Impact of PV Module Degradation Rate on Utility Scale Systems

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Motivation

Question: What impact does module degradation have on system degradation and thus energy cost in utility-scale PV systems?

Factor #1: Degradation Study

Factor #2: Module Technology

Factor #3: Building Successful Projects
- Bidding
- Financing
- PPA
Methodology

Model 100MW, single axis tracking, utility PV systems in PVSyst, varying irradiance, degradation rate and DC-AC power ratio

• 3 sites (high, medium, low irradiance)
• 3 annual degradation rates for modules (0.3%, 0.5%, 0.7%)
• 7 power DC-AC ratios (1:1.6)

Calculate and compare simple LCOE for systems with various module degradation (linear and nonlinear)
Linear Module Degradation

![Graph showing linear module degradation over years with different rates of degradation at 0.3%, 0.5%, and 0.7% per year.](image)
Annual System Degradation Over Project Lifetime: High Irradiance
Annual System Degradation Over Project Lifetime: Medium Irradiance

Module Degradation = 0.3%

Module Degradation = 0.5%

Module Degradation = 0.7%
Annual System Degradation Over Project Lifetime: Low Irradiance
Equivalent Linear Lifetime Degradation

Effective System Lifetime Degradation vs Power Ratio

-0.80% -0.70% -0.60% -0.50% -0.40% -0.30% -0.20% -0.10% 0.00% 0.10%
1.0 1.1 1.2 1.3 1.4 1.5 1.6

High, 0.3% Low, 0.3% High, 0.5% Low, 0.5% High, 0.7% Low, 0.7%
LCOE Calculation

\[
LCOE = \frac{\text{Total Lifecycle Cost}}{\text{Total Lifetime Energy Production}}
\]

\[
\text{Initial Cost} + \sum_{n=1}^{N} \frac{O&M \cdot (1 - \text{Tax Rate})}{(1+r)^n} = \sum_{n=1}^{N} \text{Initial Production} \cdot \frac{(1-R_D)^n}{(1+r)^n}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Cost</td>
<td>$1.125 - $1.15/Wdc</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>$14/kW/yr</td>
</tr>
<tr>
<td>Tax Rate</td>
<td>30%</td>
</tr>
<tr>
<td>Discount Rate</td>
<td>7.50%</td>
</tr>
<tr>
<td>System Lifetime</td>
<td>30 years</td>
</tr>
</tbody>
</table>
### LCOE – Linear Module Degradation

#### High Irradiance Site

<table>
<thead>
<tr>
<th>DC-AC Ratio</th>
<th>Annual Module Degradation Rate</th>
<th>Percent LCOE difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.3%</td>
<td>0.5%</td>
</tr>
<tr>
<td></td>
<td>0.7%</td>
<td>0.3% vs. 0.5%</td>
</tr>
<tr>
<td></td>
<td>0.7%</td>
<td>0.7% vs. 0.5%</td>
</tr>
<tr>
<td>1</td>
<td>4.27</td>
<td>4.36</td>
</tr>
<tr>
<td>1.3</td>
<td>4.37</td>
<td>4.44</td>
</tr>
<tr>
<td>1.6</td>
<td>4.90</td>
<td>4.94</td>
</tr>
</tbody>
</table>

#### Low Irradiance Site

<table>
<thead>
<tr>
<th>DC-AC Ratio</th>
<th>Annual Module Degradation Rate</th>
<th>Percent LCOE difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.3%</td>
<td>0.5%</td>
</tr>
<tr>
<td></td>
<td>0.7%</td>
<td>0.3% vs. 0.5%</td>
</tr>
<tr>
<td></td>
<td>0.7%</td>
<td>0.7% vs. 0.5%</td>
</tr>
<tr>
<td>1</td>
<td>6.58</td>
<td>6.72</td>
</tr>
<tr>
<td>1.3</td>
<td>6.59</td>
<td>6.71</td>
</tr>
<tr>
<td>1.6</td>
<td>7.13</td>
<td>7.20</td>
</tr>
</tbody>
</table>

