System-Level Performance and Degradation of 21 GW_{DC} of Utility-Scale PV Plants in the United States

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Presentation overview

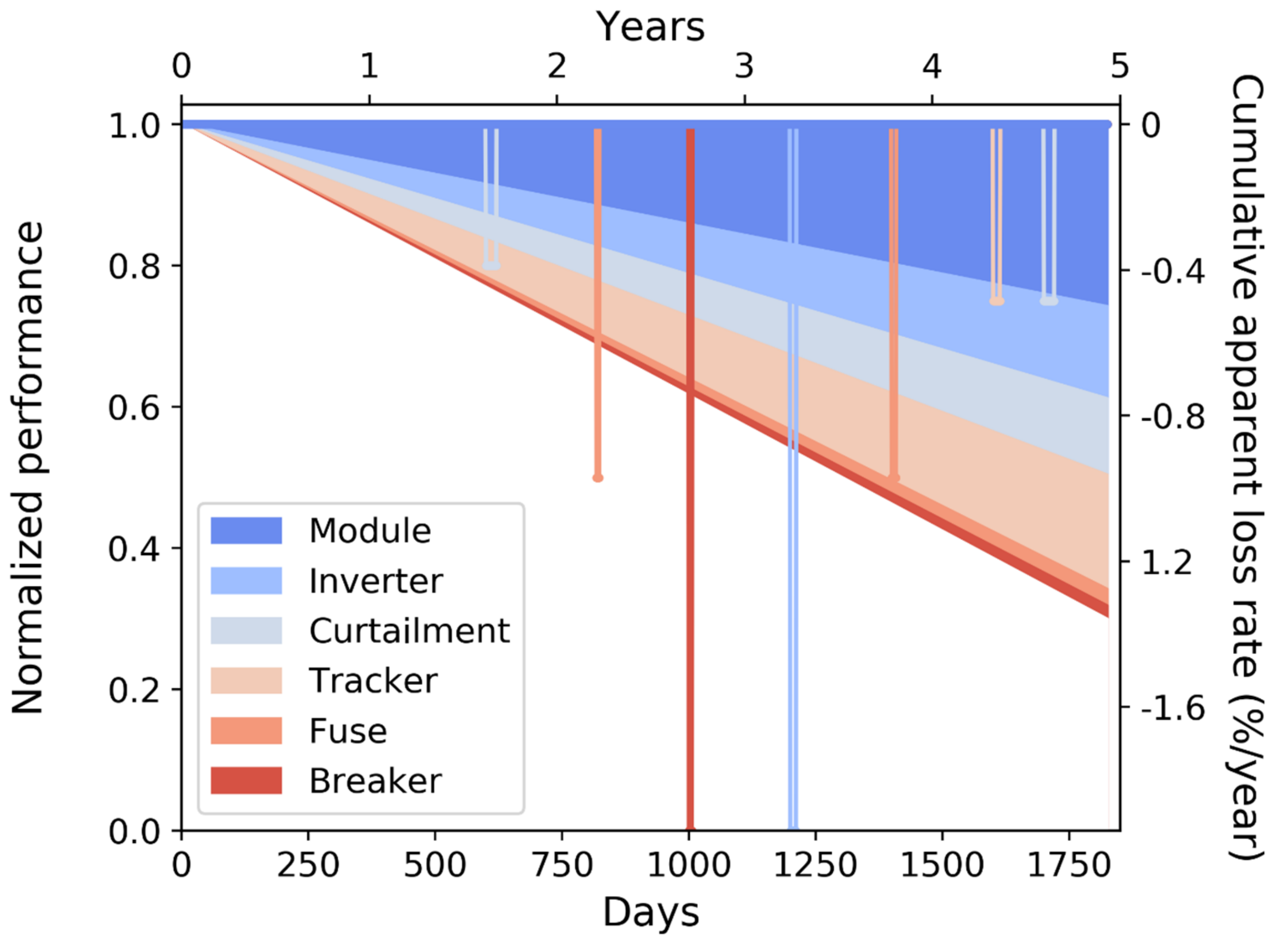
- Introduction
- System-level performance decline vs. module-level degradation
- Data sample
- First-year system-level performance
- Performance decline over time
- Q&A

