More Than Recycling: How Should We Define Circularity Goals for PV in a Global Energy Transition?

Preprint

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MORE THAN RECYCLING: HOW SHOULD WE DEFINE CIRCULARITY GOALS FOR PV IN A GLOBAL ENERGY TRANSITION?

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ABSTRACT: Energy transition to carbon-free electricity is a crucial pillar of the Circular Economy [1]. Renewable energy reduces environmental impacts and decarbonizes the production of other goods. But, manufacturing renewable energy sources, such as photovoltaic (PV) modules, require energy inputs that are currently carbon intensive. So, how do we decarbonize and circularize these critical technologies to achieve a sustainable energy transition? This work proposes that effective capacity—the installed capacity accounting for degradation rates and failures—is a critical metric to evaluate renewable energy technologies on the path toward circular economy and energy transitions. Our analyses also emphasize the importance of examining a suite of metrics incorporating mass and energy flows to identify potential tradeoffs and inform design or lifecycle management decisions holistically.
Keywords: circular economy, energy transition, reliability

1 INTRODUCTION

Proposals for sustainable PV range from high-yield, high-efficiency paradigms, to short-lived but fully recyclable module designs, to long-lasting, reliable, indestructible modules [2]. Our work quantifies the benefits and tradeoffs of various PV design strategies in the energy transition context.

In this study, we analyze the mass and energy flows of several PV technologies on their ability to address energy transition and circular economy challenges, including:

- a high-efficiency module that is open-loop recycled at low rates (e.g., high-efficiency bifacial silicon),
- a short-lived module where components can be remanufactured or closed-loop recycled into a new module (e.g., perovskite),
- a long-lived, re-usable module with low recyclability (e.g. 50-year silicon module),
- a 100% recycled silicon wafer with a lower module efficiency [3]

We compare the ability of these module design scenarios to achieve energy transition deployment schedules and meet capacity targets. Then, we examine the quantities of virgin material demands, lifecycle wastes, energy demands, and energy generation. The module designs are compared on a module product basis and at an energy system scale. The analysis leverages the open-source, peer reviewed PV in Circular Economy (PV ICE) tool [4], [5]. PV ICE can quantify each module's embodied materials and energy and its energy generation capability. Additionally, the PV ICE tool can examine the effect of deploying each module design at the energy system scale, accounting for replacements, and quantifying progress toward circular economy and energy transitions.

2 RESULTS & CONCLUSIONS

Please see the full manuscript of this journal submitted to EUPVSEC EPJ for the expanded set of scenarios, methods, and results for the various mass and energy metrics. The complete paper should not exceed **1 MB including illustrations**. This is a very good proven capacity for final papers. Note that there is no limit in the number of pages. An adequate number is 3 to 6 pages.

3 RESULTS & CONCLUSIONS

Ideally, a renewable energy technology would be long-lived and fully circular—however, such a PV module does not yet exist, and aspects of one design priority may interfere with another (e.g., remanufacturing vs. indestructible). Therefore, this analysis compares PV design choices' material and energy impacts to meet and

Table I: Key parameters of 2022 module designs compared for sustainability in achieving Energy Transition. Module efficiency improves from 2022 to 205

Module Type	Lifetime (years)	Degradation Rate	Circular Features	Module efficiency	Bifacial Factor	Package
PV ICE Baseline [4]	35	0.5%	Downcycling	21%-25%	NA	Marketshare Weighted
SHJ	30	0.5%	Downcycling	23.5%-25.3%	0.9	Glass-glass
Idealized Perovskite Si-Tandem	15	1.47%	98% Remanufacture glass 98% Closed-loop Recycling Perovskite, Si, and Al frame	17.9%-32.5%	NA	Glass-glass
50-year PERC	50	0.445%	None, slowly increase to downcycling	21%-24.5%	0.7	Glass-glass
Recycled Si PERC [3]	25	0.5%	Glass downcycling 100% closed-loop recycled Si 98% closed-loop recycled Al frame	19% - 22%	0.6	Glass-glass

maintain deployment targets, prioritizing PV module improvements and lifecycle management. PV module designs under consideration are described in Table 1. This enables us to explore the extreme boundary cases of potential futures. PV ICE Baseline [4] is used as the comparison point throughout, as it captures historical and current trends of PV modules and represents a conservative projection of future PV module improvements.

This study analyzes these PV technologies' required mass and energy quantities to address energy transition and CE challenges. Furthermore, we compare the ability of these module designs to achieve energy transition deployment schedules and meet capacity targets. We compare the entailed quantities of virgin material demands, lifecycle wastes, energy demands, and energy generation for the Energy Transition scale deployments.

3 SCIENTIFIC AND INNOVATION RELEVANCE

Traditional CE metrics, such as the MCI [1], prioritize increased circularity over extension of the use phase and do not always align with a reduction in environmental impacts as measured by LCA [6]. However, the use phase for renewable energy technology is critical for both CE and Energy Transition goals; thus, a suite of mass and energy metrics should be used. Additionally, renewable energy technologies are infrastructure, so they should be circularized more like buildings than consumer products.

Five component materials of c-Si PV modules are tracked dynamically in the PV ICE tool and baselines: glass, silicon (Si), silver, aluminum (Al) frames, and encapsulated copper (excludes junction box). Historical shifts in material intensity are accounted for (e.g., decreasing silicon wafer thickness). The PV ICE tool accounts for manufacturing inefficiencies, quality or material purity levels, and several circular pathways for PV modules, including reuse, repair, remanufacture, and recycle in both open and closed loops. The energy flows parallel the mass flows, accounting for the energy demands throughout the lifecycle of the PV module.

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Inclusion and Diversity Statement: One or more of the authors of this paper self-identifies as an underrepresented ethnic minority in science. While citing references scientifically relevant for this work, we also actively worked to promote gender balance in our reference list.

Data and Code Availability Statement: Analyses process and source data for this publication support open-science and are available in the GitHub repository: https://github.com/NREL/PV_ICE/.

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