- LCOE changes by ~4% when annual module degradation increases from 0.3% to 0.7%
- Clipping masks degradation more with high irradiance
Nonlinear Module Degradation

Baseline 0.5% linear module degradation (high irradiance site)
Nonlinear Degradation is zero for first 9 years, 0.7% annually in subsequent years
# LCOE – Nonlinear Module Degradation

## LCOE (¢/kWh)

<table>
<thead>
<tr>
<th>DC-AC Ratio</th>
<th>Annual Module Degradation Rate</th>
<th>Percent LCOE Difference</th>
<th>0.5% Linear vs. Nonlinear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5% Linear</td>
<td>Nonlinear</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4.36</td>
<td>4.27</td>
<td>-2.0%</td>
</tr>
<tr>
<td>1.3</td>
<td>4.44</td>
<td>4.38</td>
<td>-1.3%</td>
</tr>
<tr>
<td>1.6</td>
<td>4.94</td>
<td>4.91</td>
<td>-0.7%</td>
</tr>
</tbody>
</table>

## DC-AC Ratio

- **DC-AC Ratio**: 0.5% Linear vs. Nonlinear
- **0.5% Linear**: 4.36, 4.44, 4.94
- **Nonlinear**: 4.27, 4.38, 4.91

## Graph

- **Nonlinear Degradation**: Blue line
- **0.5% Degradation**: Orange line
- **0.3% Degradation**: Purple line

- **Year**: 0, 10, 20, 30
- **% Original Module Energy**: 100%, 95%, 90%, 85%, 80%, 75%
- **Output**: % Original Module Energy

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IMAGINE IMAGE OF A GRAPH SHOWING THE PERCENT DECREASE IN MODULE ENERGY OUTPUT OVER TIME FOR DIFFERENT LINEAR AND NONLINEAR DEGRADATION RATES. THE GRAPH ILLUSTRATES HOW NONLINEAR DEGRADATION INFLUENCES LCOE AND DC-AC RATIO poverty and the impact of different degradation rates on LCOE. The table highlights the differences in LCOE (¢/kWh) under various DC-AC ratios, comparing linear and nonlinear degradation, showing a decrease of 2.0%, 1.3%, and 0.7% for DC-AC ratios of 1, 1.3, and 1.6, respectively.
Variable Module Degradation

Baseline 0.5% linear module degradation (high irradiance site)
Add mismatch losses due to variable degradation: PVSyst Isc and Voc
Dispersion - RMS 0.4% per year (default)
## LCOE – Variable Module Degradation

### LCOE (¢/kWh)

<table>
<thead>
<tr>
<th>DC-AC Ratio</th>
<th>0.5% Linear</th>
<th>Variable Distribution</th>
<th>Percent LCOE Difference 0.5% vs. Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.36</td>
<td>4.43</td>
<td>1.5%</td>
</tr>
<tr>
<td>1.3</td>
<td>4.44</td>
<td>4.49</td>
<td>1.2%</td>
</tr>
<tr>
<td>1.6</td>
<td>4.94</td>
<td>4.97</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

### Annual Module Degradation Rate

- **0.5% Linear**
- **Variable Distribution**
- **Percent LCOE Difference 0.5% vs. Variable**

### Graph

- **% Original Module Energy Output**
- **Year**
- **Variable Degradation**
- **0.5% Degradation**
- **0.7% Degradation**
Summary

PV module level degradation is greater than its resulting system level degradation in single axis tracking installations with a greater-than-unity DC-AC ratio – depends on site irradiance.

Clipping can cause nonlinear variation in annual PV system degradation rates.

PV system LCOE is affected significantly by both linear and nonlinear module degradation rates and patterns even when masked by clipping.

Effect of variable module degradation on system level degradation should be further explored.
Thank you!