PV Evolution in the Light of Circular Economy

Preprint

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PV Evolution in the light of Circular Economy

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Abstract—**As photovoltaic (PV) deployments increase, the increasing material volume presents challenges throughout the supply chain and eventual end-of-life waste management. Quantifying the value of lifetime, reliability, repair, reuse, recycling, and other options to increase circularity can help identify and prioritize research and technical solutions required to integrate PV into the circular economy. In this work, we capture the evolution of PV module technology, such as improved reliability and increasing market share of glass/glass modules. We discuss material circularity, lifetime and reliability, and energy return on investment as quantitative metrics to define and evaluate circularity and sustainability.**

Keywords—circular economy, photovoltaics, energy return on investment (EROI), bifacial, technology evolution, reliability, repair, reuse, recycle

I. Introduction

Developing a circular economy (CE) for infrastructure and materials is necessary for a successful, lower impact, clean energy transition. As renewable energy deployment increases, ensuring a sustainable supply chain requires quantifying the material demands for exponential deployment and end-of-life (EoL) management for PV systems. Additionally, we need to understand how the composition and total mass of EoL PV will change over time. Several attempts have been made to predict future PV waste's mass and material composition. However, they have revealed a need for more detailed and accurate input data and a better understanding of PV components and system lifetimes. If we understand the potential material and energy flows during the entire lifecycle, we can assess how EoL and scrap material can follow circular material pathways to partially offset the massive virgin stock requirements for the energy transition.

The material composition of the PV waste stream is essential for stakeholders seeking to utilize the PV waste to offset virgin materials. The PV waste stream is currently sufficiently small that a dedicated recycling infrastructure is not economically feasible [1]–[4]. However, this waste stream is projected to grow exponentially. Foresight into the potential of the PV waste stream to meet the energy transition's material demands can enable stakeholders to make more intelligent decisions toward designing a CE for energy materials.

Similarly, accounting for the energy needed for different linear versus CE processes is critical for evaluating tradeoffs in technologies or processing. In particular, as module and cell efficiencies increase, enabling higher energy generation per area, and as modules become more reliable with longer lifetimes, the material and energetic needs, the energy produced, and the EoL pathways change significantly. All these changes must be considered for a complete evaluation of a circular PV module's impact on the environment. The shift to glass-glass packaging of bifacial silicon modules exemplifies this trend towards high energy density modules with potentially longer lifetimes.

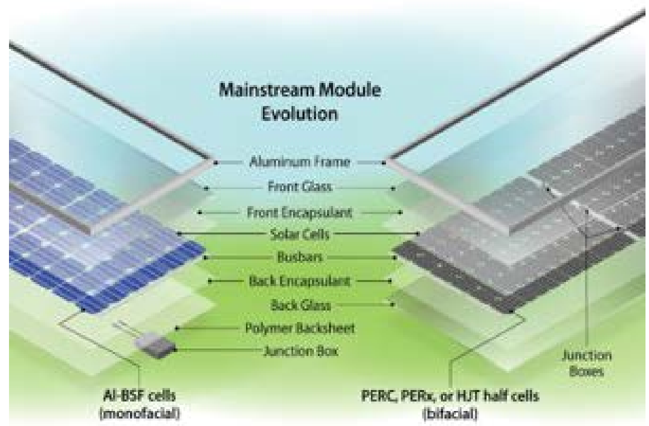

Fig. 1. PV module technology evolves quickly. Even with increased efficiencies, more materials are needed to meet demand. Increased quantities and rates of decommisioned modules can become valuable feedstock.

Previous waste projection methods to estimate PV waste mass and material composition are top-down; they use a single factor for mass per Watt peak of installed nameplate capacity (kg/W_p), a fixed lifetime or Weibull functions, and fixed percentages of module component materials per PV technology. Modifications accounting for PV technology evolutions are made primarily to the kg/W_p factor and Weibull parameters, as exemplified by the IRENA 2016 EoL Management Report [5]. Works by [1], [6], and [7] derive their waste projections methods from the IRENA 2016 report. Other authors use more straightforward fixed-lifetime assumptions and material composition as derived from sources such as Ecoinvent 3.3 ([8]–[10]). However, these methods do not capture the significant technological advances in PV modules and manufacturing.

