Enhancements in voltage degradation modeling for multi-year analyses

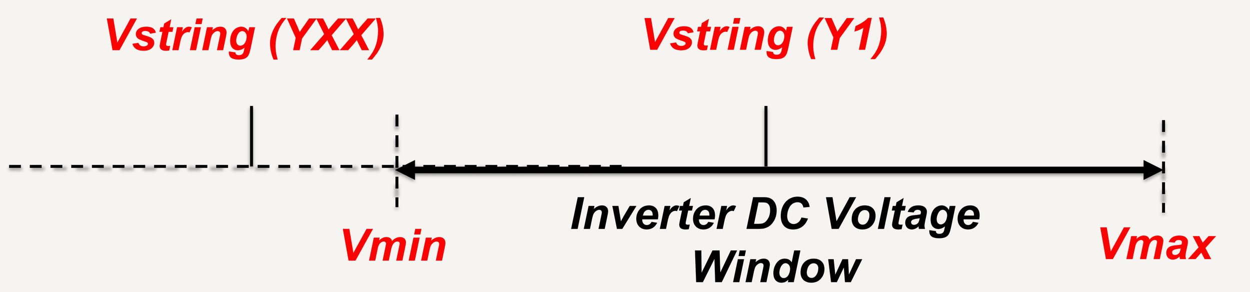
Matthew Prilliman, Janine Keith, Will Hobbs

Southern Company

National Laboratory of the Rockies

Introduction

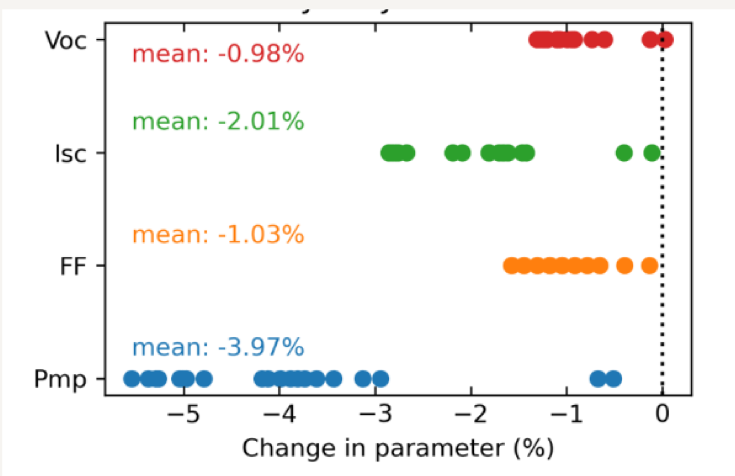
- Traditionally, PV performance models calculate module and string level voltage and current outputs in great detail for a single year of weather data, with many robust models having been developed to do so. Typically, this 'first-year' performance calculation is then carried over into PV system period-of-performance analysis and financial estimates, degradation of the system output is applied as a percentage decrease in power based on empirical or estimated annual power degradation rates.
- This approach, however, forgoes important detail of how much the string voltages and current degrade over the lifetime of the project, which can have a non-linear impact on system output depending on the operating voltage window of the inverter. While some models for specific voltage and current corrections do exist, there has not yet been a comprehensive evaluation of the best way to model voltage and current degradation.



