Evaluating material circular efficacy of waste-management scenarios using PV ICE (PV in the Circular Economy) tool

Acadia Hegedus[1], Silvana Ovaitt[2], Julien Walzberg[2], Heather Mirletz[2,3], Teresa Barnes[2]

[1]Middlebury College, [2]National Renewable Energy Laboratory, [3]Colorado School of Mines

Introduction

- To meet the nation's clean energy needs, it is projected that at least 1 TW of solar photovoltaics (PV) will be installed by 2050 [1]. To make this transition to solar energy sustainable, planning for a circular economy that maximizes reuse, repair, and recycle is crucial.
- PV ICE (PV in the Circular Economy) is a modeling tool that quantifies future mass flows of PV based on dynamic, real-world data.
- **Objective:** Evaluate circular efficacy of waste-management interventions, while considering social factors, using PV ICE [2].

Methods

PV ICE baseline (Fig. 1) and 9 intervention scenarios from Walzberg et al.'s agent-based model (ABM) were analyzed [3]. An ABM integrates behavioral science to predict the decision-making of simulated actors, considering the influence of social factors. The ABM quantified future recycle, reuse, and repair rates for certain waste-management interventions (Fig. 2).

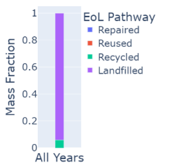

Figure 1: Yearly Mass Fraction of Material in EoL Pathways PV ICE Baseline

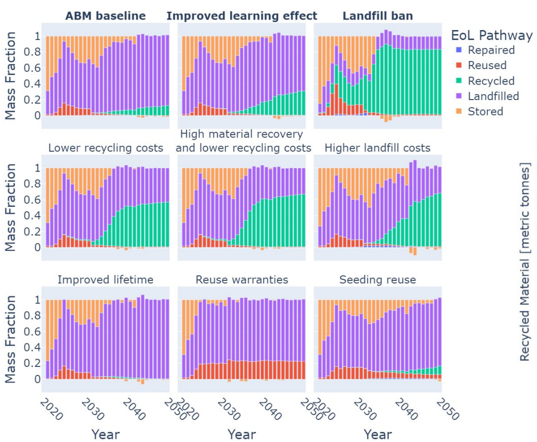

Figure 2: Yearly Mass Fraction of Material in EoL Pathways from ABM

Simulation types* run in PV ICE:

- Current Recovery (S1): Reuse, repair, and recycle rates modified based on the ABM outputs. Recovery rates left at default values.
- Ideal Recovery (S2): Recycling efficiencies replaced with Full Recovery End-of-Life Photovoltaic (FRELP) [4] recovery rates. All recycled end-of-life (EoL) materials reused for manufacturing.
- Reliability Same New Installs (S3): For **relevant scenarios**, reliability parameters modified to represent modules of different quality [5].
- Reliability Maintaining Capacity (S4): New installs modified so installed capacity is maintained, compensating for lower reliabilities.

*Each simulation includes all previous simulations' parameter modifications

Results

Improving Material Recovery Rate Increases Circularity

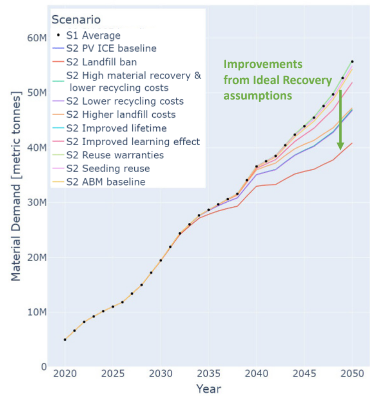

Figure 3: Cumulative Virgin Material Demand

Improving circular pathway rates in Current Recovery (S1, dotted line) has no effect on virgin material demand, unless ideal recovery rates and a closed loop are assumed as in Ideal Recovery (S2, solid lines).

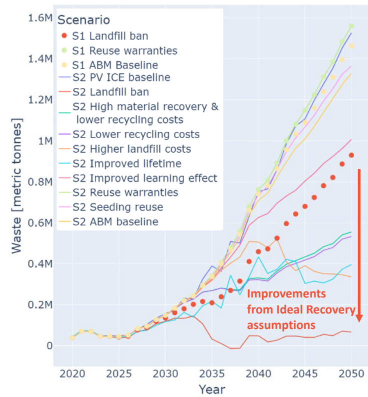

Figure 5: Yearly Waste (EoL + MFG)

In Ideal Recovery (S2, solid lines), waste is decreased further than in Current Recovery (S1, dotted lines).

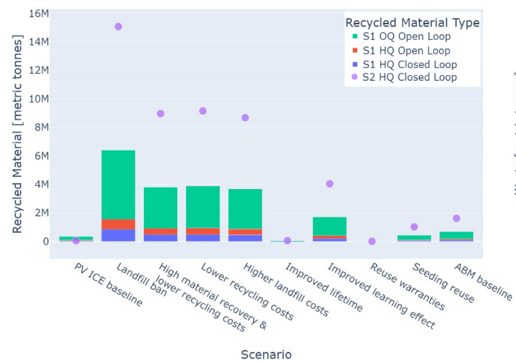

Figure 4: Cumulative Recycled Material at 2050

In Current Recovery (S1), the loop remains mostly open (see bars). In Ideal Recovery (S2), the loop is closed, with all recycled material going back into PV manufacturing (see dots).

