Utility-Scale Wind and Solar Technology, Cost, and Performance Trends: Nationally and in Nebraska

Mark Bolinger (MABolinger@lbl.gov)

Lawrence Berkeley National Laboratory

9th Annual Nebraska Wind and Solar Conference

Lincoln, Nebraska

November 7, 2016

This research was supported by funding from the U.S. Department of Energy's Wind Energy Technologies Office and Solar Energy Technologies Office.

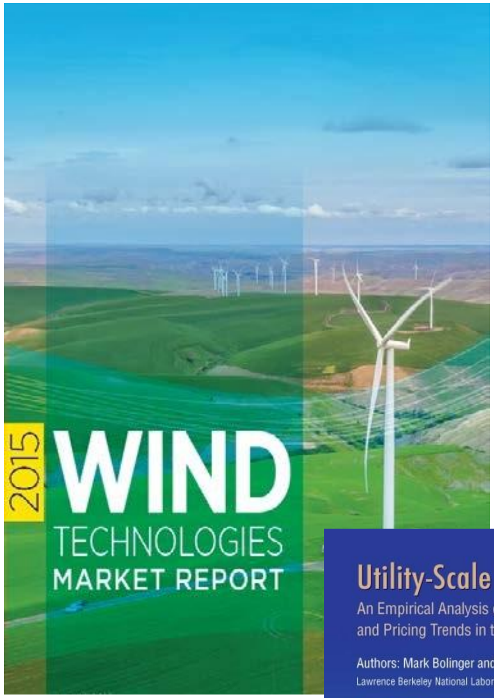
Presentation Outline

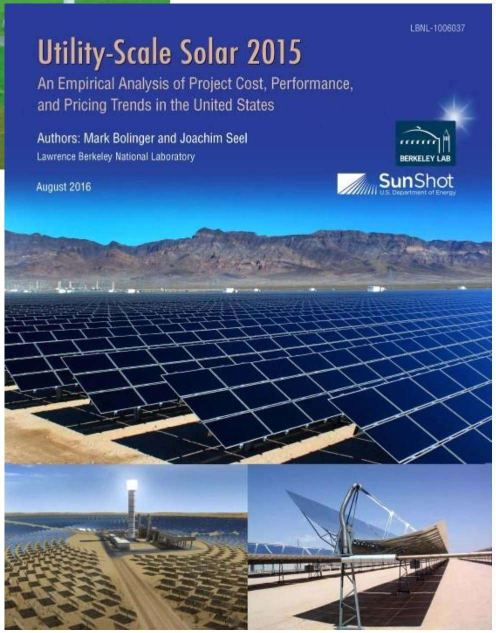
1) **Utility-scale <u>wind</u> technology, installed cost, performance, and PPA price trends**

   - Most material is drawn from the DOE's *2015 Wind Technologies Market Report*
   - Available at **windreport.lbl.gov**

2) **Utility-scale <u>solar</u> technology, installed cost, performance, and PPA price trends**

   - Most material is drawn from LBNL's *Utility-Scale Solar 2015*
   - Available at **utilityscalesolar.lbl.gov**

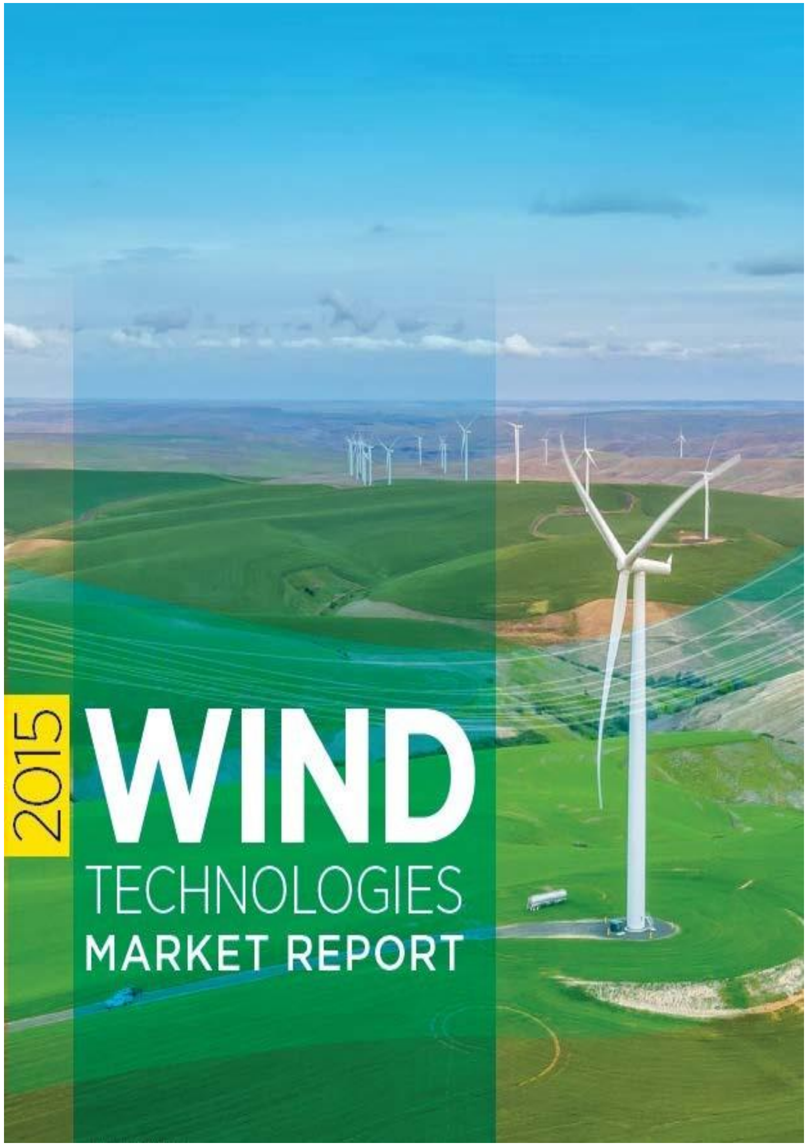




1) Utility-Scale Wind

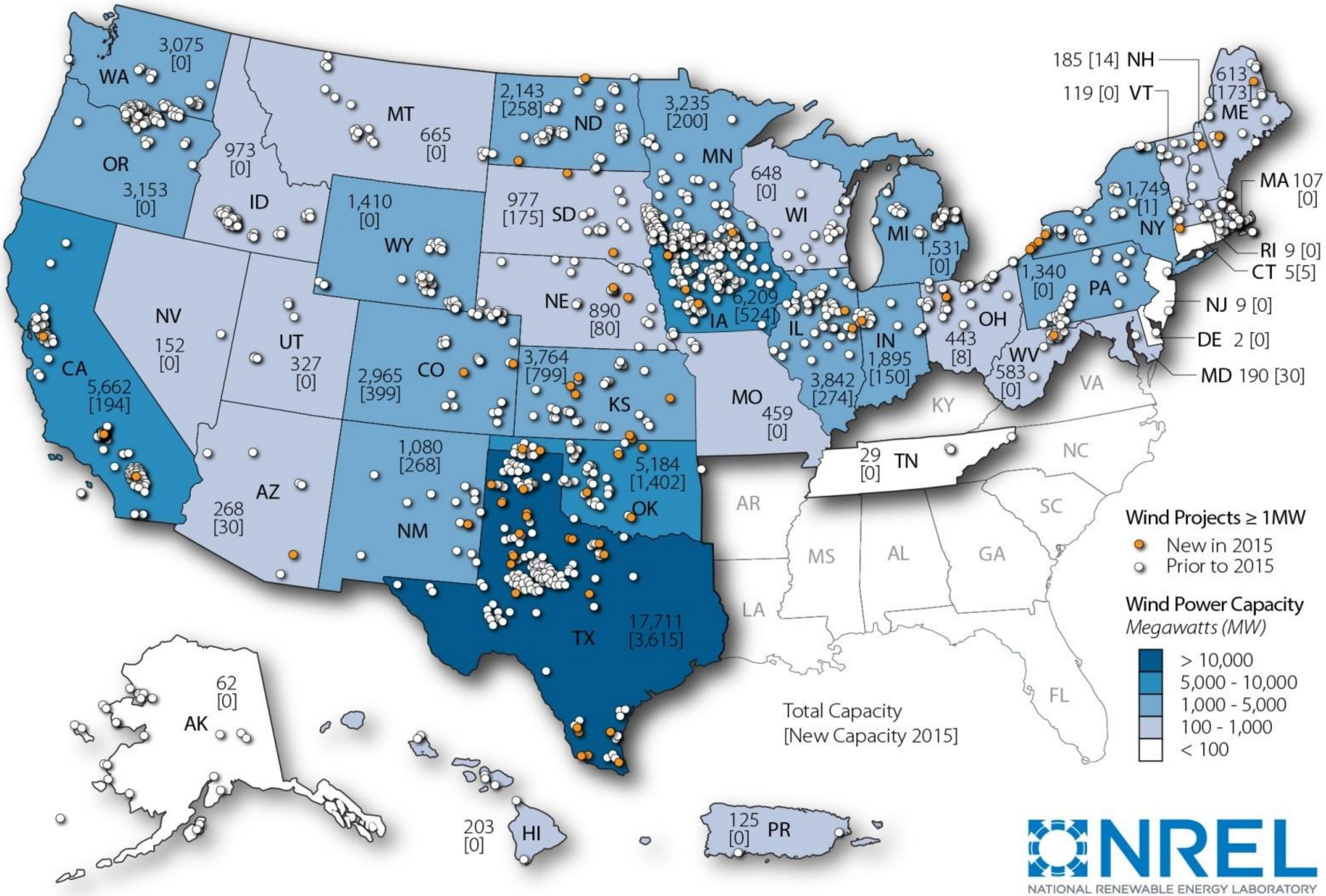
Utility-scale <u>wind</u> technology, installed cost, performance, and PPA price trends

- Most material is drawn from the DOE's *2015 Wind Technologies Market Report*
- Available at **windreport.lbl.gov**



Note: We define "utility-scale wind" to include any wind project that uses turbines larger than 100 kW

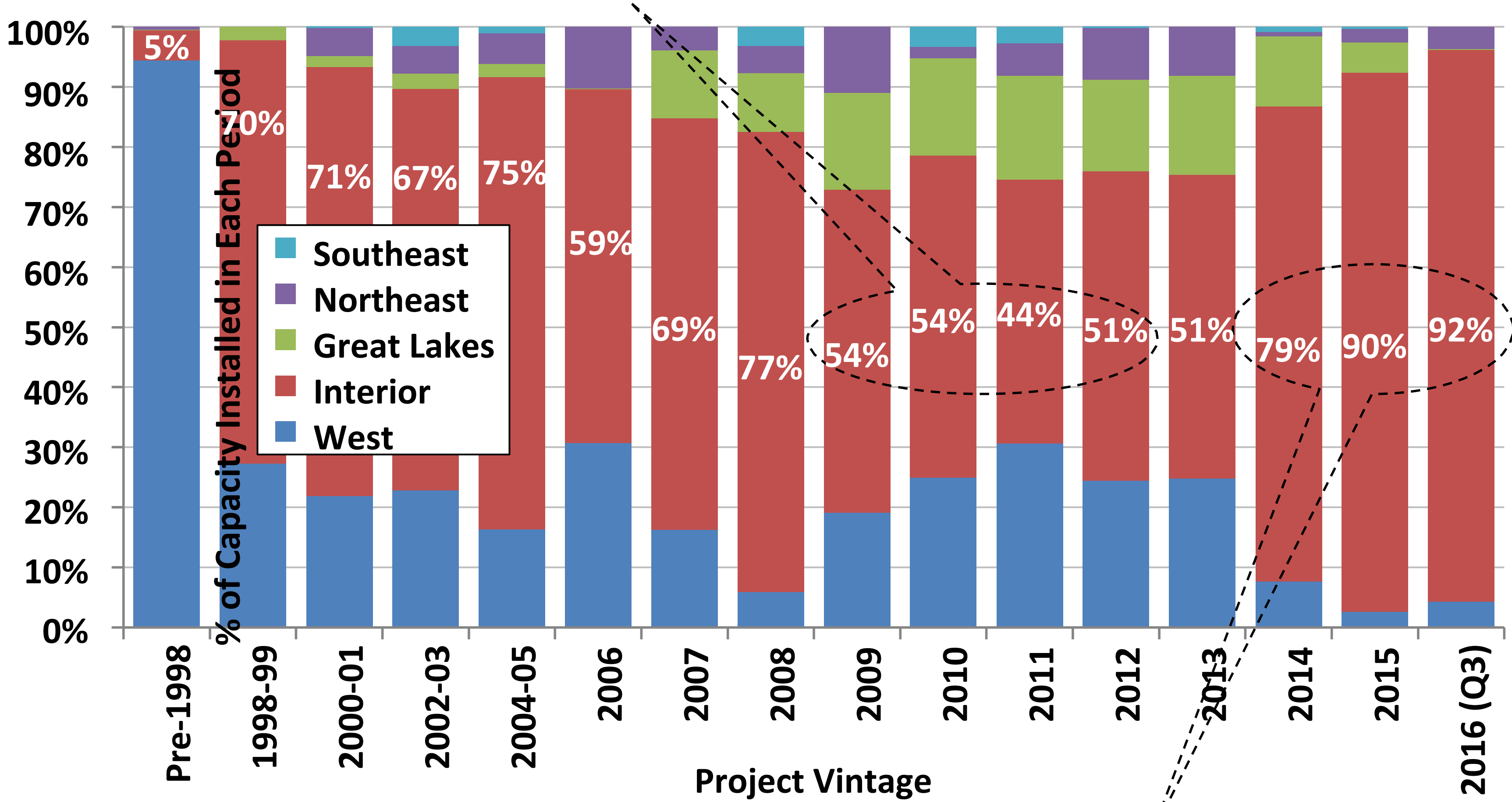
Geographic spread of wind projects in the United States is reasonably broad…



Note: Numbers within states represent cumulative installed wind capacity and, in brackets, annual additions in 2015

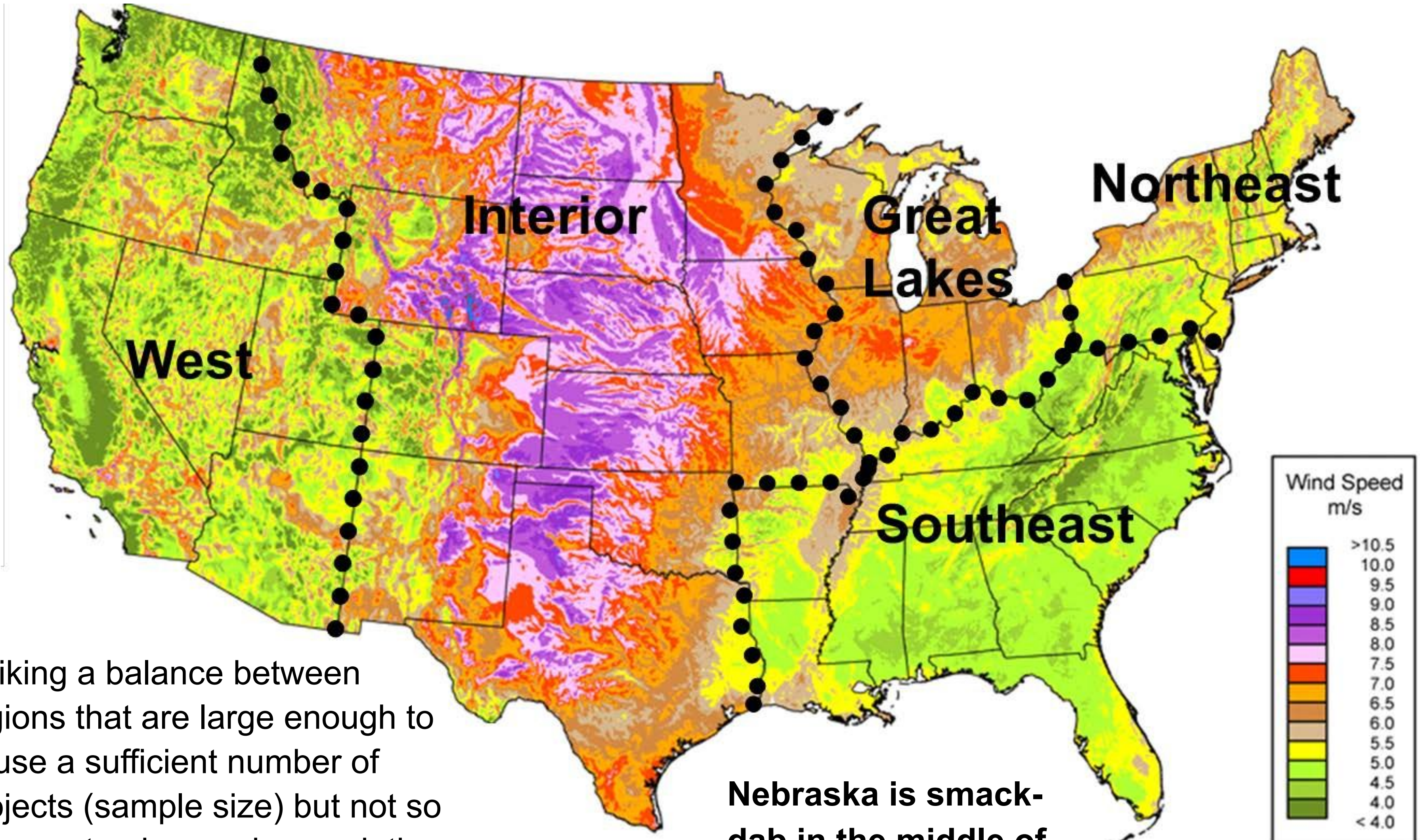
…but in recent years most activity has been concentrated within the Interior region

Relatively low buildout of the energetic Interior region from 2009-2012 perhaps attributable in part to the availability of the Section 1603 cash grant?



Renewed and unprecedented focus on the Interior region since 2014

Five regions defined based on (1) comparable wind resource strength and (2) traditional state groupings



Striking a balance between regions that are large enough to house a sufficient number of projects (sample size) but not so large as to obscure key variations between regions

Nebraska is smack-dab in the middle of the Interior region

U.S. wind power rankings: the "top 20" states

Installed Capacity (MW)				Percentage of In-State Generation	
Annual (2015)		Cumulative (end of 2015)		Actual (2015)*	
Texas	3,615	Texas	17,711	Iowa	31.3%
Oklahoma	1,402	Iowa	6,209	South Dakota	25.5%
Kansas	799	California	5,662	Kansas	23.9%
Iowa	524	Oklahoma	5,184	Oklahoma	18.4%
Colorado	399	Illinois	3,842	North Dakota	17.7%
Illinois	274	Kansas	3,764	Minnesota	17.0%
New Mexico	268	Minnesota	3,235	Idaho	16.2%
North Dakota	258	Oregon	3,153	Vermont	15.4%
Minnesota	200	Washington	3,075	Colorado	14.2%
California	194	Colorado	2,965	Oregon	11.3%
South Dakota	175	North Dakota	2,143	Maine	10.5%
Maine	173	Indiana	1,895	Texas	10.0%
Indiana	150	New York	1,749	Nebraska	8.0%
Nebraska	80	Michigan	1,531	Wyoming	7.7%
Arizona	30	Wyoming	1,410	Montana	6.6%
Maryland	30	Pennsylvania	1,340	Washington	6.5%
New Hampshire	14	New Mexico	1,080	New Mexico	6.3%
Ohio	8	South Dakota	977	California	6.2%
Connecticut	5	Idaho	973	Hawaii	6.1%
New York	1	Nebraska	890	Illinois	5.5%
Rest of U.S.	0	*Rest of U.S.*	5,203	*Rest of U.S.*	1.0%
TOTAL	**8,598**	**TOTAL**	**73,992**	**TOTAL**	**4.7%**

* Based on 2015 wind and total generation by state from EIA's *Electric Power Monthly*.

