Degradation of Utility-Scale PV

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1. Introduction

Most of this post is based on a Lawrence Berkeley National Lab (LBNL) Paper that studied the title subject. This was released earlier this month as I'm starting to write this (March 2022), and is an update of a similar study that was released two years ago: *In this updated study, which samples 50% more capacity than the original and adds two additional years of operating history, we assess the performance of a fleet of 631 utility-scale PV plants totaling 31.0 GWDC (23.6 GWAC) of capacity that achieved commercial operations in the United States from 2007-2018 and that have operated for at least two full calendar years.*[1]

This paper is a summary of the above-referenced paper, and I will add some additional information and an opinion in the last section of this post about the implications of these findings.

2. Background

Measurements of anticipated degradation to date have been mainly in the lab, and have focused on the photovoltaic (PV) cells, and yet the full PV plant consists of many more active components, any of which can degrade over many years. The primary "balance of plant" components include:

- The remainder of the module (a.k.a. panel), and not just the PV cells
- The racking (mounting) which can either be fixed or single-axes sun-tracking
- The project's electric conductors and related structures
- Inverter(s)
- Transformer(s)

We use detailed information on individual plant characteristics, in conjunction with modeled irradiance data, to model expected or "ideal" capacity factors in each full calendar year of each plant's operating history. A comparison of ideal versus actual first-year capacity factors finds that this fleet has modestly underperformed initial expectations (as modeled) on average, though perhaps due as much to modeling issues as to actual underperformance. We then analyze fleet-wide performance degradation in subsequent years by employing a "fixed effects" regression model to statistically isolate the impact of age on plant performance. The resulting average fleet-wide degradation rate of -1.2%/year (±0.1%) represents a slight improvement (seemingly driven by the oldest plants in our sample) over the -1.3%/year (±0.2%) found in our original study, yet is still of greater magnitude than is commonly found. We emphasize, however, that these

[1] Mark Bolinger (LBNL), Will Gorman (LBNL), Dev Millstein (LBNL), DirkJordan (1National Renewable Energy Laboratory), "Plant-level performance and degradation of 31 GWDC of utility-scale PV in the United States," March 2022, https://eta-publications.lbl.gov/sites/default/files/plant-level_performance_and_degradation_of_31_gw-dc_of_utility-scale_pv_in_the_united_states.pdf

fleet-wide estimates reflect both recoverable and unrecoverable degradation across the entire plant, and so will naturally be of greater magnitude than module- or cell-level studies, and/or studies that focus only on unrecoverable degradation.

2.1. Recoverable Degradation

An example of "recoverable" degradation might include dirty light-collecting surfaces, corroded hardware (mainly in wiring or racking), and parts that prematurely failed. Also note that part of the development of expertise in deploying PV projects includes design elements to minimize and/or detect recoverable degradation.

2.2. Survey Sample

The deployment of photovoltaic (PV) modules in large, utility-scale configurations is a relatively recent phenomenon. In the United States, the first two utility-scale PV plants—defined here to include any ground-mounted PV plant larger than 5 MWAC—achieved commercial operations as recently as late 2007. Thus, at the time of writing (in late 2021), the oldest utility-scale PV plants in the United States had only been operating for thirteen full calendar years (2008-2020), or less than half of their expected useful lives of 30 year or longer. Moreover, most utility-scale PV plants in the United States are much younger than these oldest plants: at the end of 2020, there were ~38.7 GWAC (~50.9 GWDC) of utility-scale PV operating in the United States, with an average plant age of less than four years.

With such a young and rapidly growing fleet of utility-scale PV plants supplying the majority of solar generation in the United States, it is crucial to understand how these utility-scale plants have performed to date. We found that a fleet of 21.0 GWDC of utility-scale PV plants built in the United States from 2007-2016 had generally lived up to forecasted expectations for initial performance, but that average plant-level degradation of -1.3%/year through 2018 had been worse than both forecasted expectations and results from other degradation studies. A review of power purchase agreements (PPAs) and the existing literature found that most PPAs codify an expected performance degradation rate of just -0.5%/year, based in part on earlier studies in the literature, many of which focus on unrecoverable degradation at the module, rather than plant, level…

Author's comment: one would hope that any performance guarantees would be based on the module performance, and have minimal penalties.

