO-NE boost is highly location dependent→ much higher where transmission constraints are greatest
- Relatively little value enhancement for most sites in CAISO, PJM, NYISO

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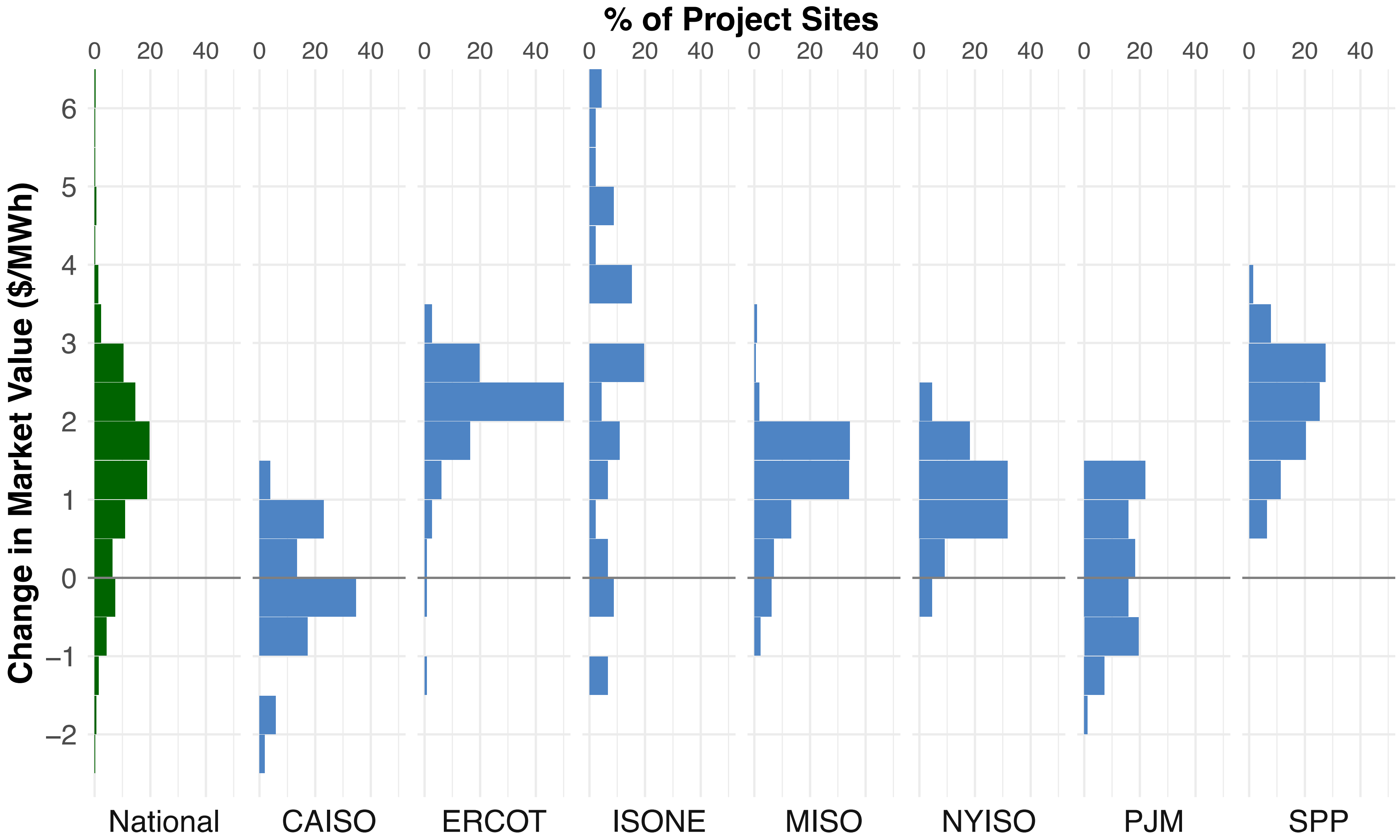
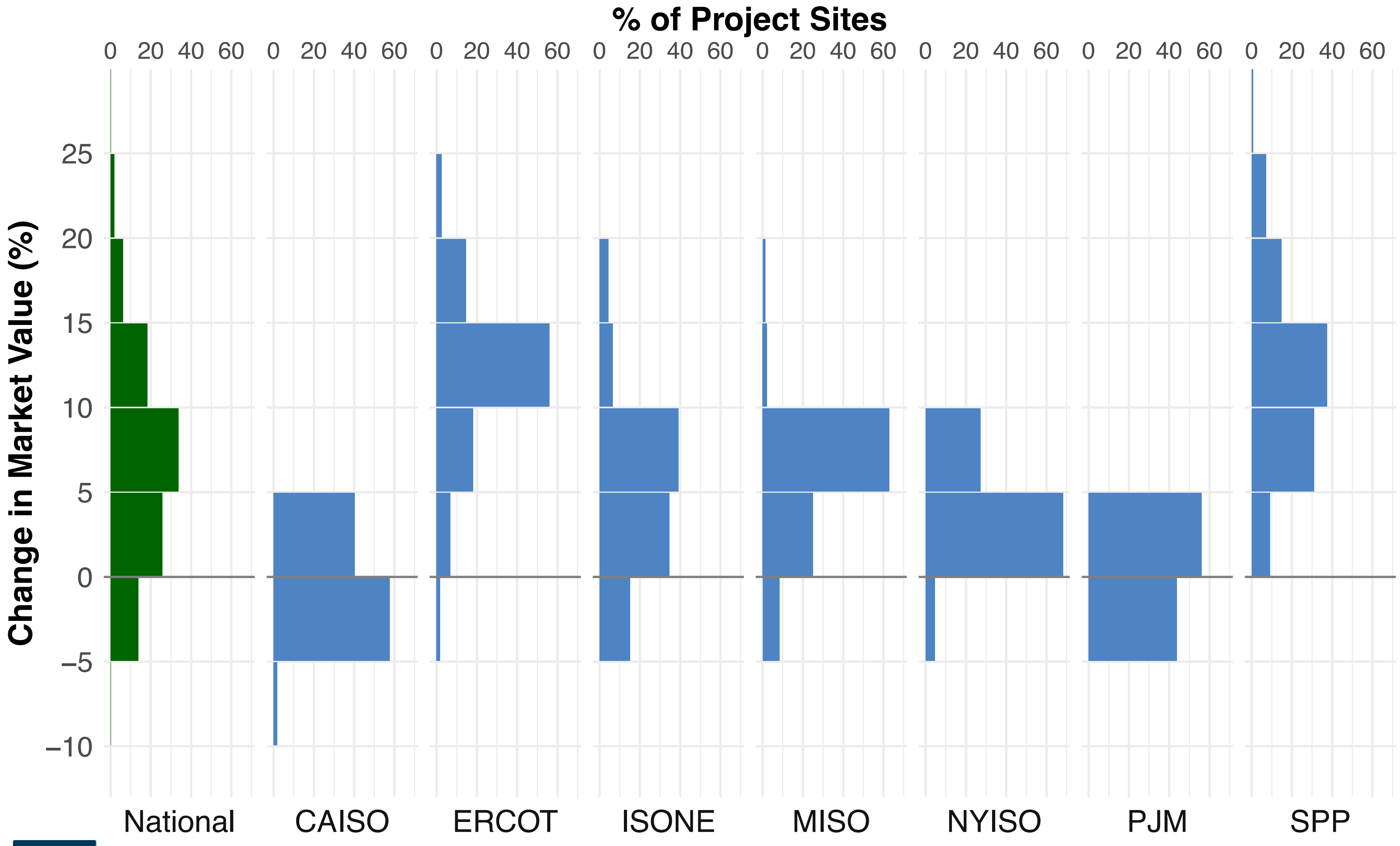
ISO-level ABSOLUTE change in value (energy + capacity) when moving from *2018 Avg* to *Low SP* turbine



