System-Level Performance Decline with Age of 26 GW_{DC} of Utility-Scale PV Plants in the United States

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(https://emp.lbl.gov/publications/system-level-performance-and)

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Presentation overview

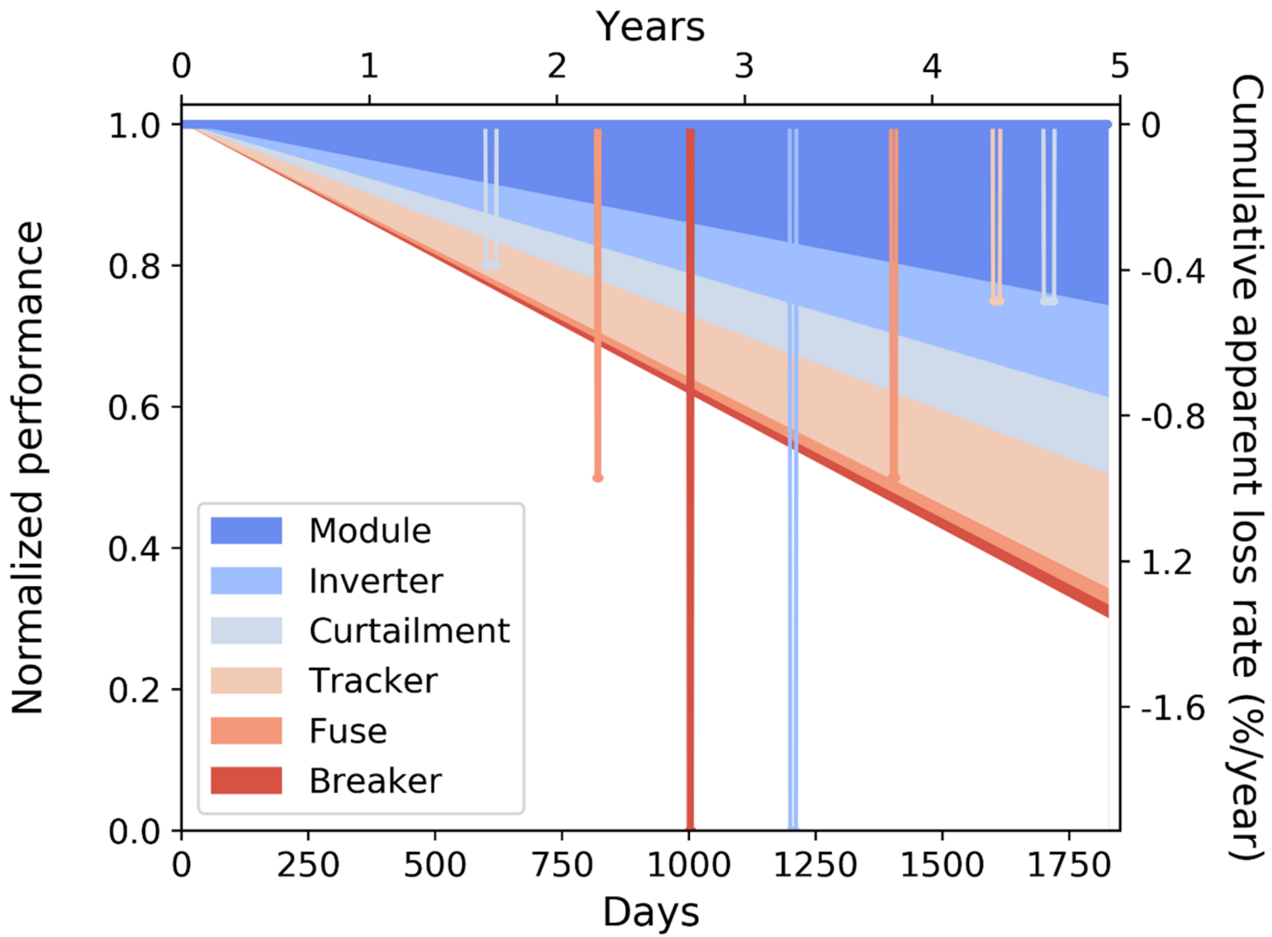
- Introduction—why this matters
- System-level performance decline vs. module-level degradation
- Data sample and description
- Overview of analysis approach—the fixed effects model
- Updated performance decline over time (and comparison to prior results)
- Potential drivers of performance decline with age

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
  - ***This September 2020 update adds another year of sample (2017 projects) and performance period (2019)***
- 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*



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Project sample description (1)