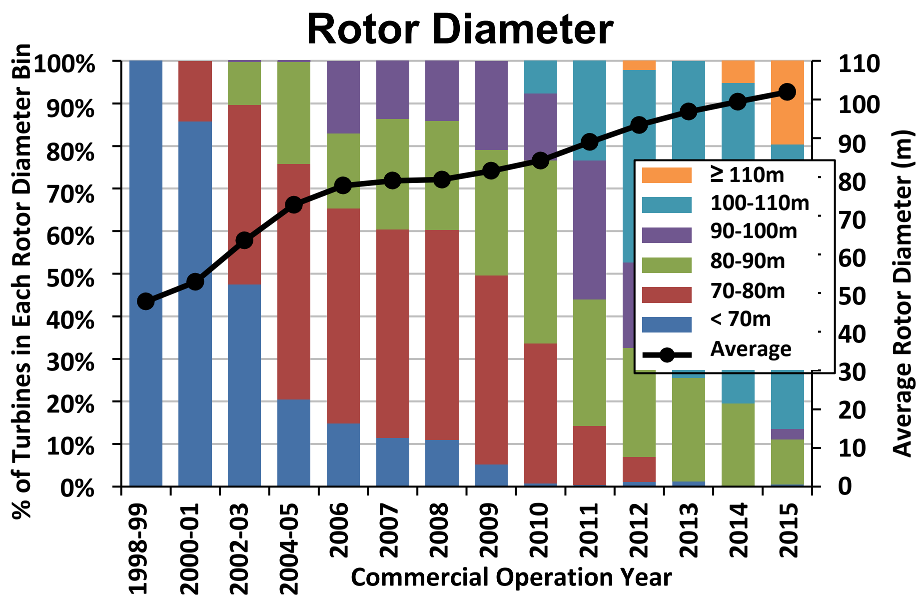
Source: AWEA project database, EIA

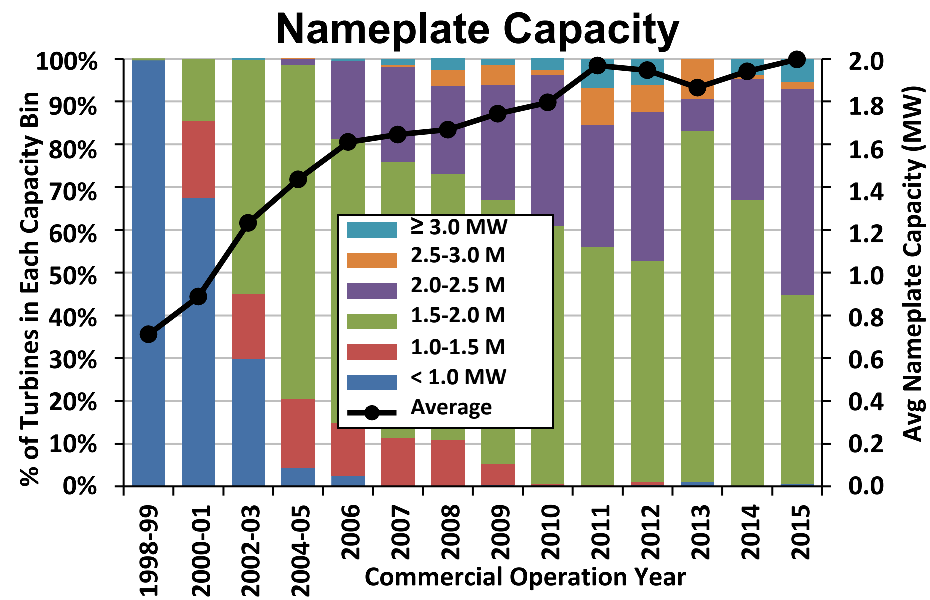
Three of Nebraska's closest neighbors exceed 20% wind penetration (>30% in Iowa)

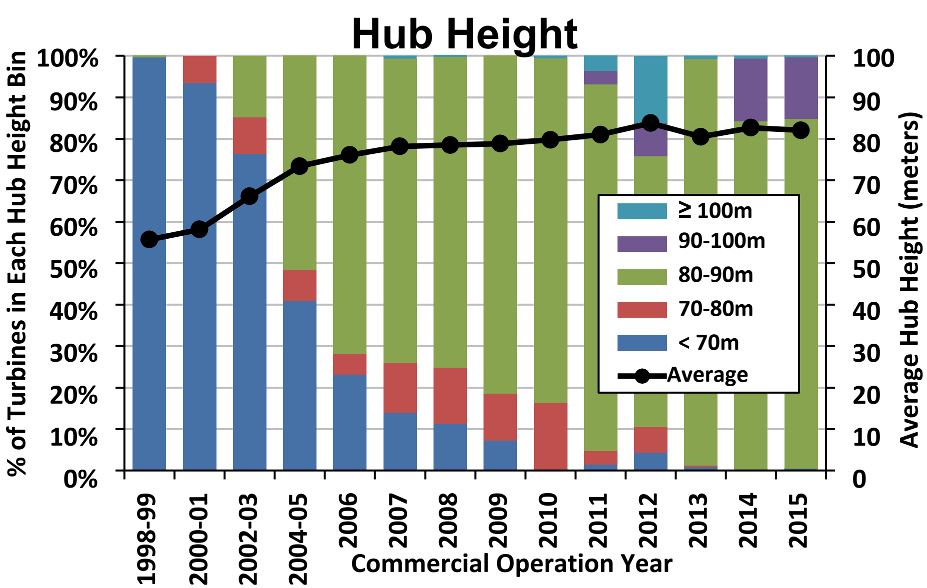
Although Nebraska ranks 4th in the "lower 48" (behind TX, MT, KS) for technical wind potential, at the end of 2015 it ranked 20th in cumulative installed wind capacity (with 890 MW) and 13th in wind penetration (at 8.0%)

In other words…***there's plenty of room for growth***

U.S. wind turbines have been growing: larger rotors, taller towers, greater capacity

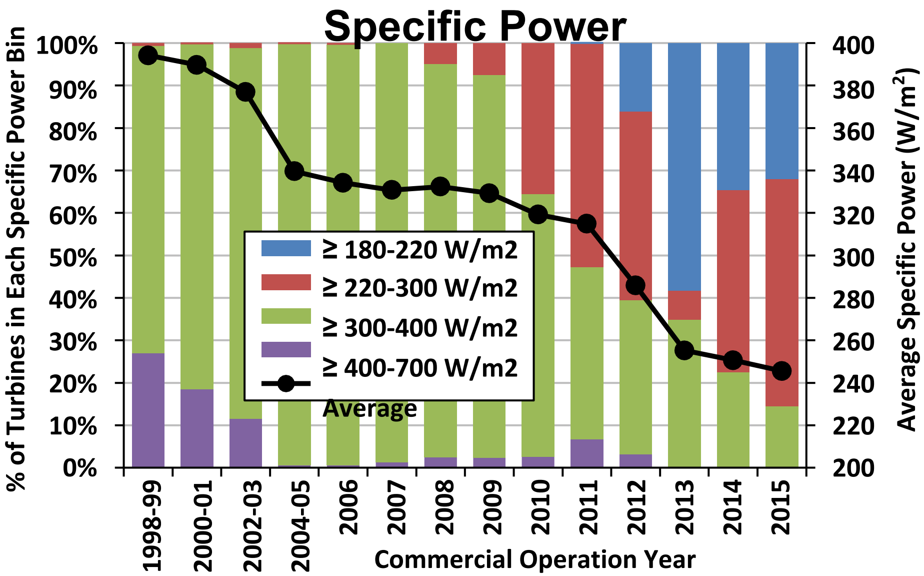


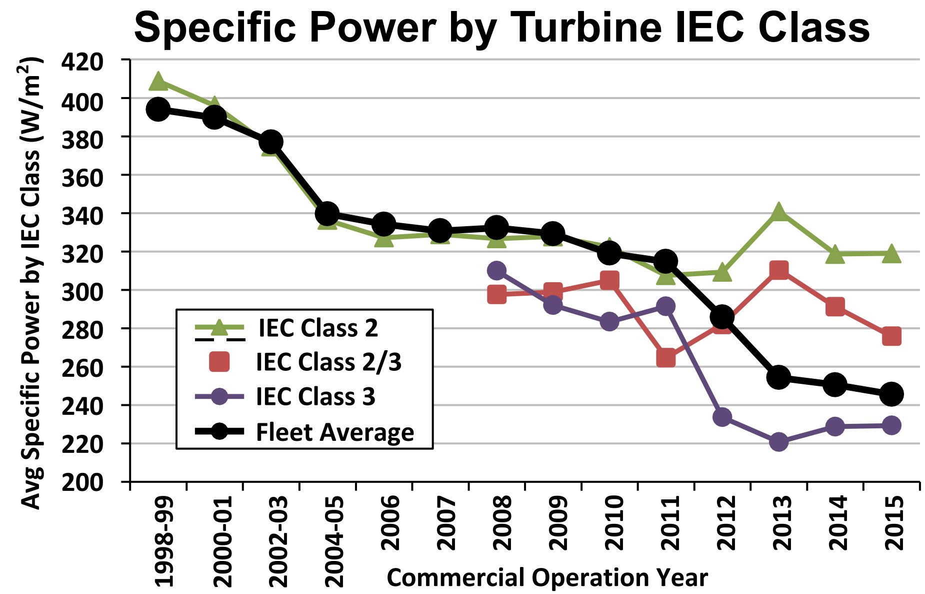


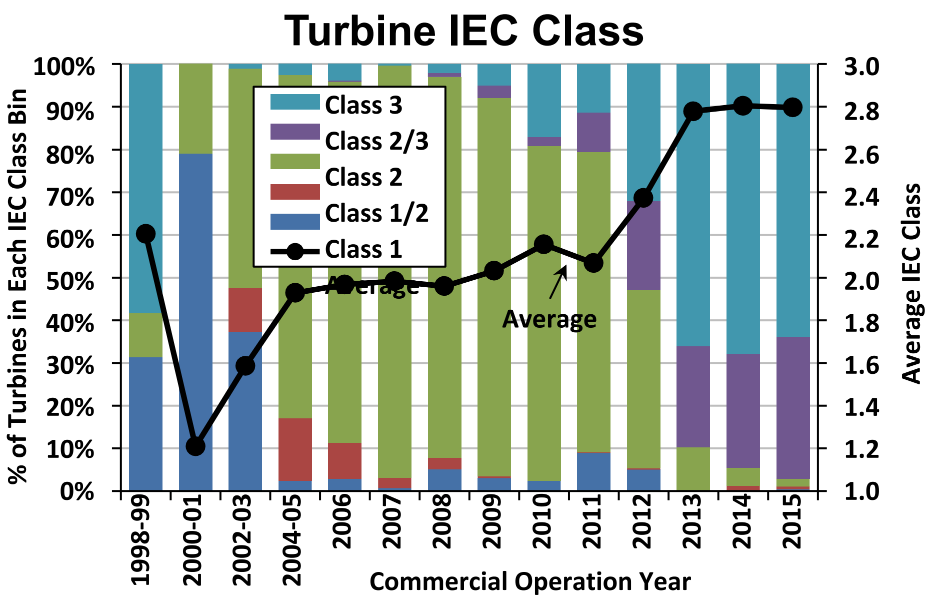


Since 2011, growth in the average fleet-wide rotor diameter *(top left)* has outpaced growth in the average hub height *(bottom left)* and nameplate capacity *(top right)*

An increase in rotor diameter relative to nameplate capacity causes "specific power" to decline

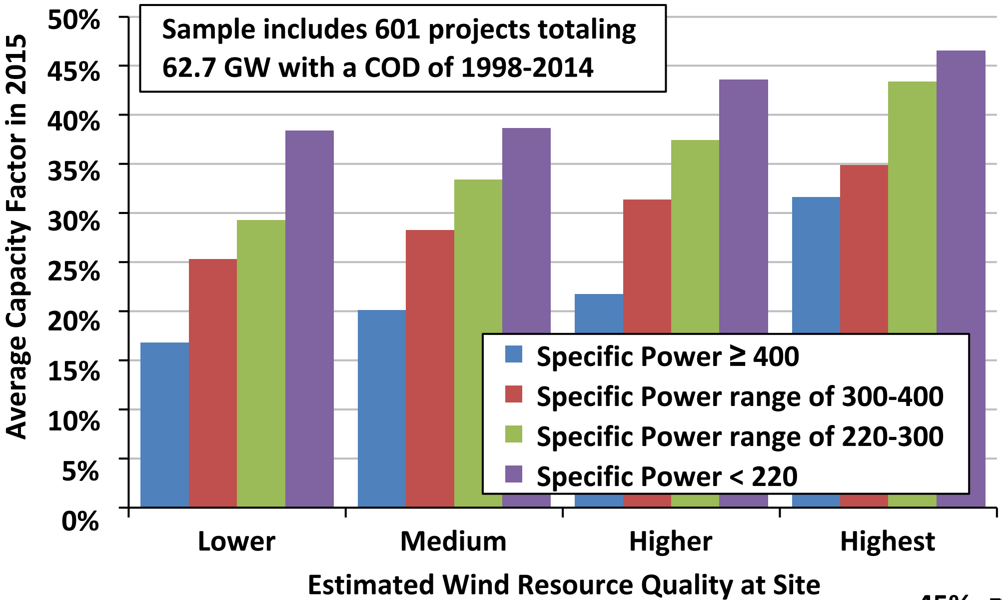






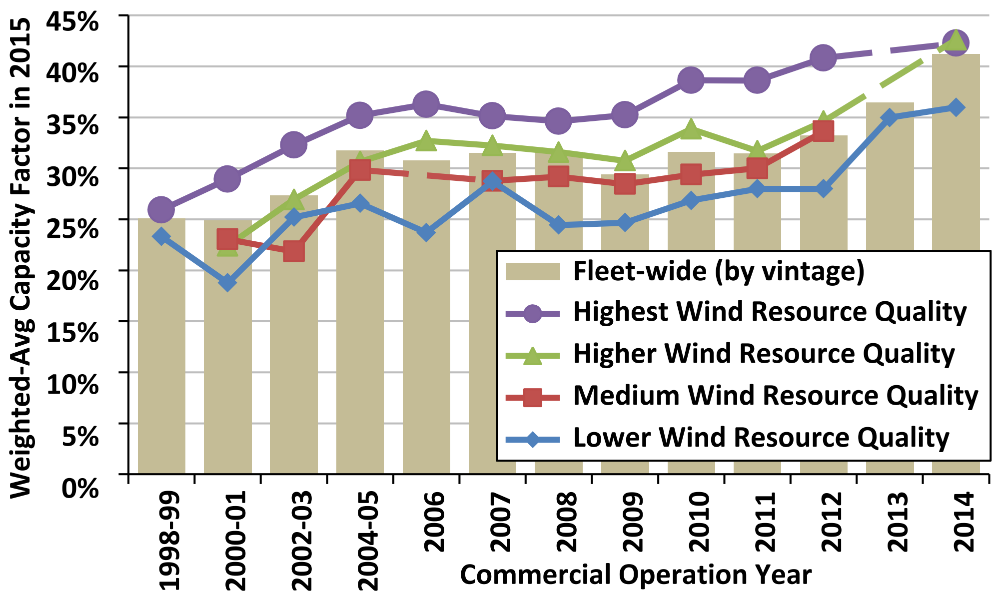
- Specific power = Watts of capacity per square meter of rotor swept area (W/m^2)
- The fleet-wide decline in specific power *(top left)* reflects not just the shift towards higher "IEC Class" turbines designed for lower wind speeds *(bottom left)*, but also a decline in specific power **within** each turbine IEC Class *(top right)*

All else equal, lower specific power boosts capacity factor

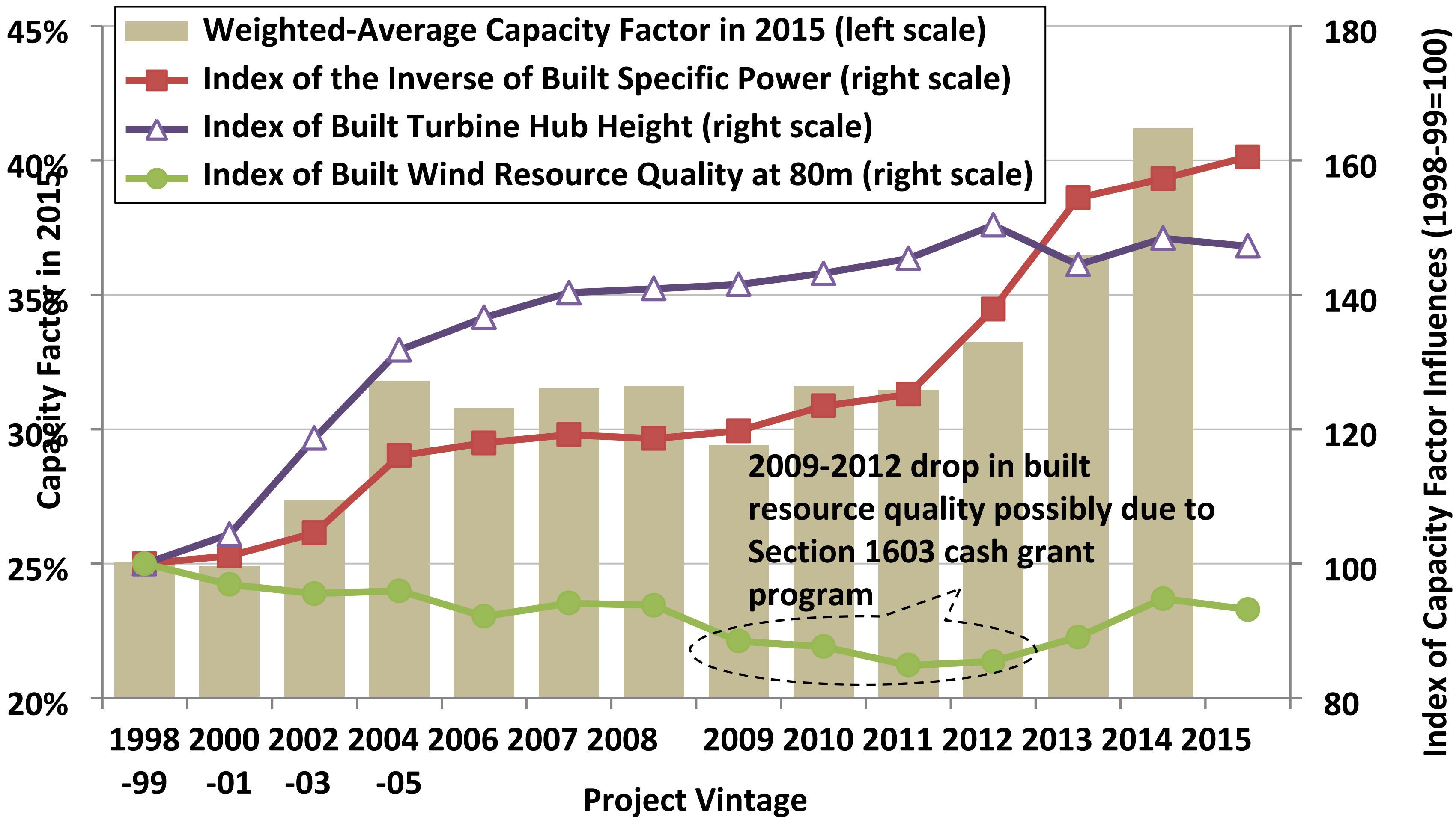


The effect of specific power on capacity factor is most easily seen when controlling for site-specific wind resource quality

But the recent boost in capacity factor is also now evident fleet-wide when viewed by project vintage

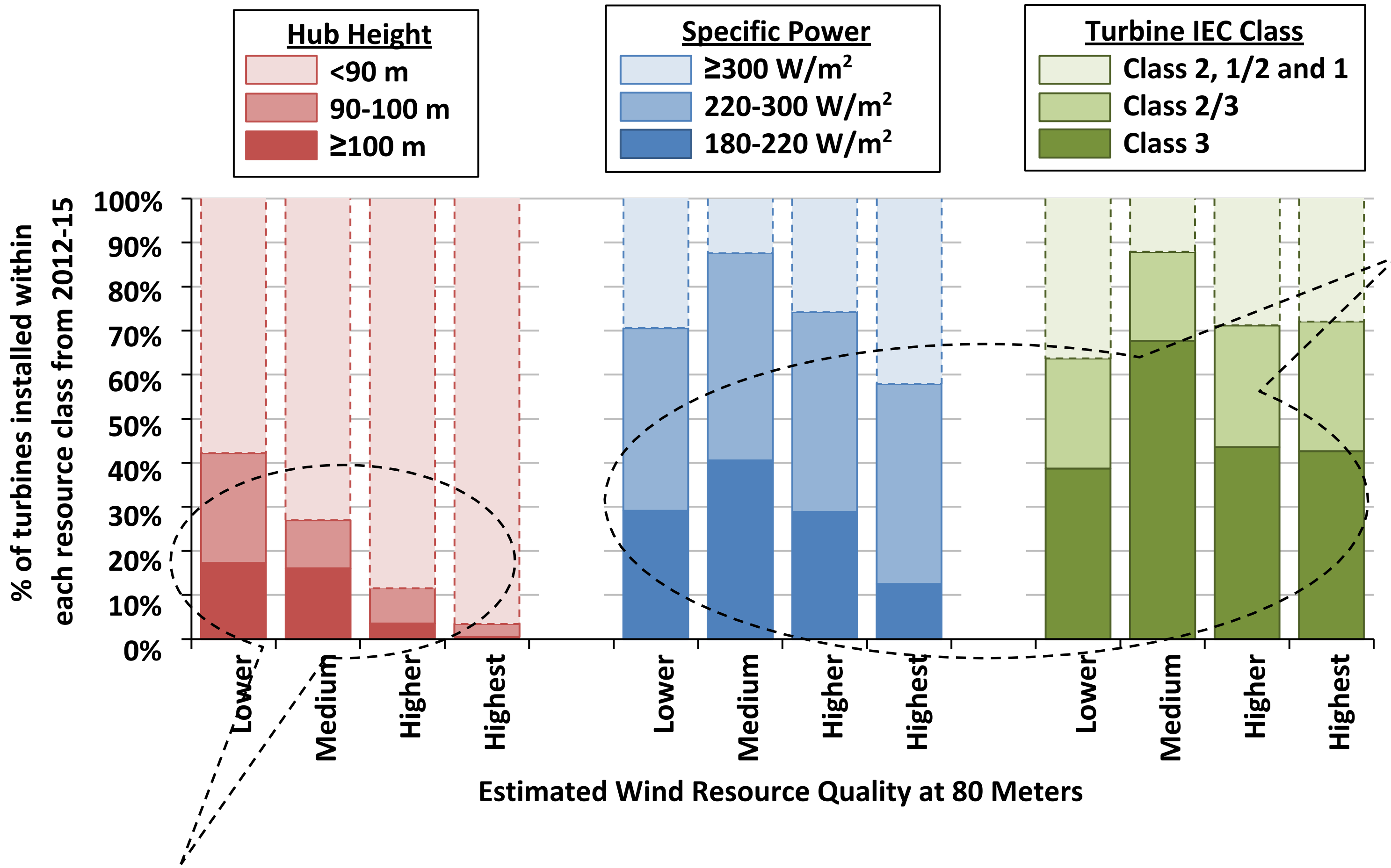


2013-2015 reversal of build-out of lower quality wind resource sites (particularly from 2009-2012) also helps



Positioning of these three drivers among 2015-vintage projects suggests similarly high capacity factors as seen in 2014-vintage projects

