Quantifying Energy Flows in PV Circularity Processes

Preprint

Heather M. Mirletz,[1,2] Silvana Ovaitt,[1] Ashley Gaulding,[1]
Seetharaman Sridhar,[3] and Teresa Barnes[1]

1 National Renewable Energy Laboratory
2 Colorado School of Mines
3 Arizona State University

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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Quantifying Energy flows in PV Circularity Processes

Heather M. Mirletz[1,2], Silvana Ovaitt[1], Ashley Gaulding[1], Seetharaman Sridhar[3], Teresa Barnes[1]

[1]National Renewable Energy Laboratory, Golden CO 80401 US,
[2]Advanced Energy Systems Graduate Program, Colorado School of Mines, Golden CO 80401,
[3]Arizona State University, Research and Innovation Fulton Schools of Engineering, Tempe, AZ 85281 USA

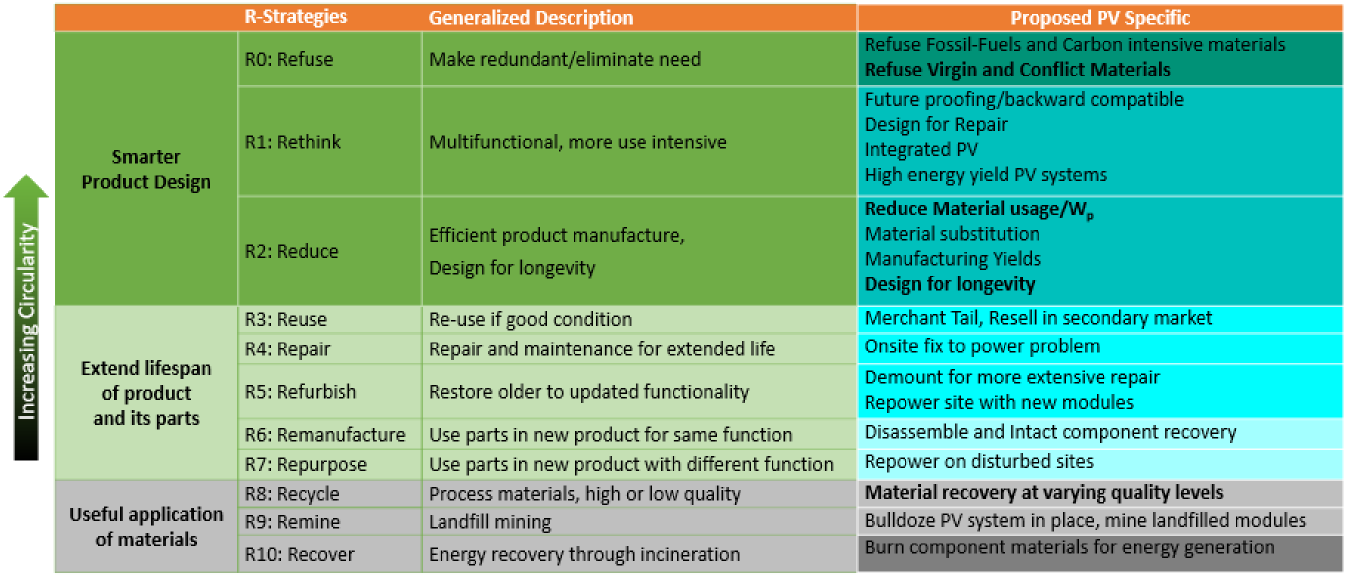
***Abstract*—As sustainable deployment and end-of-life management become a hot topic to timely address in the PV community, a dynamic comparative evaluation of the benefits of circular pathways such as reuse, and remanufacturing, recycling has not been performed holistically beyond material flows or LCA analysis. Energy flows are critical for evaluating energy generation technologies. Previously they have been used to compare renewables to fossil generation and then between PV technologies. This paper quantifies energy flows to evaluate circular pathways for PV. The energy flows tracking manufacturing, generation, and losses complementary to the mass flows of silicon are quantified leveraging the PV ICE framework.**

***Keywords*—circular economy, photovoltaics, energy return on investment (EROI), remanufacture, recycle, energy flows**

I. INTRODUCTION

To avoid catastrophic climate change, we need to decarbonize our energy sectors by deploying renewables, such as PV. But this requires unprecedented scale-up for manufacturing and deployment. For example, the US currently has 100 GW on-grid and 5.5 GW of PV manufacturing capacity, and the recent Solar Futures study from NREL [1] projects that 1 TW is required by 2035 and 1.5 TW by 2050. This entails 30 GW annual deployment through 2025 and 60 GW annually through 2030. But this scale-up must occur globally, which will further strain global supply chains, as seen for glass and polysilicon. Alternate and transparent supply chains, such as those enabled by the circular economy (CE), are an opportunity to move away from price shocks, shortages, and negative environmental and social impacts. CE is an economic and industrial model for materials circulation, minimizing wastes and decoupling economic growth from the use of virgin resources, and underpinned by decarbonization [2]–[5].