Introduction—why this matters

- Utility-scale PV is the largest segment of the US solar market, and is growing rapidly
- The utility-scale PV market is relatively young, and lacks a lengthy track record
  - In the United States, the first utility-scale PV plants—defined here as ground-mounted and larger than 5 MW_{AC}—came online in 2007
  - The average plant is just a few years old
- With such a young fleet contributing the bulk of all solar generation, understanding performance is key, particularly given that:
  - The federal investment tax credit has begun to phase down, elevating the importance of good performance
  - The price and duration of power purchase agreements (PPAs) has been declining, elevating the importance of long-term performance and reliability in the post-PPA period
- Much of the performance/reliability literature has focused on module degradation, but total system performance is what impacts the bottom line (see distinction on next slide)

System performance decline versus module degradation

- Graph shows stylized example of how module degradation (dark blue) is just one element of system-level performance loss over time
- Vertical bars show hypothetical loss events related to different BOS components, while the corresponding shaded areas track cumulative loss over time. For example:
  - ➢ Failure of inverters and/or breakers may cut the entire output of the plant for some period, blown fuses may cut output in half, misaligned/stuck trackers and curtailment might each cut 20-30% on occasion
  - ➢ As explained later, we do attempt to control for curtailment within our analysis—*but don't have good visibility into these other causes*



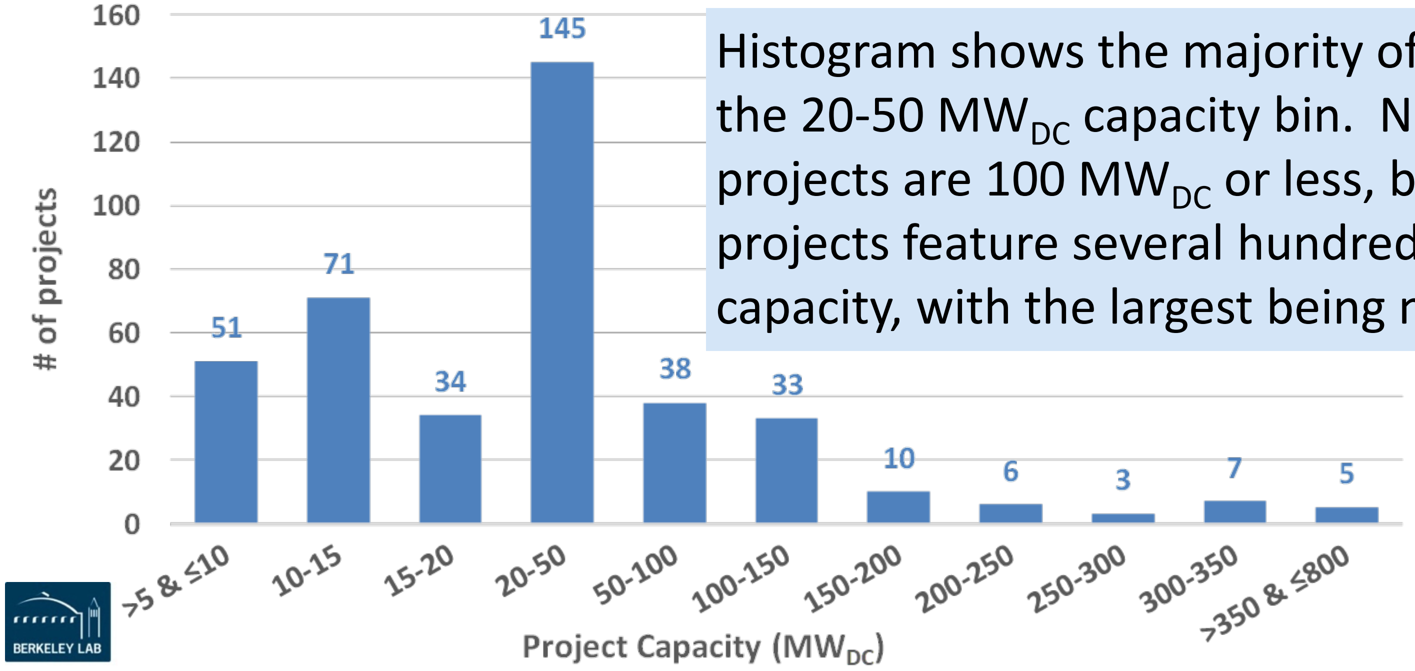
Project sample description (1)

