Value of stability in photovoltaic life cycles

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***Abstract*—PV module stability, in terms of reduced degradation rate and increased lifetime, provides an important lever for reducing the levelized cost of energy and life cycle environmental impacts of PV systems. Adapting an earlier value of efficiency methodology, the PV module cost per watt entitlement for a 30-year system lifetime is estimated to be $0.0125/W per 0.1% reduction in annual degradation rate, based on LCOE calculations. From an environmental perspective, the life cycle carbon footprint of a ground-mount PV system in a high solar resource location can be reduced by 0.3-1.0 g CO_2-eq/kWh per 0.1% reduction in annual degradation rate. Increasing average PV module lifetime from 30 to 50 years will further increase these benefits, would reduce annual replacements by 40% and would result in net deferment of 62% of the projected module decommissioning through 2050 for PV modules installed in 2020. Increasing lifetime of state-of-the-art PV modules by 20 years to harvest the value of stability fully will require reducing PV module degradation rates to 0.2%/yr.**

I. Introduction

When evaluating progress towards SunShot program goals, the U.S. Department of Energy (DOE) postulated that stability (in terms of degradation rate and system lifetime) may be equally important as photovoltaic (PV) module conversion efficiency in achieving aggressive levelized cost of energy (LCOE) targets [1]. Specifically, the SunShot 2030 LCOE targets for utility PV installations were based on an degradation rate of 0.2%/yr and explored an extension of system lifetime from 30 to 50 years [2][3].

In 2019, Peters et al. [4] developed a new metric, the value of efficiency that can be adapted to evaluate the DOE's hypothesis regarding stability. The value of efficiency metric estimates the PV module cost increase ($\$/m^2$) that would be justified by a 1% improvement in PV module conversion efficiency, while keeping PV system LCOE fixed. In 2018, the value of efficiency for utility-scale systems in the U.S. was estimated to be $\$9.2/m^2$ per % change in efficiency [4], or $0.046/W per % change in efficiency for a PV module with 20% efficiency (0.2 kWp/m^2).

With respect to PV life cycles, degradation has a strong effect on not only life cycle cost, but also life cycle environmental impacts. A standard assumption in life cycle assessment (LCA) of PV systems is a long-term degradation rate of 20% over 30 years (or 0.7%/yr) [5]. In addition, waste projections regarding end-of-life PV modules assume a PV module lifetime of 30 years [6], which could potentially be extended to 50 years given a 0.2%/yr degradation rate.

In this study, the value of stability in PV life cycles is evaluated from the perspectives of life cycle cost, embodied carbon, and future waste projections.

II. Methods

The U.S. National Renewable Energy Laboratory (NREL) System Advisor Model (SAM) was utilized to estimate the economic value of stability. The model inputs from the SunShot 2020 utility-scale scenario were utilized as a baseline [2]. The baseline degradation rate of 0.2%/yr was varied between 0.1% to 1.0%/yr and the PV module direct capital cost ($/W) was co-varied to keep PV system LCOE fixed at the SunShot 2020 utility-scale target of 4.5 US cents per kWh for a high solar resource location in the U.S. (Daggett, CA) with 30 year system lifetime.

To assess the value of stability on embodied carbon of PV systems, the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) ENVI-PV LCA screening tool [7] was used to estimate the life cycle carbon footprint of ground-mount PV systems in a high solar resource location in the U.S. (Daggett, CA) with 30 year system lifetime. In addition to the default degradation rate of 0.7%/yr [8], the ENVI-PV tool output was varied with rates between 0.1% to 1.0%/yr.

To assess the value of stability on future PV module decommissioning, the Weibull distribution for module failure is taken from the IRENA/IEA PVPS Task 12 [6] case of 30 year average lifetime (T; in years), and also modeled with a 50 year average lifetime. The cumulative probability of loss (F) as function of time (t; in years) is:

$$F(t) = 1 - e^{-(t/T)^{\alpha}} \quad (1)$$

where α: Weibull shape factor (5.3759 for T=30 yr; 8.7484 for T=50 yr) [9].