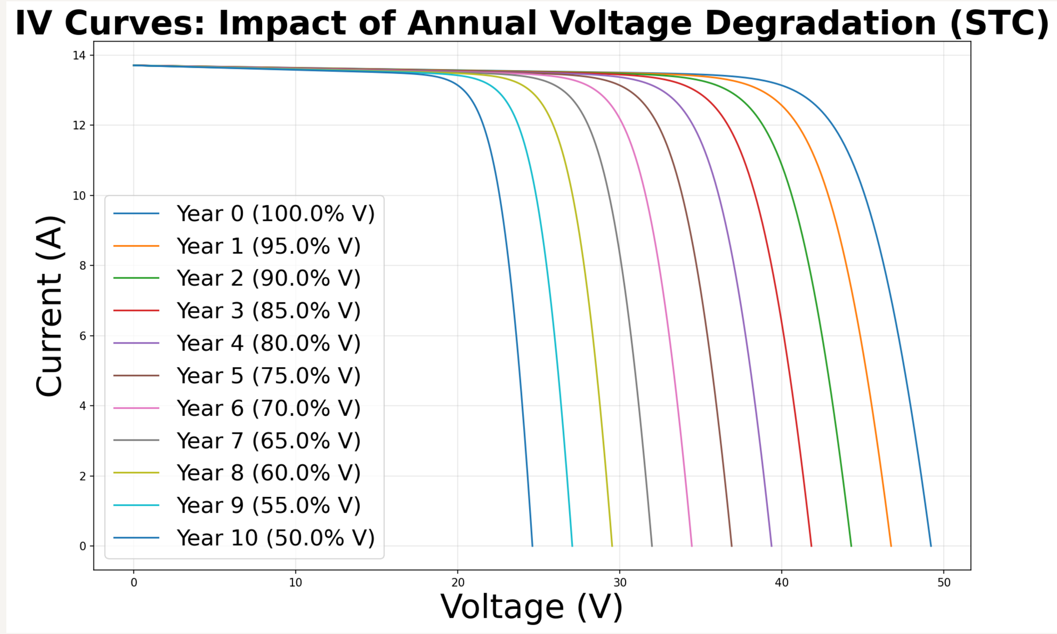
Vstring degrades over time, more occurrences of MPPT window clipping!

Methodology

- Evaluating multiple approaches for calculating this voltage and current degradation over module lifetime:
- **Re-solve module parameters each year** – As module stress testing shows degraded Voc, Isc, FF [1], the module has new Voc, Isc, Pmp conditions not accounted for in existing single diode circuit model. The proposed approach takes user input for voltage degradation (%) and applies to Voc and Vmp, likewise for current degradation (%) applied to Isc and Imp

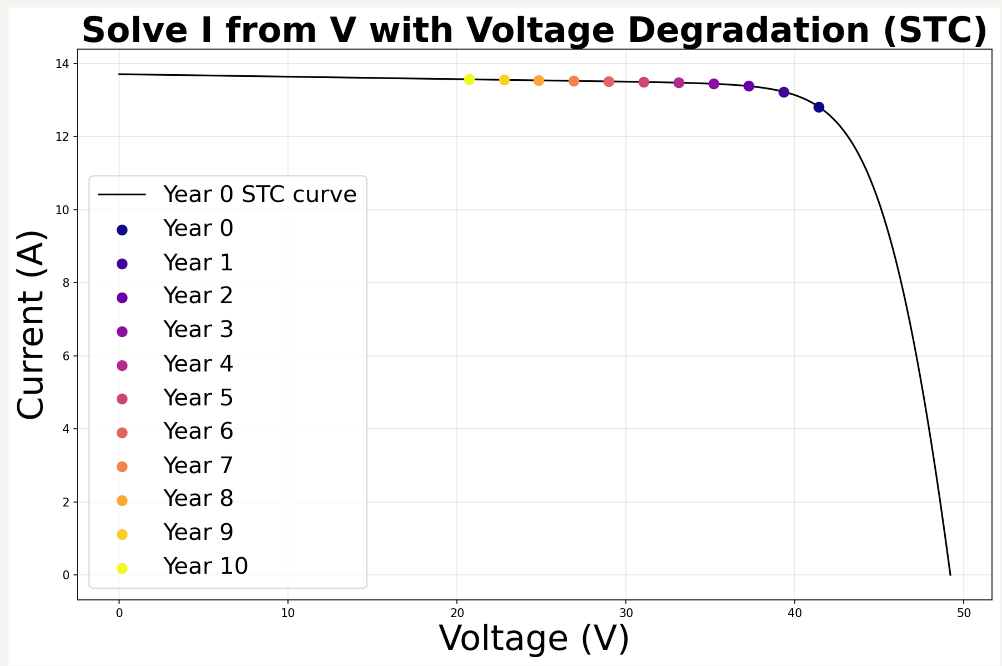


Measured changes in module Voc, Isc, FF, and Pmp after 7 years in the field [1]. Depending on the technology, voltage and current degrade at different rates, which % power degradation rates don't automatically account for



Resolve model approach: After year 0 of modeled performance, recalculate single diode equivalent circuit model fit based on user-specified voltage, current degradation inputs