Manufacturing is notoriously the most environmentally impactful step in a PV system lifecycle. PERC module (~80% of market share) manufacturing contributes to approximately 24 gCO_2 eq/kWh, or 92% of the technology's lifecycle global warming potential [6]. Manufacturing steps are an excellent opportunity to reduce the footprint of PV modules through steps like improved efficiencies, reducing embodied material mass, and alternate supply chains enabled by CE. For example, glass cullet presents an opportunity to reduce waste and lower energy requirements. Silicon kerf loss is also an opportunity for reduced costs, energy and manufacturing scrap, through use of diamond wire sawing and kerf slurry recycling.



	R-Strategies	Generalized Description	Proposed PV Specific
Smarter Product Design	R0: Refuse	Make redundant/eliminate need	Refuse Fossil-Fuels and Carbon intensive materials **Refuse Virgin and Conflict Materials**
	R1: Rethink	Multifunctional, more use intensive	Future proofing/backward compatible Design for Repair Integrated PV High energy yield PV systems
	R2: Reduce	Efficient product manufacture, Design for longevity	**Reduce Material usage/W$_p$** Material substitution Manufacturing Yields **Design for longevity**
Extend lifespan of product and its parts	R3: Reuse	Re-use if good condition	Merchant Tail, Resell in secondary market
	R4: Repair	Repair and maintenance for extended life	Onsite fix to power problem
	R5: Refurbish	Restore older to updated functionality	Demount for more extensive repair Repower site with new modules
	R6: Remanufacture	Use parts in new product for same function	Disassemble and Intact component recovery
	R7: Repurpose	Use parts in new product with different function	Repower on disturbed sites
Useful application of materials	R8: Recycle	Process materials, high or low quality	**Material recovery at varying quality levels**
	R9: Remine	Landfill mining	Bulldoze PV system in place, mine landfilled modules
	R10: Recover	Energy recovery through incineration	Burn component materials for energy generation

Fig. 1. Circular economy provides various value retention options or pathways. These pathways can reduce the environmental intensity of decarbonization-scale PV deployment, but an evlauation not only of the virgin material needs and waste reductions but of the energy flows is necessary.

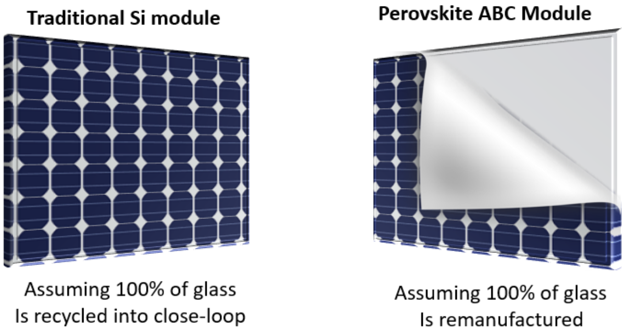


Fig. 2 Diagram of the two evaluated scenarios: 100% recycled modules, vs 100% remanufactured modules. Glass remanufacture is potentially enabled by technology designs such as the perovskite all-back-contact architectures. Scenarios are evaluated on material and energy flows of glass.

Most energy transition studies focus on critical or near-critical material demands, such as Ag, Cu, In, Te [7]. Suggested mitigation strategies for material supply shortages include recycling and decreased embodied material mass, but impacts on energy demands and generation are not quantified. Circularity is not correlated to reduced environmental impacts [7], [8]. The energy demands of recycling have been studied, but there is a lack of studies comparing the energy demands of other circular pathways, such as those shown in Fig. 1.

Glass is an ideal target for increasing PV material circularity. Glass represents ~80% of a module’s weight and accounts for significant energy demands in manufacturing (second to silicon) [9]. PV glass is high-quality, low-iron, and not currently closed-loop recycled. Closing the loop would reduce sand mining requirements—but quality and lifetime must be maintained to maintain capacity and avoid increased deployment [10]. Currently, closed-loop recycling is cost and energetically expensive. Alternatively, PV glass remanufacturing could be enabled by reliable and innovative module designs.