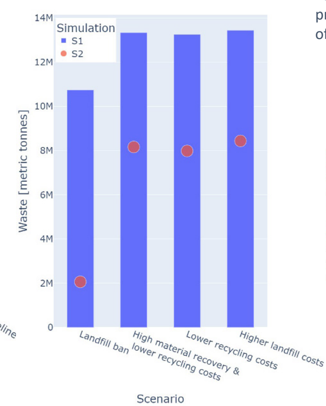

Figure 6: Cumulative Waste (EoL + MFG) at 2050

Increasing recycling efficiencies to ideal values (Ideal Recovery (S2), dots) minimizes cumulative waste compared to Current Recovery (S1, bars).

Installed Capacity

Installed capacity, or the amount of active, generating PV in the field, remained the same between S1 and S2. The installed capacity at 2050 was 0.77 TW for all scenarios, except for Improved lifetime, which had 0.95 TW. This points to the importance of Reliability for maintaining renewable energy generation.

Improving Reliability Increases Circularity

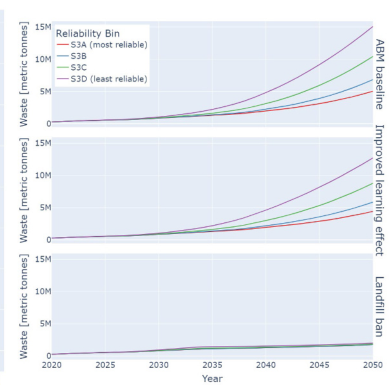

Figure 7: Cumulative Waste Varying Reliability

In Reliability Same New Installs (S3), more reliable modules minimize waste (Fig. 7) and maximize installed capacity (Fig. 8). However, virgin material demand (Fig. 9) is highest for more reliable modules. Less reliable modules produce more EoL material, providing more opportunities for recycling and offsetting virgin material demand.

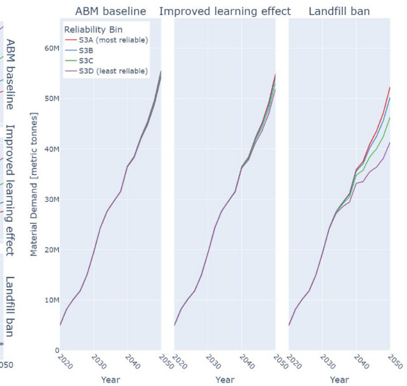

Figure 9: Cumulative Virgin Material Demand for Various Reliability Bins

When new installs are increased for lower reliability bins to match bin A's installed capacity (Reliability Maintaining Capacity (S4)), less reliable modules demand more virgin material (Fig. 10).

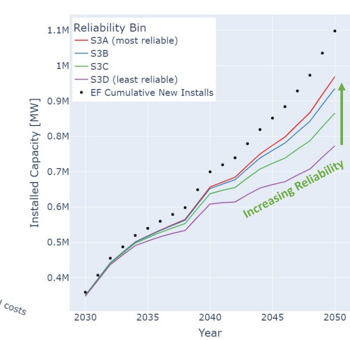

Figure 8: Installed Capacity Varying Reliability

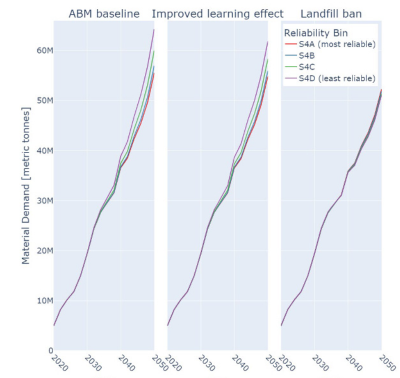

Figure 10: Cumulative Virgin Material Demand Varying Reliability & Maintaining Installed Capacity

Conclusion

- Agreeing with results from the ABM, the landfill ban scenario minimizes waste. This intervention also demands the least virgin material when ideal recovery and closed loop values are assumed.
- Installed capacity, however, depends on reliability. Improving reliability not only maximizes installed capacity but all other circularity metrics within a scenario when capacity is maintained.
- However, mass circularity does not provide a complete picture. Further research is needed to understand energy and cost effectiveness of the given waste-management interventions.

[1] Murphy, Caitlin, et al. 2021. *Electrification Futures Study: Scenarios of Power System Evolution and Infrastructure Development for the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72330.
[2] Silvana Ayala, Heather Mirletz, & Acadia Hegedus. (2021). NREL/PV_ICE: Release version 2 (v0.2.0). Zenodo.
[3] Walzberg, Julien, et al., accepted. *Role of social factors in success of solar photovoltaic reuse and recycle programs*. Nature Energy.
[4] Heath, G.A., Silverman, T.J., Kempe, M. et al. *Research and development priorities for silicon photovoltaic module recycling to support a circular economy*. Nature Energy **5**, 502–510 (2020)
[5] Hieslmair, Henry, et al. *Assessing the useful life of PV modules*. PVRW 2021.

This work was authored [in part] by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. It was also supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internship (SULI). The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

NREL/PO-5K00-80715

NREL Intern Symposium
Golden, CO
August 12, 2021