- 411 plants totaling 21.1 GW_{DC} (16.3 GW_{AC}) installed across 28 states from 2007-2016
- Operational history ranges from two (2017-2018) to eleven (2008-2018) full calendar years, with an average of 3.7 years—indicative of the relative youth of the utility-scale PV sector
- In aggregate, these plants contributed >50% of all solar electricity generated in the United States in 2017 (across all sectors—residential, commercial, and utility-scale—and including concentrating solar thermal power)
- They collectively offer 1,536 project-years of operational experience, more than 1/3 of which are in California

State	# of Projects	# of MW_{DC}	# of MW_{AC}	MW_{AC}/Project		# of Project-Years	Years per project			% of US sample		
				Average	Median		Min	Avg	Max	Projects	MW_{AC}	Project-Years
CA	150	10,133	7,958	53	20	539	2	3.6	9	36%	49%	35%
AZ	32	1,915	1,431	45	19	151	2	4.7	7	8%	9%	10%
NM	25	579	462	18	10	118	2	4.7	8	6%	3%	8%
NJ	28	297	243	9	8	113	2	4.0	7	7%	1%	7%
NC	31	1,174	883	28	20	94	2	3.0	6	8%	5%	6%
NV	17	1,841	1,383	81	48	79	2	4.6	11	4%	8%	5%
TX	14	716	569	41	22	64	2	4.6	8	3%	3%	4%
GA	23	1,240	953	41	30	61	2	2.7	5	6%	6%	4%
CO	12	420	338	28	16	50	2	4.2	11	3%	2%	3%
FL	8	436	283	35	19	41	2	5.1	9	2%	2%	3%
IN	11	116	87	8	9	40	2	3.6	5	3%	1%	3%
MD	7	109	84	12	13	27	2	3.9	6	2%	1%	2%
UT	12	1,049	810	68	80	26	2	2.2	3	3%	5%	2%
MN	9	299	208	23	7	18	2	2.0	2	2%	1%	1%
IL	2	33	28	14	14	15	6	7.5	9	0%	0%	1%
OH	2	22	18	9	9	15	7	7.5	8	0%	0%	1%
OR	7	83	63	9	10	14	2	2.0	2	2%	0%	1%
TN	3	50	39	13	16	14	4	4.7	6	1%	0%	1%
DE	2	26	22	11	11	13	6	6.5	7	0%	0%	1%
MA	3	44	33	11	12	8	2	2.7	4	1%	0%	1%
VA	4	180	136	34	20	8	2	2.0	2	1%	1%	1%
NY	1	38	32	32	32	7	7	7.0	7	0%	0%	0%
PA	1	11	10	10	10	6	6	6.0	6	0%	0%	0%
SC	2	24	17	8	8	4	2	2.0	2	0%	0%	0%
ID	2	163	120	60	60	4	2	2.0	2	0%	1%	0%
AR	1	17	13	13	13	3	3	3.0	3	0%	0%	0%
AL	1	100	75	75	75	2	2	2.0	2	0%	0%	0%
KY	1	14	10	10	10	2	2	2.0	2	0%	0%	0%
Total	**411**	**21,130**	**16,308**	**40**	**20**	**1,536**	**2**	**3.73**	**11**	**100%**	**100%**	**100%**

Project sample description (2)

COD Year:	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Total
# of Projects:	2	1	3	7	31	36	49	50	83	149	411
# of MW_{DC}:	22	12	63	172	532	1,133	2,249	3,564	3,596	9,785	21,130
# of MW_{AC}:	19	10	54	144	448	886	1,761	2,726	2,764	7,496	16,308
Average DC:AC Ratio:	1.18	1.21	1.16	1.19	1.19	1.28	1.28	1.31	1.30	1.31	1.30
Average MW_{AC}/Project:	9	10	18	21	14	25	36	55	33	50	40
% projects with tracking:	100%	0%	67%	14%	52%	50%	57%	62%	66%	74%	64%
% projects with Si modules:	100%	0%	67%	29%	74%	83%	82%	74%	76%	88%	80%



Histogram shows the majority of projects fall into the 20-50 MW_{DC} capacity bin. Nearly 85% of projects are 100 MW_{DC} or less, but a number of projects feature several hundred MW_{DC} of capacity, with the largest being nearly 760 MW_{DC}

- Table shows progressively larger sample of projects and capacity added each year since 2008
- Also increasing prevalence of tracking, as well as a higher DC:AC ratio
- Roughly 80% of projects use Si modules