This paper establishes a methodology for capturing PV technology energy requirements, generation, and losses considering manufacturing evolutions and emerging technology trends. Two module technologies are compared: a traditional G/G Si module with closed-loop glass recycling, and a hypothetical perovskite module with all-back-contact (ABC) architecture enabling front glass remanufacturing (Fig. 2). The energy analysis is run parallel to material flows for each step in a circular photovoltaic lifecycle. Finally, a discussion of the tradeoffs of different pathways is presented.

II. METHODOLOGY

A. PV ICE Tool Overview

PV in Circular Economy (PV ICE) [11] is an open-source tool providing decision-makers with a data-backed, energy and mass-flow-based evaluation of CE pathway decisions for PV. Given known (historic) and expected (future) average bill of materials and processes for deployed PV, it can estimate material demands, wastes, installed capacities, and energy expenditure, accounting for changes in PV designs, performance, and market shares. Here, we use PV ICE's ability to track energy and mass flows to estimate the impact of various circular pathways available for PV. We compare recycling versus remanufacture of glass.

Energy flows are quantified for each lifecycle stage; virgin material extraction, manufacturing, use phase, EoL, and circular pathways. Where possible, technology-based energy flows are used. For example, the energy demand to grow monocrystalline silicon ingots has decreased with time. Similarly, the energy requirements to cast mc-Si are not the same as mono-Si ingot growth—the energy demands will be weighted by technology market share. Technology evolution is reflected in the dynamic annual energy flows.

The recycling process considers how many modules are recycled, if each module material(s) is a recycling target, and the yield and the energy needs associated with recycling of that material. Quality and disposition (i.e., closed-loop) of the recycled material are also considered. Recycling energies for low- and high-qualities and closed-loops are calculated. This is compared to module collection and material(s) remanufacturing. The yield of the remanufacturing process accounts for losses due to reverse logistics, contamination, and broken components for remanufacturing and the energetic needs.

For this paper, lifetime assumptions (including reliability and economic project lifetime) are the same for both technologies. Collection efficiencies are also assumed to be the same at 100%. Reuse and repair are set to 0% to explore only recycling and remanufacture pathways. In the first case, 100% of the modules are recycled, with 100% of the glass in those modules recycled at variable yield between 50-80%. For the second case, 50-80% of the glass+TCO is recovered intact for remanufacture.

B. PV Energy Framework

Renewable energy technologies generate power over their useful life, offsetting energy required for manufacturing in a quantity known as Energy Return on Investment (EROI). For this tool, EROI is defined as:

$$EROI = \frac{\sum E_{out}}{\sum E_{in}}$$

In addition to nameplate installed capacity, the PV ICE tool calculates effective capacity in the use phase by considering both newly installed modules and module degradation by years in service. This consideration of degradation along with the bottom-up material and energy accounting enables evaluation of circular decisions such as field repair, off-site refurbishment, reuse, or recycling in both energy and material dimensions.

DISCUSSION

As modules with higher efficiency and power become the new norm and PV deployment increases, understanding the impacts of virgin material extraction, waste, and energies can enable stakeholders to plan for improved circularity or energy efficiency. Fig. 3 shows diagrams material and energetic needs of a Si module with glass recycling, where glass is crushed and remelted, vs. a hypothetical ABC perovskite module where the glass is directly offset at the manufacturing stage, avoiding recycling or extraction energy needs.

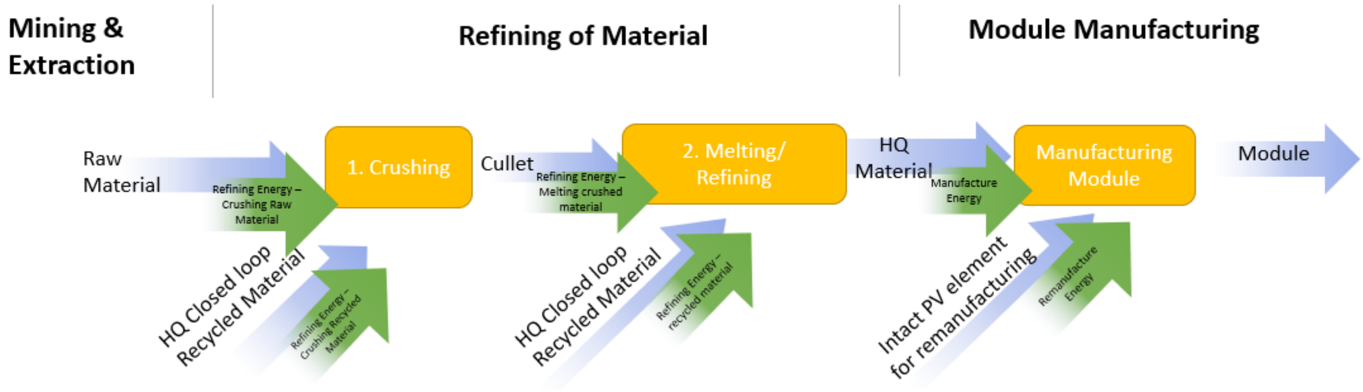


Fig. 3 Detail of the main energy pathways for recycled and remanufactured glass. PV ICE evaluates closed-loop energy offsets accounting for the manufacturing process; for example, energies for crushing and melting are captured separately to account for different circular feedstocks. Remanufactured PV glass is removed intact and feeds directly into the manufacturing of the module.