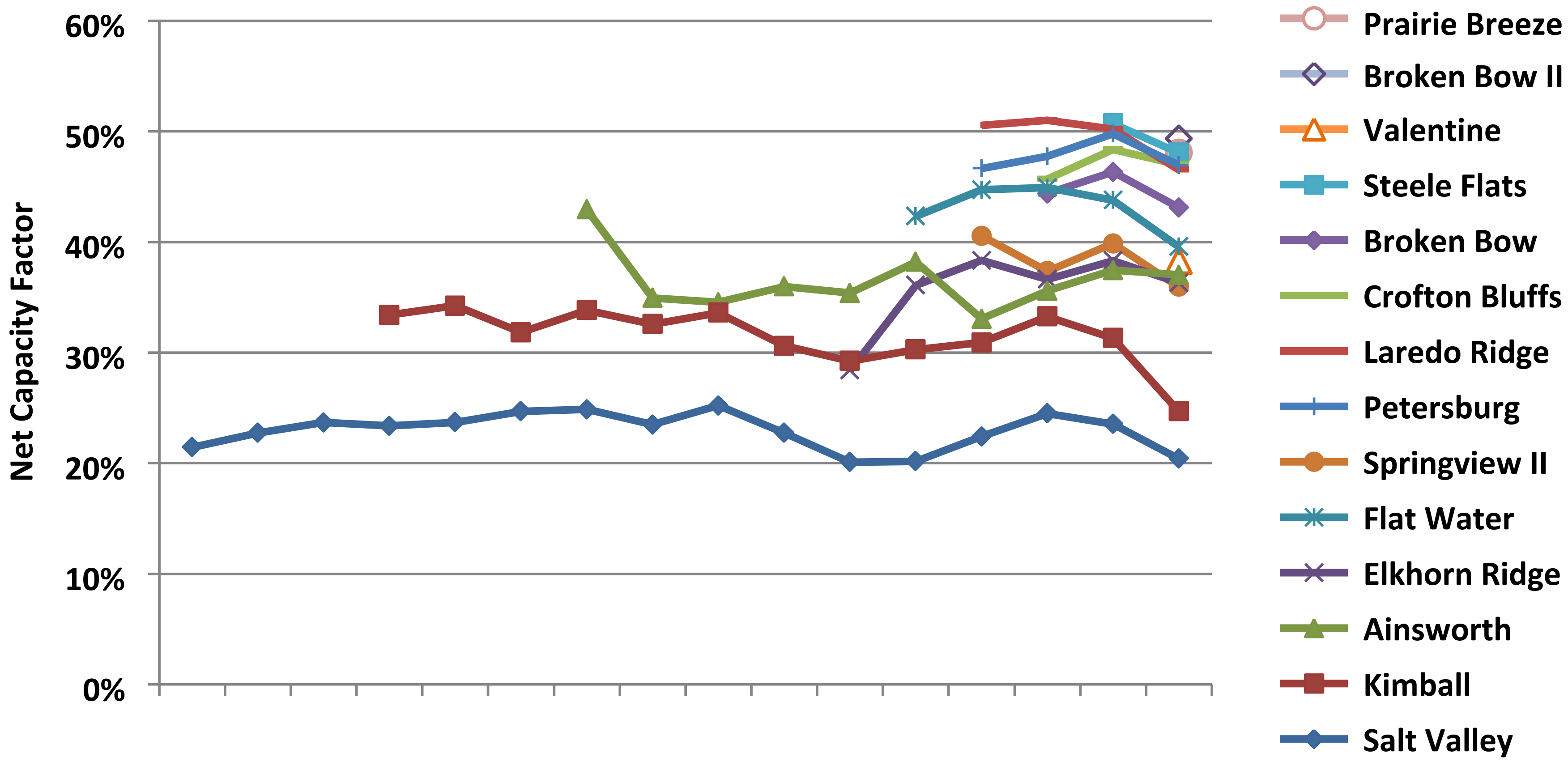
Though designed for low wind speed sites, Class III low-specific-power turbines have been widely deployed



Surprisingly little difference in deployment across the full range of wind resource regimes

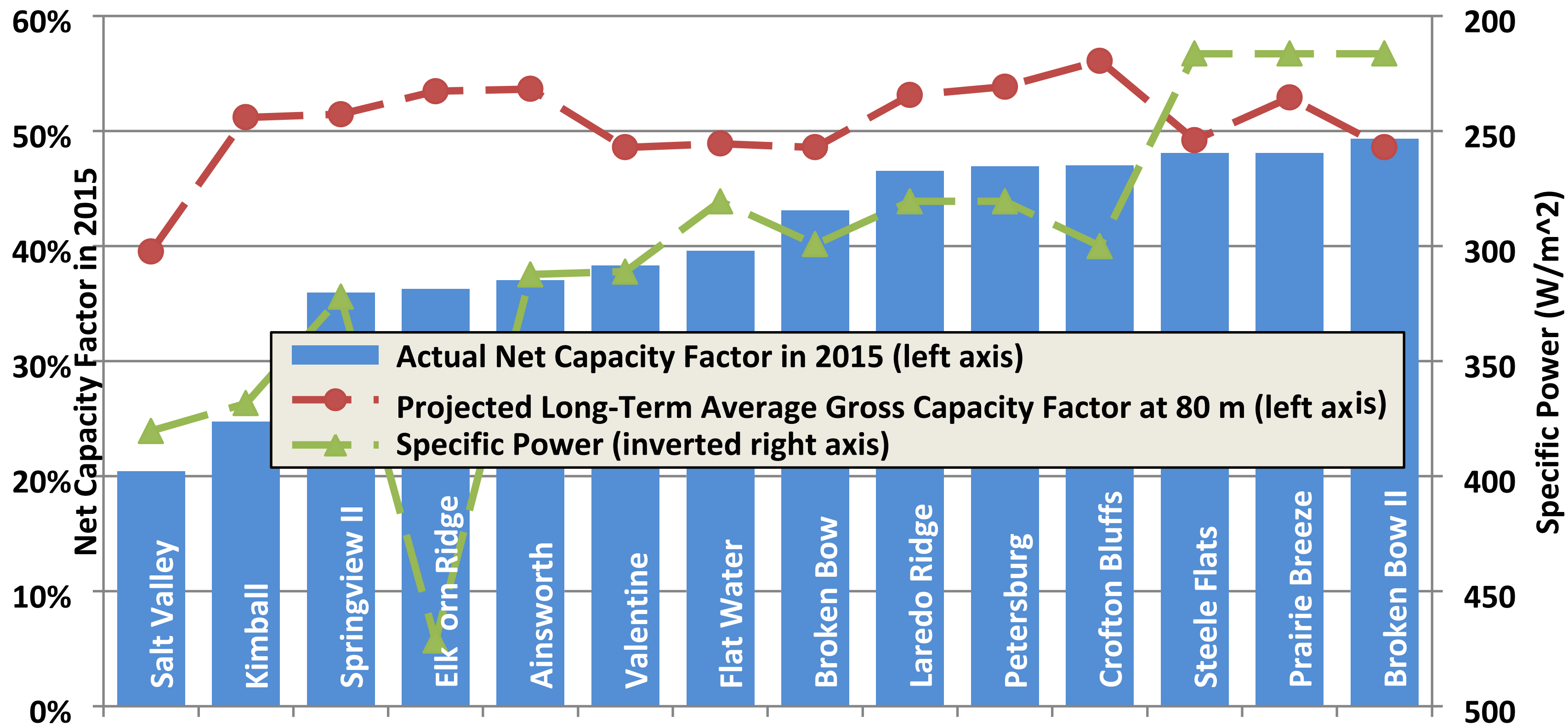
In contrast, taller towers (90 meters or higher) have been deployed primarily in low-to-medium wind speed sites

In Nebraska, newer projects (with shorter operational histories) generally have much higher capacity factors



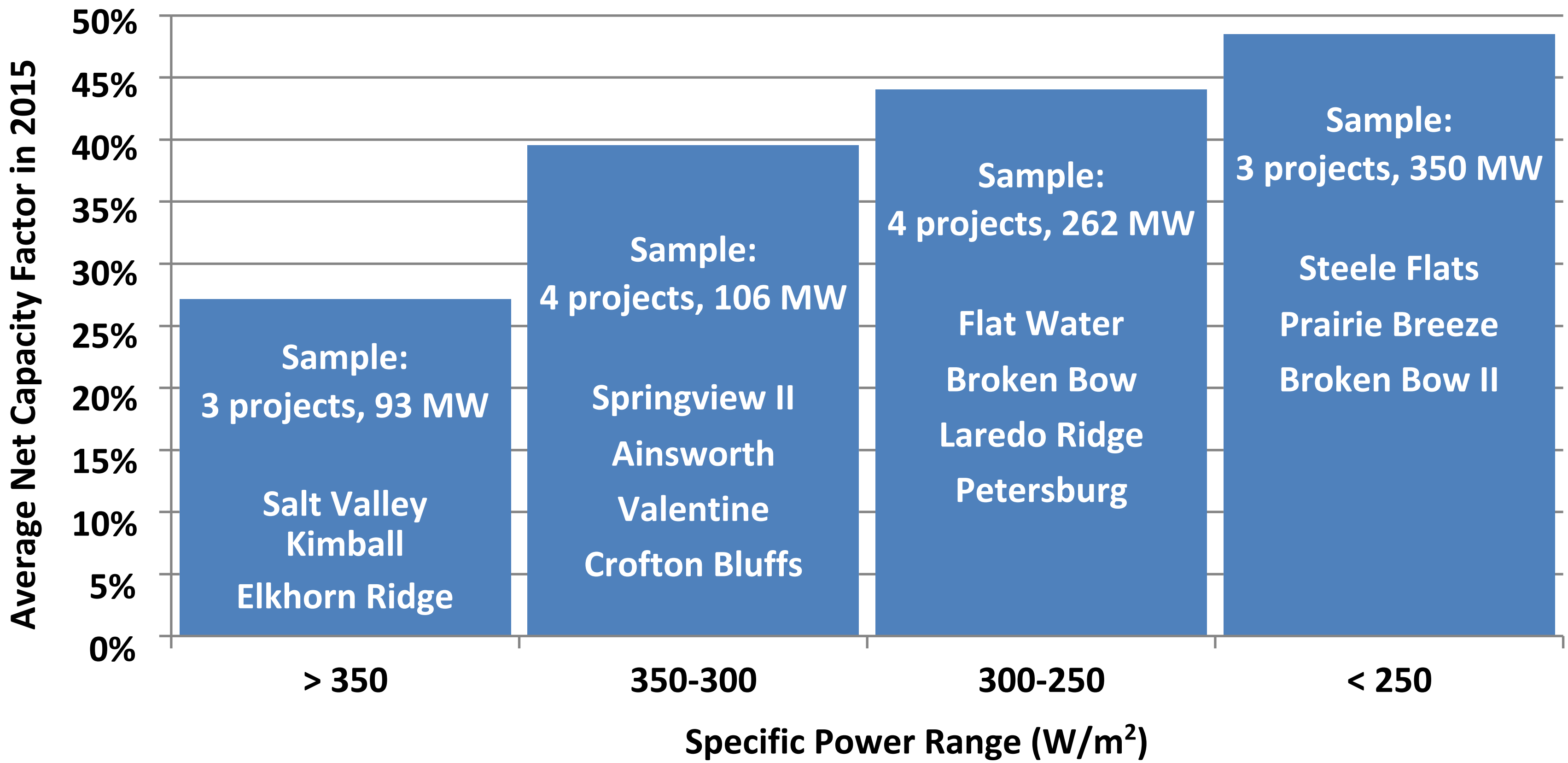
- Capacity factors in Nebraska have nearly ***doubled*** since the first Nebraska wind projects were built 15+ years ago (e.g., Salt Valley, Kimball)
- 2015 was a bad wind year (look for better performance among the 2014 projects in the future)

Improvement in Nebraska capacity factors driven primarily by declining specific power



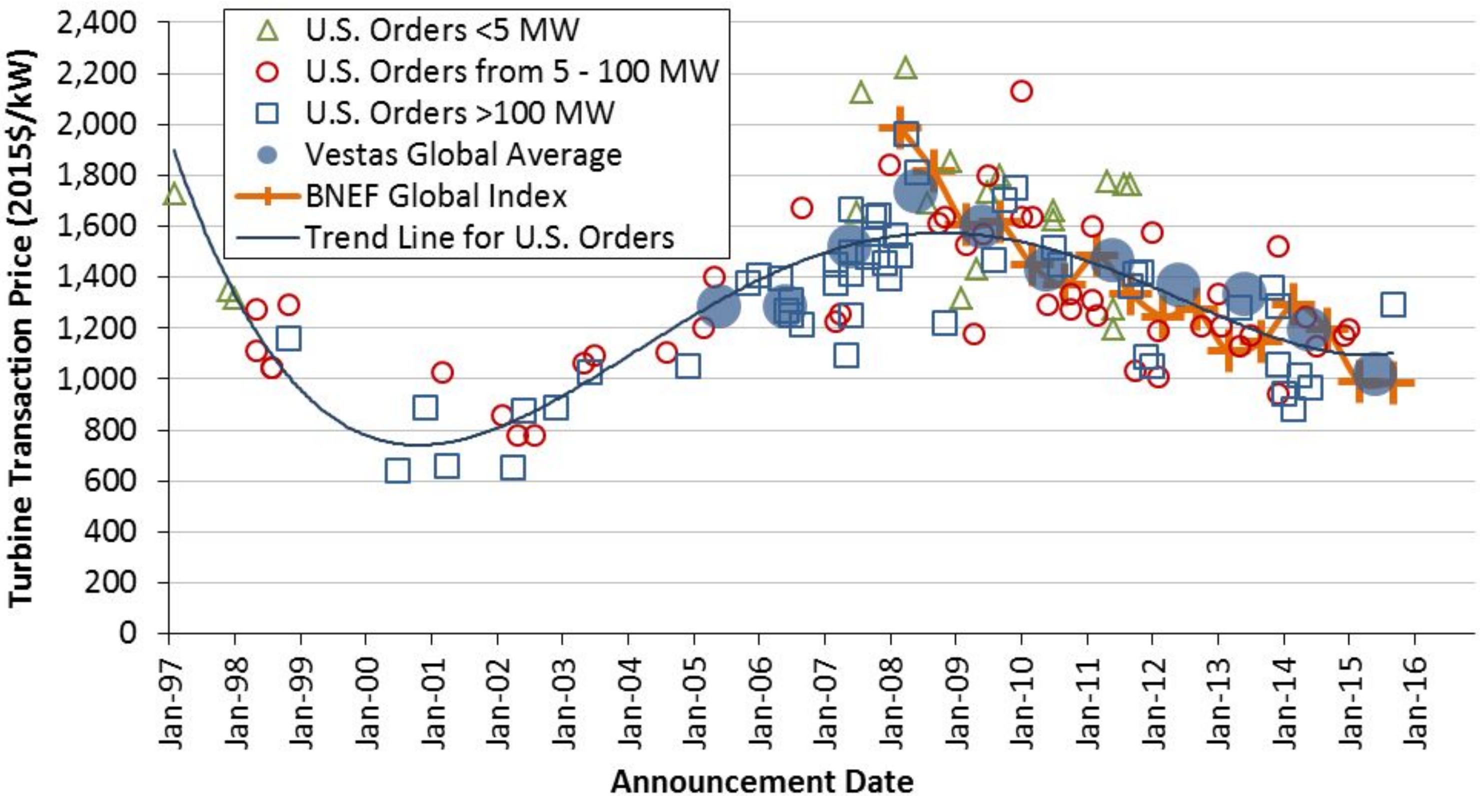
- With the exception of Salt Valley, the long-term average wind resource quality (dashed red line) is fairly similar across Nebraska project sites
- Though not shown, tower height is 80 m for all but 4 of the first 5 projects on the left
- Suggests that specific power (dashed green line) is the primary driver of capacity factor

Yet another way of looking at it: Capacity factor differences driven largely by specific power



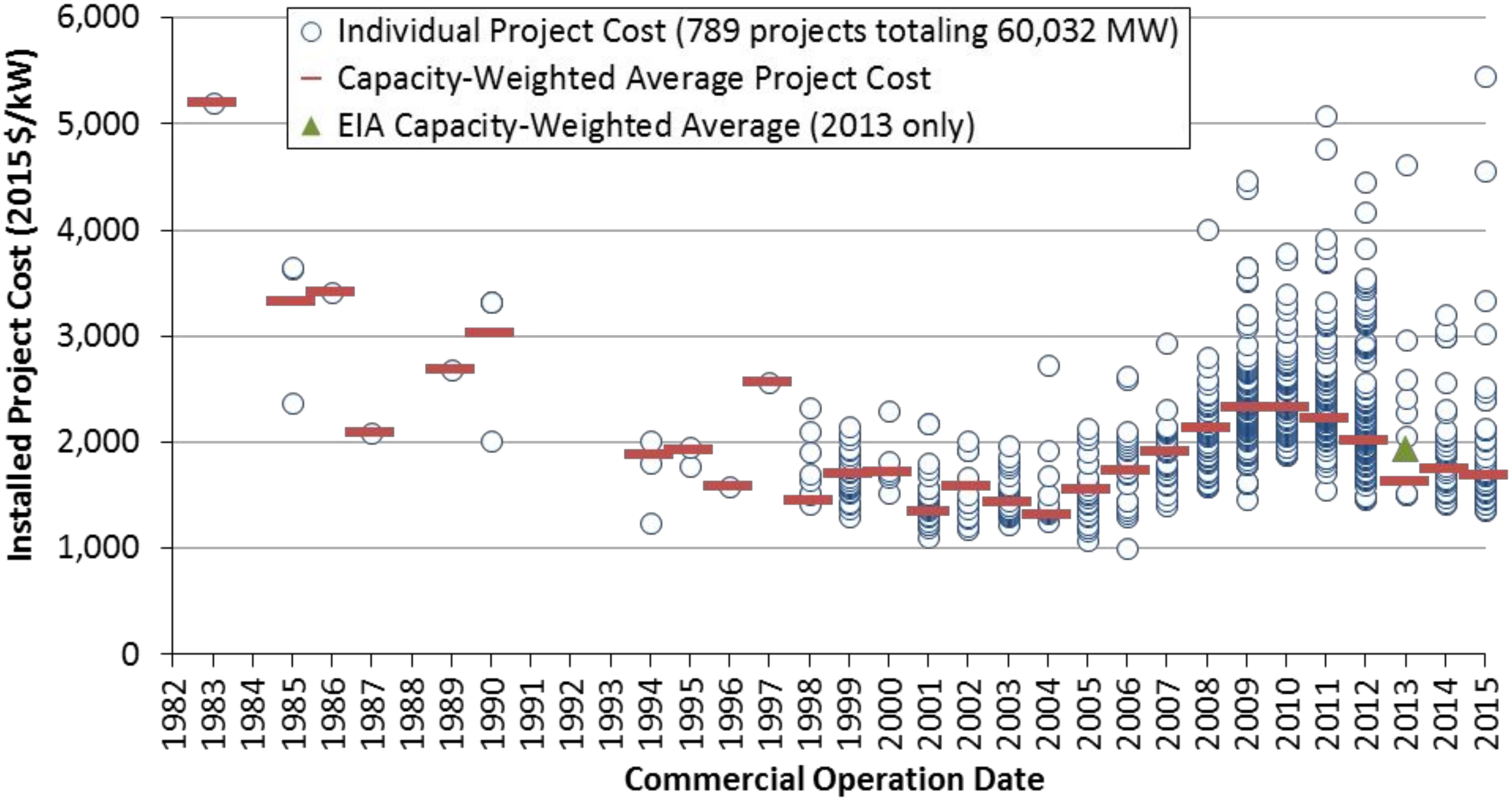
Specific power of 2015/2016 Nebraska wind projects — Prairie Breeze II and III, Creston Ridge, Grande Prairie, Arbuckle Mountain (OK), Buckeye(KS) — range from 204-227 W/m^2, suggesting more high capacity factor projects

Turbines are not only bigger and more efficient than they were a few years ago—they're also cheaper



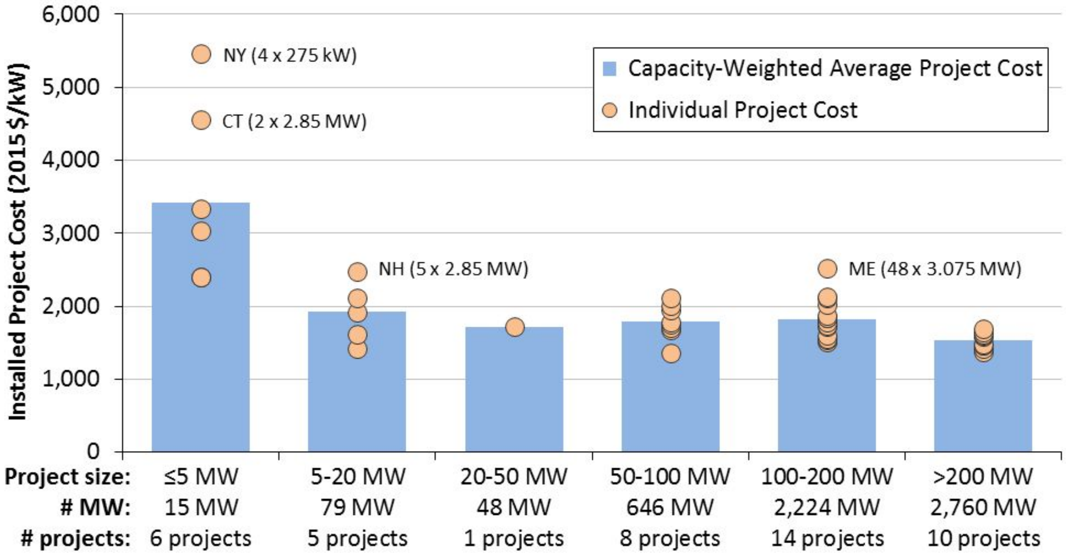
- **Decline in turbine prices since 2008 driven by a variety of factors**
  - Strengthening U.S. dollar, falling cost of raw materials and energy, stable-to-declining labor costs, lower warranty provisions, turbine scaling
- **Turbine prices have declined *in spite of* higher OEM profitability**

Lower turbine prices drive reductions in reported installed project costs

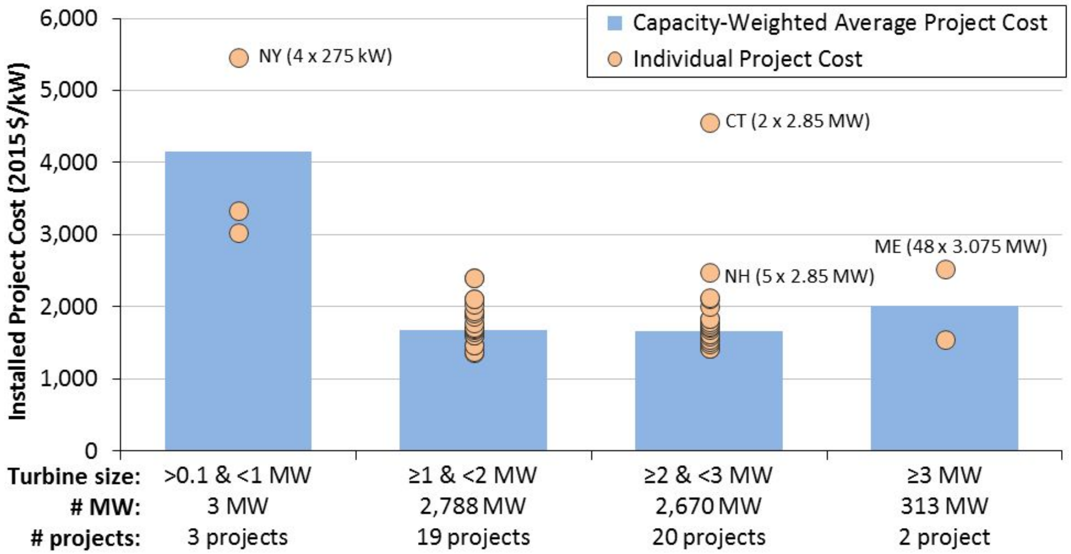


- 2015 projects had an average cost of $1,690/kW, down $640/kW since 2009-2010
- Though not shown, limited sample of projects slated for completion in 2016 suggests no material change in costs