The sample is spread across U.S. States based on the number of projects ≥5MWAC in each state over the sample period, thus it is reasonable that the number and size of projects would be higher in "early adopter" states. The table below (next page) defines this distribution.

3. Analysis & Results

The overall goal of reference 1 seems to be not just accurately measure and model the degradation, but to tease out the individual causes of this degradation.

3.1. Analysis

Using detailed information on individual plant characteristics, in conjunction with modeled irradiance data, we assess the extent to which actual first-year performance

Table 1. Geographic descriptive statistics of sample

State	# of Plants	# of MW_{DC}	# of MW_{AC}	MW_{AC}/Plant		# of Plant-Years	Years per Plant		
				Average	Median		Min	Avg	Max
CA	186	12,321	9,605	52	20	935	2	5.0	11
NC	59	2,625	1,938	33	20	233	2	3.9	8
AZ	36	2,102	1,567	44	20	225	2	6.3	9
NJ	38	402	328	9	8	190	2	5.0	9
NM	27	606	484	18	10	161	2	6.0	10
TX	34	2,182	1,692	50	23	144	2	4.2	10
NV	21	2,157	1,623	77	50	125	3	6.0	13
GA	24	1,351	984	41	30	109	2	4.5	7
FL	28	1,935	1,332	48	61	104	2	3.7	11
CO	14	510	404	29	18	79	2	5.6	13
OR	22	329	251	11	10	66	2	3.0	4
IN	13	147	109	8	8	66	2	5.1	7
MD	11	250	190	17	12	52	2	4.7	8
UT	12	1,049	810	68	80	50	4	4.2	5
VA	16	577	435	27	20	50	2	3.1	4
SC	17	331	240	14	10	48	2	2.8	4
MN	14	363	252	18	7	43	2	3.1	4
TN	8	187	147	18	16	35	2	4.4	8
ID	8	323	240	30	20	26	3	3.3	4
OH	3	51	38	13	10	22	3	7.3	10
NY	5	103	81	16	10	21	2	4.2	9
IL	2	33	28	14	14	19	8	9.5	11
AL	6	266	198	33	13	18	2	3.0	4
MA	4	52	39	10	9	17	3	4.3	6
DE	2	26	22	11	11	17	8	8.5	9
MI	4	87	72	18	18	10	2	2.5	3
MS	3	215	155	52	52	9	3	3.0	3
PA	1	11	10	10	10	8	8	8.0	8
AR	2	122	94	47	47	7	2	3.5	5
KY	2	25	19	9	9	7	3	3.5	4
MO	2	22	16	8	8	5	2	2.5	3
CT	2	56	40	20	20	4	2	2.0	2
NE	1	7	6	6	6	3	3	3.0	3
WY	1	98	80	80	80	2	2	2.0	2
VT	1	26	20	20	20	2	2	2.0	2
WA	1	28	19	19	19	2	2	2.0	2
OK	1	13	10	10	10	2	2	2.0	2
Total	**631**	**30,990**	**23,579**	**37**	**20**	**2,916**	**2**	**4.6**	**13**

has lived up to expected (as modeled) performance. We then analyze fleet-wide degradation in energy output in subsequent years, by employing a "fixed effects" regression model to statistically isolate the impact of age on system performance.

In what is perhaps an indication of the robustness of our methods, we find results similar to our original study. On average, these plants' first-year performance has fallen short of modeled expectations to a modest degree. The fleet-wide degradation rate of -1.2%/year (±0.1%) represents a slight improvement over the -1.3%/year (±0.2%) found in our original study, yet is still of greater magnitude than is commonly assumed. We emphasize, however, that these fleet-wide estimates reflect both recoverable and unrecoverable degradation across the entire plant, and so will naturally be of greater magnitude than module- or cell-level studies, and/or studies that focus only on unrecoverable degradation. ***Moreover, application of the fixed effects model to a variety of sub-samples in an attempt to tease out potential degradation drivers suggests that newer and larger plants with higher DC:AC ratios—i.e., plants that more closely resemble recent plants—have experienced a lower magnitude of degradation—-0.7%/year (±0.4%)—that is more in line with other estimates from the recent literature.***

Reference 1 does much slicing and dicing of data. Go through the reference's link to see this. The one additional graphic I found interesting is the one below. CAISO and ERCOT are the only two grids that publish curtailed PV data.