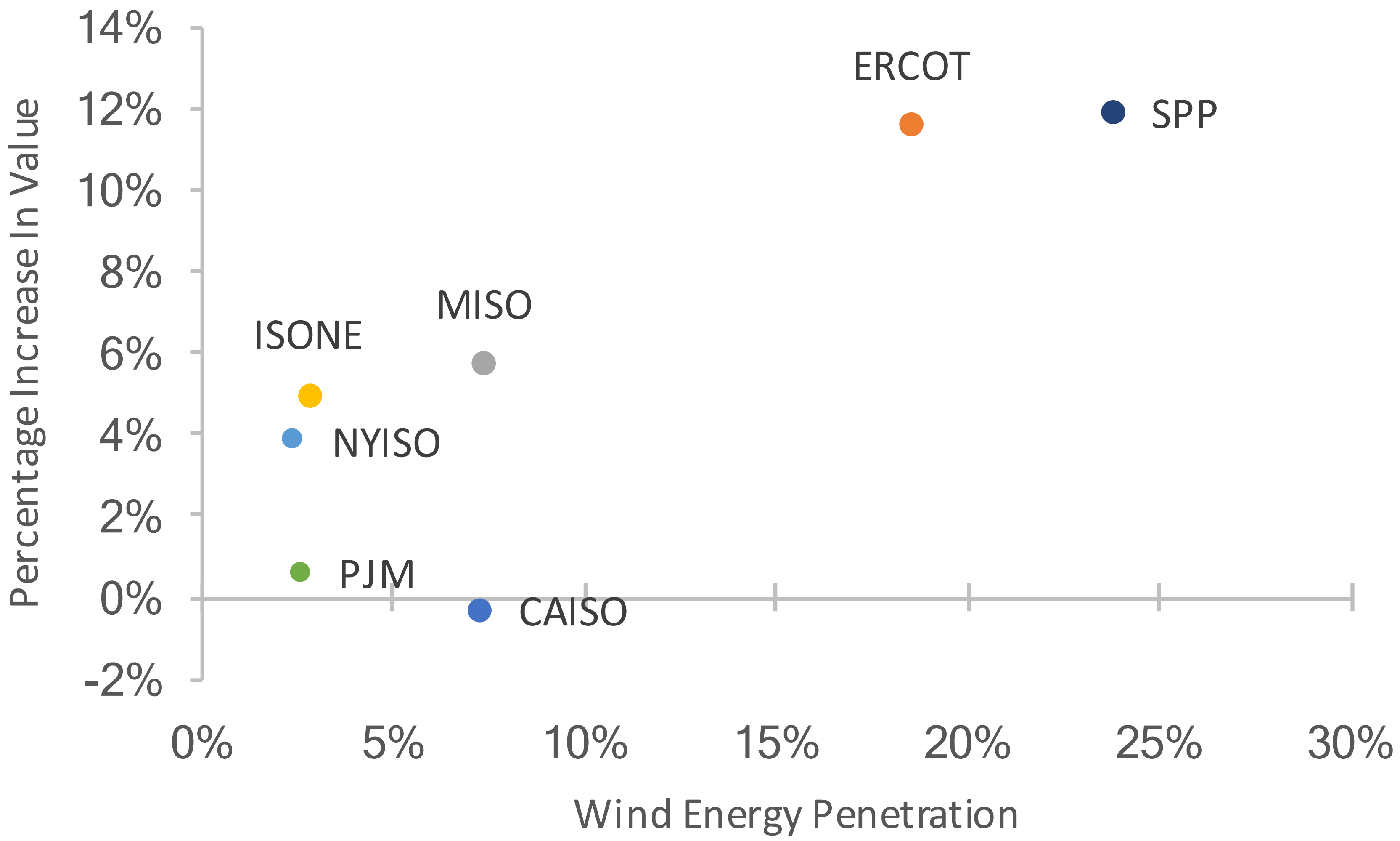
- National change in market value is normally distributed around a mean \$1-\$2/MWh value boost
- ERCOT and SPP are centered on a \$2-\$3/MWh boost
- ISO-NE change varies across an exceptionally large range of values based on location→ due to transmission constraints
- CAISO and PJM are centered on no change in market value