Project-level cost variation driven in part by economies of scale, particularly at lower end of size range

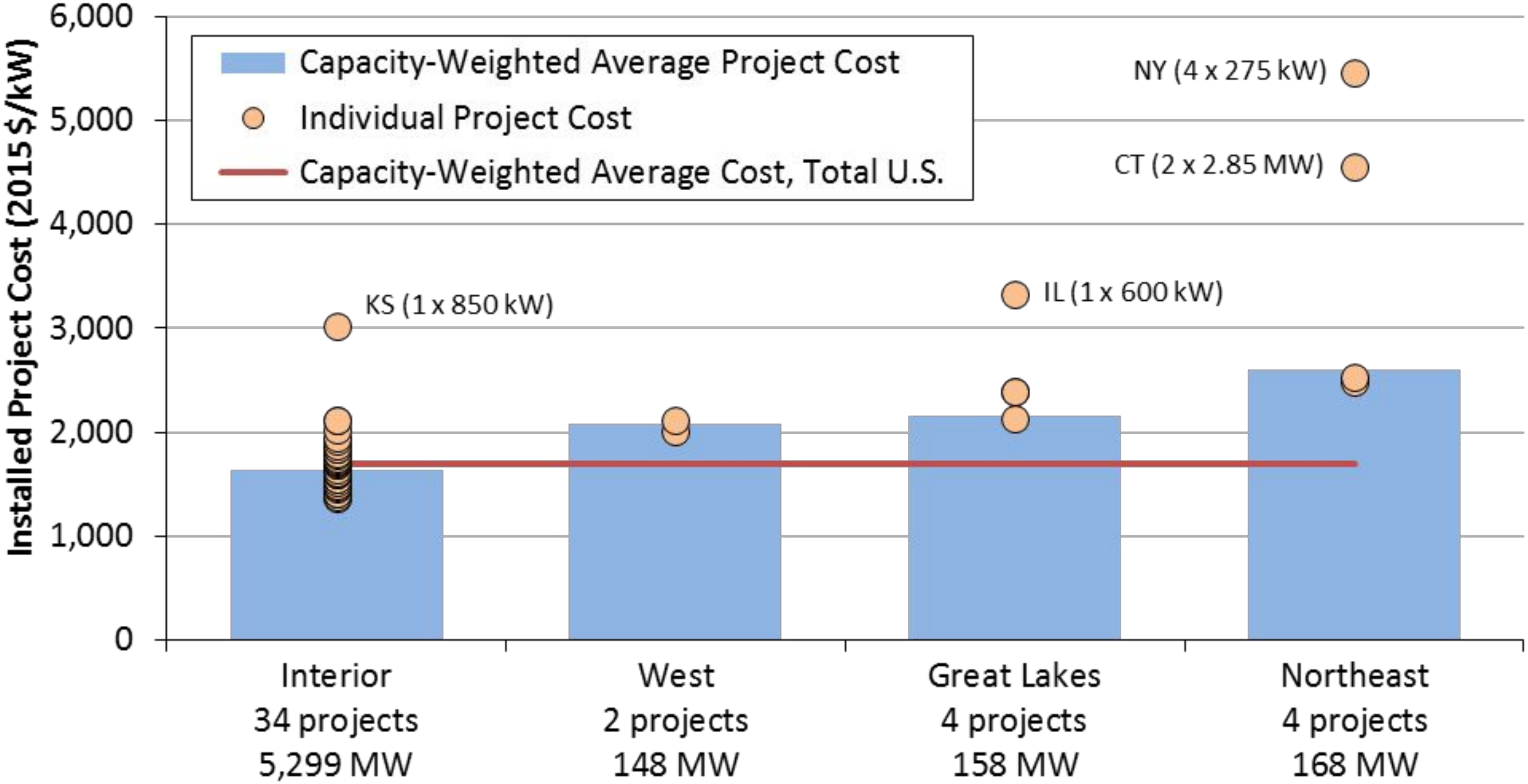


Project Size



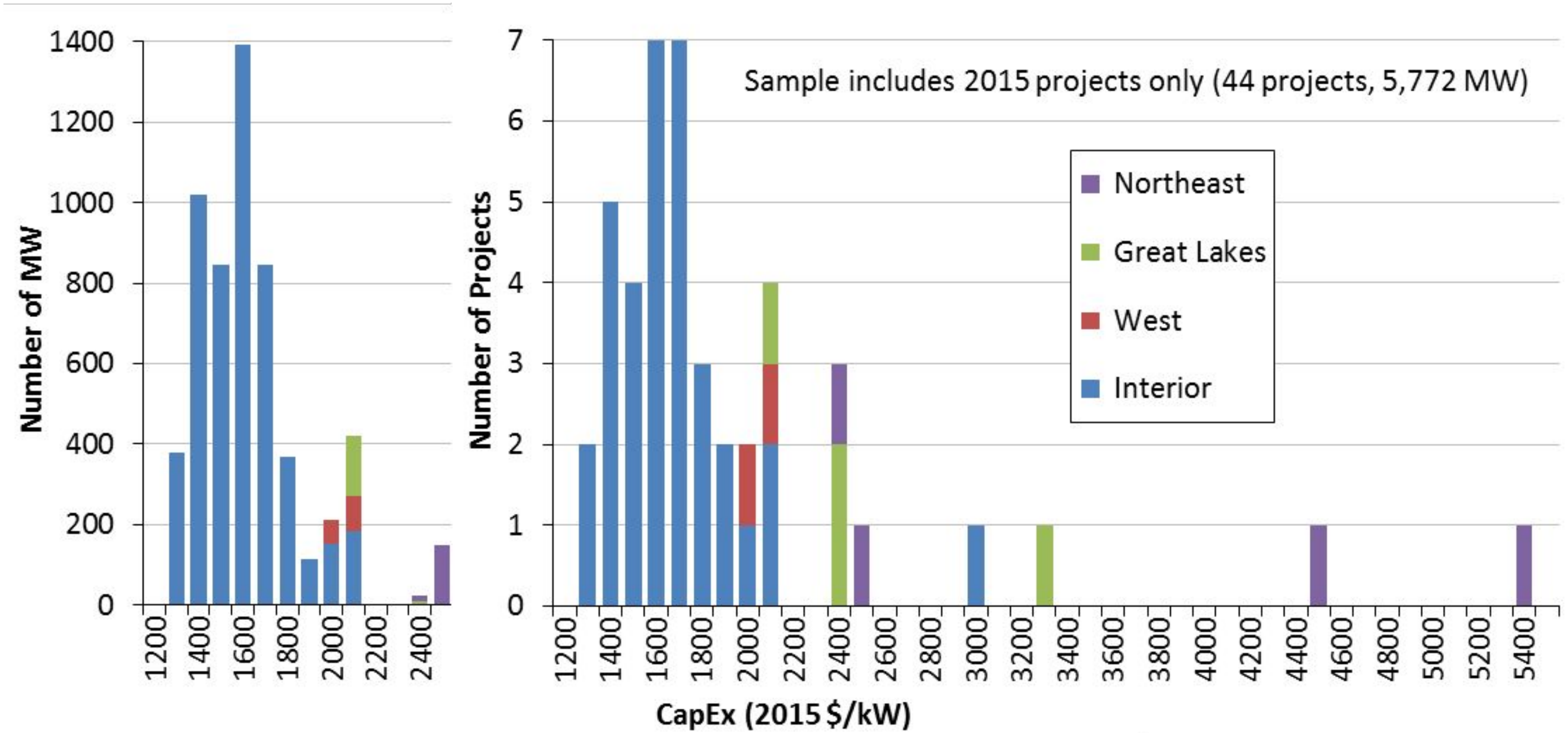
Turbine Size

Regional differences in average wind power project costs are also apparent (but sample size is limited)

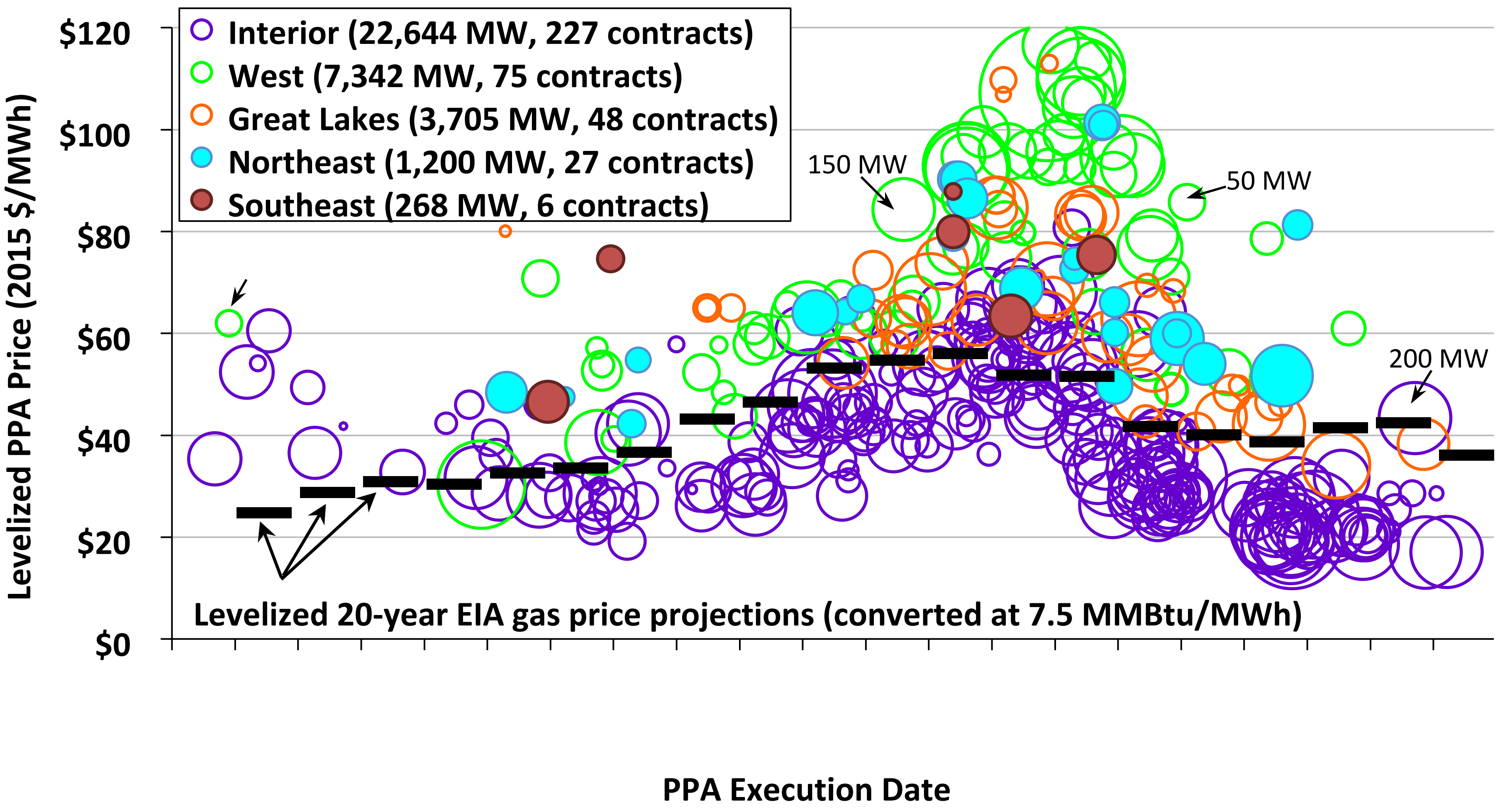


Sample includes only projects completed in 2015

Most 2015 projects—and all of the low-cost projects—are located in the Interior

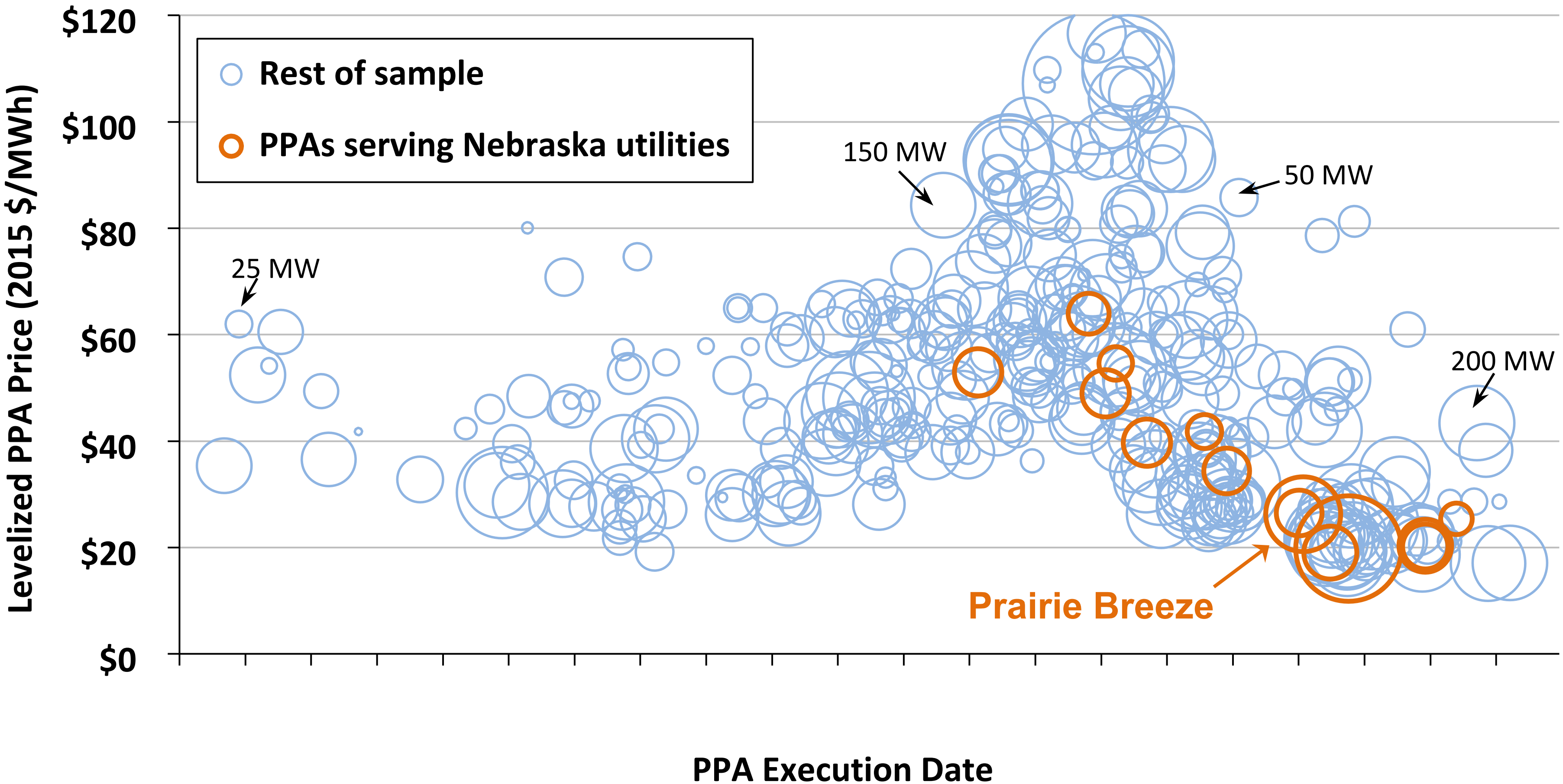


The combination of lower costs and higher capacity factors has driven PPA prices to all-time lows



Levelized wind PPA prices in the Interior have regularly beat the projected cost of burning natural gas in an existing combined cycle generator

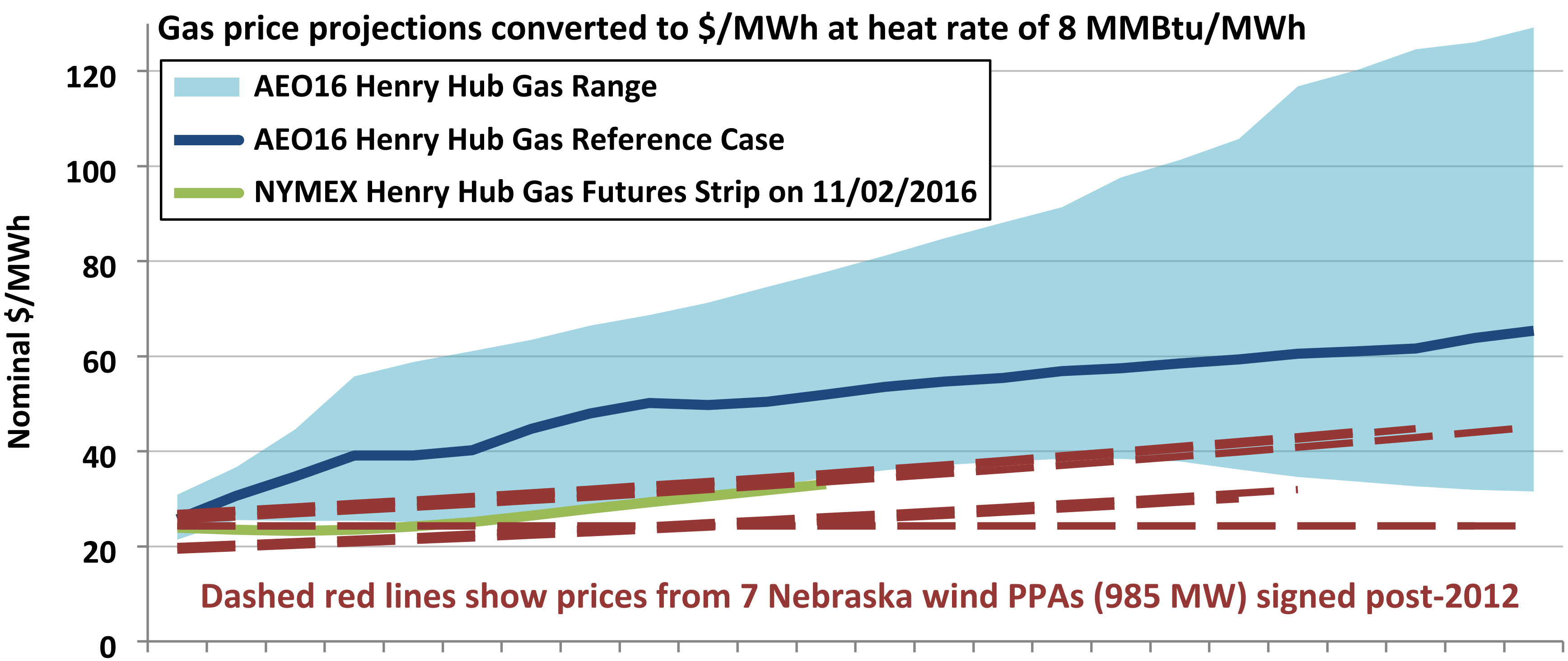
Nebraska wind PPAs have followed a similar pattern as the rest of the sample



"[Prairie Breeze] is comparable in cost to other OPPD generation and therefore there is no impact on OPPD rates. OPPD simply backs down other generation resources when the wind is blowing and replaces it with similarly priced energy from the Prairie Breeze Wind Project."