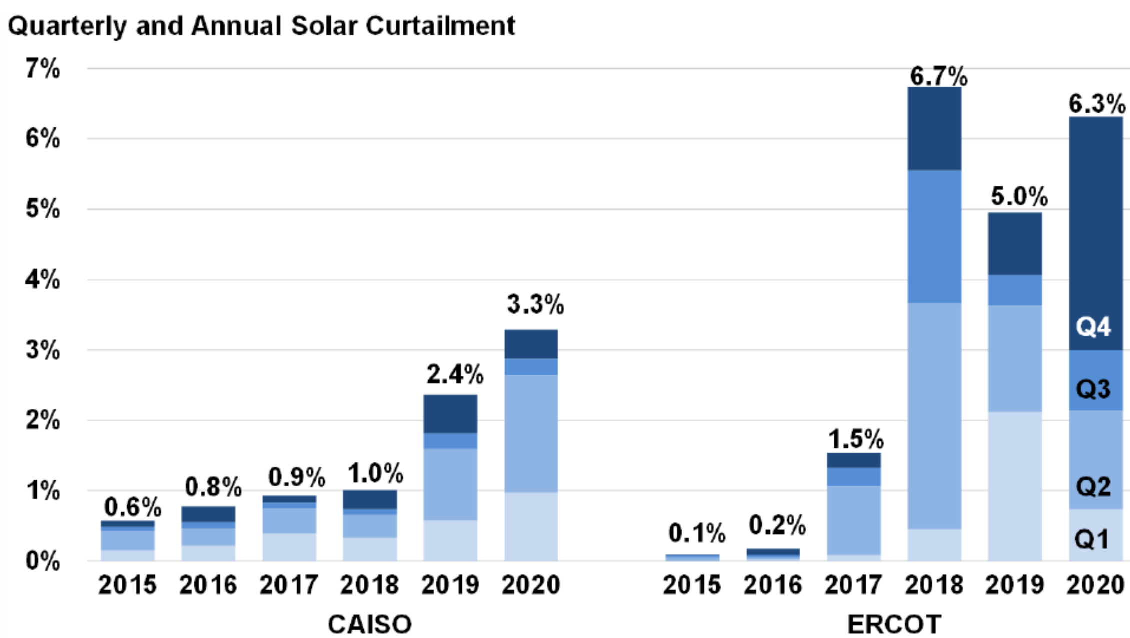

Figure 2. Solar curtailment history in CAISO and ERCOT

One long-term trend I have recently explored with my posts is the increase in green hydrogen use by a number of sectors. Green hydrogen uses renewable electricity to produce hydrogen (and oxygen) via electrolysis, and stores the hydrogen (and perhaps oxygen) in large tube-clusters. The latter allows the hydrogen to be produced with the lowest-cost renewable power, and stored for later use. I would expect that PV (and wind) power that would otherwise be curtailed is the bargain-basement in this process.

3.1.1. First Year Production

The first year production is the parameter against which the later year's production will be measured and analyzed to extract degradation characteristics.

Based on the data described in the previous section, Figure 3 plots "actual" capacity factors (as grossed up to correct for curtailment in California and Texas, if appropriate) versus modeled or "ideal" capacity factors (simulated using NREL's System Advisor Model) for each plant in our sample, focusing on the first full calendar year of each plant's operational history. This first-year comparison provides an indication of how well the plants in our sample have performed before degradation can muddy the waters over time. The scatterplot is shown two ways: (a) color-coded by calendar year (which is always one year greater than the year of each plant's commercial operation date) and (b) color-coded by the region in which each plant is located.