ISO-level PERCENTAGE change in value (energy + capacity) when moving from *2018 Avg* to *Low SP* turbine



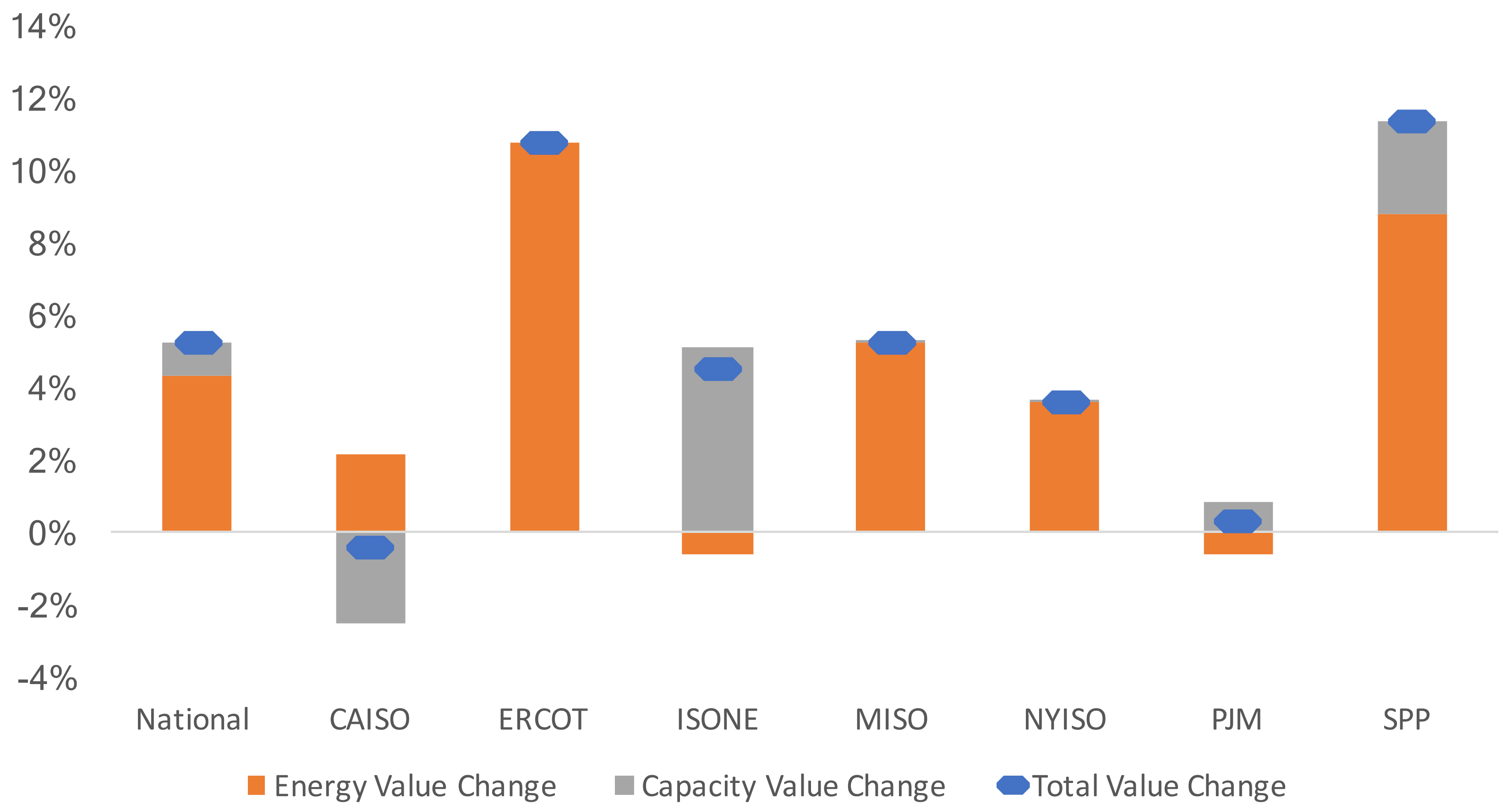
- Nationally, there is a normal distribution centered on a 5% to 10% increase in value
- ERCOT and SPP are centered on a 10% to 15% increase
- CAISO and PJM are centered on a 0% change
- Other regions are in between these two groupings
- Project-level results are distributed widely around these central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