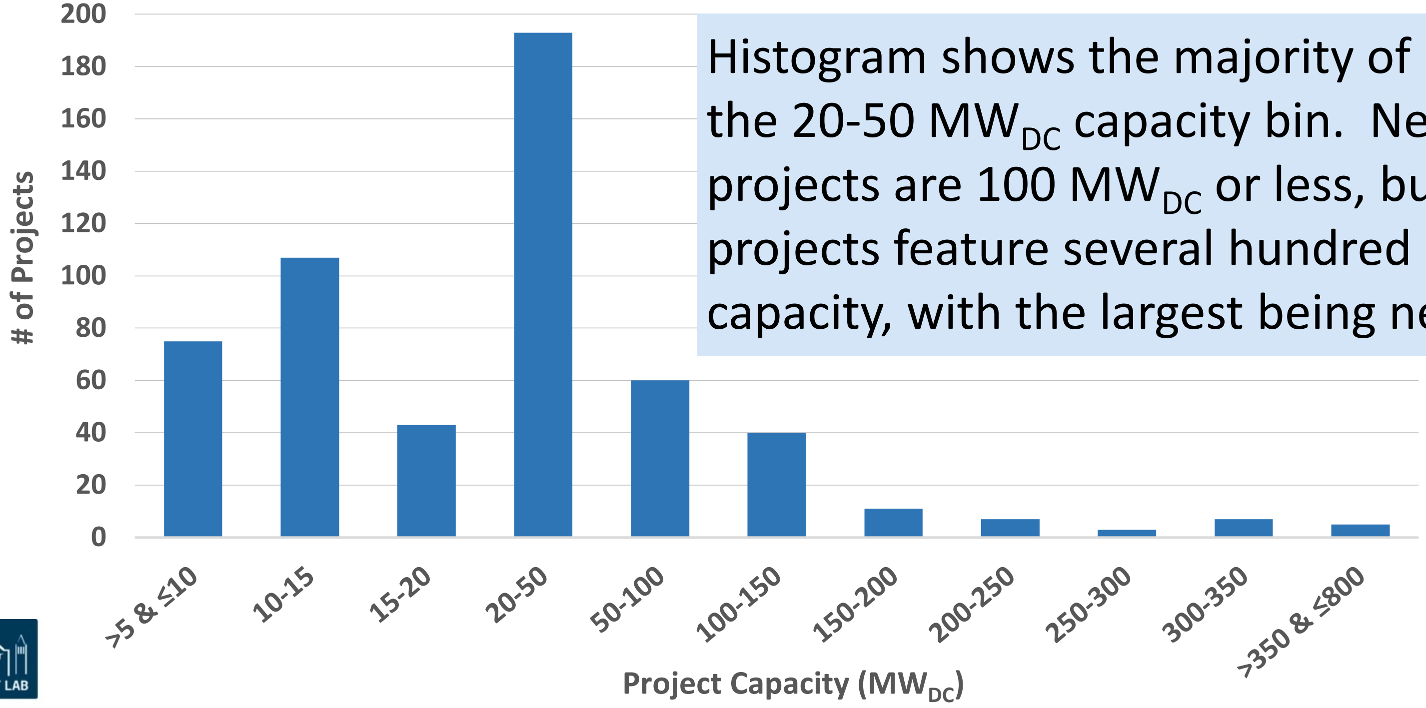
- 551 plants totaling 26 GW_{DC} (20 GW_{AC}) installed across 32 states from 2007-2017
- Operational history ranges from two (2018-2019) to twelve (2008-2019) full calendar years, with an average of 4.0 years—indicative of the relative youth of the utility-scale PV sector
- In aggregate, these plants contributed ~50% of all solar electricity generated in the United States in 2018 (across all sectors—residential, commercial, and utility-scale—and including concentrating solar thermal power)
- They collectively offer 2,211 project-years of operational experience, 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	177	11,035	8,643	49	20	740	2	4.2	10	32%	43%	33%
AZ	34	2,006	1,501	44	20	186	2	5.5	8	6%	8%	8%
NC	52	2,077	1,553	30	20	166	2	3.2	7	9%	8%	8%
NJ	33	344	282	9	8	147	2	4.5	8	6%	1%	7%
NM	26	592	472	18	10	145	2	5.6	9	5%	2%	7%
NV	21	2,157	1,623	77	50	103	2	4.9	12	4%	8%	5%
TX	26	1,543	1,210	47	23	102	2	3.9	9	5%	6%	5%
GA	23	1,307	953	41	30	84	3	3.7	6	4%	5%	4%
CO	13	442	354	27	16	64	2	4.9	12	2%	2%	3%
FL	15	674	458	31	20	63	2	4.2	10	3%	2%	3%
IN	12	137	102	8	8	52	2	4.3	6	2%	1%	2%
MD	9	133	103	11	10	39	2	4.3	7	2%	1%	2%
UT	12	1,049	810	68	80	38	3	3.2	4	2%	4%	2%
OR	14	232	177	13	10	35	2	2.5	3	3%	1%	2%
VA	14	537	403	29	20	32	2	2.3	3	3%	2%	1%
MN	13	354	245	19	8	28	2	2.2	3	2%	1%	1%
SC	12	230	169	14	10	26	2	2.2	3	2%	1%	1%
TN	6	99	79	13	16	23	2	3.8	7	1%	0%	1%
OH	3	51	38	13	10	19	2	6.3	9	1%	0%	1%
ID	8	323	240	30	20	18	2	2.3	3	1%	1%	1%
IL	2	33	28	14	14	17	7	8.5	10	0%	0%	1%
DE	2	26	22	11	11	15	7	7.5	8	0%	0%	1%
NY	4	71	56	14	9	15	2	3.8	8	1%	0%	1%
MA	4	52	39	10	9	13	2	3.3	5	1%	0%	1%
AL	5	246	182	36	11	11	2	2.2	3	1%	1%	0%
PA	1	11	10	10	10	7	7	7.0	7	0%	0%	0%
MS	3	216	155	52	52	6	2	2.0	2	1%	1%	0%
KY	2	25	19	9	9	5	2	2.5	3	0%	0%	0%
AR	1	17	13	13	13	4	4	4.0	4	0%	0%	0%
MI	2	58	48	24	24	4	2	2.0	2	0%	0%	0%
MO	1	11	8	8	8	2	2	2.0	2	0%	0%	0%
NE	1	7	6	6	6	2	2	2.0	2	0%	0%	0%
Total	**551**	**26,095**	**20,000**	**36**	**20**	**2,211**	**2**	**4.0**	**12**	**100%**	**100%**	**100%**