III. Results

A. Economic value of stability

As shown in Figure 1, PV module costs meeting the SunShot 2020 LCOE targets range from $0.41/W at 0.1%/yr degradation rate to $0.30/W at 1.0%/yr degradation rate, with system lifetime of 30 years. Based on the slope of the graph, the economic value of stability is $0.0125/W per 0.1% change in annual degradation rate. For example, a reduction in degradation rate from 0.6%/yr to the SunShot target of 0.2%/yr would be consistent with a module price advantage of $0.05/W (currently about 15% relative), while keeping system LCOE constant.

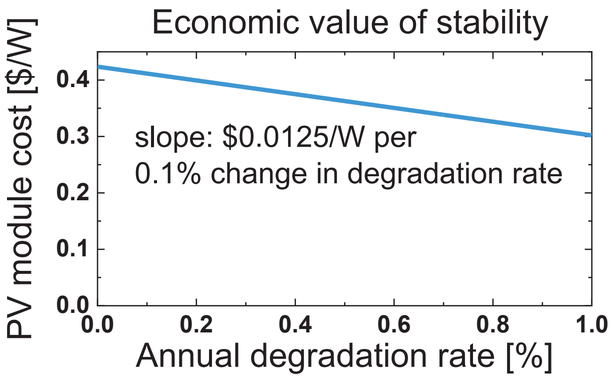

Fig. 1. Iso-LCOE plot (obtained with NREL SAM) displaying variations in PV module cost and annual degradation rate for achieving SunShot 2020 utility-scale LCOE target of 4.5 cents per kWh for a high solar resource location (Daggett, CA, USA) with system lifetime of 30 years. Lower annual degradation rates result in a cost advantage for achieving the fixed LCOE target. The slope of the iso-LCOE plot indicates the economic value of stability.

B. Embodied carbon value of stability

From an LCA perspective (Fig. 2), the life cycle carbon footprint of a ground-mount PV system in a high solar resource location (Daggett, CA, USA) ranges from 56 g CO_2-eq/kWh at 0.1%/yr degradation rate to 65 g CO_2-eq/kWh at 1.0%/yr degradation rate for mono-crystalline silicon (mono-c-Si PV). For thin-film cadmium telluride (CdTe PV), the life cycle carbon footprint of a ground-mount PV system in a high solar resource location ranges from 17 g CO_2-eq per kWh at 0.1%/yr degradation rate to 20 g CO_2-eq per kWh at 1.0%/yr degradation rate. These calculations use a global production mix for each of the PV technologies based on relative contributions of Asian & Pacific, Chinese, European, and North American supply chains [8] Based on the slope of these two cases, the embodied carbon value of stability is 0.3to1.0 g CO_2-eq/kWh per 0.1% change in annual degradation rate, depending on technology. Following the above example, a reduction in degradation rate from 0.6%/yr to the SunShot target of 0.2%/yr would decrease the system life cycle carbon footprint by 1.2 g CO_2-eq/kWh in the CdTe PV case and by 4 g CO_2-eq/kWh in the mono-c-Si PV case, or 6% relative for both.

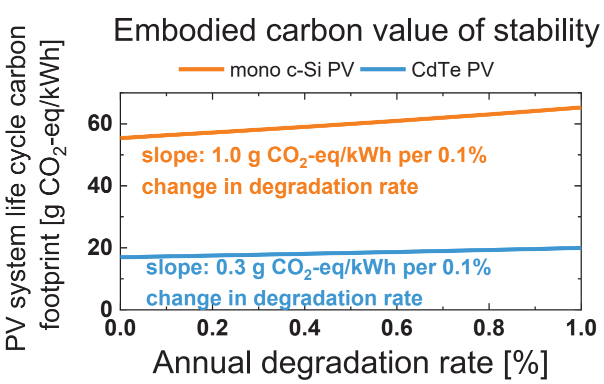

Fig. 2. Life cycle carbon footprint (obtained with ENVI-PV) as a function of annual degradation rate for a ground-mount PV system in a high solar resource location (Daggett, CA, USA) with system lifetime of 30 years. mono-c-Si-PV) Mono-c-Si and CdTe PV are shown with slope indicating the embodied carbon value of stability.

