Closing the Loops on Solar Photovoltaics Modules

An agent-based modeling approach for the study of circular economy strategies

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Background

- ***Problem:*** ***Between 2015 and 2060, demand for raw materials are expected to increase (87000% for electric vehicles, 3000% for PV) [1]***
- ***Solution:*** ***The circular economy (CE) encourages material efficiency, e.g., through reusing or recycling products***
- ***Example:*** ***2050 projected PV waste: 7.5-10 million t → CE could capture value from waste, lowering demand for raw materials [2]***
- ***How?*** ***Industrial symbiosis (IS) and end of life (EoL) behaviors are key enablers for closing the loops of solar photovoltaics [3-4]***

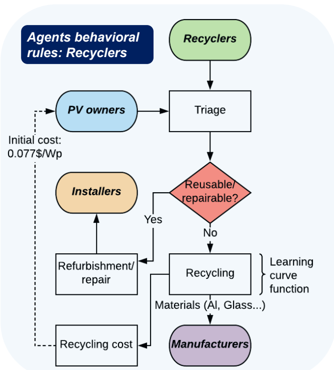
Approach

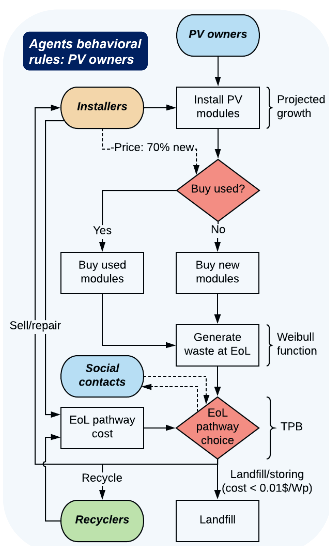
- ***Research question:*** ***What factors behind relationships and decisions of PV actors will help lead to increased circularity of PV systems?***
- ***Agent-based modeling (ABM): bottom-up method simulating a system's behavior from its entities (agents) which interact with each other and their surroundings***
- ***EoL behaviors based on Theory of Planned Behavior (TPB) [5] → depend on people's attitude, subjective norms (peer pressure), and cost (Fig. 1)***
- ***Manufacturers-recyclers relationship based on industrial symbiosis [3]***
- ***Baseline scenario based on literature: 30% initial recycling rate [2], 55% potential repair rate [6], TPB parameters from [5] (Table 1)***

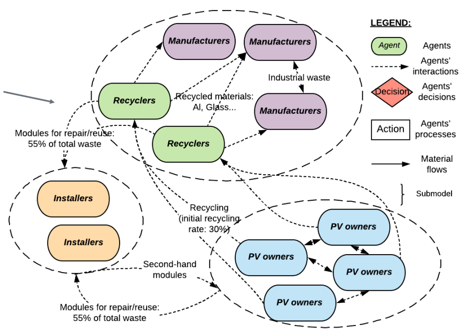
Model's parameters	Values
Initial recycling rate	30%
Repair rate	55%
Recycling costs	25-30 ($/Module)
Landfilling costs	0.6-2.1 ($/Module)
Second/first-hand module price ratio	40-100%
Repair cost	3.5-49 ($/Module)

Table 1: Model's parameters and values (We welcome your feedback!)

Figure1: Architecture of the ABM and agents' behavioral rules







Results

- ***The secondary market quickly becomes the EoL pathway of choice because it is financially beneficial but is limited by the repair potential of modules (Fig. 2)***
- ***The recycling and reuse EoL pathways compete with one another: selling is beneficial for PV owners, and subjective norms drive recycling behaviors***
- ***As recycled PV waste increases, recycling costs decrease, which further drive recycling behaviors (Fig. 3, Table 2)***

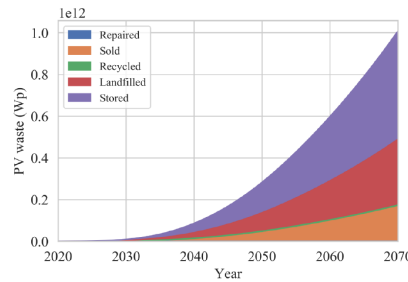


Figure 2: Distribution of PV waste according to each EoL pathway for the baseline scenario

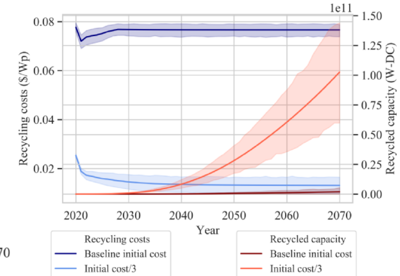


Figure 3: As recycled PV volumes increase, recycling costs plummet

Table 2: A lower initial recycling cost leads to a greater amount of PV waste diverted from landfill

Shares of waste in each EoL pathway	Initial recycling cost	Recycling cost / 3
Recycled	1%	10%
Repaired /sold	17%	16%
Landfilled /stored	82%	74%

Conclusion

- ***ABM enables identifying factors favoring certain EoL pathway e.g., the subjective norms, the cost related to each behavior and the initial recycling cost (Table 2)***
- ***Based on available data, one factor leading to increased circularity of PV systems is a low initial recycling cost which could be achieved through R&D in recycling processes***

References

[1] Sovacool, B. K., et al. (2020). "Sustainable minerals and metals for a low-carbon future." Science.
[2] IRENA & IEA (2016). End-of-Life Management: Solar Photovoltaic Panels.
[3] Mathur, N., et al. (2020). "Promoting a circular economy in the solar photovoltaic industry using life cycle symbiosis." Resources, Conservation and Recycling
[4] Salim, H. K., et al. (2019). "Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: A systematic literature review." Journal of Cleaner Production
[5] Tong, X., et al. (2018). "Behaviour change in post-consumer recycling: Applying agent-based modelling in social experiment." Journal of Cleaner Production.
[6] Tsanakas, J. A., et al. (2019) "Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification." Progress in Photovoltaics

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