– *Minutes from OPPD Board of Directors meeting on January 17, 2013*

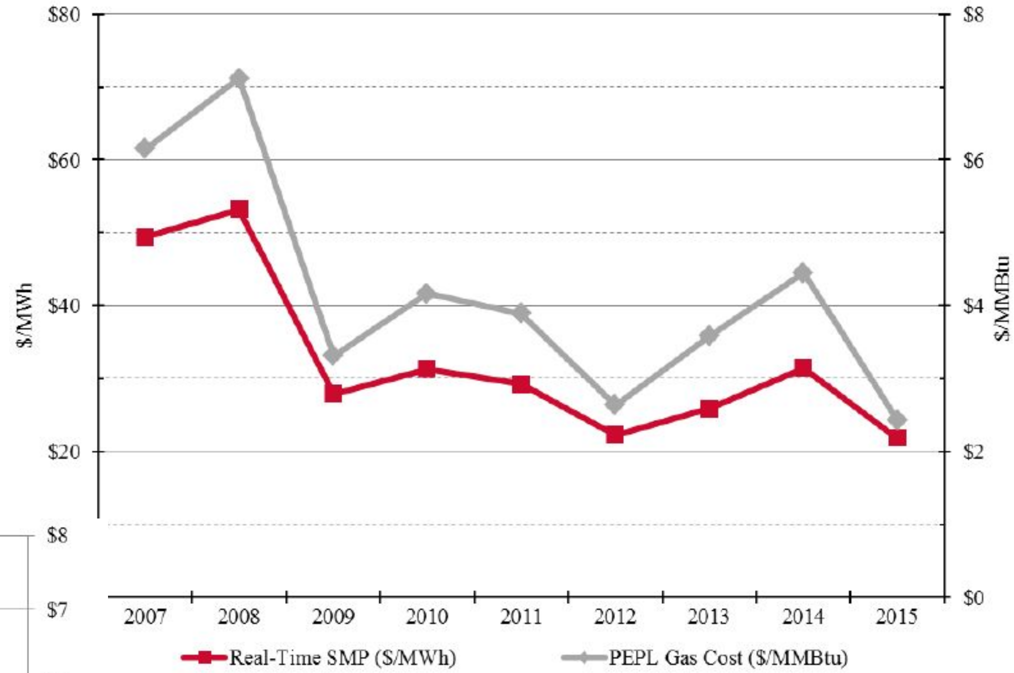
Recent Nebraska wind PPAs are competitive with the cost of burning gas in existing combined cycle units

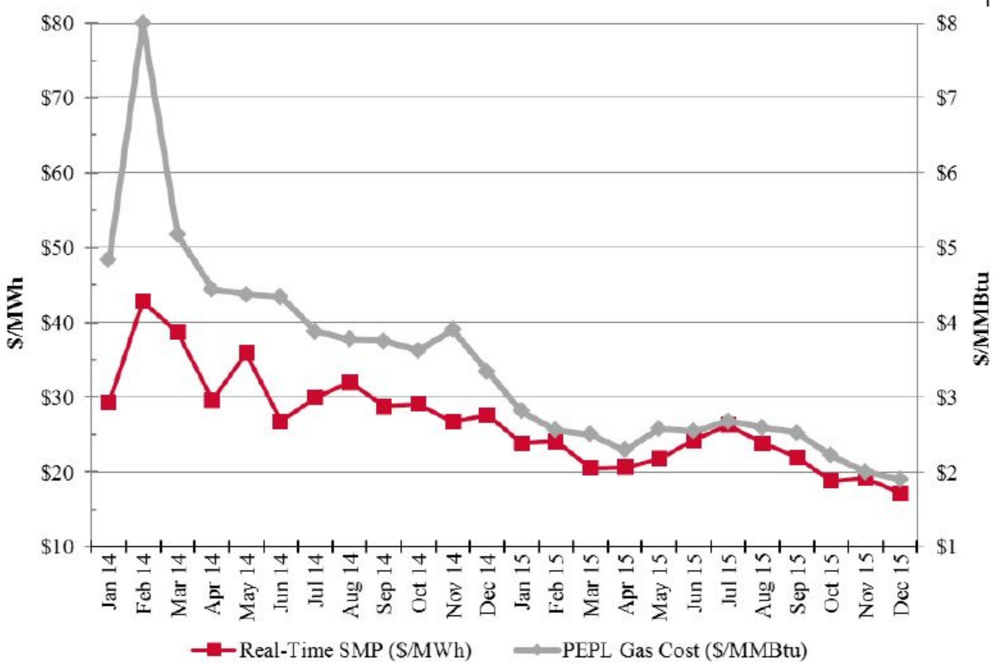


- Recent Nebraska wind PPAs—and the NYMEX gas futures strip—are at the low end of AEO 2016 gas price projections (converted to power terms at 8 MMBtu/MWh)
- There is seemingly little long-term risk to contracting with wind at these price levels
- Should gas prices move higher longer term, wind will be increasingly "in the money"
- *Note that this comparison excludes non-fuel O&M costs and CapEx on the gas side*

Why do gas prices matter? Because wholesale power prices in SPP closely track natural gas prices

Annual comparison from 2007-2015





Monthly comparison in 2014 and 2015

Source: SPP 2015 State of the Market Report

With the PTC phase-down, there is reason to act sooner rather than later

Construction Start Deadline	Four-Year Safe Harbor Completion Deadline	PTC %	First-Year PPA Price $/MWh	Nominal Levelized PPA Price $/MWh	Real Levelized PPA Price $/MWh	Leverage
2016	2020	100%	21.2	24.2	20.8	23.3%
2017	2021	80%	24.3	27.8	23.8	30.7%
2018	2022	60%	27.7	31.6	27.1	38.7%
2019	2023	40%	31.0	35.5	30.4	46.7%
2020	2024	0%	38.3	43.8	37.6	64.2%

- First row roughly matches the economics of recent Nebraska wind projects
- Leverage increases as PTC declines and more of the sponsor's return comes from cash revenue via the higher PPA price (which, unlike the PTC, can support debt)
  - Shift towards cheaper capital (i.e., debt rather than equity) partially mitigates the loss of the PTC
  - But there is still a sizable impact: +$16.8/MWh real levelized or +$19.6/MWh nominal levelized

Modeling Assumptions: $1600/kW CapEx; $50/kW-year OpEx; 50% net capacity factor; 20-year PPA with 2% escalator; 2% inflation; 15-year debt at 4.5% interest and 1.4 DSCR; 10% after-tax IRR for sponsor; PTC as indicated in table; 5-year MACRS depreciation; 35%/8% federal/state income tax rate

The outlook for wind in the US: strong through 2020, uncertain thereafter

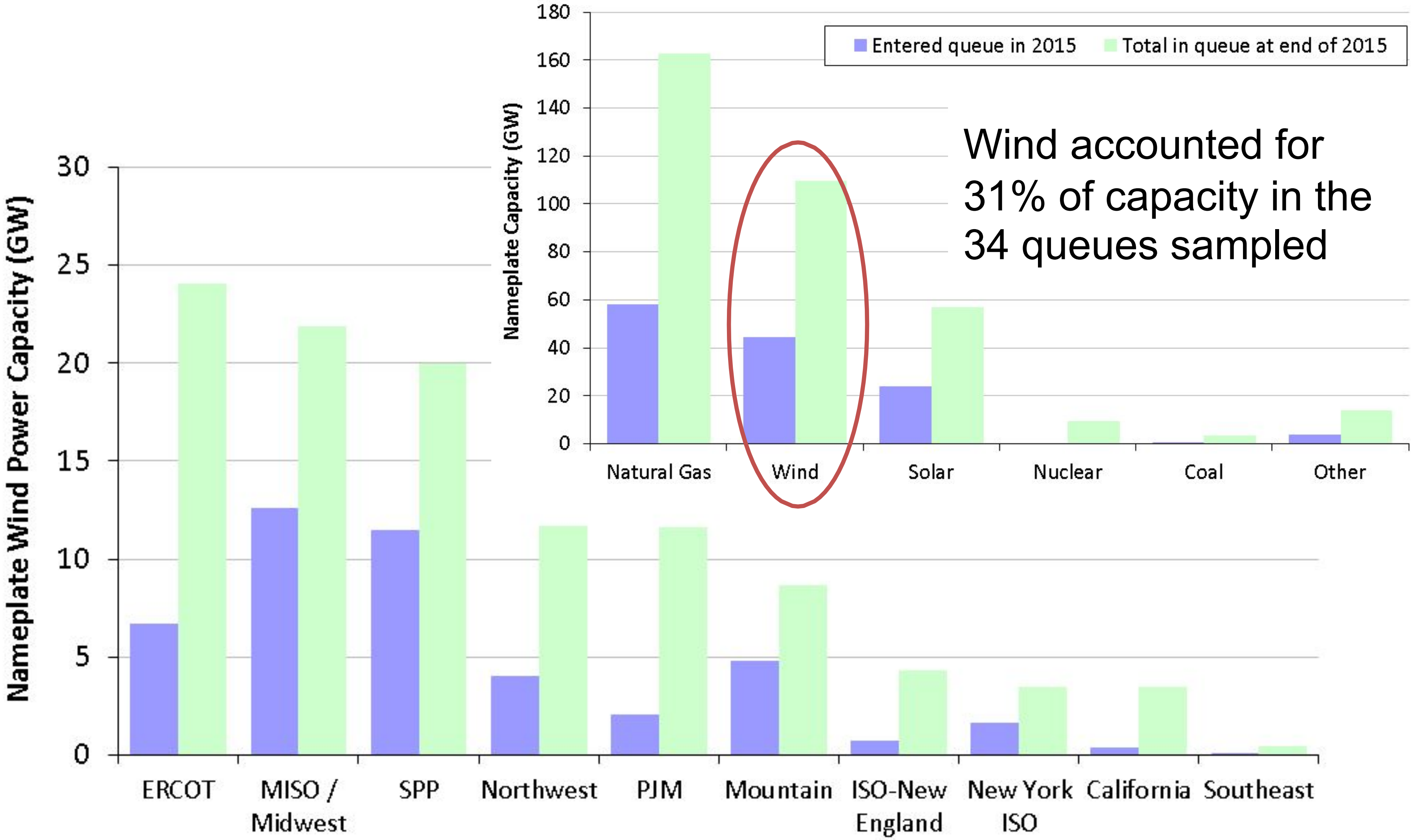
Tailwinds:

- PTC extension and 4-year IRS safe harbor window
- Competitive low wind PPA prices
- Ongoing technological advancement
- Growth in direct retail sales to non-utility offtakers
- Clean Power Plan(?)

Headwinds:

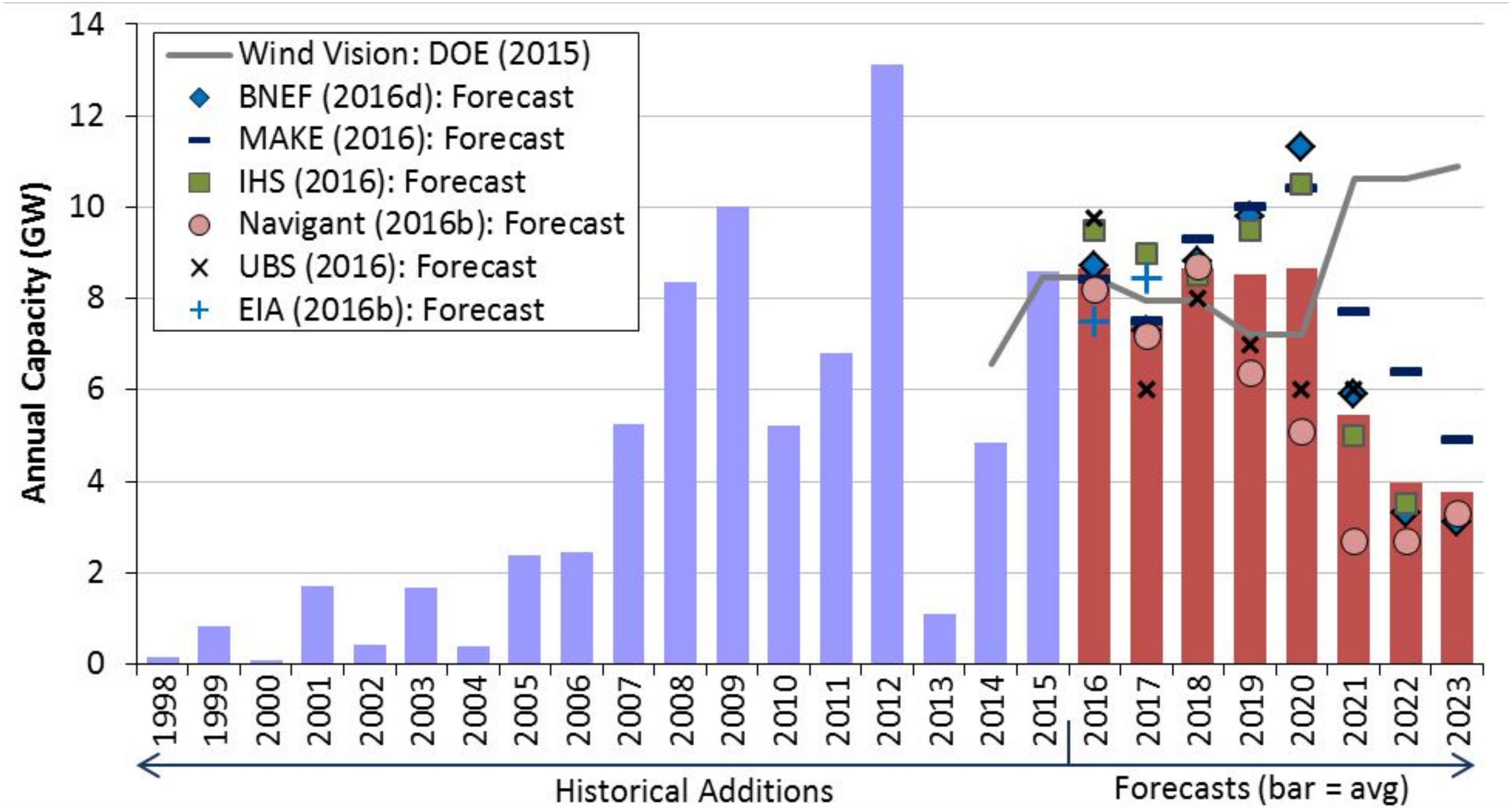
- Phase-down of federal tax incentives
- Continued low natural gas and wholesale electricity prices
- Modest electricity demand growth
- Limited near-term demand from state RPS policies
- Inadequate transmission infrastructure in some areas
- Growing competition from solar in some regions

~110 GW of wind in interconnection queues at the end of 2015 (much of it in the Interior)



Not all of this capacity will be built….

The average projected wind build from 2016-2023 is ~55 GW (only half of the ~110 GW in queues)



Projected wind additions through 2020 are consistent with deployment trajectory analyzed in DOE's *Wind Vision* report—***but not so after 2020***

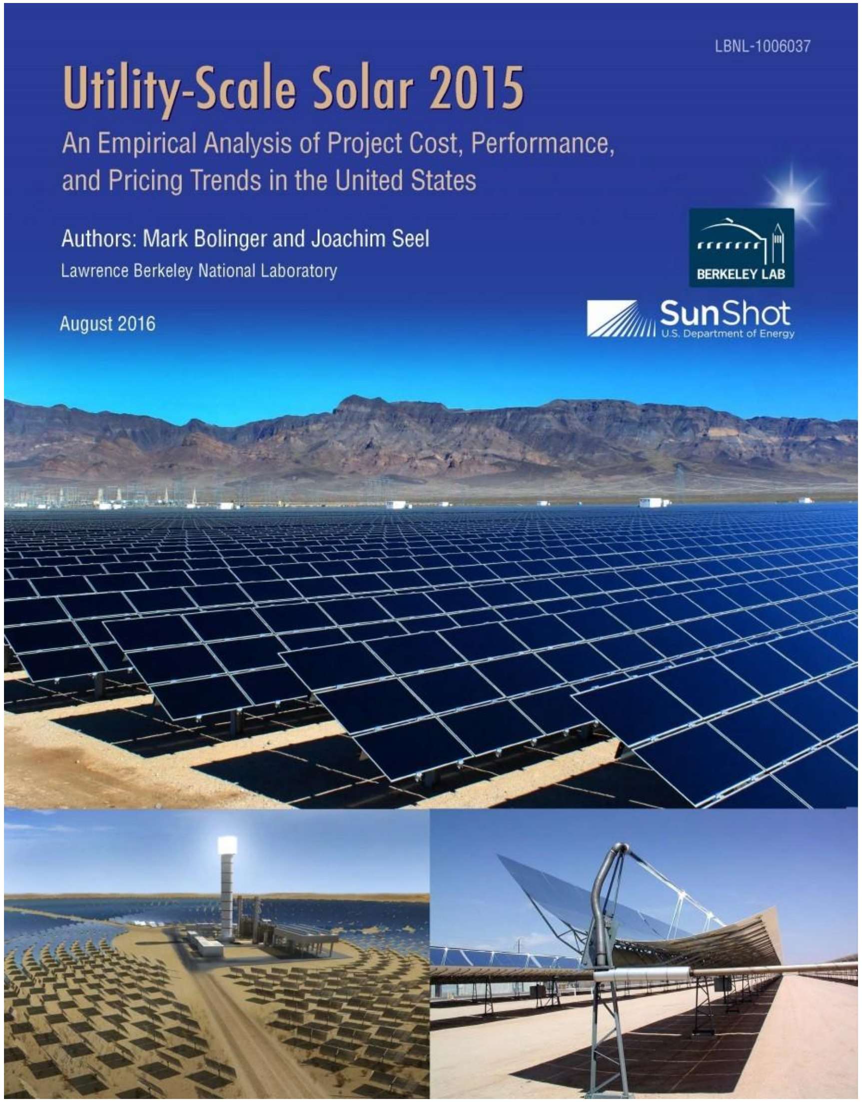
2) Utility-Scale Solar

Utility-scale PV technology, cost, performance, and PPA price trends

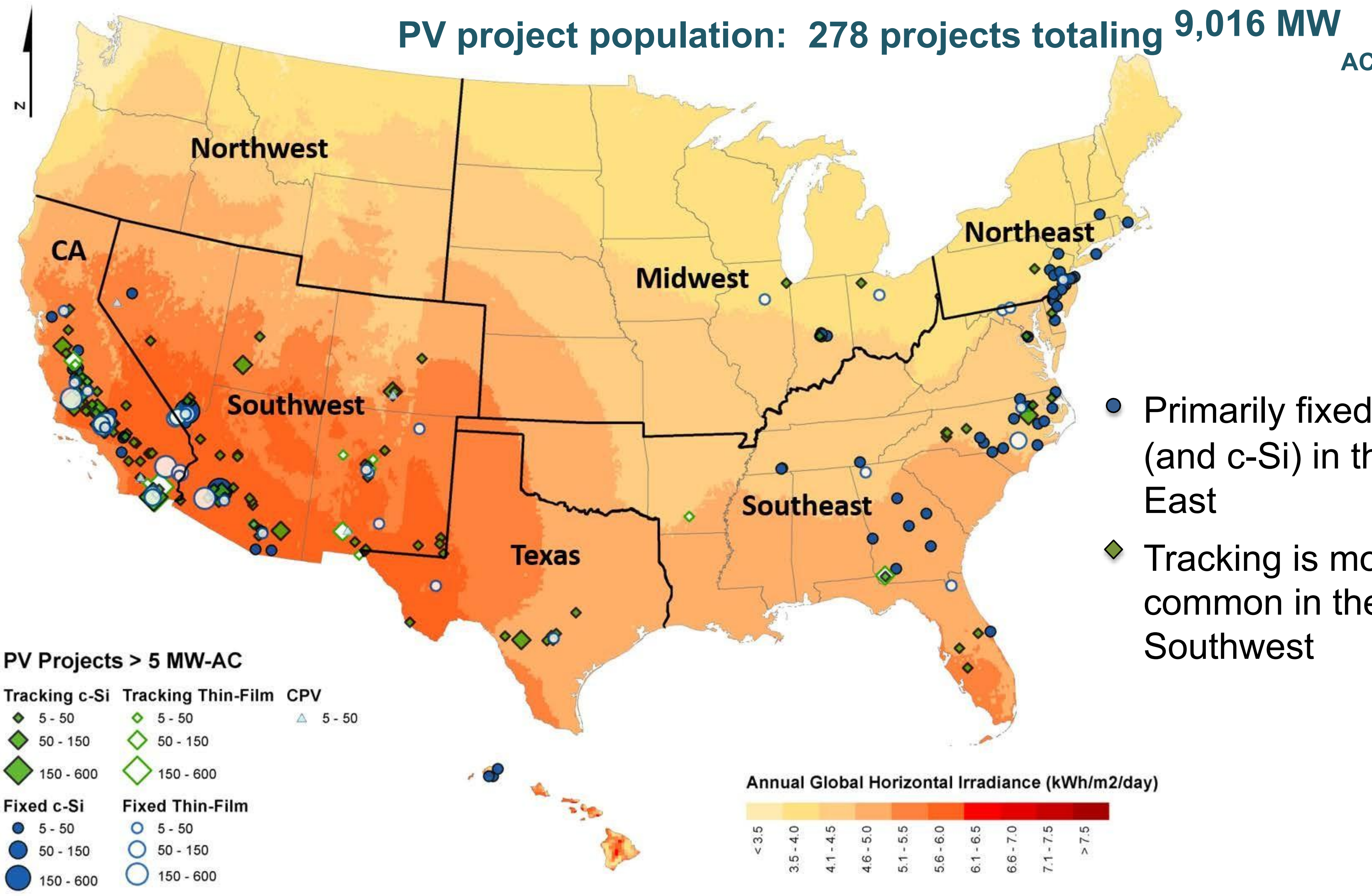
- Most material is drawn from LBNL's *Utility-Scale Solar 2015*
- Available at **utilityscalesolar.lbl.gov**

Note: We define utility-scale solar to include any ground-mounted project that is larger than 5 MW_{AC}

This slide deck focuses only on PV (see report for info on CSP)

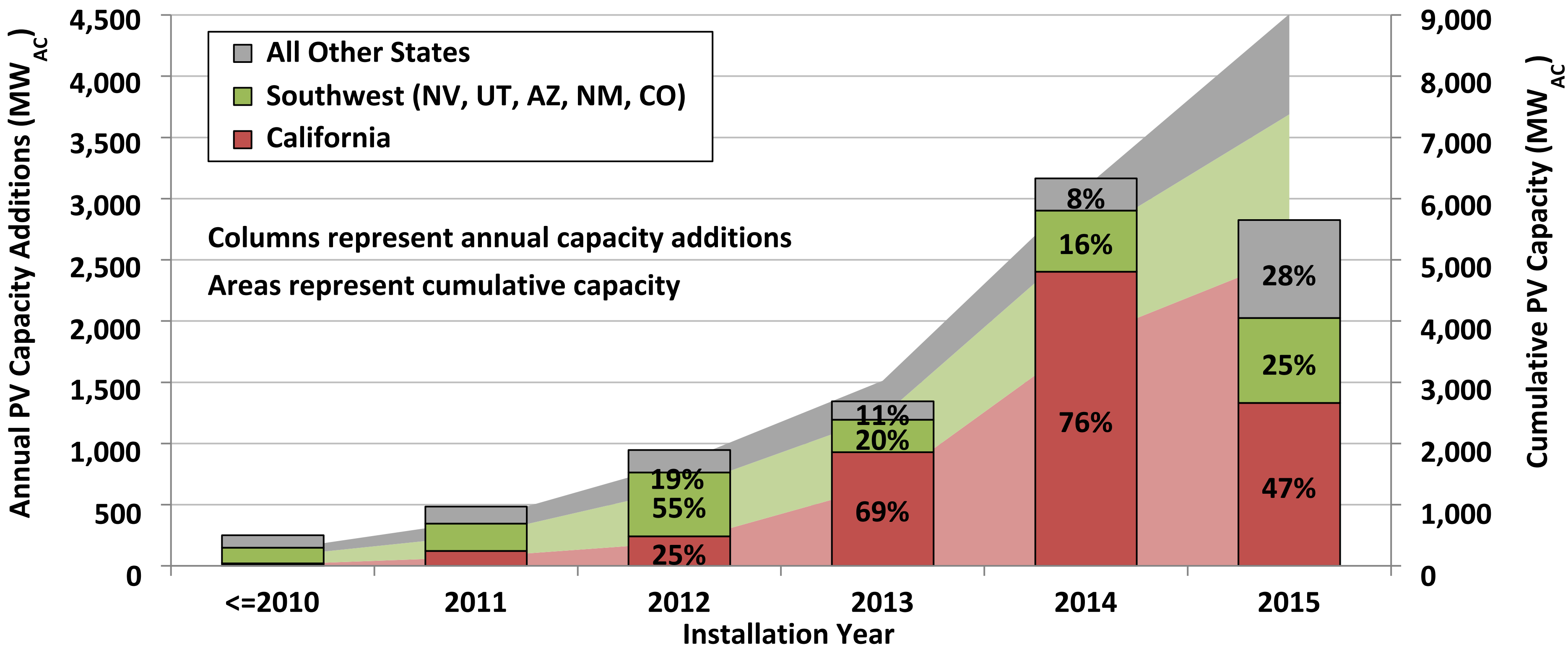


Historically heavy concentration in the Southwest and mid-Atlantic, but now spreading to other regions