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Data collected for each project

- **Key plant characteristics:** Module type (Si vs. thin-film), module manufacturer, mount type (fixed-tilt vs. tracking), tilt (for fixed-tilt mounts), azimuth, latitude and longitude, commercial operation date, capacity (MW_{DC} and MW_{AC}), and DC:AC ratio
  - These "metadata" are sourced from LBNL's "Utility-Scale Solar" report series (utilityscalesolar.lbl.gov)
- **Net generation data over time:** Compiled from a variety of sources, including Form EIA-923, FERC Form 1, FERC Electric Quarterly Reports, the California Energy Commission
- **Irradiance data over time:** 2008-2018 data for each site come from the National Solar Radiation Database (NSRDB)
- **Hourly curtailment data over time:** Sourced from the California Independent System Operator (CAISO) and the Electric Reliability Council of Texas (ERCOT), and used to gross up the actual capacity factors of plants that have been curtailed in California and Texas

We use these data to calculate *actual* and *ideal* "capacity factors" for each plant:

$$Capacity\ Factor_y = \frac{MWh\ generated\ in\ calendar\ year\ y}{(MW_{DC}\ of\ capacity\ in\ calendar\ year\ y\ *\ number\ of\ hours\ in\ calendar\ year\ y)}$$

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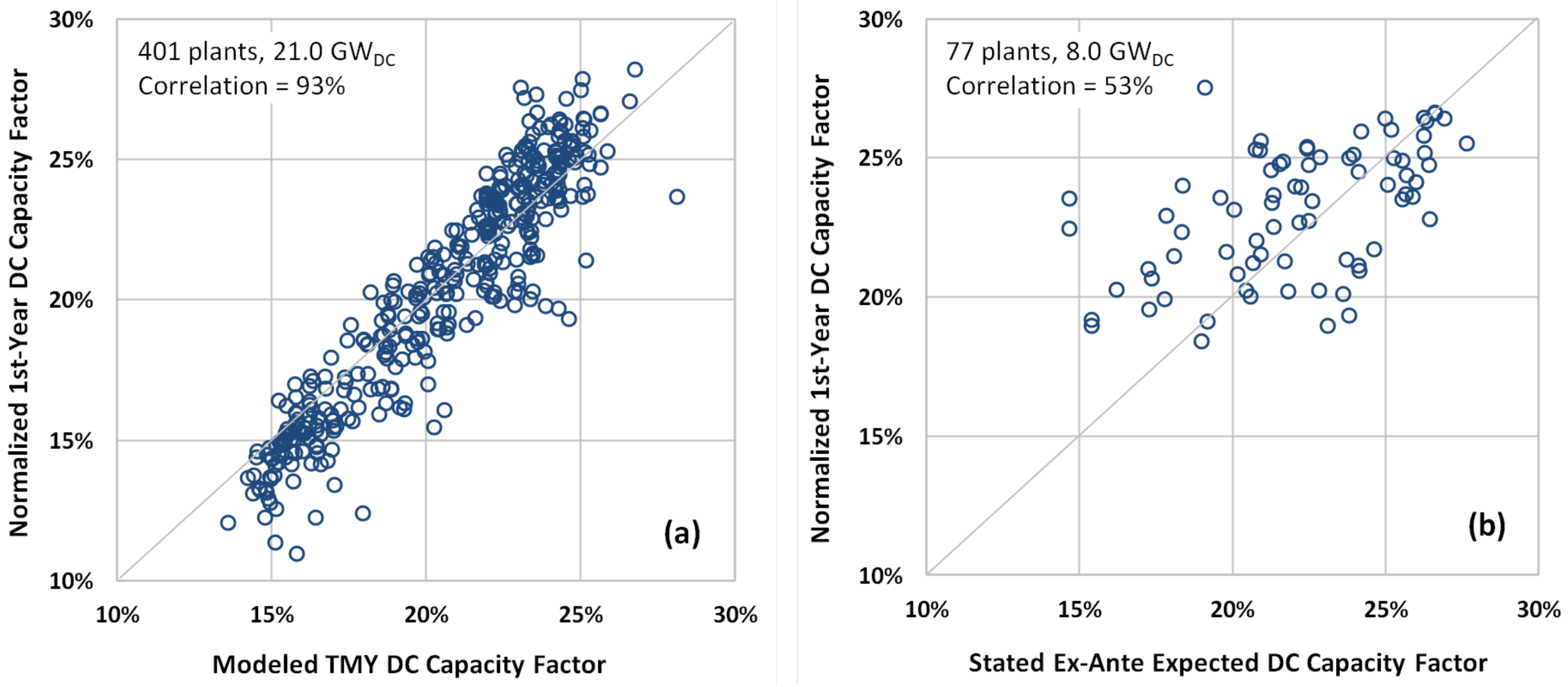
First-year system-level performance generally matches expectations