This paper establishes a methodology for capturing PV technology evolution and evaluating emerging technology trends with the novel PV ICE tool. A dynamic material mass-flow analysis of different technology scenarios is performed, identifying key decision, policy, and research points that can significantly reduce PV material demands and wastes for a clean energy transition.

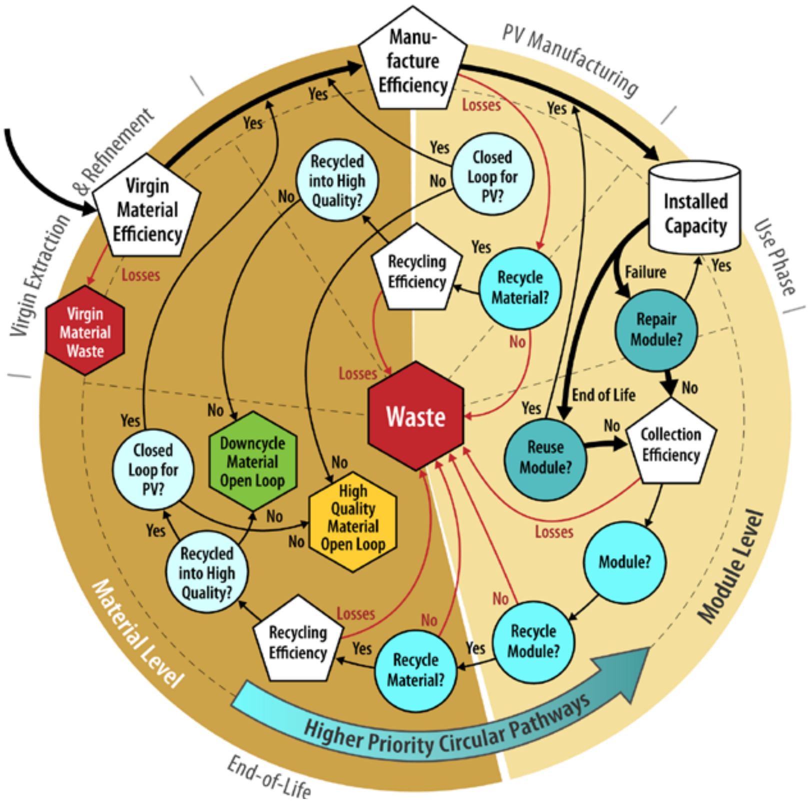

Fig. 2. Framework for evaluating material and energy needs throught the various processes and stages in a PV lifetime. Decision nodes enable circular pathways. Efficiencies on each stage capture the losses of material. Arrows identify the eneregitc needs for each process, with energy generated by the PV module during the lifetime or extended lifetime through mor reliable modules, repair/reuse a positive.

II. METHODOLOGY

A. PV ICE Tool Overview

Material circularity and lifetime energies are assessed through the PV In Circular Economy (PV ICE) tool [11]. This open-source tool was developed with a flexible framework using dynamic material flow simulation. The PV module lifecycle stages are represented in material dimensions (with future expansions into energy) and circular pathways encompassing reuse, repair, and recycling. As shown in Fig. 2, these circular pathways offset material demands at different points in the PV module lifecycle; ex: repair reduces EoL modules, recycling offsets virgin materials. PV module and material flows are distinguished, and spatial-temporal aspects of PV module deployment are explored using U.S. deployment predictions.

Modules reach EoL by degrading beyond 80% of nameplate power rating, by a designated project lifetime, or by Weibull probability failure. Shape parameters controlling the Weibull probability are calculated for each generation dynamically from PV module warranties, which have continuously increased to up to currently 30 years [12].

B. PV Technology Evolution

We utilize a bottom-up approach to calculate the mass material in an average-technology module through time, capturing material usage changes (ex: the decrease in silver per cell) and manufacturing process improvements (ex: diamond wire sawing). Additionally, by examining the module's complete lifecycle, we capture the mining and manufacturing wastes and EoL waste. Thus, the tool can explore the impacts of all CE levers (ex: reducing virgin mining and eco-efficiency), not just EoL management. Historical trends for PV modules and each component material are captured in separate baselines, 1995 through 2050. Sources and citations for all values can be found in the Jupyter journals and text documentation [11]. To populate future values, we utilize ITRPV 2021 projections, holding 2031 values constant through 2050.