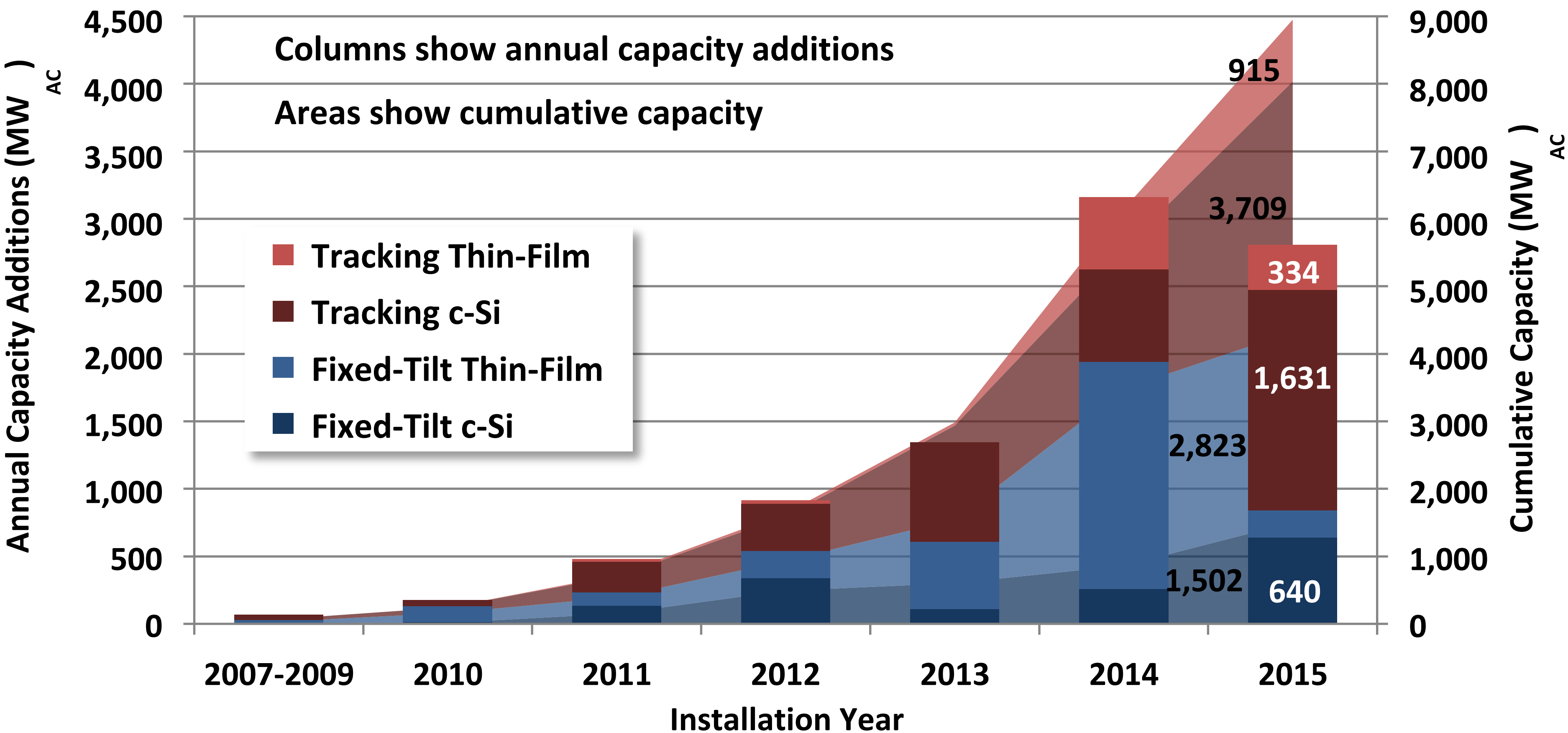
- Primarily fixed-tilt (and c-Si) in the East
- Tracking is more common in the Southwest

Strong growth in 2015 outside of California and the Southwest



28% of new utility-scale PV capacity installed in 2015 was outside of California and the Southwest, compared to just 8% in 2014

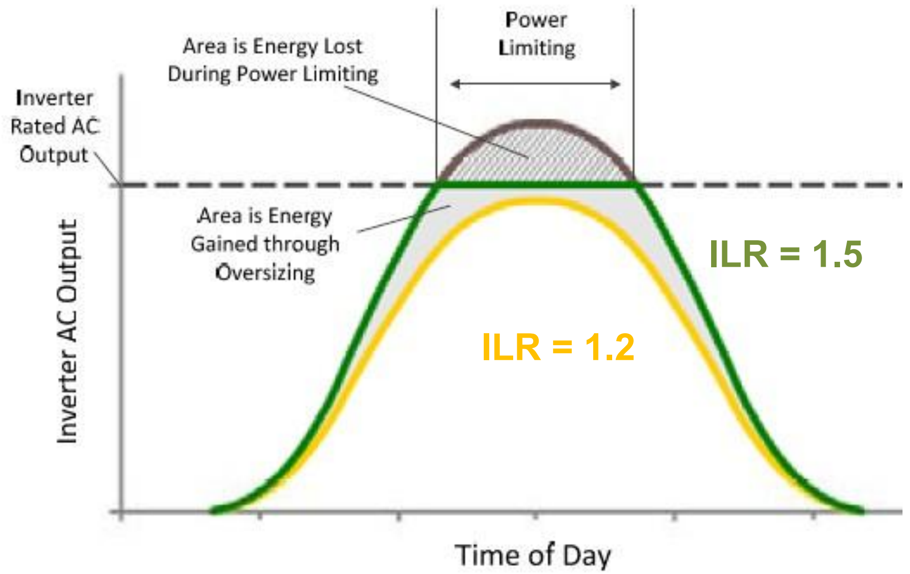
PV project population broken out by tracking vs. fixed-tilt, module type, and installation year



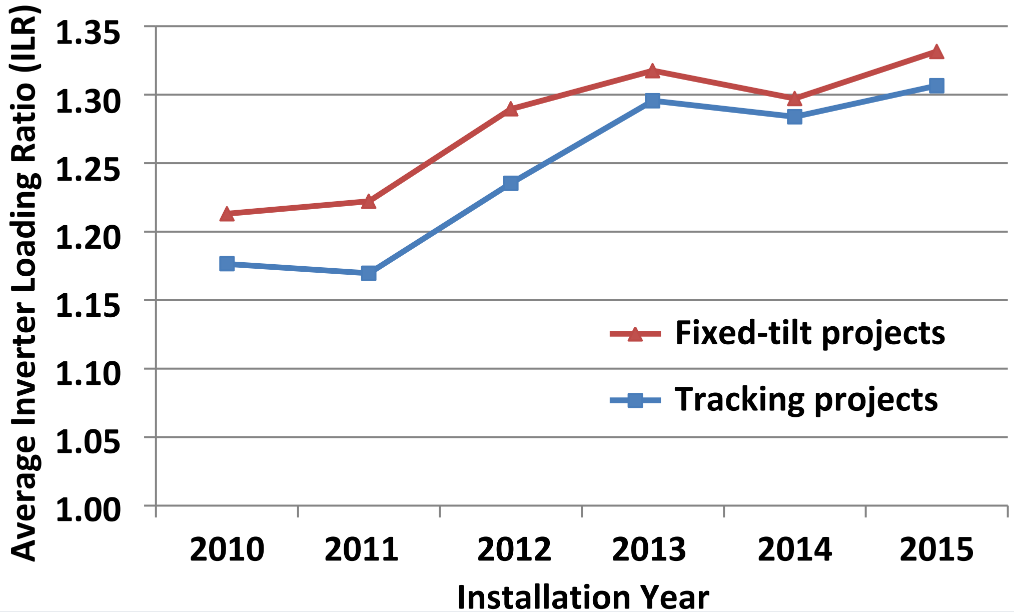
An increasing share of projects use tracking:

- 70% of new installed capacity in 2015 uses tracking (rather than fixed-tilt mounts)
- Primarily horizontal single-axis (east to west daily) tracking
- Notably, even thin-film projects now mostly use tracking

The average inverter loading ratio (ILR) has increased over time, to 1.31 in 2015

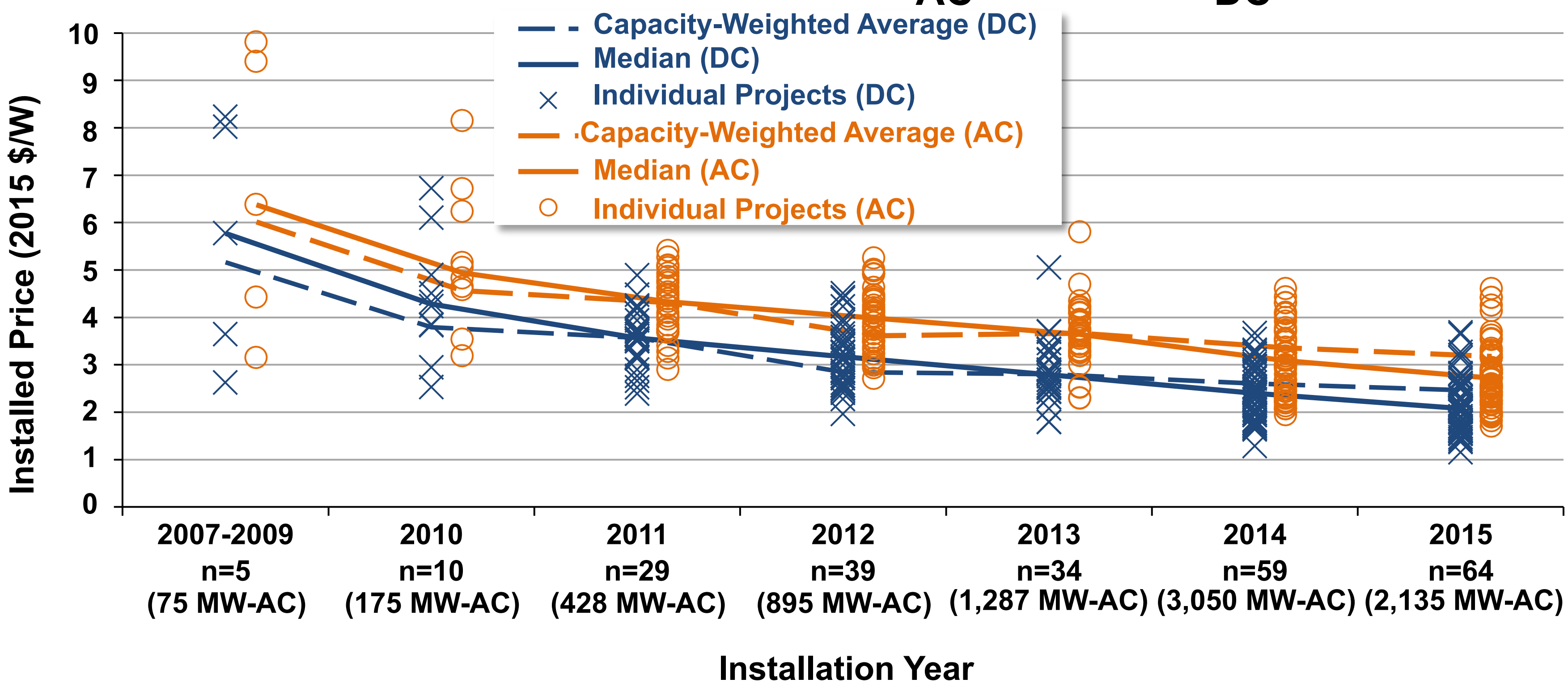


- As module prices have fallen (faster than inverter prices), developers have increasingly oversized the DC array capacity relative to the AC inverter rating (boosting the "inverter loading ratio" or "ILR") as a way to enhance revenue
- Extra output/revenue in shoulder periods outweighs losses from "power limiting" (aka "clipping"–area above dashed line)



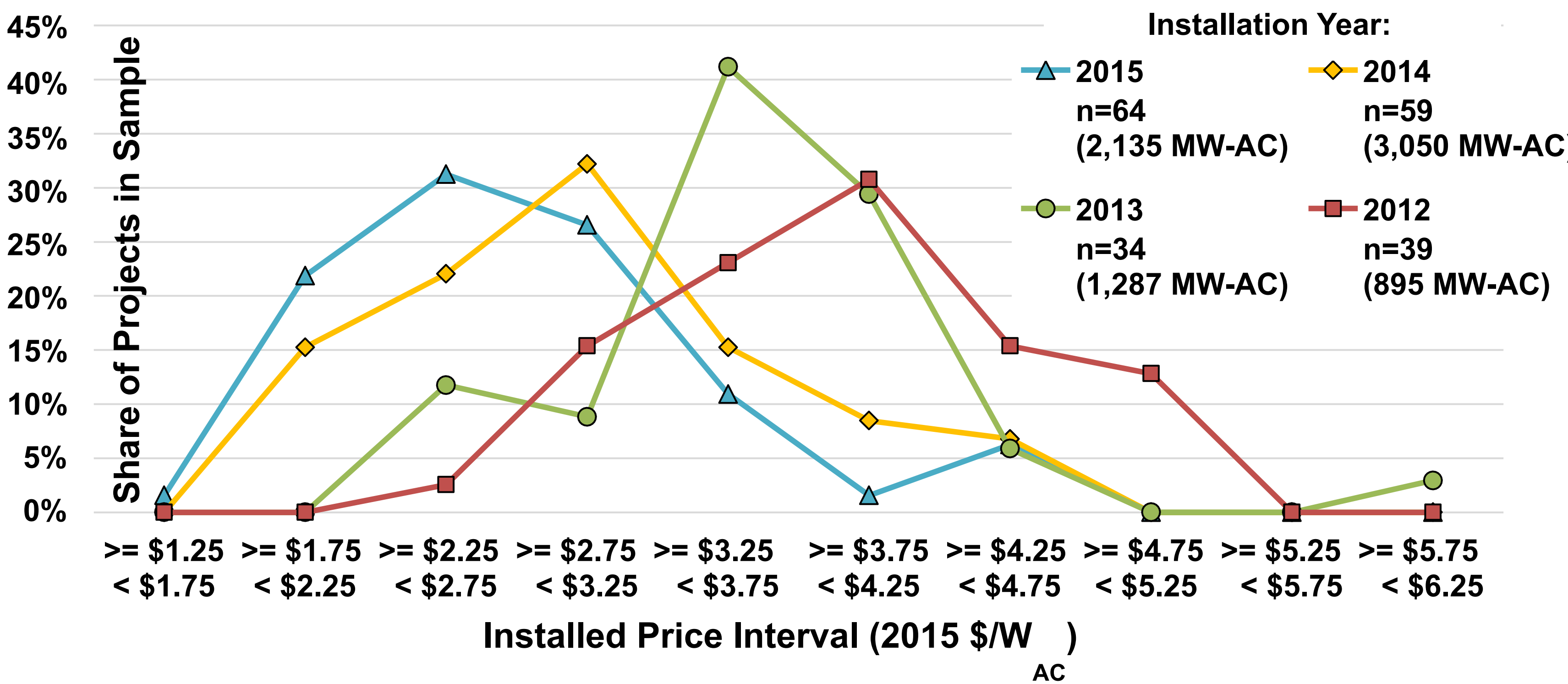
- Analogous to increasing the rotor diameter of a wind turbine
- Fixed-tilt PV projects generally have a higher average ILR than tracking PV projects (fixed-tilt projects have more to gain from a higher ILR)
- All else equal, a higher ILR should boost capacity factor (in AC terms) — *see later slides*

Median installed price of PV has fallen steadily, by nearly 60%, to around $\$2.7/W_{AC}$ ($\$2.1/W_{DC}$) in 2015



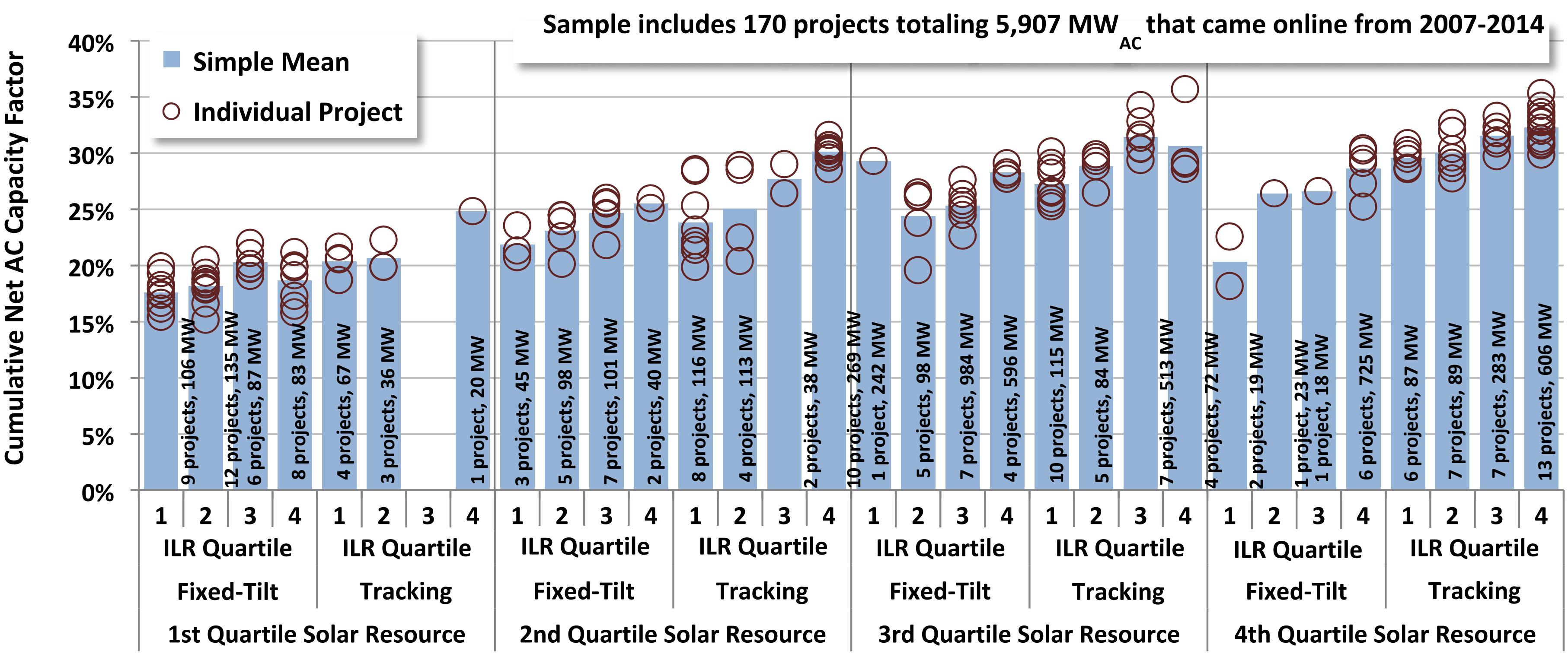
- Installed prices are shown here in both DC and AC terms, but because AC is more relevant to the utility sector, all metrics used in the rest of this slide deck are expressed solely in AC terms
- The lowest 20^{th} percentile fell from $\$2.3/W_{AC}$ ($\$1.8/W_{DC}$) in 2014 to $\$2.2/W_{AC}$ ($\$1.6/W_{DC}$) in 2015
- Capacity-weighted average prices were inflated in 2014 and 2015 by several very large projects that had been under construction for several years (but only entered our sample once complete)
- This sample is backward-looking and may not reflect the price of projects built in 2016/2017

Pricing distributions have shifted towards lower prices over the last 4 years



- Both medians and modes have fallen (shifted to the left) each year
- Share of relatively high-cost (low-cost) projects decreases (increases) each year
- Interquartile price spread is the narrowest in 2015, suggesting a reduction in underlying heterogeneity of prices across all installed projects

25.7% average sample-wide PV net capacity factor, but with large project-level range (from 15.1%-35.7%)