- **(a)** Actual first-year capacity factors **underperform** the TMY-based simulations by 0.6% (median), 1.2% (simple mean), or 1.3% (capacity-weighted average)
- 89% of projects generated more than 90% of their simulated TMY estimate in their first full calendar year

- **(b)** Actual first-year capacity factors **outperform** the stated expectations by 3.4% (median), 5.8% (capacity-weighted average), or 6.3% (simple mean)
- 88% of projects generated more than 90% of their stated expectations in their first full calendar year

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Measuring performance decline with age using a "fixed effects" regression model—defining terms

Actual capacity factor of plant f at time t (raw empirical data, but grossed up for curtailment in CAISO and ERCOT)

Site-level "fixed effects" of plant f:
Dummy variable to control for differences in capacity factor ***across plants*** that are not already captured via the "ideal" capacity factor

Residual of plant f at time t

$$CF_{f,t}^{actual} = CF_{f,t}^{ideal} + S_f + A_T + \epsilon_{f,t} \qquad \textbf{Eq. 1}$$

"Ideal" capacity factor of plant f at time t:
estimated based on physical plant characteristics and solar resource at the site

Age "fixed effects" at time t:
Dummy variable to control for differences in capacity factor ***within plants,*** over time, that are not already captured via the "ideal" capacity factor (i.e., this variable isolates the impact of plant age on capacity factor)

Measuring performance decline with age using a "fixed effects" regression model—equation transformations

$$\boldsymbol{CF_{f,t}}^{\boldsymbol{actual}} = \boldsymbol{CF_{f,t}}^{\boldsymbol{ideal}} + \boldsymbol{S_f} + \boldsymbol{A_T} + \boldsymbol{\epsilon_{f,t}} \qquad \textbf{Eq. 1}$$

Equation 1 is known as a "fixed effects" regression because it holds constant or "fixes" the average "effects" of each variable. We can illustrate this through the following two transformations of Equation 1.

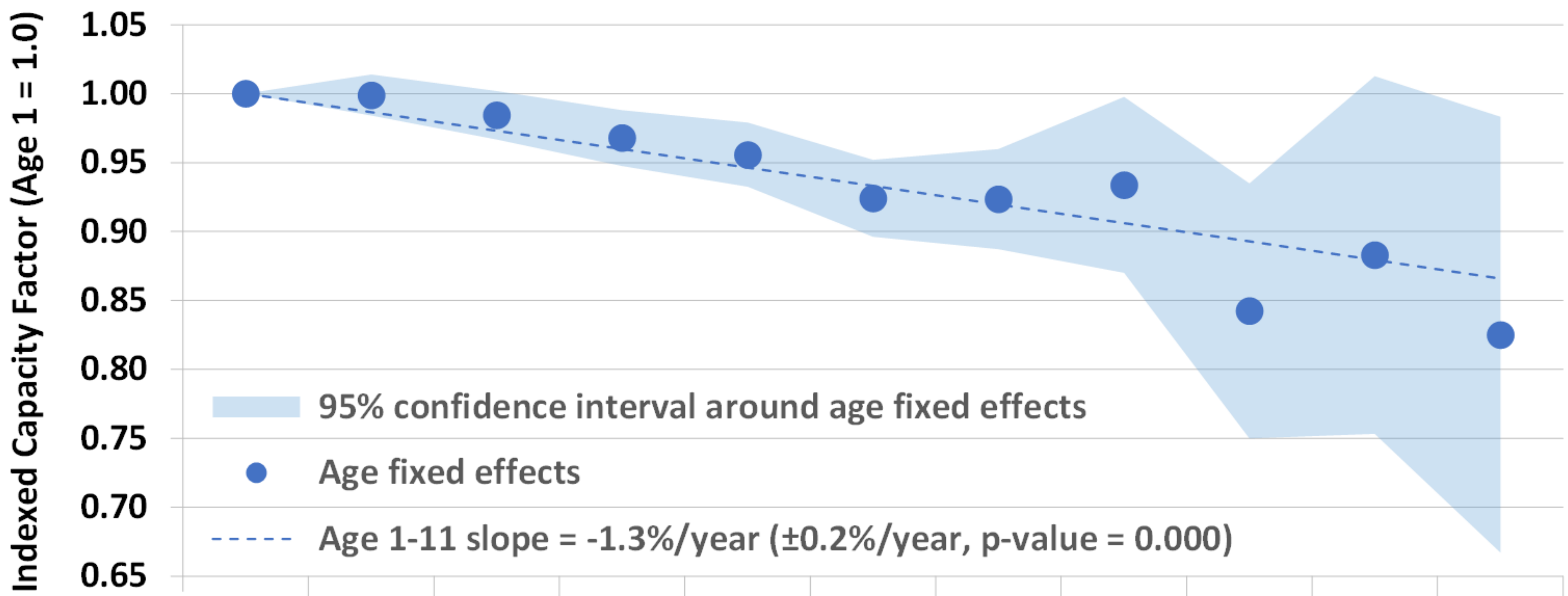
$$\overline{\boldsymbol{CF_f}^{\boldsymbol{actual}}} = \overline{\boldsymbol{CF_f}^{\boldsymbol{ideal}}} + \boldsymbol{S_f} + \overline{\boldsymbol{A}} + \overline{\boldsymbol{\epsilon_f}} \qquad \textbf{Eq. 2}$$