Average percentage change in value when moving from *2018 Avg* to *Low SP* turbine is correlated with regional 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 when moving from *2018 Avg* to *Low SP* turbine is driven more by energy value than capacity value



- Low wind penetration in ISO-NE and PJM lead to small decreases in energy value, although the capacity value increase is large in ISO-NE
- ERCOT has no capacity requirement, 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

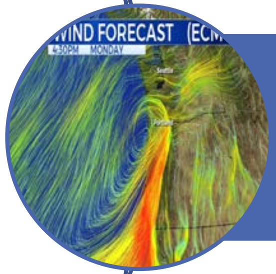
Wholesale market value impacts – Key takeaways

- Industry has already made progress boosting market value via turbine design, but more progress is possible
- Value enhancement is greatest in markets with high wind penetrations (and/or with transmission constraints)
  - And value enhancement is dominated by energy value enhancement rather than capacity value enhancement
- 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

Possible additional benefits of taller, lower-specific-power turbines

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

Lower transmission expenditures

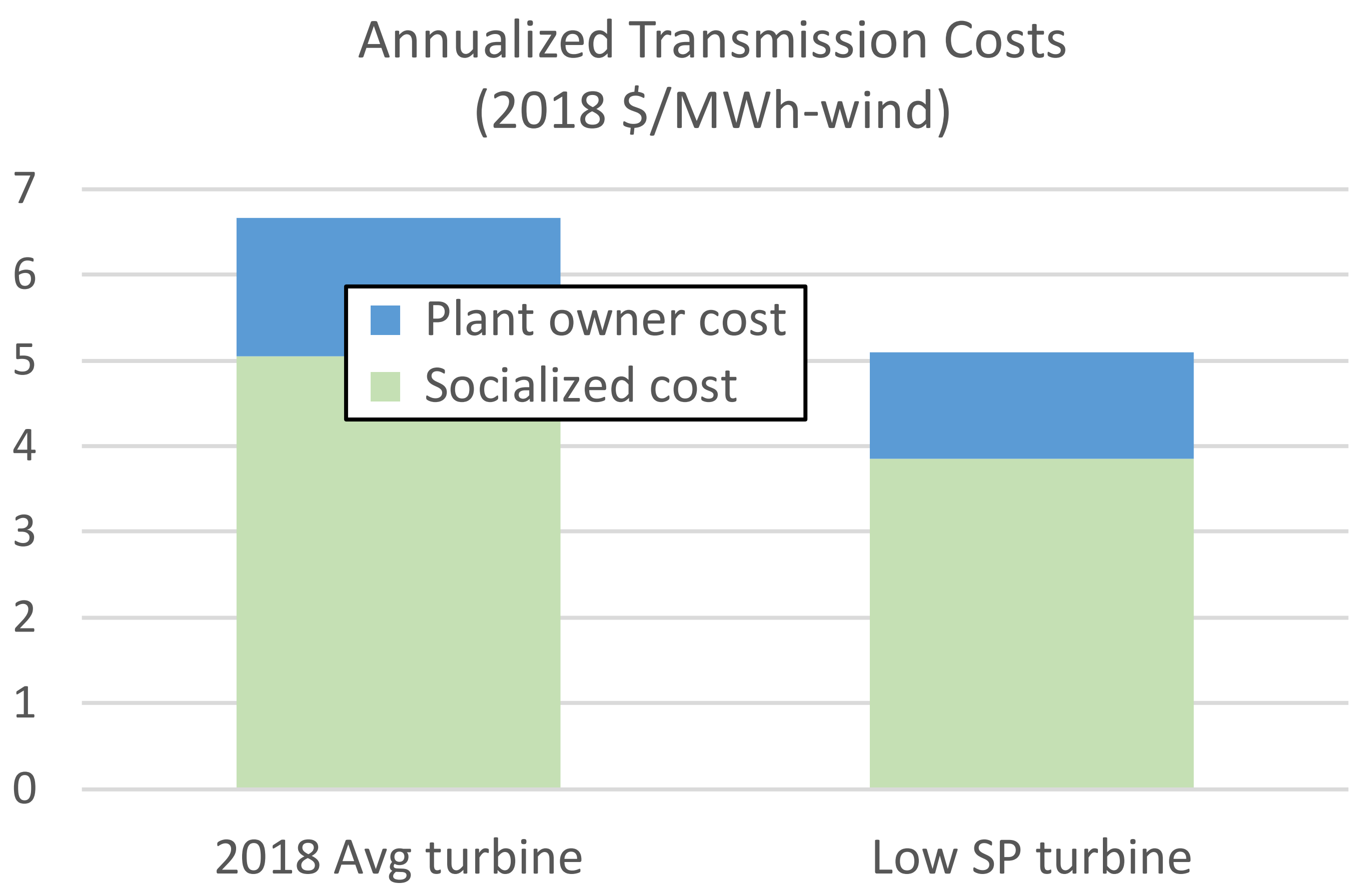


Lower balancing / ancillary service costs

Lower cost of wind-plant financing

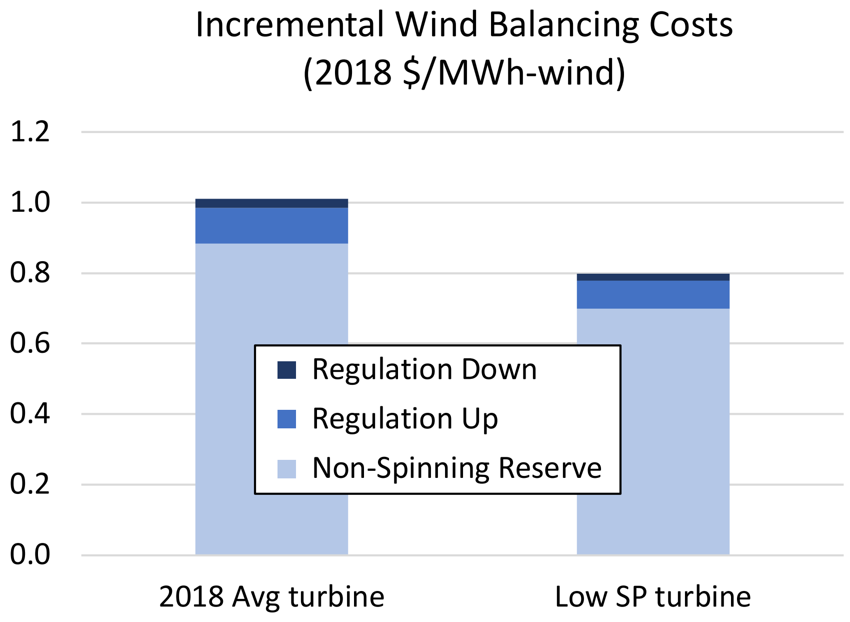
Low SP turbine reduces transmission costs by ~$1.6/MWh relative to *2018 Avg* turbine

- *Low SP's* higher capacity factor increases the utilization of transmission lines, reducing the $/MWh-wind cost of transmission by ~$1.6/MWh 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



Low SP turbine reduces balancing costs by ~$0.2/MWh relative to *2018 Avg* turbine