A conservative 98% module manufacturing yield is assumed [13] with a 100% collection efficiency of manufacturing scrap from modules and materials. Some circularity is assumed in both scenarios. Module CE pathways are set to approximate current values; repair and reuse are 0%, 15% of EoL modules are collected for disposition, of which 40% are recycled. Effective rates of closed-loop recycling by PV component material are shown in Table 1, which is calculated from the multiple steps and decisions that lead to recycling. Open-loop recycling rates are higher, as they reflect a lower quality requirement, but do not offset the virgin material needs calculation for PV, so they are not addressed in this paper.

Table I Effective Close-Loop Recycling rate by material from Manufacturing Scrap and EoL material. These rates are calculated from the multiple yields and decisions along the recycling process, including module and material collection and recycling.

Closed-Looped Recycling	Glass	Silicon	Aluminum (frames)	Copper	Silver
Manufacturing	0.8%	0%	59%	23%-27%	11%-17%
EoL	0.03%	0%	2.5%	0%	0%

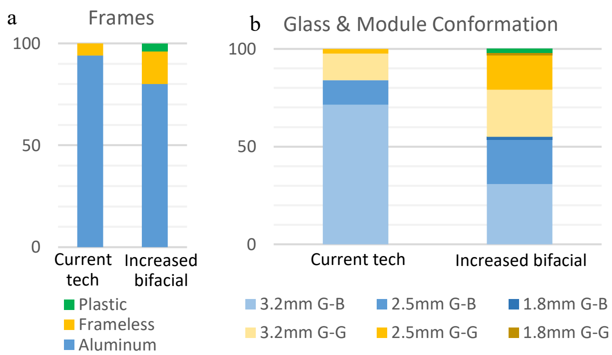

Fig. 3 Scenarios considered for module composition: 'Current tech', based in module composition of 2020, and 'Increased bifacial' trend, following ITRPV 2021 projections weighted for market share, module conformation, and front and glass thicknesses data.

For this study, we compare two scenarios with different predominant module technologies. The first is intended to reflect the state of the 2020 PV market with module composition and performance from 2020 held constant through 2050. The second scenario is reasonably likely but illustrates a significant change in module material requirements, identifying different potential material constraints. This scenario leverages ITRPV 2021 projections for bifacial modules and cells to increase market share up to 55% of module technology and 78% of cell technology in 2031, with glass-glass packaging comprising 43% of the market. These projections change the module composition, mainly in glass-per-module and aluminum, from an increase in frameless modules. Both scenarios are summarized in Fig. 3a and b as "Current tech" and "Increased bifacial." Calculations of mass per module for this projection can be found on Github. Aluminum in the cell is currently excluded from the analysis.

In addition to exploring 2020 technology versus a high bifacial technology future in terms of module composition, the potential installed capacity increase from the bifacial modules increased energy yield was calculated. Bifacial modules can yield higher production than their nameplate power, as the contribution from the rear irradiance is not considered when defining the nameplate power rating. Therefore, when designing a PV system for a targeted generation, it is possible to install fewer bifacial modules because of this increased yield. The reduction in the number of bifacial modules depends on its predicted energy yield, which depends on the bifaciality factor, the installation parameters, solar resource of the location, albedo, and desired DCtoAC ratio. PV ICE framework is based on newly installed capacity [W]. While there is not a correct way to assess bifacial energy gain without calculating the generation, a simplified model has been used where the effective irradiance for the bifacial modules is modified following the IEC TS 60904-1-2 bifacial measuring standard:

$$G_{eff} = 1000\ W/m^2 + 100\ W/m^2 * \phi \qquad [W/m^2]$$

This definition of effective irradiance G_{eff} for Bifi100 represents a commonly seen value of rear irradiance in bifacial installations to inform installers through its inclusion in bifacial modules datasheets, so it's adopted here as a way to assess the bifacial energy gain.