Equation 2 calculates the average over time for each variable in Equation 1. Because S_f does not vary over time in Equation 1, the average of S_f over time in Equation 2 is simply equal to S_f.

$$\boldsymbol{CF_{f,t}}^{\boldsymbol{actual}} - \overline{\boldsymbol{CF_f}^{\boldsymbol{actual}}} = \left(\boldsymbol{CF_{f,t}}^{\boldsymbol{ideal}} - \overline{\boldsymbol{CF_f}^{\boldsymbol{ideal}}}\right) + \left(\boldsymbol{S_f} - \boldsymbol{S_f}\right) + \left(\boldsymbol{A_t} - \overline{\boldsymbol{A}}\right) + \left(\boldsymbol{\epsilon_{f,t}} - \overline{\boldsymbol{\epsilon_f}}\right) \qquad \textbf{Eq. 3}$$

Equation 3 subtracts Equation 2 from Equation 1. The site-specific fixed effects (S_f) cancel, dropping out of the regression and leaving only those explanatory variables that vary with time. In other words, by subtracting the means, we eliminate all unobservable "across-plant" variation—a key source of omitted variable bias—and limit all variation to "within-plant" variation (i.e., which tells us how performance changes over time with age).

Performance decline with age—results of fixed effects model

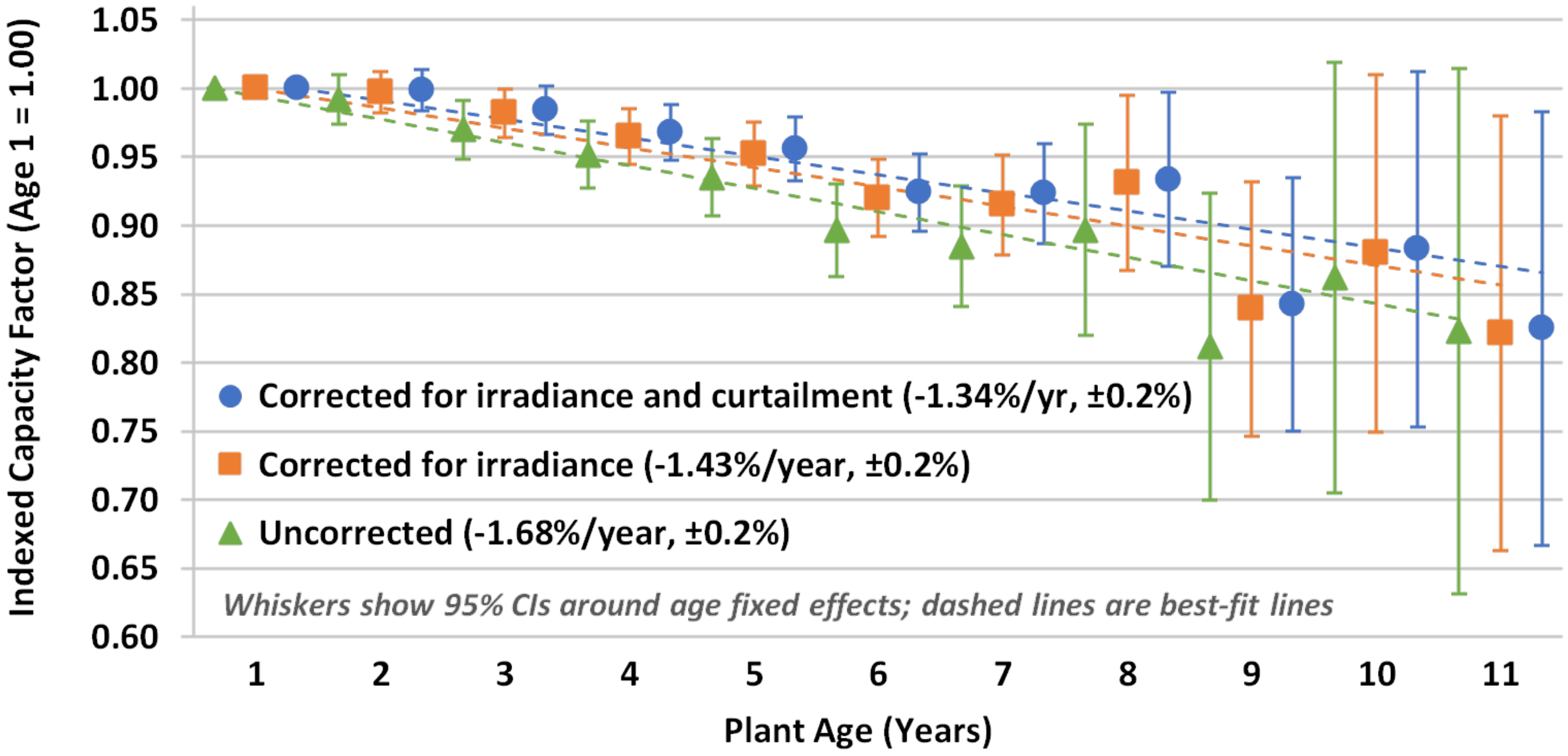


Age:	1	2	3	4	5	6	7	8	9	10	11
Projects:	399	399	258	177	125	80	44	13	6	3	2
MW_{DC}:	21,050	21,050	11,286	7,731	4,136	1,935	801	269	97	34	22

The slope (-1.3%/year) is weighted by the number of projects at each age, so ages 8-11 (which have wide 95% confidence intervals) do not receive much weight

The slope is almost identical if only looking at ages 1-7 (i.e., later ages do not have much impact)

Impact of correcting for variation in irradiance and curtailment



Removing CF^{ideal} from the equation and not grossing up CF^{actual} for curtailment yields a slope of -1.7%/year (green, uncorrected)

Adding back CF^{ideal} reduces the decline in performance to -1.4%/year (orange)