Project sample description (2)

COD Year:	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
# of Projects:	2	1	3	7	32	36	47	50	82	148	143	551
# of MW_{DC}:	22	12	63	172	540	1,133	2,231	3,566	3,575	9,869	4,911	26,095
# of MW_{AC}:	19	10	54	144	455	886	1,746	2,728	2,745	7,517	3,695	20,000
Average DC:AC Ratio:	1.18	1.21	1.16	1.19	1.19	1.28	1.28	1.31	1.30	1.31	1.33	1.30
Average MW_{AC}/Project:	9	10	18	21	14	25	37	55	33	51	26	36
% projects with tracking:	100%	0%	67%	14%	50%	50%	60%	62%	65%	73%	75%	66%
% projects with Si modules:	100%	0%	67%	29%	75%	83%	81%	74%	76%	86%	84%	81%

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



Histogram shows the majority of projects fall into the 20-50 MW_{DC} capacity bin. Nearly 87% 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}

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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:** 2008-2019 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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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

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

“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

$$\boldsymbol{CF_{f,t}}^{\boldsymbol{actual}} = \boldsymbol{CF_{f,t}}^{\boldsymbol{ideal}} + \boldsymbol{S_f} + \boldsymbol{A_T} + \boldsymbol{\epsilon_{f,t}}$$

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.

$$\overline{\boldsymbol{CF_f}^{\boldsymbol{actual}}} = \overline{\boldsymbol{CF_f}^{\boldsymbol{ideal}}} + \boldsymbol{S_f} + \overline{\boldsymbol{A}} + \overline{\boldsymbol{\epsilon_f}}$$