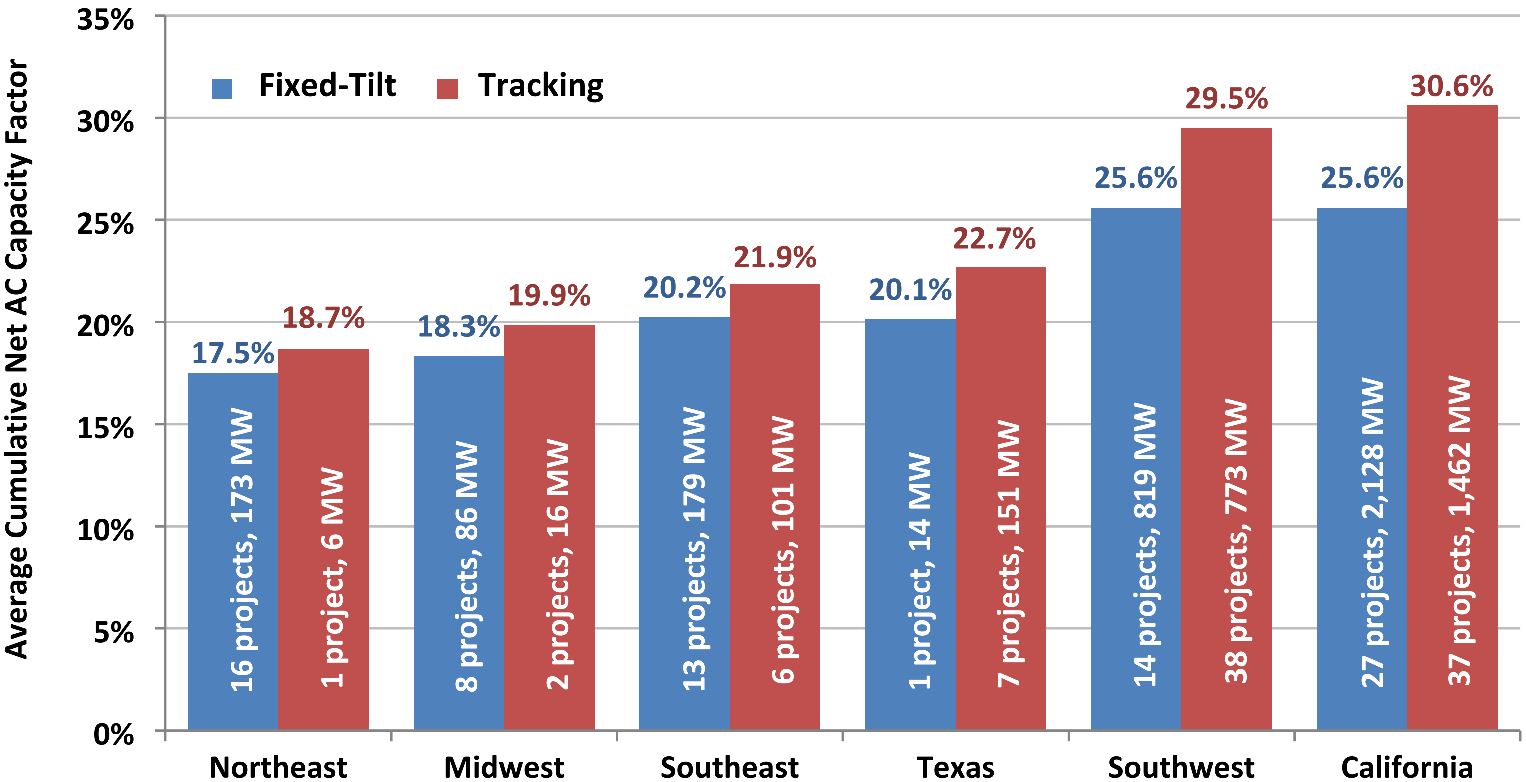


Project-level variation in PV capacity factor driven by:

- **Solar Resource (GHI):** Highest resource quartile has ~8 percentage point higher capacity factor than lowest
- **Tracking:** Adds ~4 percentage points to capacity factor on average across all four resource quartiles
- **Inverter Loading Ratio (ILR):** Highest ILR quartiles have ~4 percentage point higher capacity factor than lowest

Nebraska projects would likely fall in the 2nd or 3rd solar resource quartiles (suggesting an AC capacity factor range of 25-30%, with tracking)

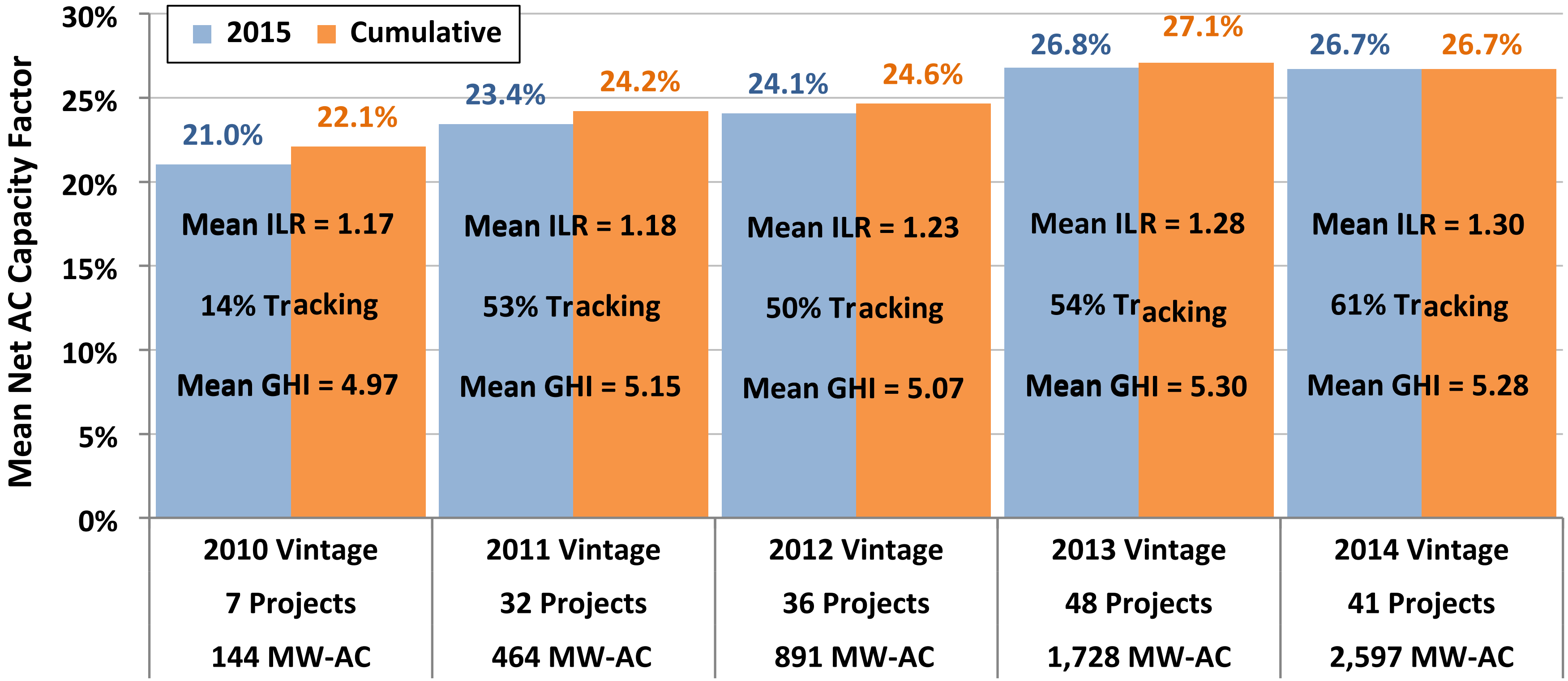
For those who prefer to think geographically rather than in terms of insolation quartiles…



Regions are defined in the map on slide 30

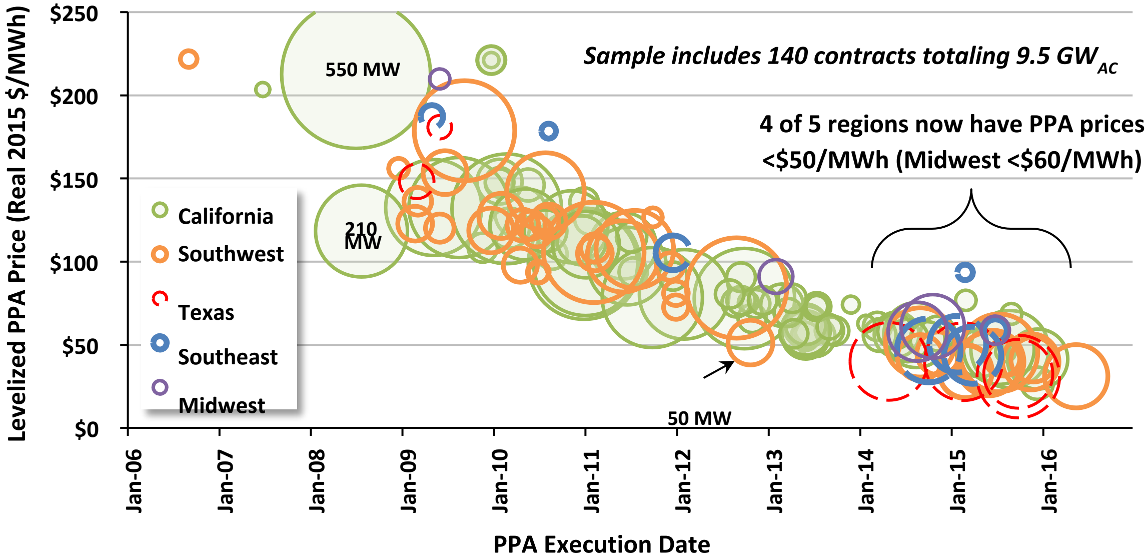
- Not surprisingly, capacity factors are highest in California and the Southwest, and lowest in the Northeast and Midwest (with the Southeast and Texas in between)
- Although sample size is small in some regions, the greater benefit of tracking in the high-insolation regions is evident, as are the greater number of tracking projects in those regions

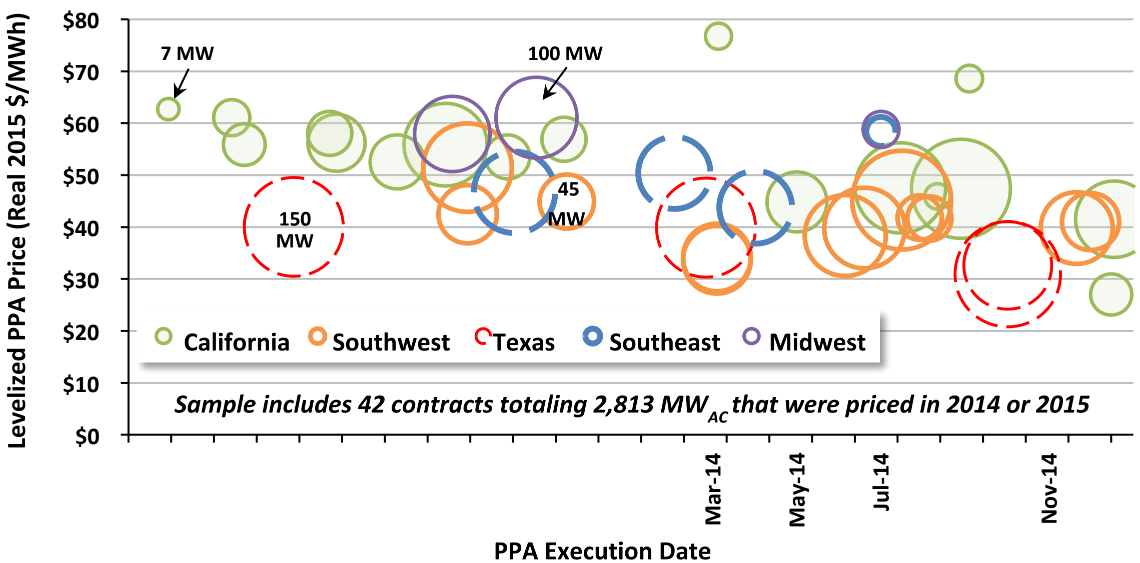
More recent PV project vintages have higher capacity factors on average



- Higher capacity factors by vintage driven by an increase in tracking (most notably in 2011 and 2014), average inverter loading ratio (in every year), and long-term global horizontal irradiance (GHI) at project sites (in 2011 and 2013)
- The fact that single-year 2015 capacity factors (blue columns) show same trend as cumulative capacity factors (orange columns) suggests that inter-year resource variation is not much of a driver

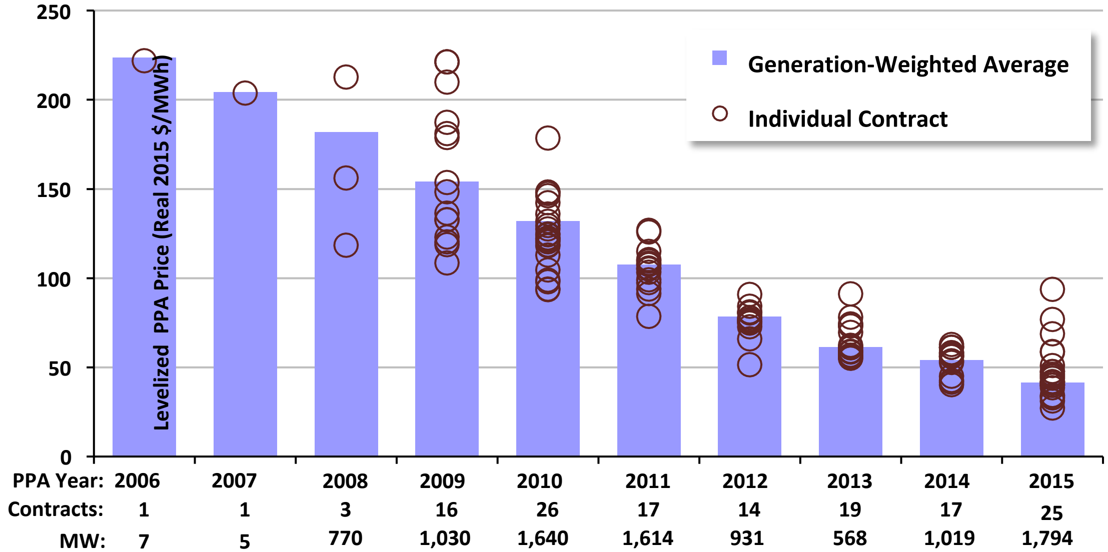
Combination of falling installed prices and better project performance enables lower PPA prices

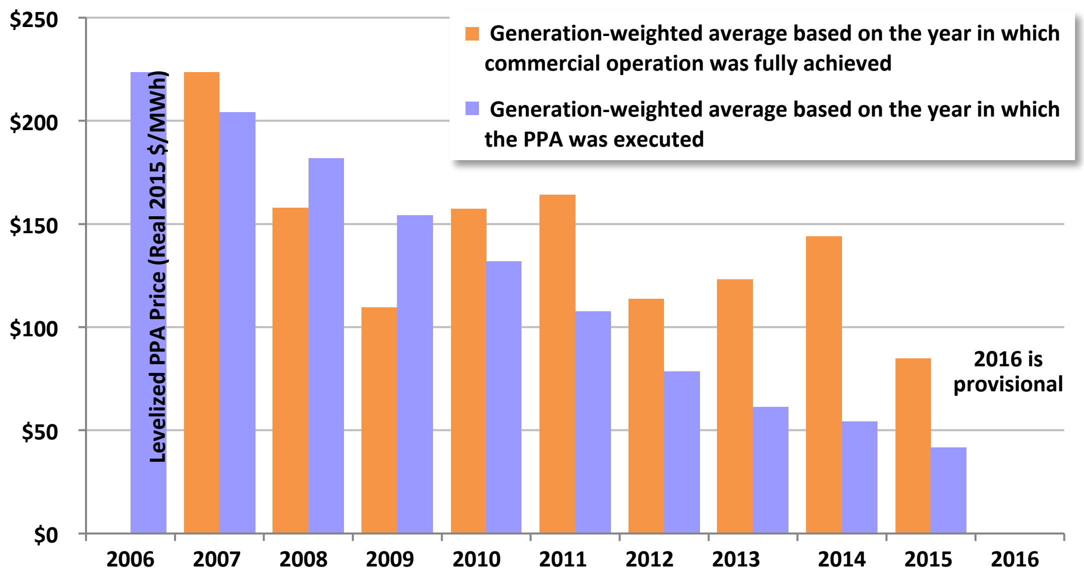




- PPA prices are levelized over the full term of each contract, after accounting for escalation rates and/or time-of-delivery factors, and are shown in real 2015 dollars
- Top graph shows the full sample; bottom graph shows a sub-sample of PPAs signed in 2014 or 2015
- CA and the Southwest dominate the sample, but 2014 and 2015 saw a broadening of the market to TX, AR, AL, FL, GA — ***and even MN and MI, with 3 projects priced around $60/MWh***
- Steady downward price trend since 2006 to **<50$/MWh in 2015**
- Smaller projects (e.g., 20-50 MW)

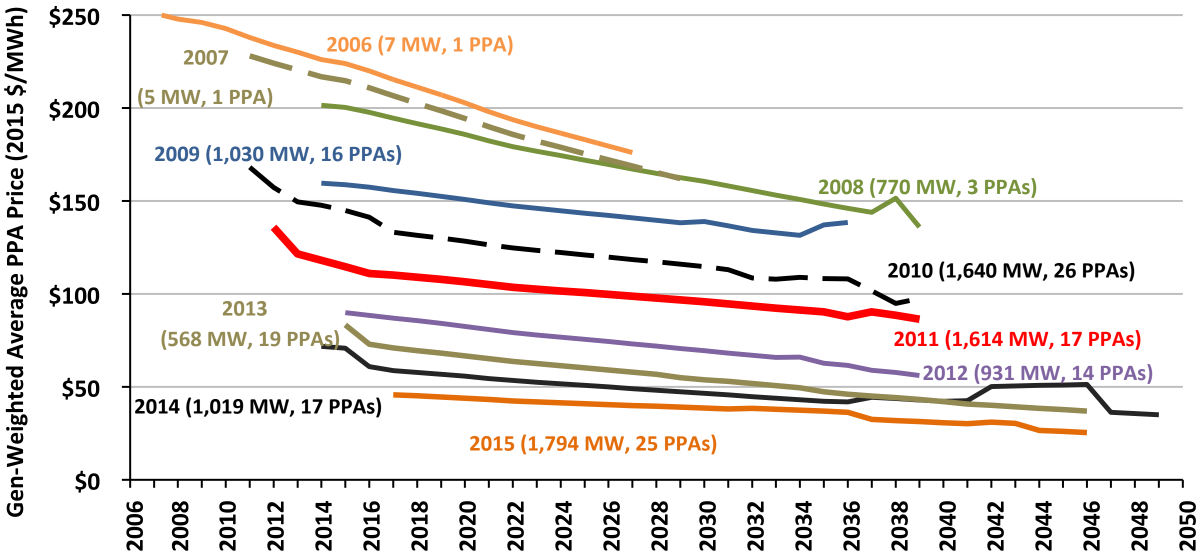
On average, levelized PPA prices have fallen by nearly 75% since 2009

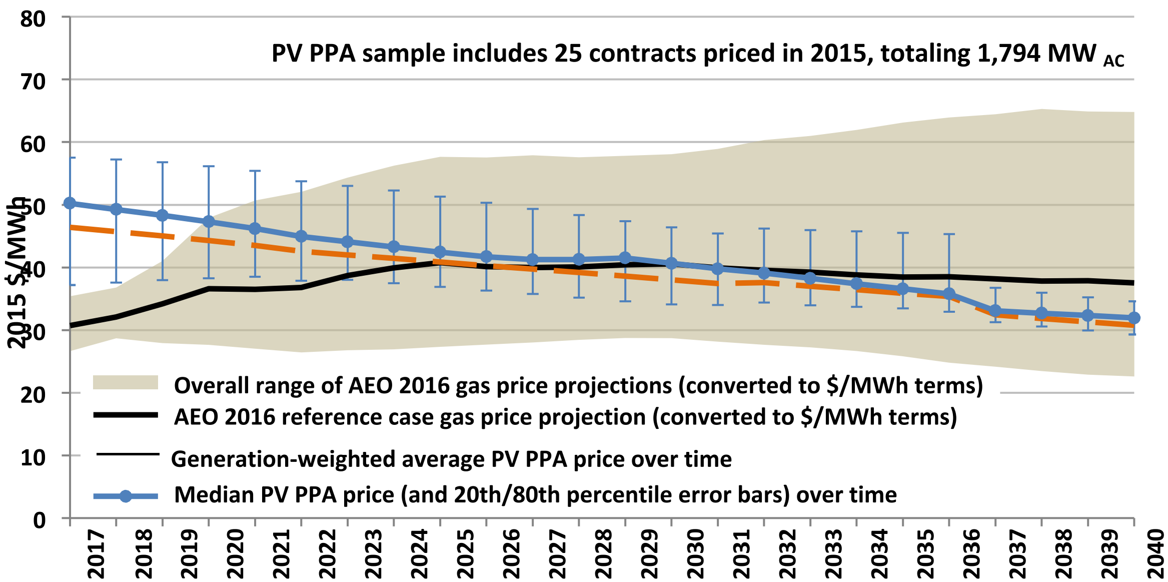




- Top figure presents same data as previous slide, but differently: each circle is an individual contract, and the blue columns show the average levelized PPA price each year
- Remarkably steady downward trend in the average PPA price over time has slowed in recent years as average prices approached and then fell below $50/MWh
- Price decline over time is more erratic when viewed by commercial operation date (orange columns in bottom graph) rather than PPA execution date (blue columns)
- Though the average levelized price of PPAs signed in 2015 is ~$40/MWh, the average levelized PPA price among projects that came online in 2015 is significantly higher, at ~$85/MWh

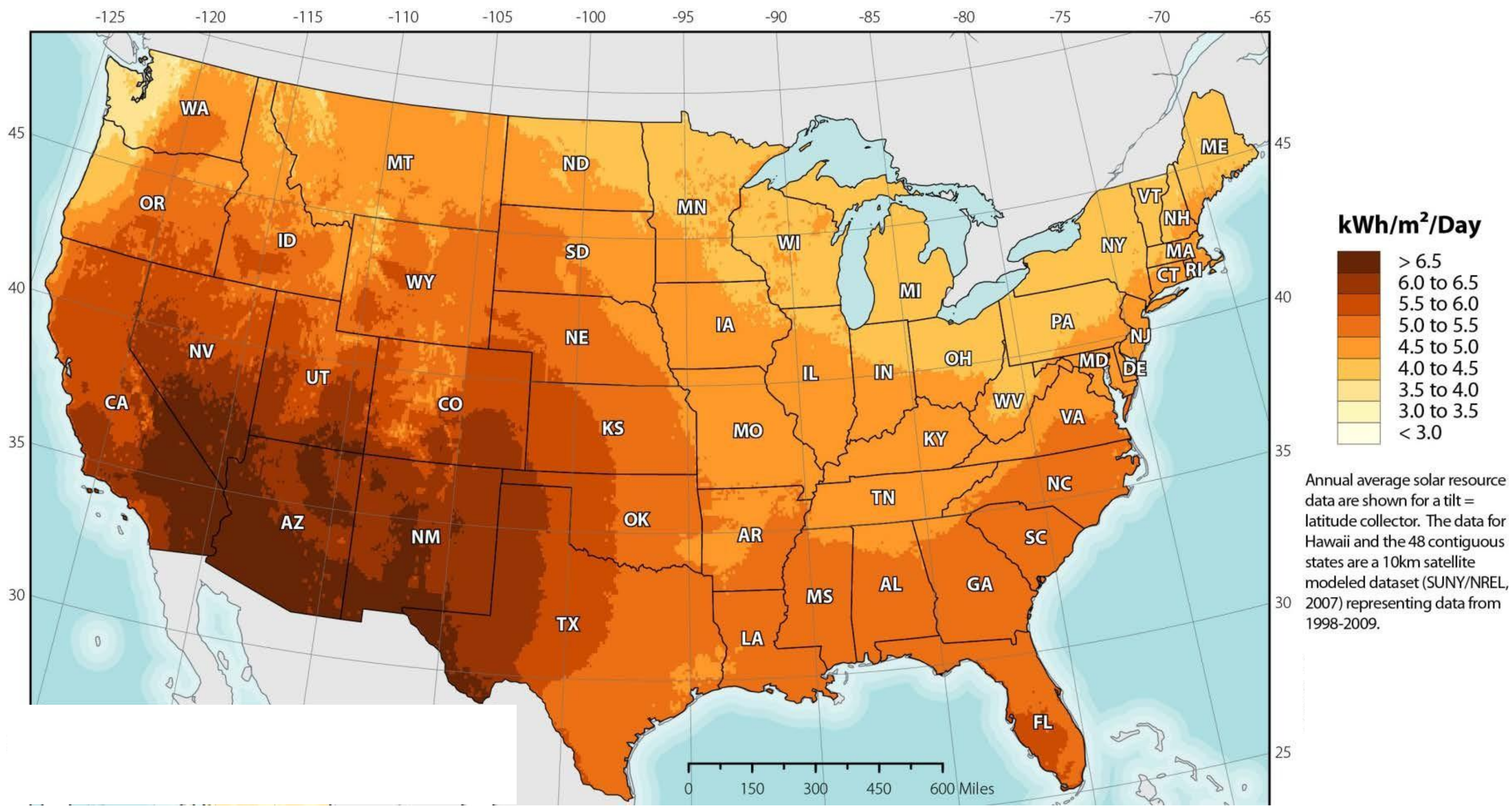
PV PPA prices generally decline over time in real dollar terms, in contrast to fuel cost projections