Technology advances can improve efficiencies throughout the PV module lifecycle. Policies can shape research focus and economically viable pathways through incentives. Research and policy priorities should be data-driven, and priorities can be clarified in terms of EROI and material benefits. We use the PV ICE tool to highlight key areas for improvements and tradeoffs:

- Design with alternative materials.
- O&M for increased system lifetime.
- In-field and out-of-field repairs vs repowering.
- Repair reliability, re-certification and warranty.
- Improved end-of-life module collection
- Industry targets for recycling yields and energies.
- Reducing material per module while maintaining or increasing production and operational efficiency.
- Recycling complexity and design for remanufacture.
- Identify complementary/symbiotic sectors for recycled PV materials of varying quality
- Understand current repowering practices.

III. SUMMARY

The PV ICE tool is flexible and scalable to accommodate temporal and geographical information, with dynamic flows that can consider multiple materials and energy flows. Future work includes implementing different energy technologies within this framework. For the conference, targeted efficiency improvements and potential CE pathways in the PV lifecycle will be evaluated on best material efficiency and EROI.

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REFERENCES

[1] K. Ardani *et al.*, "Solar Futures Study," EERE DOE, Sep. 2021. [Online]. Available: https://www.energy.gov/eere/solar/solar-futures-study

[2] E. A. Olivetti and J. M. Cullen, "Toward a sustainable materials system," *Science*, vol. 360, no. 6396, pp. 1396–1398, Jun. 2018, doi: 10.1126/science.aat6821.

[3] D. Smith and S. Jones, "Circularity Indicators: An Approach to Measuring Circularity: Methodology," Ellen MacArthur Foundation, 2019.

[4] J. Kirchherr, D. Reike, and M. P. Hekkert, "Conceptualizing the Circular Economy: An Analysis of 114 Definitions," *SSRN Electron. J.*, vol. 127, Jan. 2017, doi: 10.2139/ssrn.3037579.

[5] P. van Loon, D. Diener, and S. Harris, "Circular products and business models and environmental impact reductions: Current knowledge and knowledge gaps," *J. Clean. Prod.*, vol. 288, p. 125627, Mar. 2021, doi: 10.1016/j.jclepro.2020.125627.

[6] M. M. Lunardi, J. P. Alvarez-Gaitan, J. I. Bilbao, and R. Corkish, "A Review of Recycling Processes for Photovoltaic Modules," in *Solar Panels and Photovoltaic Materials*, B. Zaidi, Ed. InTech, 2018. doi: 10.5772/intechopen.74390.

[7] E. Gervais, S. Shammugam, L. Friedrich, and T. Schlegl, "Raw material needs for the large-scale deployment of photovoltaics – Effects of innovation-driven roadmaps on material constraints until 2050," *Renew. Sustain. Energy Rev.*, vol. 137, p. 110589, Mar. 2021, doi: 10.1016/j.rser.2020.110589.

[8] S. Harris, M. Martin, and D. Diener, "Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy.," *Sustain. Prod. Consum.*, vol. 26, pp. 172–186, Apr. 2021, doi: 10.1016/j.spc.2020.09.018.

[9] D. D. Furszyfer Del Rio *et al.*, "Decarbonizing the glass industry: A critical and systematic review of developments, sociotechnical systems and policy options," *Renew. Sustain. Energy Rev.*, p. 111885, Dec. 2021, doi: 10.1016/j.rser.2021.111885.

[10] H. Mirletz, S. Ovaitt, S. Sridhar, and T. Barnes, "PV Lifetime and Recycling to Mitigate Material Impacts of Decarbonization," *(submitted)*.

[11] S. Ovaitt & H. Mirletz, S. Seetharaman, and T. Barnes, "PV in the Circular Economy, A Dynamic Framework Analyzing Technology Evolution and Reliability Impacts," *ISCIENCE*, Jan. 2022, doi: https://doi.org/10.1016/j.isci.2021.103488.