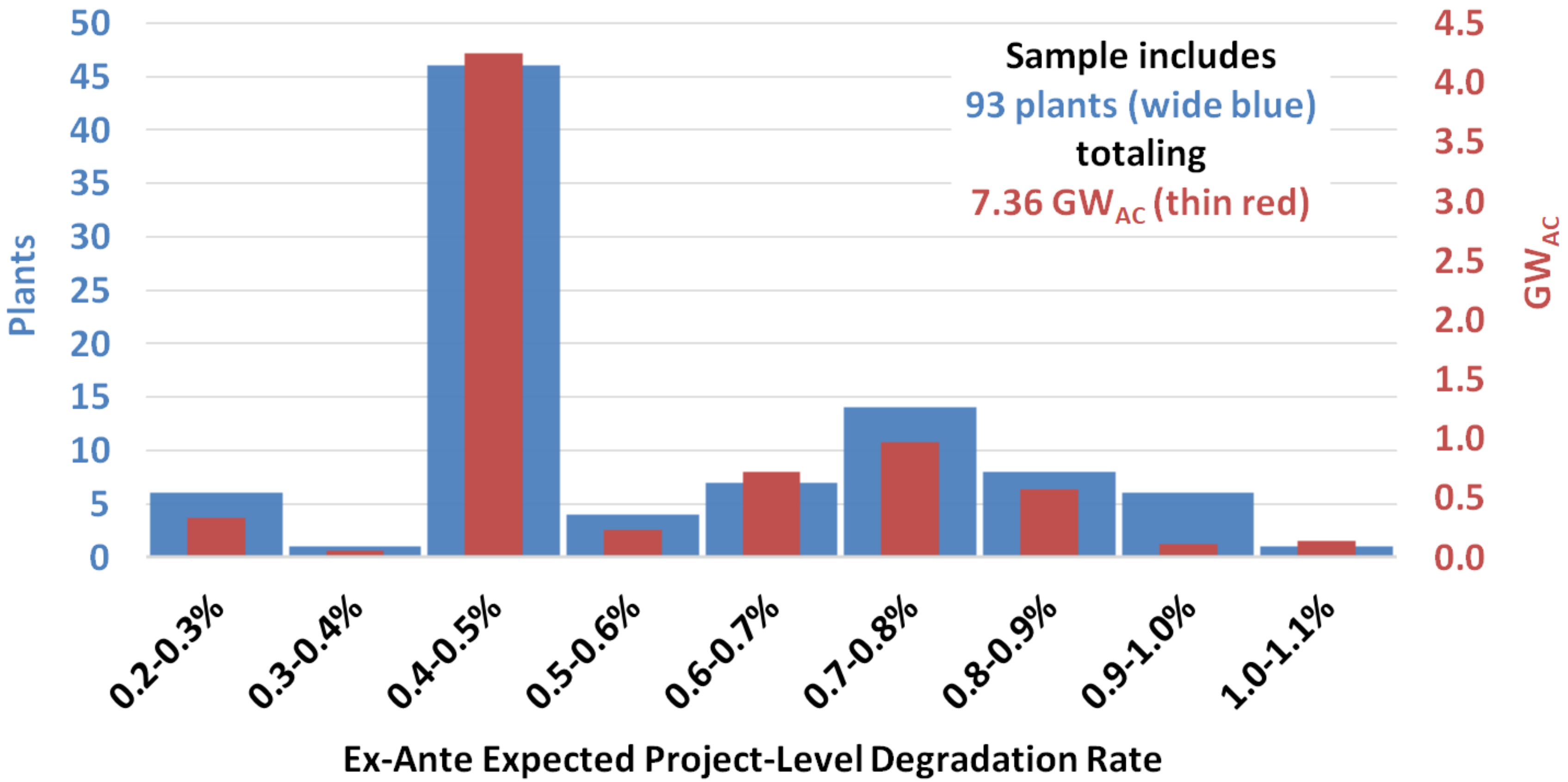
Grossing up CF^{actual} for curtailment (in CAISO and ERCOT) improves it even further, to -1.3%/year (blue)

Rate of performance decline varies based on a number of statistically significant factors

- **Project vintage:** Post-2012 projects (-0.9%/year, ±0.3%) have declined less than pre-2013 projects (-1.5%/year, ±0.2%)
- **Project size:** Projects of 25 MW_{AC} or larger (-0.8%/year, ±0.3%) have declined less than projects less than 25 MW_{AC} (-1.5%/year, ±0.2%)
- **Site climate:** Projects with an average site temperature of less than 15 degrees Celsius (-0.9%/year, ±0.4%) have declined less than projects at warmer sites (-1.4%/year, ±0.2%)
- **Solar resource:** Projects at sites with an average long-term global horizontal irradiance of less than 210 W/m^2 (-0.8%/year, ±0.3%) have declined less than projects at sunnier sites (-1.4%/year, ±0.2%)
- **Project design:** Projects with a DC:AC ratio of 1.25 or greater (-1.2%/year, ±0.2%) degrade less than projects with lower ratios (-1.4%/year, ±0.2%)

A separate multivariate regression confirms some, but not all, of these fixed effects findings

Many power purchase agreements (PPAs) seem to be underestimating performance decline with age



- We reviewed 93 utility-scale PV PPAs totaling 7.4 GW$_{AC}$
- Roughly two-thirds expect performance to decline by 0.5%/year or less (see figure)
- Possibly confusing system-level performance decline with module degradation?
- Impact: A project expecting to earn a 10% internal rate of return (IRR) assuming 0.5%/yr performance decline will earn only half as much if actual decline is 1%/yr

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For more information

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