Eq. 2

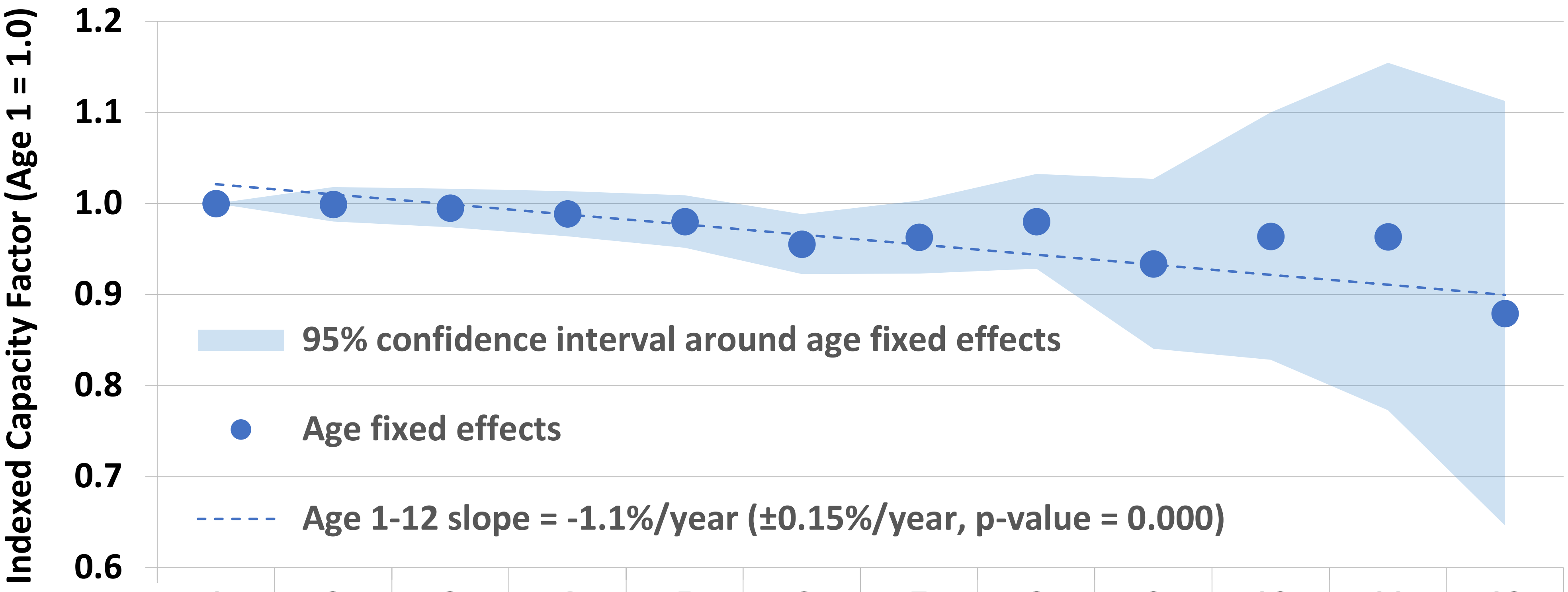
Equation 2 calculates the average over time for each variable in Equation 1. Because S_f does not vary over time in Equation 1, the average of S_f over time in Equation 2 is simply equal to S_f.

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

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—updated results from fixed effects model