- Two Re-solve approaches:
  - Existing SAM [2] simulation core (**SSC**) CEC model solver (Newton's method)
  - Open-source **Pyomo** Interior Point Optimizer (IPOPT) solver: in development, open-source in PySAM [3], [4], [5]
- **Solve I from V** – keep the same single diode fit from year 1, then degrade voltage and use existing SAM, pvlib, etc. calculations to get new current from degraded voltage. Then apply any current degradation
- **Postprocess** – store year 1 module/string voltages and currents, degrade them by user-specified percentage through out years of project lifetime



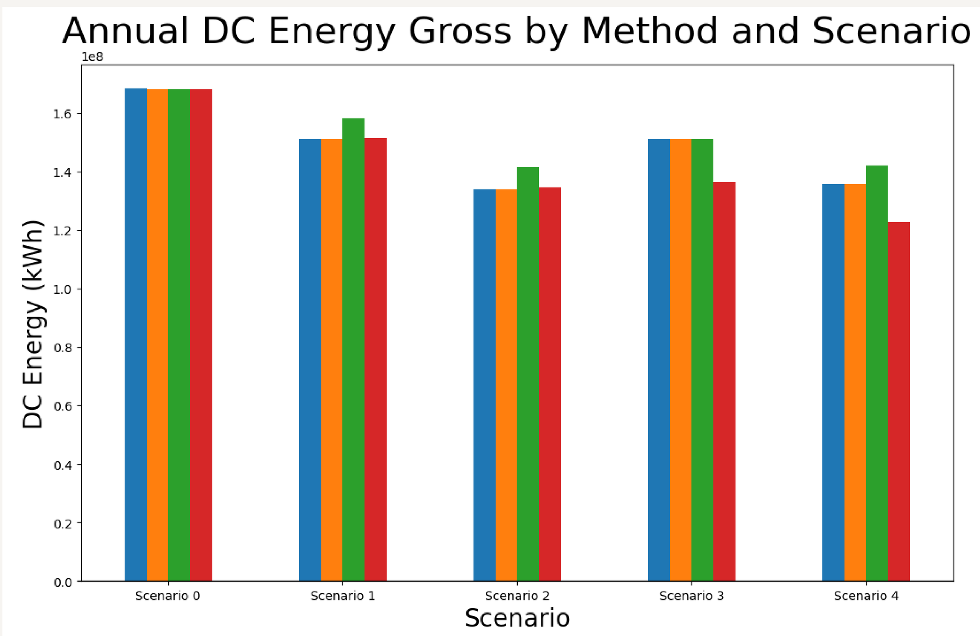
Solve I from V approach: After year 0 calculations, degrade voltage by user-specified amount, then use existing single diode fit to solve for new current along curve