C. End-of-life deferment value of stability

Concerning projections of module decommissioning, Fig. 3 shows a dramatic difference in loss rates over the next 30 years (through 2050 for modules deployed in 2020), with a cumulative probability of loss of 63% for PV modules with average 30 year lifetime compared to a cumulative probability of loss of 1% for PV modules with average 50 year lifetime. The increase in average lifetime results in net deferment of 62% of projected module decommissioning through 2050 for PV modules installed in 2020, and an overall decrease of end-of-life waste based on ~40% fewer modules needed over a 50 year period.

There are multiple advantages to deferring module decommissioning. One is the additional time gained for developing a full recycling infrastructure; another is the lower required recycling capacity. Thirdly, the efficiency of resource utilization is proportionally increased with product lifetime. Resource depletion has been identified as a hotspot in the product environmental footprint of PV [10]. Over the next decades, as PV manufacturing transitions from rapid growth to maintenance of existing capacity, end-of-life resource recovery can provide a meaningful contribution to raw material supply for the industry.

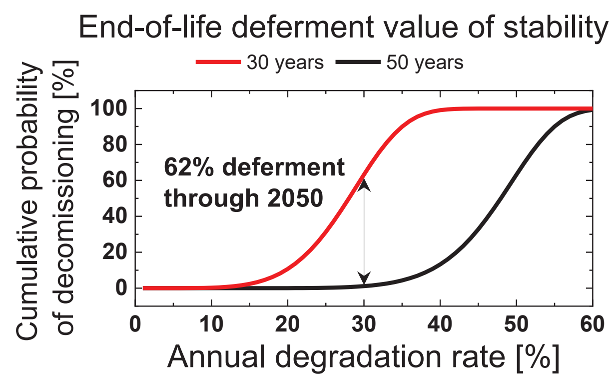

Fig. 3. Probability of PV module loss based on 30 and 50 year average lifetime obtained with Weibull distribution (Eq. 1). Difference between loss curves indicates end-of-life deferment value of stability.

IV. Discussion

A. Economic value of stability

The results in Fig. 1 help evaluate DOE's hypothesis that stability could be equally important to module efficiency in achieving LCOE targets. As shown in the slope of Fig. 1, the PV module cost per watt entitlement is estimated to be over 1 U.S. cent/W per 0.1% reduction in annual degradation rate. Based on Peters et al. [4], the PV module cost per watt entitlement is about half a U.S. cent/W per 0.1% improvement in module efficiency, supporting DOE's hypothesis. In their analysis, Peters et al. also indicated that degradation has a strong effect on LCOE, with a variation in module cost of ~$0.10/W for a variation in module degradation rate of 0.6%/yr to 1.1.%/yr while keeping LCOE fixed at 5.2 cents per kWh. Their analysis indicates a value of stability of ~$0.02/W per 0.1%/yr change in module degradation rate. This value is similar to and slightly higher than the estimate in this study.

B. Embodied carbon value of stability

As with improvements in module efficiency, reductions in annual degradation rate can proportionally reduce the life cycle carbon footprint of PV systems, but more energy efficient manufacturing and/or use of low carbon electricity in manufacturing would be needed for more significant reductions in embodied carbon [11].

C. End-of-life deferment value of stability

Following the waste management hierarchy of reduce, reuse, and recycle, stability can make a significant contribution to reducing waste through 2050 if lower annual degradation rates result in longer lifetimes for PV modules. Given a 0.2%/yr annual degradation rate, PV modules would retain 94% of their nameplate power rating after 30 years. The ability to increase average module lifetime from 30 to 50 years would then not be limited by power loss from long-term degradation.

In recent years, a number of research initiatives have tackled PV module reliability including the International Photovoltaic Quality Assurance Task Force (PVQAT) and the IEA PVPS Task 13 committee on performance, operation and reliability of PV systems. NREL has evaluated field data from thousands of PV modules and systems with regard to historical and current failure and degradation mechanisms and rates [12-15]. Along with power loss from long-term degradation, failure mechanisms such as those related to encapsulant, backsheet, frame, solder bond, cell cracking, glass breakage, and diode/junction box [13] would have to be minimized to enable longer average module lifetimes for PV modules.