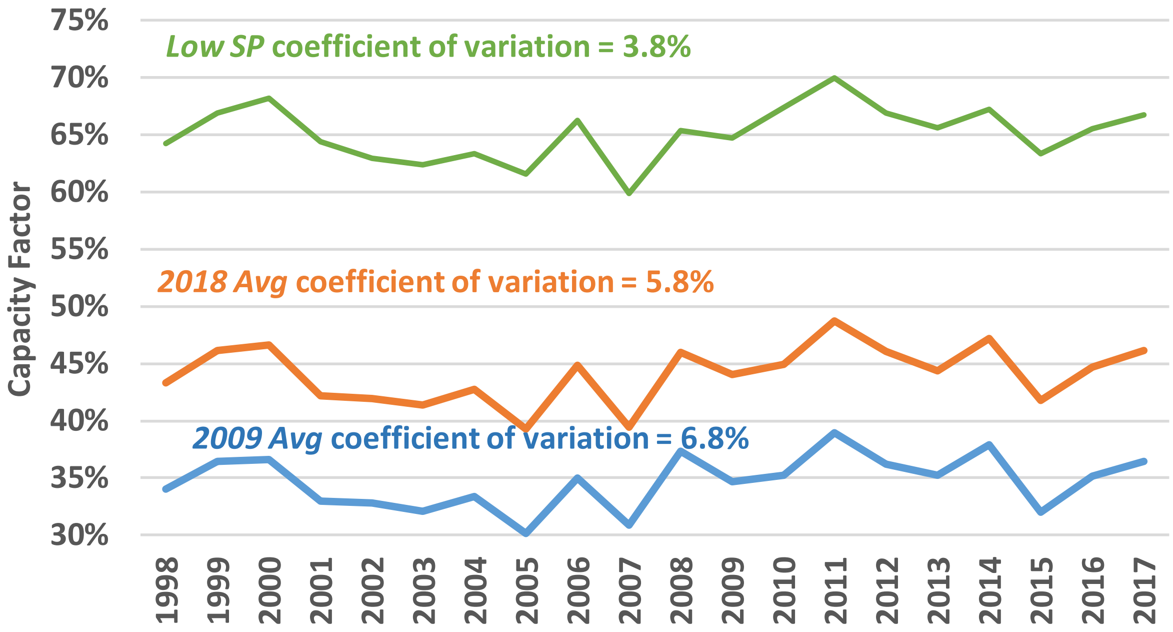
- *Low SP* imposes slightly greater reserve requirements, but this extra cost is spread over much more energy
- Non-Spinning Reserves:
  - The price for non-spinning reserves in ERCOT was $9.2/MWh in 2018
  - With current turbines, ERCOT increases non-spin reserves by ~40 MW per GW of wind at a cost of $0.88/MWh-wind with a capacity factor of 42%
  - Slightly greater forecast errors for *Low SP* turbines (3.6% greater) increases the incremental reserve requirement to ~42 MW per GW of wind, which costs only $0.7/MWh-wind with a *Low SP* 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* turbines
  - With the higher capacity factor for *Low SP* turbines, regulation costs go from $0.13/MWh-wind with current turbines to $0.10/MWh-wind with *Low SP* turbines