III. RESULTS

The results of this analysis can be explored at https://openei.org/wiki/PVSC_PVICE. As modules with higher efficiency and power become the norm, and PV deployment increases, understanding the resulting impacts on virgin material extraction, waste, and energies can enable stakeholders to plan for improved circularity or energy efficiency. Fig. 4 shows virgin material demands and waste mass calculated by the PV ICE tool using inputs from Electric Futures Study [14] for the reference US PV deployment projections. For the 'Current tech' and 'Increased bifacial' module composition projections, three different lifetime assumptions are explored: a) the Weibull-only methodology of "early loss" (2.49) and b) "regular loss" (5.3759), and c) the PV ICE lifetime model, which includes project lifetime, degradation, and Weibull failure probabilities that vary for each generation deployed.

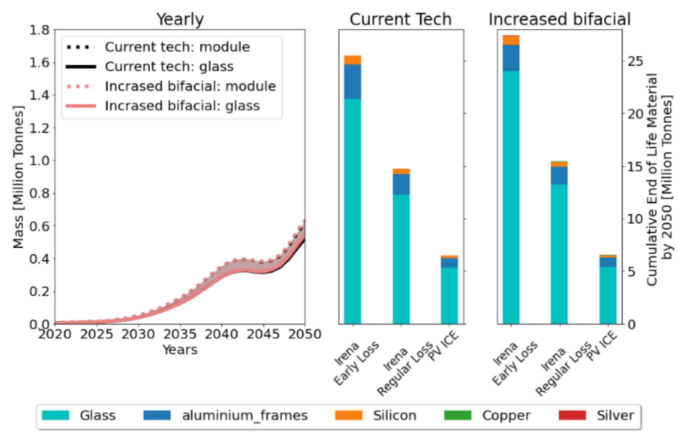

Fig. 4 End-of-life materials for the two module composition scenarios evaluated, 'Current tech' and 'Increased bifacial.' The yearly results (left) consider the PV ICE lifetime and reliability approach, which predicts a cumulative 6.5 Million Tonnes of module waste by 2050 for the 'Current Tech' module composition. There is only a 1% increase for the 'Increased bifacial' projection as most of the bifacial-module composition modules are projected to still be in service in 2050. Lifetime approaches from Irena capture the difference in module composition reaching the waste stream earlier, thus showing up to a 7% difference between scenarios. PV ICE can also consider Manufacturing Scrap waste, which increases the predicted EoL Material shown here by 20%.

These results are for a primarily linear lifecycle; CE pathways are held at current levels (see Table), but CE pathways are expected to increase during this time, possibly to levels that could disrupt and offset virgin material requirements. For example, an increase in Reuse, Repair and Recycle rates can reduce waste by 40% and increase installed capacity by 2% by 2050. A sensitivity study is presented in [15], which also highlights the ability of technology reliability to offset waste and maintain installed capacity.

To assess more accurately the impact of the Bifacial projection scenario, two deployment scenarios were created: the first one where installs for bifacial modules are done according to the nameplate, and the second one where the installations are reduced following the proxy method outlined in the previous section. Both scenarios are then evaluated for their installed capacity accounting for their performance under the effective irradiance G_{eff}. Keeping the installs based on nameplate requires close to 56 Million Tonnes of material, most of it glass (88%). The reduced installs lead to a reduction of virgin stocks needed by 7.6%.

Figure 5 shows the installed capacity predicted through the different reliability approaches for the bifacial module composition scenario. Using the lifetime predictions from the 2016 IRENA report, the Early Loss and Regular Loss lifetime approach project that installed capacity will be 50% and 70% of the cumulative new installs (in black) by 2050. Doing an equivalent installation considering the bifacial gain reduces the total number of modules required for the same capacity. PV ICE projects an installed capacity of 84%. Current reliability estimates and projected improvements to lifetime mean modules will stay in the field longer, thus keeping installed capacity much closer to the initial installations until 2050 compared with other lifetime projections. Finally, installing bifacial modules by their nameplate (without considering energy output increase from bifaciality on the installs) can increase the *effective* installed capacity by 2050 by 4%, assuming proper bifacial installation. This points to the importance of an accurate assessment of module material, lifetime approaches, reliability, and accounting for power rating and efficiencies for PV projections.