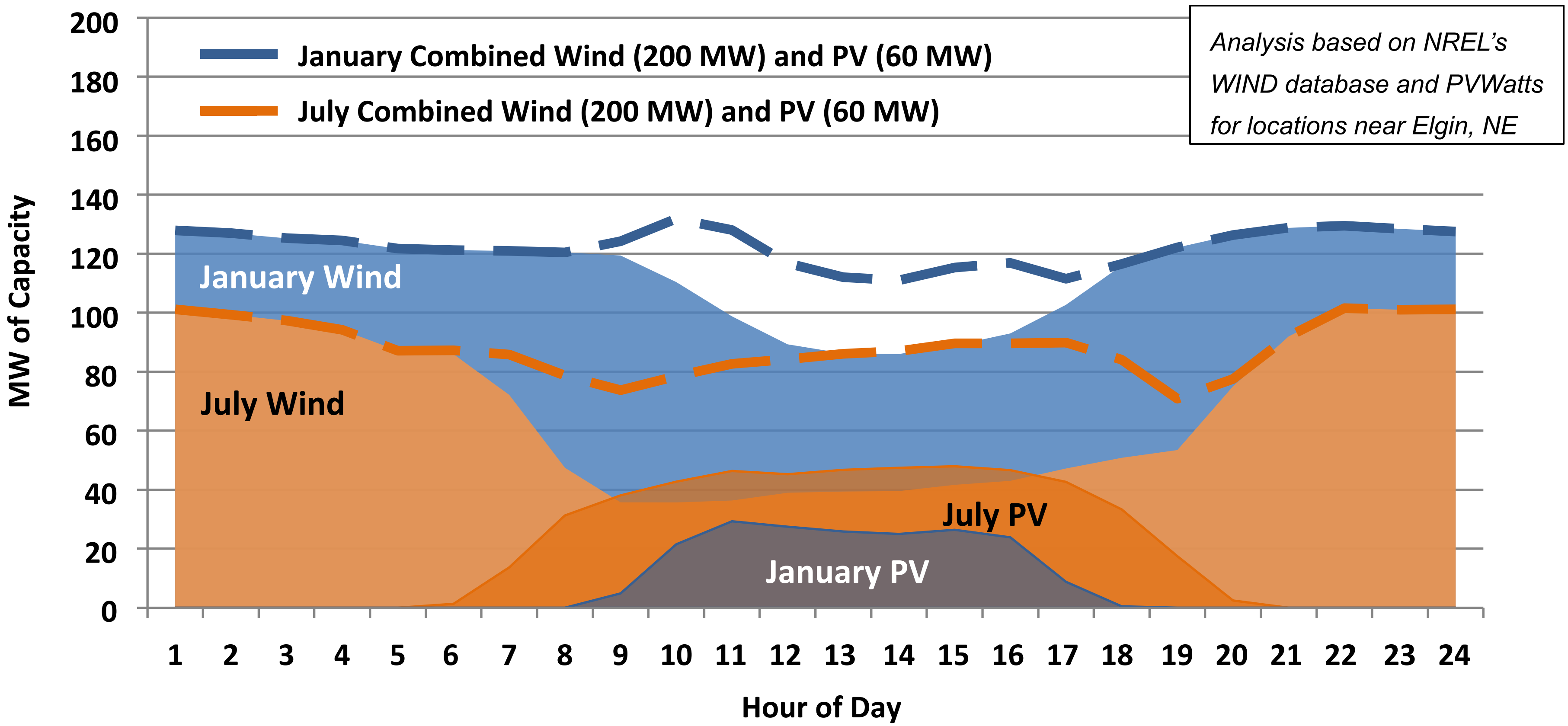
- ~70% of PV sample has flat annual PPA pricing (in nominal dollars), while the rest escalate at low rates
- Thus, average PPA prices ***decline*** over time in real dollar terms (top graph)
- Bottom graph compares 2015-vintage PPA prices to range of gas price projections from *AEO 2016*, showing that…
- …although PV is currently priced higher than the cost of burning fuel in a combined-cycle unit, over longer terms PV is likely to be more competitive, and can help protect against fuel price risk

Though solar isn't the first resource that comes to mind when thinking of Nebraska, the insolation is not bad at all



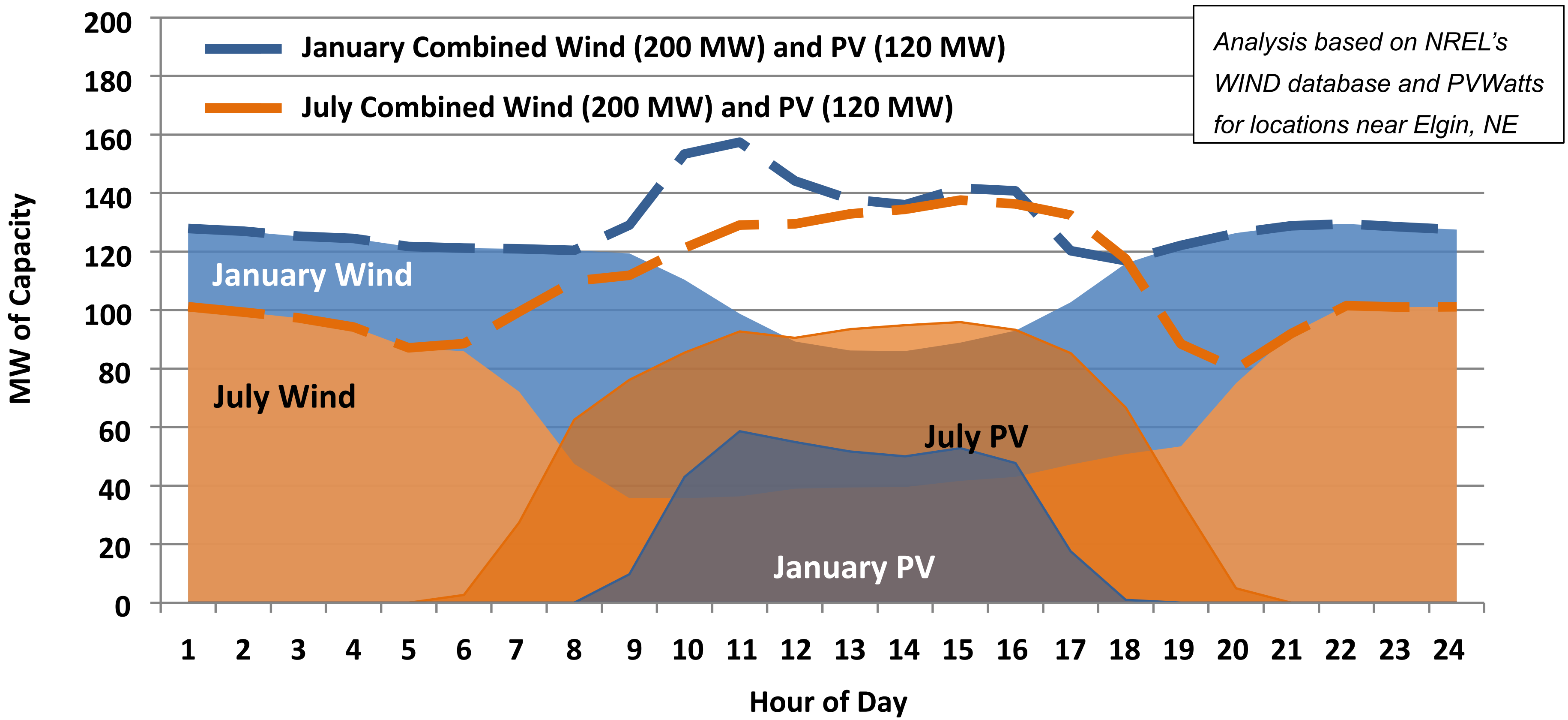
- In fact, Nebraska ranks 5th in utility-scale PV technical potential (behind TX, NM, AZ, and KS — see http://www.nrel.gov/docs/fy15osti/64503.pdf)
- Nebraska has a better solar resource (and latitude) than Minnesota and Michigan, where solar PPA prices of ~$60/MWh (levelized in real 2015 dollars) were signed back in 2014 and 2015

Solar and wind are diurnal and seasonal complements in Nebraska



- Solar is better correlated with wholesale power prices (SPP North Hub), thus providing more wholesale market value than wind — but solar is also more expensive
- Assuming the 200 MW of wind is priced at $22.50/MWh and the 60 MW of PV is priced at $60/MWh, the combination of the two is a blended price of $27.4/MWh
  - Is the flatter combined generation profile worth the incremental ~$5/MWh over wind alone?
  - This incremental premium will decline as the cost of solar continues to fall

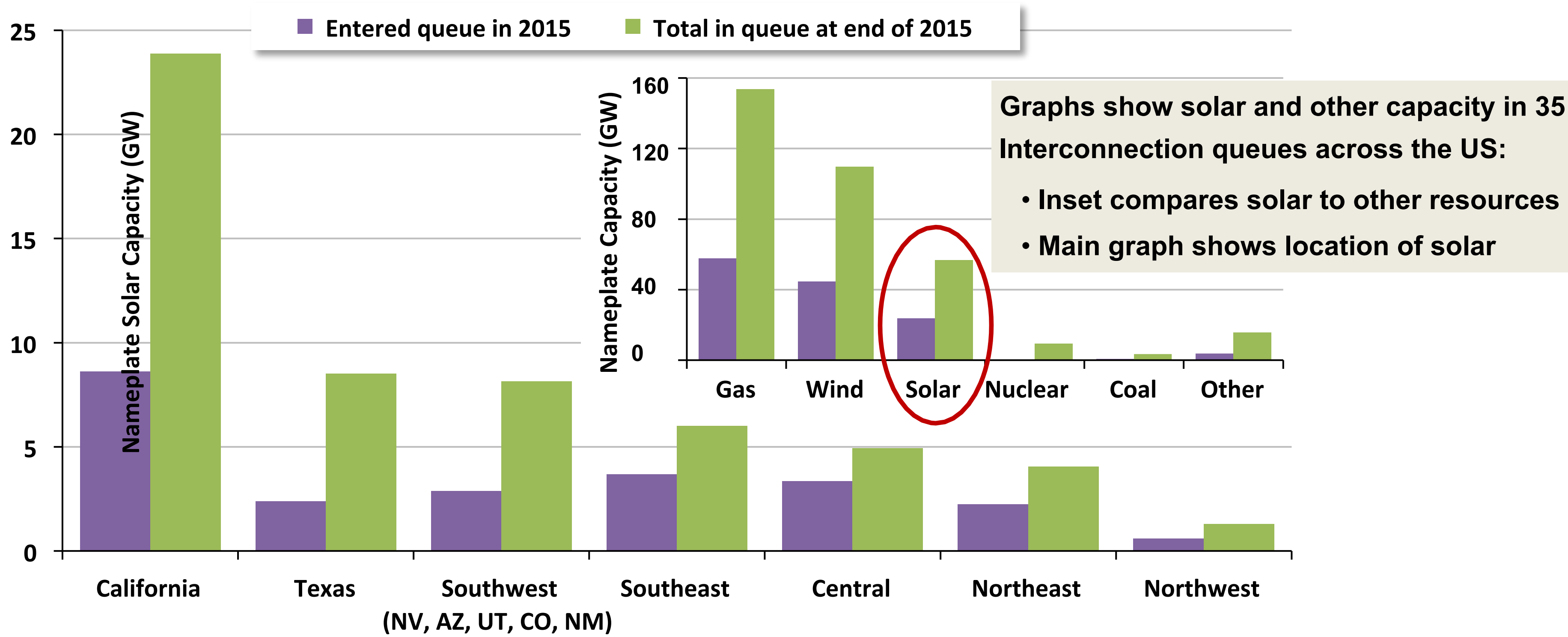
Doubling the capacity of the solar portion likely better matches the daily load profile



Assuming the 200 MW of wind is priced at $22.50/MWh and the 120 MW of PV is priced at $60/MWh, the combination of the two is a blended price of $31.2/MWh

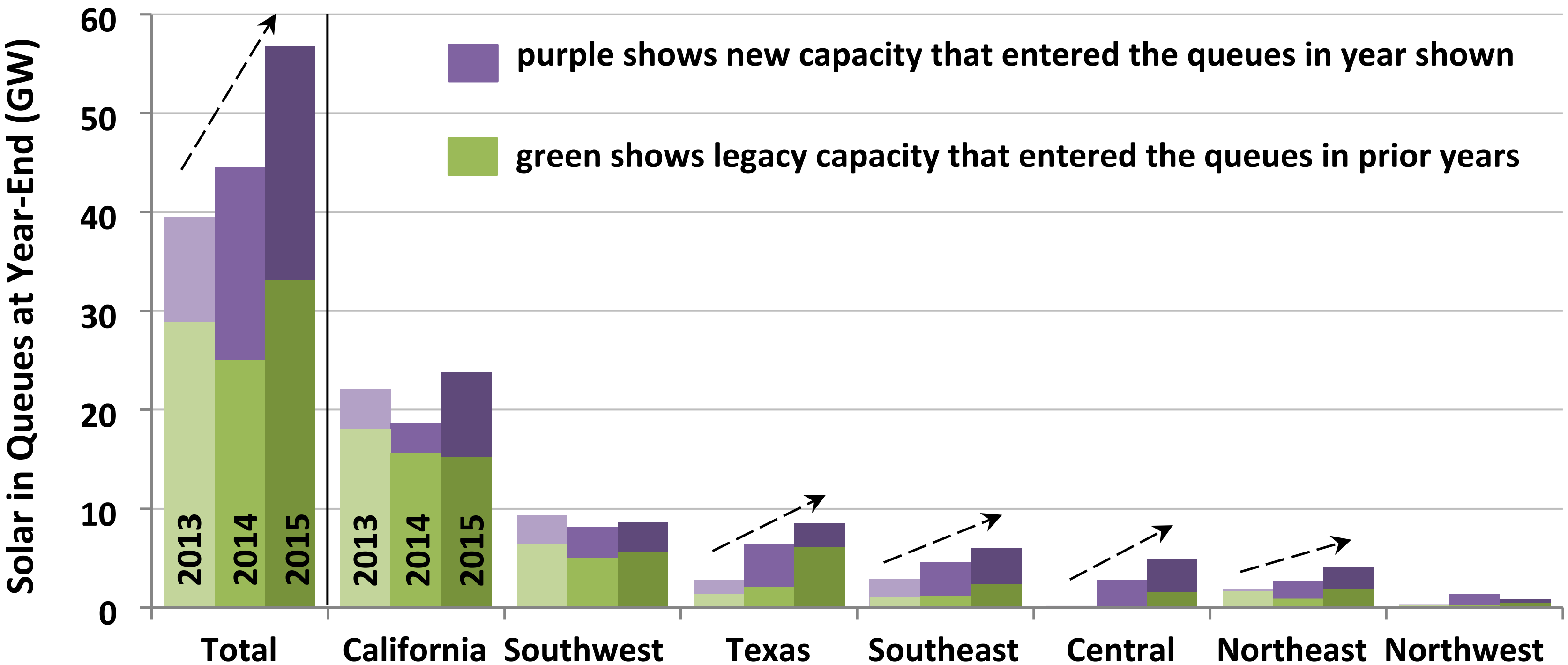
- Is the more-attractive combined generation profile worth the incremental $8.7/MWh over wind alone?
- Alternatively, is the peakier generation profile (which presumably follows load more closely) worth the extra $3/MWh over the flatter generation profile provided by just 60 MW of PV (shown in previous slide)?

Looking ahead: long-term ITC extension should support continued growth in the utility-scale solar pipeline



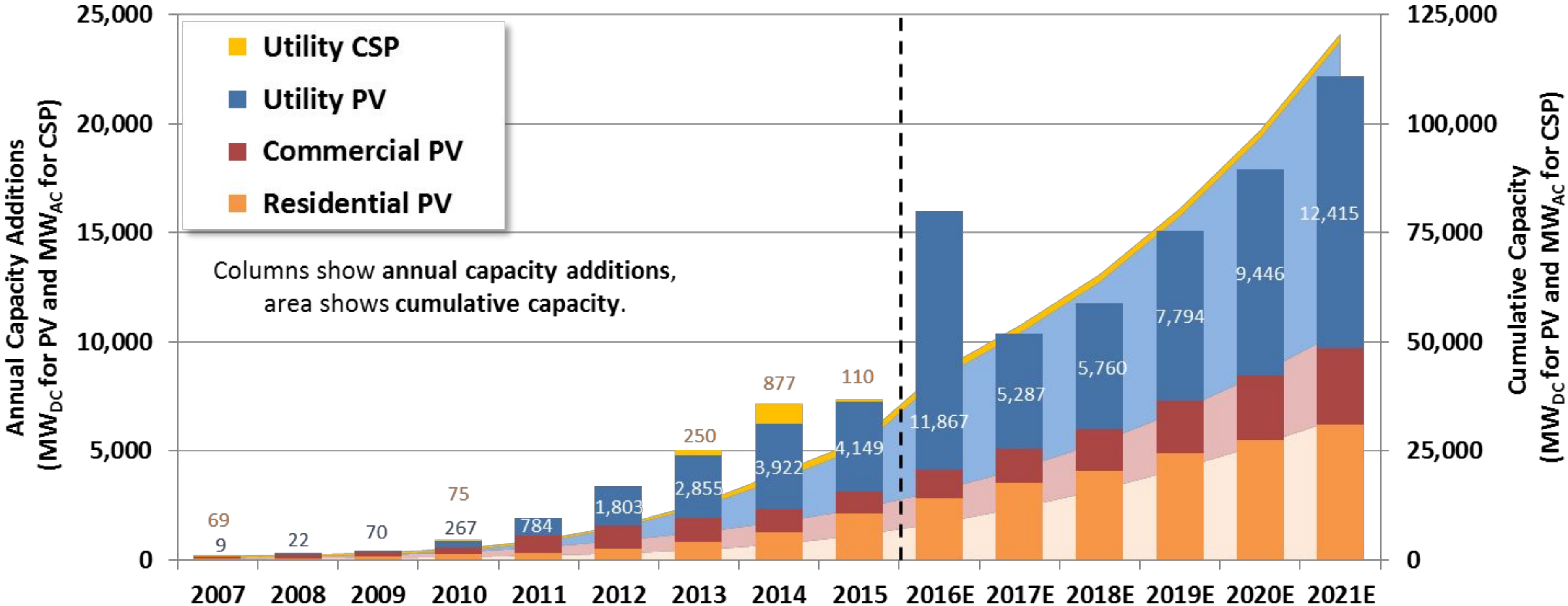
- December 2015's extension of the 30% ITC through 2019 (along with the switch to a "start construction" rather than "placed in service" deadline), with a gradual phase down to 10% thereafter, should ensure continued momentum for the foreseeable future
- 56.8 GW of solar was in the queues at the end of 2015 (up from 44.6 GW at end of 2014): ***more than 5 times** the installed solar capacity in our project population at the end of 2015*
- Solar was in third place in the queues, behind natural gas and wind

Relative growth of solar pipeline in various regions suggests a broadening market



- The utility-scale solar pipeline has been replenished and has even grown in recent years, despite the record buildout in 2014 and 2015
- Although California and (to a lesser extent) the Southwest still dominate the interconnection queues, recent ***growth*** in the queues has come largely from outside of those two traditional markets—e.g., Texas and the Southeast, Central, and Northeastern regions
- ***Not all of these projects will ultimately be built (some will no doubt fall by the wayside)***

GTM/SEIA project nearly 12 GW of new utility-scale PV in 2016 alone, and more than 52 GW new by 2021



Sources: GTM / SEIA Solar Market Insight Reports, LBNL Database

- Utility-scale PV projected to remain the largest segment of the overall US solar market
- Setting aside 2016 (as an anomalous year due to the previously-scheduled ITC expiration), utility-scale PV is projected to overtake wind in terms of new annual capacity as early as 2019

High-Level Conclusions

- Nebraska has a world-class wind resource and a good solar resource
- With the PTC, wind in Nebraska is competitive with the cost of burning natural gas in existing combined cycle units, and so can serve as a cost-competitive "fuel saver" (with a built-in price hedge) — *even if no new energy or capacity resources are needed*
- Though solar is currently 2-3x as costly as wind in Nebraska, that gap will narrow over the next few years as the cost of solar continues to decline
- Wind and solar complement each other well in Nebraska, both daily and seasonally, providing opportunities to evaluate and perhaps combine these two resources on a "portfolio" basis
- Utility-scale solar (>5 MW_{AC}) will soon come to Nebraska!

Thank you!