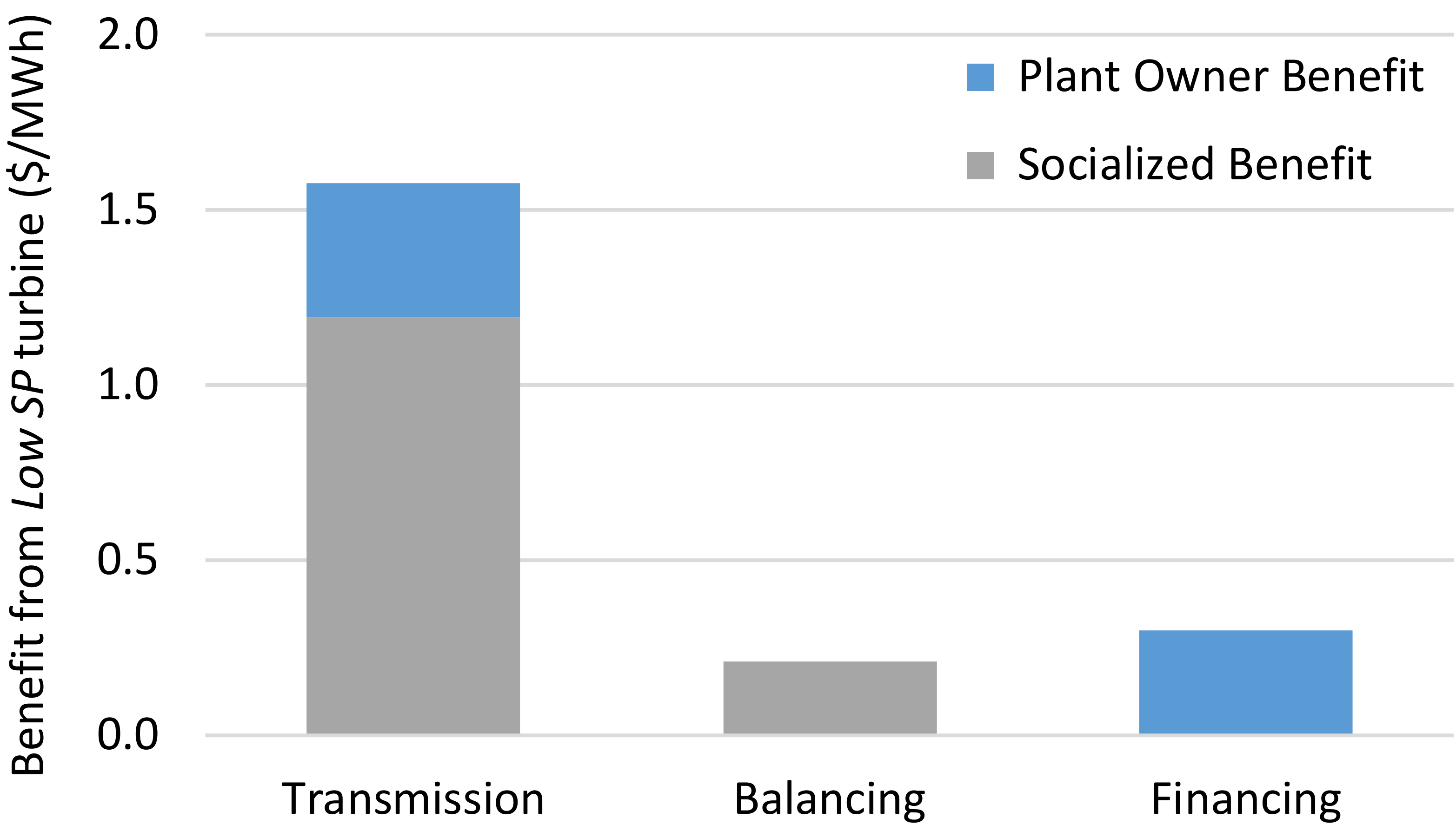
The *Low SP* turbine should have less-variable annual energy production over time, enabling better financing terms

- The graph shows capacity factors by calendar year at a site in Texas for the *2009 Avg* (329 W/m^2, 79m HH), *2018 Avg* (230 W/m^2, 88m HH), and *Low SP* (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* turbine's lower coefficient of variation would allow for greater debt leverage (i.e., more low-cost debt, and less higher-cost equity), leading to a lower LCOE (by ~$0.3/MWh)



These 3 supplemental factors sum to a ~$2/MWh benefit of the *Low SP* turbine relative to the *2018 Avg* turbine

- All of the financing benefits and some of the transmission benefits accrue to wind project owners: **$0.7/MWh**
- All of the balancing benefits and the remaining transmission benefits accrue to the overall electricity system: **$1.4/MWh**
- These benefits *are in addition to* the energy and capacity value impacts shown earlier



Conclusions

Conclusions

- Significant turbine scaling has already provided both LCOE and value benefits
- Further benefits are possible through a continuation of this trend:
  - **LCOE:** ~$6/MWh median LCOE advantage for *Low SP* turbine (150 W/m^2), presuming it has an 8% ($120/kW) higher CapEx than the *Constant SP* turbine (230 W/m^2)
  - **Market Value:** $1-$2/MWh median value boost ($2-$3/MWh in higher penetration areas) in 2018 when moving from 230 W/m^2 to 150 W/m^2
    - Lower specific power is a stronger lever for value enhancement than is higher hub height
    - Value boost is mostly due to higher energy value; capacity value is a smaller driver
  - **Other:** ~$1.6/MWh from better transmission utilization; ~$0.2/MWh from lower balancing costs; ~$0.3/MWh from improved financing terms

In Aggregate: ~$10/MWh of incremental savings/value in moving from 230 W/m^2 to 150 W/m^2

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