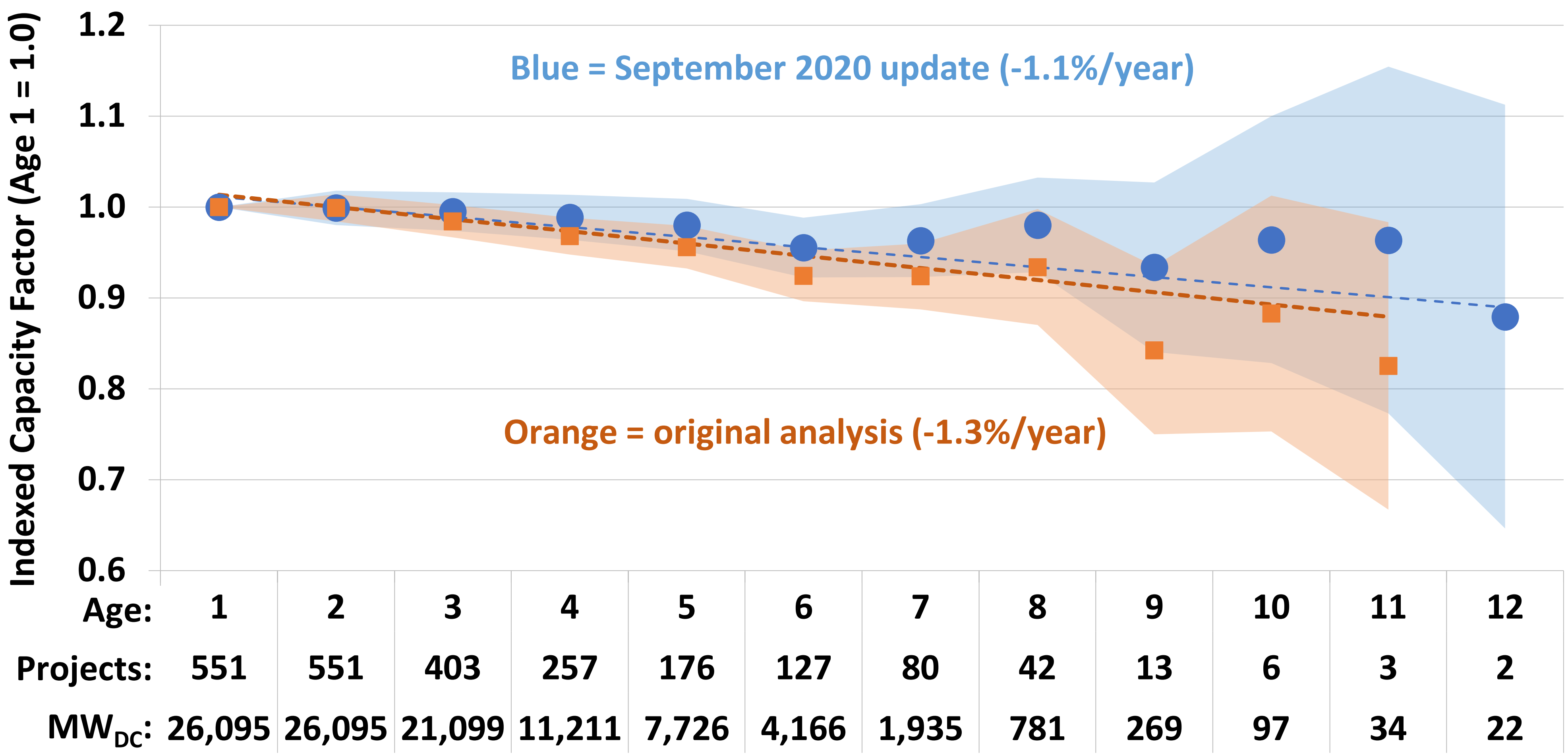


Age:	1	2	3	4	5	6	7	8	9	10	11	12
Projects:	551	551	403	257	176	127	80	42	13	6	3	2
MW_{DC}:	26,095	26,095	21,099	11,211	7,726	4,166	1,935	781	269	97	34	22

The slope (-1.1%/year) is weighted by the number of projects at each age, so ages 9-12 (which have wide 95% confidence intervals) do not receive much weight

The slope is almost identical (-1.1%/year) if only looking at ages 1-7 (i.e., later ages do not have much impact)

Performance decline with age—comparison to last year's results



Additional year of sample (2017 projects) and performance period (2019) improved slope from -1.3%/year (original analysis) to -1.1%/year (September 2020 update)

Improvement seems to be driven primarily by performance in 2019 (rather than by adding 2017 projects to the sample)

But confidence interval has widened, particularly for older ages….

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Potential drivers of performance decline with age

Project Characteristics (all differences are statistically significant):

- **Vintage:** Post-2012 projects (-0.7%/year, ±0.2%) have declined less than pre-2013 projects (-1.3%/year, ±0.2%)
- **Capacity:** Projects of 25 MW_{AC} or larger (-0.8%/year, ±0.3%) have declined less than projects less than 25 MW_{AC} (-1.2%/year, ±0.2%)
- **DC:AC ratio (ILR):** Projects with a DC:AC ratio of 1.25 or greater (-0.9%/year, ±0.2%) degrade less than projects with lower ratios (-1.2%/year, ±0.2%)
- **COMBINATION:** Newer (post-2012), larger (≥25 MW_{AC}) projects with higher DC:AC ratios (≥ 1.25) have declined less (-1.0%/year, ±0.5%) than their counterparts (-1.5%/year, ±0.2%)

Site Characteristics (all differences are statistically significant):

- **Solar resource:** Projects at sites with an average long-term global horizontal irradiance of less than 210 W/m^2 (-0.6%/year, ±0.3%) have declined less than projects at sunnier sites (-1.2%/year, ±0.2%)
- **Site climate:** Projects with an average site temperature of less than 15 degrees Celsius (-0.7%/year, ±0.3%) have declined less than projects at warmer sites (-1.3%/year, ±0.2%)

Module OEMs (OEM DIFFERENCES ARE NOT STATISTICALLY SIGNIFICANT):

- First Solar projects (-1.0%/year) have declined less than “Other” projects (-1.2%/year), but p-value=0.324 (i.e., not significant)
- SunPower projects (-0.8%/year) have declined less than “Other” projects (-1.2%/year), but p-value=0.149 (i.e., not significant)
- SunPower (-0.8%/year) has declined less than First Solar (-1.0%/year), but p-value=0.733 (i.e., not significant)

A separate multivariate regression supports only some of these fixed effects findings (e.g., vintage)

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For more information

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