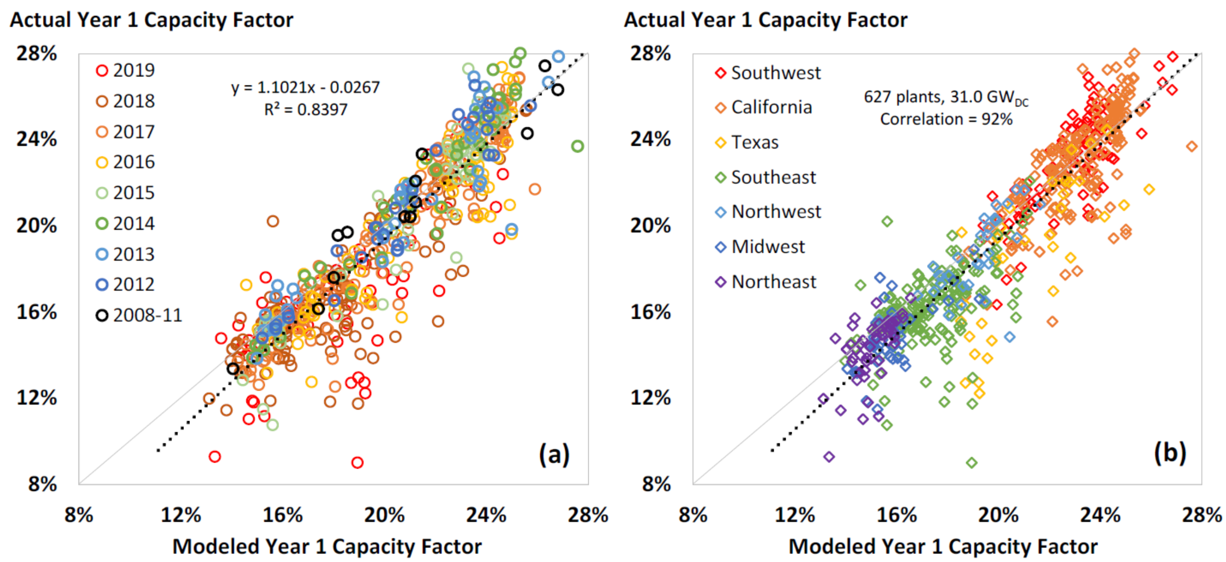

Figure 3. Actual vs. modeled first-year capacity factor by (a) year and (b) region

The actual first-year capacity factor falls short of modeled for 61% of the plants in our sample, and the scatterplot visually confirms the intuition that there should be more underperforming than over-performing outliers (since there are relatively few reasons that a plant would ever outperform its ideal capacity factor to any significant degree)…

Turning to the temporal and regional aspects of Figure 3, the underperformance seems to be somewhat skewed to the lower end of the capacity factor range (per the dashed best-fit regression line), with the most significant outliers seemingly concentrated among both newer plants (e.g., those whose first full operational years were 2018 or 2019) and those located in Texas, California, the Southeast, and the Northeast. There are a number of potential explanations for these temporal and regional results. For example, newer plants are more likely than older plants to have experienced curtailment in their first year (as curtailment has increased with solar market penetration—see Figure 2), and although we correct for curtailment in both California and Texas, our correction is not perfect…, and there may very well be unaccounted-for curtailment happening in other regions, such as the Southeast… Newer plants are perhaps more likely to be sited on uneven terrain as the market expands and the availability of flat sites diminishes; recent research suggests that uneven terrain is a challenge for backtracking algorithms, *as well as performance models, and can reduce plant output by 1%-2%. Newer plants are also more likely to have experienced catastrophic weather events in their first year, as the frequency and intensity of hailstorms, hurricanes, tornadoes, and wildfires have increased with global climate change. For example, smoke from wildfires—which is difficult to capture in performance models—reportedly reduced solar generation in the West by as much 6% in 2020. Finally, underperformance in the Northeast in particular may be related to snow cover, which is also hard to model yet is one of the more significant contributors to losses. In short, some or maybe even much of the underperformance shown in Figure 3 may be attributable to inaccurate modeling (or modeling inputs) rather than poorly performing plants. Moreover, despite our attempt to limit the impact of degradation on the comparison in Figure 3 by focusing on just the first full year of operations, early first-year degradation (or even first-year "teething" issues, for plants that came online late in the prior year) could nevertheless be contributing to the apparent underperformance to a limited degree.*