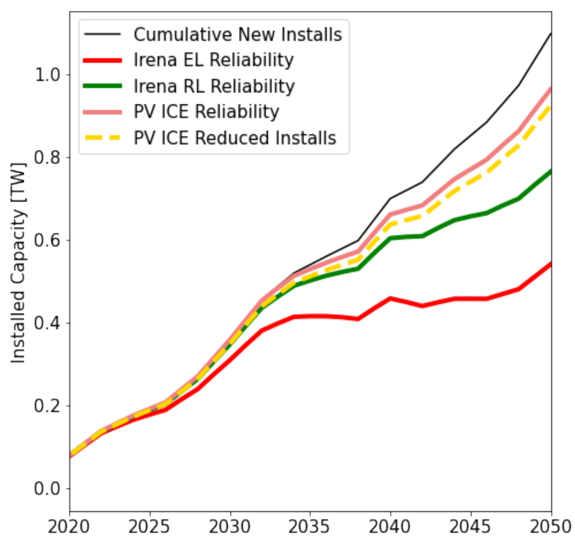

Fig. 5 Installed Capacity for the bifacial module composition, considering the different reliability and lifetime approaches as well as installation options (same installs by nameplate or reduced installs)

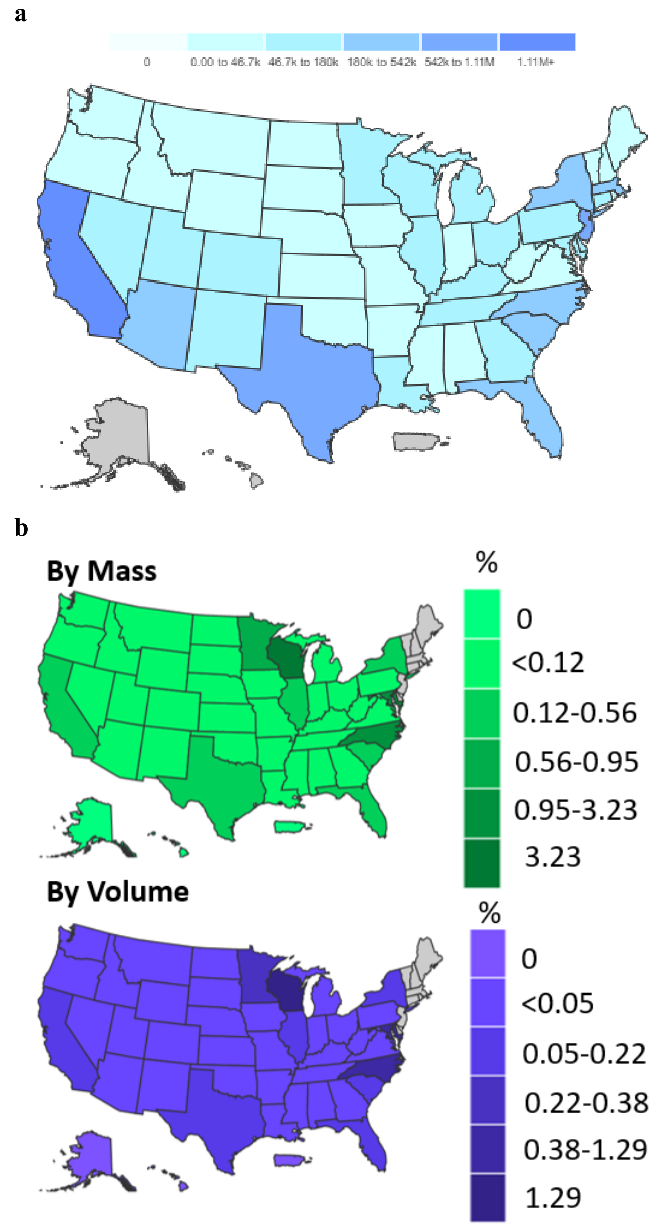

Fig. 6 a) Cumulative Mass of PV material at End of Life by state, in Metric Tonnes, for the bifacial projection scenario with PV ICE lifetime and reliabliity approach. Identifying where PV modules will reach End of Life can help us identify where collection methods, recycling facilities, and other areas of opportunity can take place.b) Shows the percent of the US remaining landfill capacity by 2050 that would be occupied by PV Waste. Landfill facilities considers the landfills in the LMOP database that have remaining capacity, and their projected capacity is calculated for 2050 following their the acceptance rate.