D. Module versus system degradation

Annual degradation rates can apply to both PV modules and systems. In this study, long-term PV module degradation is assumed to govern the PV system degradation rate. In reality, module degradation is one of several factors that determines system degradation. While failures in balance of system components such as inverters, trackers, and breakers can cause PV system degradation, these component failures can be readily detected and addressed in the case of utility-scale PV systems that are professionally operated and maintained [12]. Therefore, in this study, PV module degradation rates are assumed to approximate PV system degradation rates in NREL SAM [16].

E. System lifetime

The economic value of stability has been shown to be significant, assuming a constant system lifetime of 30 years, but would be considerably higher if it enabled a longer system lifetime. Figure 4 shows the system lifetime multiplier associated with reducing annual degradation rate. For example, lowering degradation from 0.5%/yr to 0.3%/yr increases lifetime by a factor of 1.68, thus boosting a 30 year lifetime to 50 years.

F. Further research

While PV module reliability has improved over time, median annual degradation rates (~0.5-0.6%/yr; post-2000) [14-15] are still higher than the 0.2%/yr SunShot target. Improving these rates requires understanding the primary mechanisms of long-term degradation and addressing them. In the case of thin-film PV modules, pathways to improving long-term degradation rates have been identified by eliminating diffusion of Cu, a key determinant of stability for CdTe PV technology [17].

Research on improving PV module conversion efficiency beyond Shockley-Queisser limits has focused on thin-film-silicon tandem devices. These devices require a "marriage of equals" [18] between the top and bottom cell both with regard to efficiency and stability, in order to outcompete single junction devices. The value of stability is clearly exemplified in research on perovskite-silicon tandem devices, where minimizing degradation of the perovskite top cell is a major research priority [19].

The SunShot LCOE targets discussed in this study were achieved even without maximizing the value of stability. For example, the median LCOE in the U.S. in 2018 for utility-scale solar (without the 30% investment tax credit) was $53.8/MWh [20], comparable to the SunShot 2020 utility-scale target of 6 cents per kWh for a moderate solar resource location in the U.S. [2]. The value of stability offers an opportunity to further accelerate PV deployment from both an economic and environmental perspective.

V. Conclusion

Estimates on the value of stability (module cost entitlement of $0.0125/W per 0.1% reduction in annual degradation rate) support the hypothesis that stability (in terms of degradation rate and system lifetime) may be equally important as PV module conversion efficiency in achieving aggressive LCOE targets. From an environmental perspective, the life cycle carbon footprint of a ground-mount PV system in a high solar resource location can be reduced by 0.3-1.0 g CO_2-eq/kWh per 0.1% reduction in annual degradation rate. Further reductions in embodied carbon require more energy efficient manufacturing and/or use of low carbon electricity in manufacturing. Increasing average PV module lifetime from 30 to 50 years can result in net deferment of 62% of projected decommissioning through 2050 for PV modules installed in 2020, and further increase the economic value of stability.

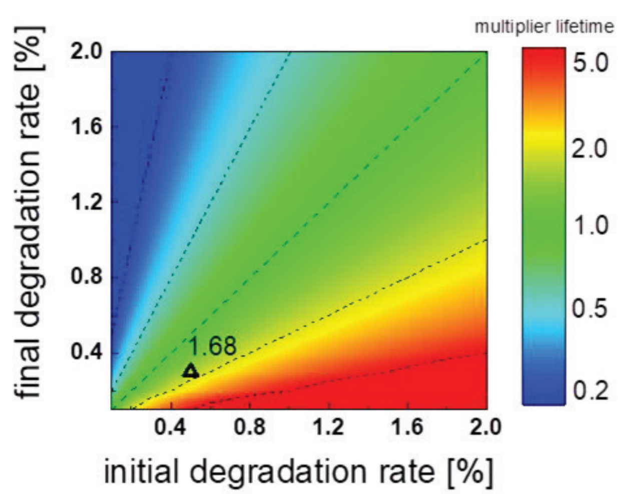

Fig. 4. System lifetime multiplier based on change in annual degradation rate.

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CORRIGENDUM: X-AXIS OF FIGURE 3 SHOULD BE “YEAR”