3.1.2. Performance Degradation

Author's comment: In performing the performance degradation analysis, reference 1 takes a deep dive into the regression model and the mathematics therein. I've decided to skip most of this, and stick to the commentary.

We used the fixed effects model to analyze and compare various sub-samples, with the goal of identifying significant degradation pathways. Though we looked at numerous sub-sample comparisons, Table 3 (below) lists only those that yielded statistically different degradation rates. The results are generally intuitive. For example, newer plants (those with CODs from 2015-2018) seem to have aged better than older plants—consistent with a story of technology improvement. Larger plants (≥25 MWAC), which perhaps receive greater attention from asset managers, seem to have aged better than smaller plants. Plants with higher DC:AC ratios (≥1.25) seem to have aged better than their counterparts have—perhaps due to some amount of degradation on the DC side of the inverter being masked through more frequent power clipping. Combining these three variables yields the starkest contrast in Table 3: the performance of newer plants with greater capacities and higher DC:AC ratios—in other words, plants that look the most like those being built today—has declined by only about half as much (-0.7%/year) as that of plants that fall outside of that sub-sample (-1.4%/year). It is worth noting that the -0.7%/year performance decline among this sub-sample is more in line with other recent estimates from the literature. Finally, the remaining sub-sample comparisons shown in Table 3 find that fixed-tilt plants age better than plants that use single-axis tracking (perhaps due to fewer moving parts), plants using thin-film (mostly CdTe) modules have aged better than those using crystalline silicon modules, and plants located at sites with a lower irradiance and/or average temperature have aged better than their counterparts.

Authors comment: I believe that the acronym "COD" stands for commercial operation date.

Also, Inverter power clipping occurs when the power of an inverter exceeds the inverter's nominal power rating due to DC overloading.

Table 3. Statistically significant comparisons of sub-samples using the fixed effects model

Variable	Less Degradation	More Degradation
Vintage	Post-2014 COD -1.1%/year, ±0.3%	Pre-2015 COD -1.2%/year, ±0.1%
Capacity	≥25 MW_{AC} -0.8%/year, ±0.2%	<25 MW_{AC} -1.4%/year, ±0.1%
DC:AC Ratio	≥1.25 DC:AC -1.1%/year, ±0.2%	<1.25 DC:AC -1.3%/year, ±0.2%
Combination (Vintage, Capacity, DC:AC)	Post-2014, ≥25 MW_{AC}, ≥1.25 DC:AC -0.7%/year, ±0.4%	Pre-2015, <25 MW_{AC}, <1.25 DC:AC -1.4%/year, ±0.2%
Mount	Fixed-Tilt -1.2%/year, ±0.2%	Single-Axis Tracking -1.3%/year, ±0.2%
Module Type	Thin-film (mostly CdTe) -1.0%/year, ±0.2%	x-Si -1.3%/year, ±0.1%
Solar Resource	GHI <210 W/m^2 -1.0%/year, ±0.2%	GHI ≥210 W/m^2 -1.2%/year, ±0.1%
Average Temperature at the Site	<15° C -0.9%/year, ±0.2%	≥15° C -1.3%/year, ±0.1%

Author's comment: I believe that GHI in the above table is Global Horizontal Irradiance, which is the total solar radiation incident on a horizontal surface.

3.2. Results

Specifically, we find that solar plants have been modestly underperforming modeled expectations in their first year, and that average fleet-wide plant-level performance has declined by 1.2%/year—a slight improvement from the -1.3%/year found in 2020. This consistency in results across studies—particularly in the face of market expansion to new regions, evolving technology, increasing solar curtailment, and growing impacts from wildfires and other natural disasters—bolsters our confidence in our approach and methods.