A. Regional End of Life Material Assessment

Figure 6 shows waste by state and percent of each states' landfill capacity used by PV wastes by 2050 in terms of Mass and Volume. The percentage of landfill capacity used by cumulative PV waste in 2050 uses methodologies like those of [16]. We emulate the authors' methods utilizing a compacted municipal waste density of 1009 kg/m^3 and leveraged the U.S. EPA LMOP database records of designed capacity, existing waste, and annual acceptance rate to quantify remaining landfill capacity in 2050 by state. Here, we use the PV ICE material baselines and densities to calculate the PV per cubic meter density, which we calculate to be 2515 kg/m^3 for the bifacial projection modules. This value is used to calculate the volume of PV waste from the PV ICE predicted mass. Finally, the volume and mass of PV waste are compared to the remaining landfill capacity in 2050, as shown in Figure 7. Identifying where modules reach their EoL is helpful to understand the best handling options in terms of cost and energy, for example, by reducing transportation distances. Such spatial-temporal resolution on future PV EoL material can help site recycling facilities, transportation, and storage and highlight potential landfilling, hazardous waste, and environmental justice concerns.

IV. DISCUSSION

For this analysis, the same module power degradation rate is used in both scenarios. However, bifacial module degradation compared to monofacial module degradation is currently unknown – the data are still being collected. So far, there are few indications of increased degradation in deployed modules [17], [18], but there are always risks in new technologies. For example, the glass-glass package has been proven for 30+ years in the field. However, it has displayed unique EVA-related degradation mechanisms, prompting exploration of new EVA and POE encapsulant technologies. The evolution of encapsulant technologies has not yet been captured in PV ICE material baselines but is targeted for future studies.

This comparison of 2020 module material composition vs. a dynamic material composition demonstrates the value of predicting a dynamic module composition. Even though the future is impossible to predict with accuracy, acknowledging changing material composition enables exploration of potential futures and provides an outer range of potentials.

Technology advances can improve process efficiencies throughout the PV module lifecycle. Policies can shape research focus and economically viable pathways through incentives. However, decisions on what research to pursue and policies to implement need direction and data to prioritize critical focus areas, such as material and energy benefits. Renewable energy technologies generate power over their useful life, offsetting the energy required for manufacturing. This offset can be quantified with the Energy Return on Investment (EROI) metric, defined as $EROI = Use\ Phase\ Energy\ Output / Embedded\ Energy$ [19]

In addition to the commonly used nameplate installed capacity, the PV ICE tool provides calculated capacity in the use phase by considering both newly installed modules and module degradation for years in service. This consideration of degradation along with the bottom-up material and energy accounting allows evaluation of circular decisions such as field repair, off-site refurbishment, reuse, or recycling in both energy and material dimensions. This project's future research goals include quantifying the EROI with the detailed understanding of installed capacity, reliability, and service-life modeled through PV ICE and the offsets that Circularity Pathways provide.

In evaluating the sustainability of module technologies, it is critical to incorporate energy yield forecasting and not simply nameplate capacity. Stakeholders utilize an energy model with energy yield forecasting to design installations. Developers are interested in making the best use of their site; it is unlikely that bifacial modules would result in fewer modules installed. It is far more probable that developers will expect a higher output from the use of bifacial modules. Therefore, comparative sustainability analyses should account for the material differences and energies entailed in bifacial modules throughout their lifecycle, including manufacturing, energy yield, and EoL management.

V. CONCLUSIONS

The PV ICE tool is flexible and scalable to accommodate temporal and geographic information, with dynamic flows considering multiple materials. As an open-source Python-based tool, it can be integrated with other tools. In this analysis, installation projections from the Electrification Futures Study were leveraged with ITRPV predicted bifacial future trends to explore changes to glass, aluminum frames, and installed capacity improvements entailed in a 55% bifacial module future. Calculations of installed capacity are also sensitive to the lifetime and reliability assumptions, and reliability itself plays a significant role in reaching our goals of installed capacity by 2050. Sustainability analyses of bifacial modules must also consider changing material composition and lifecycle energies.

ACKNOWLEDGMENTS

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