Preliminary analysis

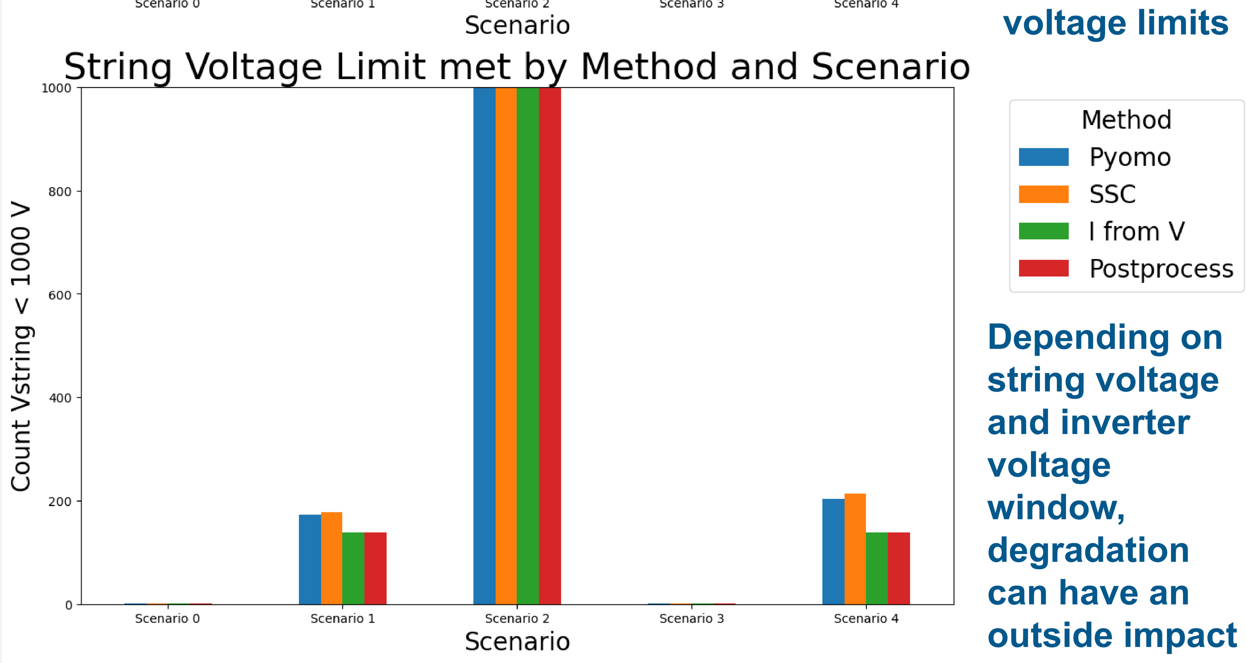
- Hypothesis: Re-solving the module each year is the most accurate approach to capture fielded conditions year-to-year
- IPOPT Solver: **99% solver success rate** for CEC Module list with 20% voltage degradation (n=20k+)
- Example: 100 MW DC, fixed tilt 20 degrees, Vmp (string): 1150 Vdc
- **Scenarios not indicative of real system behavior, but shows:**
  1) **Variation in DC energy yield from using each of these approaches (pre-inverter)**
  2) **Variation in voltage window events (especially when operating near low end of inverter window)**

Scenario	Voltage Degradation	Current Degradation
0	0%	0%
1	10%	0%
2	20%	0%
3	0%	10%
4	10%	10%

- Questions:
  - How successful are existing solvers for advanced degradation?
  - What are the computational constraints (runtime, complexity, etc.)?
  - Is a mixed approach warranted: try to re-solve equivalent circuit model, then resort to Solving I from V if it fails?



Gross DC Annual Energy can vary greatly before even considering inverter voltage limits



Depending on string voltage and inverter voltage window, degradation can have an outside impact

Discussion

- **How prevalent are voltage and current degradation issues in your projects**
- **How do you account for this effect in your expected yield modeling?**
- **Does there need to be a separate consideration for Fill Factor degradation?**
- **Future work**
  - **Implement methodologies into full PV model workflow**
  - **Validate against measured performance data / known inverter MPPT clipping use cases**
  - **Evaluate sensitivities to module cell type (thin-film, multi-junction), module size**
  - **Distribute final method through open-source versions of SAM, PySAM**

References

[1] Deline, Chris, Dirk Jordan, Bill Sekulic, Josh Parker, Byron McDanold, and Allan Anderberg. 2024. PV Lifetime Project – 2024 NREL Annual Report. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5K00-90651. https://www.nrel.gov/docs/fy24osti/90651.pdf.

[2] System Advisor Model™ Version 2025.4.16 (SAM™ 2025.4.16). National Laboratory of the Rockies. Golden, CO. Accessed May 23, 2025. https://https://sam.nlr.gov .

[3] PySAM Version 7.1.0. National Laboratory of the Rockies. Golden, CO. Accessed April 30, 2026. github.com/natlabrockies/pysam.

[4] Bynum, Michael L., Gabriel A. Hackebeil, William E. Hart, Carl D. Laird, Bethany L. Nicholson, John D. Siirola, Jean-Paul Watson, and David L. Woodruff. Pyomo - Optimization Modeling in Python. Third Edition Vol. 67. Springer, 2021.

[5] Wächter, A., & Biegler, L. T. (2006). On the implementation of a primal-dual interior point filter line search algorithm for large-scale nonlinear programming. Mathematical Programming, 106(1), 25–57.

This work was authored in part by the National Laboratory of the Rockies for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

PVPMC Workshop
Albuquerque, New Mexico
5/12/2026-5/14/2026
NLR/PO-7A40-100483