This update highlights the increasing importance of accounting for curtailment when assessing plant performance. Our original analysis found that controlling for curtailment improved the degradation rate by only about 0.1%/year (i.e., -1.3%/year controlled versus -1.4%/year uncontrolled), suggesting that curtailment was—at that time—a minor contributor to overall performance decline with age. In this updated analysis, however, the difference has grown to 0.4%/year (i.e., -1.2%/year controlled versus -1.6%/year uncontrolled), reflecting the significant growth in curtailment (particularly within CAISO; see Figure 2) in the two-year interim between studies. Had we not controlled for curtailment in either study, we would currently be reporting a slight worsening of total performance decline with age (i.e., -1.6%/year versus -1.4%/year in the original study) instead of a slight improvement (-1.2%/year versus -1.3%/year originally). And while it is possible that we are underestimating curtailment—and hence overstating degradation—in those regions that do not report curtailment data, the potential impact of this possibility is likely to be modest. For example, applying CAISO's curtailment rate to plants in the Southwest (a non-ISO region that does not report solar curtailment data, but where curtailment likely occurs on occasion) only improves the overall sample-wide degradation rate to -1.1%/year (from -1.2%/year).

Despite the slight improvement our revised -1.2%/year overall degradation rate is still large, and generally worse than what most other studies find. That said, the low temporal (i.e., annual) and spatial (i.e., plant-level) resolution of our generation data prohibits us from filtering out maintenance events and other downtime (other than curtailment, for which we do attempt to control where data exist, but may nevertheless be underestimating in some regions), which in turn means that we capture both recoverable and unrecoverable—i.e., total—degradation across the entire plant. When viewed through this lens, the magnitude of our average fleet-wide degradation rate is less surprising (and, again, may be slightly overstated if curtailment is occurring outside of CAISO and ERCOT), and our results do not appear to be as far away from others'. This is particularly the case when focusing on a sub-sample of newer and larger plants with higher DC:AC ratios—i.e., plants that more-closely resemble what is being built today—which exhibit a more moderate sample-wide average performance decline of -0.7%/year (±0.4%).

While the analysis of various sub-samples finds that newer plants have aged better than older plants, the slight improvement in the overall fleet-wide average degradation rate across the total sample appears to be coming mostly from the oldest plants in our sample—e.g., those aged 6-10 years in the original study, or 8-12 years in the current study. This finding is important for several reasons. First, the utility-scale fleet in the United States is still relatively young, with an average plant age of less than 4 years, and there have been relatively few studies of plants as old as 8-12 years. The apparent turnaround in the performance of these older plants since our original analysis affirms the notion that we are detecting recoverable (in addition to unrecoverable) degradation that can, indeed, be recovered. It also potentially highlights the role of policy in driving plant performance, to the extent that the 5-year federal investment tax credit recapture period is a factor. Finally, and perhaps most importantly, this turnaround in older plants instills optimism that plant owners do see value in maintaining solid performance over the longer term, and will not simply leave older plants to wither on the vine.

4. Author's Comments

The above results are reasonably good news, however, there is one other piece of news. We now need to consider the economic performance of PV Projects. As I've extracted from the earlier post below (section 2.1), the productivity of PV projects seems to be increasing at about 5% per decade. This is a combination of cell-efficiency increases and other design improvements.

https://energycentral.com/c/cp/pv-and-storage-spring-2022

This means at some point the owner of a PV project will need to decide if it is time to upgrade the project to new technology by completely replacing all of the components of the project. Assuming a recently operational project (say, COD is 2020). The degradation is likely to be no more than 0.7% per year. This is roughly 96.5% of the original output after 5 years, 93.2% after 10 years, and 90% after 15 years. Also the production gain that could be realized by replacing the original technology with state-of-the-art technology is increasing at about 5% per decade.

I would suggest, that at some point before the output of the original equipment becomes unacceptable (generally thought to be a degradation of 20%), there is a good chance that the owner may want to consider upgrading the technology.