A Circularity Assessment for Silicon Solar Panels Based on Dynamic Material Flow Analysis

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A Circularity Assessment for Silicon Solar Panels Based on Dynamic Material Flow Analysis

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***Abstract*— This paper examines the impacts of design, operational, and end-of-life (EOL) waste pathways' parameters on material circularity in silicon solar photovoltaic (PV) modules. Dynamic material flow analysis (DMFA) quantifies time-series material flows through systems' life cycle stages to identify hotspots of waste generation, estimate resource needs in the future, and guide sustainable material management. We introduce a DMFA framework based on U.S. electricity demand for the period 2000-2100 to assess stocks and flows of bulk PV materials (i.e., solar glass and aluminum frames). We apply the model to a range of scenarios to understand how material demands depend on selected PV-related parameters, different material circularity strategies, and recent module design trends (e.g., bifacials, large-format-high power modules). Our results enable advanced planning for future materials needs and provide insight into potential opportunities to minimize material waste.**

Keywords*— *Circular economy, waste management, dynamic material flow analysis, crystalline silicon photovoltaics.

I. INTRODUCTION

Global deployment of solar PV technologies grew from 1.4 gigawatts (GW) in 2000 to 628 GW by the end of 2019 [1][2]. This fast growth is projected to increase 10-fold in the next 30 years to rapidly decarbonize the electricity sector. This rapid and large-scale PV deployment will also leave behind an equivalent material waste stream [3]. An initial estimate of global solar panel waste is ~78 million metric tons (MT) (~13 million MT in the U.S.) by 2050, and PV is expected to make up 10% of all electronic waste as reported by the International Renewable Energy Agency (IRENA) [4]. Rapid PV deployment could strain existing material supply chains to meet soaring demand, while panel landfilling is also banned in a few countries that instead issued directives mandating recycling ~85% of panel weight as the beginning to a circular, resource-conserving economy transition. Panel recycling remains largely uneconomical because of current low waste volumes, variability of panel waste size and composition, and low selling prices of recovered scrap that diminishes recycler profit margins [5][6]. A detailed material assessment is needed to understand the impacts of different circularity practices and identify opportunities to systemically reduce waste in all life cycle stages in PV materials.

In view of these considerations, we developed a framework to quantify material flows in the life cycle of PV systems to identify bottlenecks hindering high quality material recovery and the sensitivity of factors influencing module waste generation.

II. FRAMEWORK AND ASSUMPTIONS

We applied a bottom-up, stock-driven DMFA approach to track the fate of bulk PV materials in utility-scale silicon PV systems based on U.S. PV electricity demand through 2100 in the cradle-to-cradle boundary. Fig. 1 shows the modeling framework developed for estimating material flows in each life cycle stage.

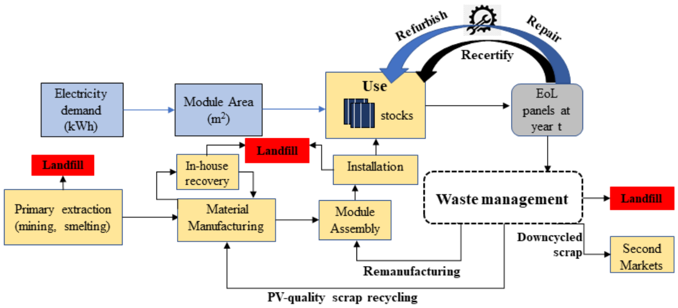


Fig. 1. Modeling framework for estimating material flows in utility-scale silicon solar panels based on solar PV electricity demand in 2000-2100. Blue arrows represent information flows. Black arrows represent material flows.

There are three major areas of the framework: energy-to-mass conversion, material life cycle calculations, and EOL waste management. Time-dependent cohorts for energy, panel area and material mass are created to capture the evolution of model parameters with time. A cohort is defined here as a PV panel generation with its own set of design and operational parameters. Each year will have multiple panel cohorts (i.e., generations) serving to meet electricity demand.

A. Calculation of Energy and Panel Area Cohorts

Energy cohorts are created to meet yearly PV electricity demand. The electricity generation capacity of the cohorts degrades each year to reflect the panel efficiency degradation and other system losses throughout their lifetime. We modeled these cohort system losses using a 2-parameter Weibull lifetime probability distribution applied for reliability analysis of silicon panels in Arizona [7].

The annual installed generation capacity (i.e., cohort inflows) is calculated by summing replacements for the retired capacity in the previous year and meeting the incremental increase in electricity demand. Panel areas are calculated from the cohort efficiency, national average solar insolation of 1700 kWh/m^2/year, and AC/DC (i.e., performance) ratio.

B. *Estimating Mass Flows and EOL waste allocation*

In-use material stocks, annual material installations and annual module discard rates are calculated by multiplying panel area by its material intensity. We calculated weighted average market shares of glass and aluminum intensity of different silicon PV technologies mainly from the International Technology Roadmap for Photovoltaics reports [8]. For PV glass intensity, a weighted average sheet thicknesses are calculated and multiplied by average flat glass density of 2,500 kg/m^3. For aluminum frames, yearly weight-per-length (kg/m) is multiplied by average mainstream module size 1.65-by-0.99 meters.

The flows of the rest of the life cycle stages are calculated using process parameters through mass conservation. A cohort of panels reaches its EOL if cumulative Weibull losses are 98% or if cohort efficiency reaches 20% degradation. In the baseline scenario, discarded panels end up in landfills. We hypothesized a projected circularity framework for allocating retired panels to different EOL waste pathways based on module efficiency and the physical condition of the retired modules.

III. BASELINE SCENARIO RESULTS

i) *Projected PV Electricity Demand*

PV electricity demand was leveraged from the Energy Information Agency for the period 2000-2050 [9]. We applied a logistic regression analysis based on the baseline scenario of the Global Climate Action Model (GCAM) that extends to 2100 [10].

ii) *Flat Glass*

PV glass is low-iron flat glass, constituting ~76-85% of panel weight and ~8% of module value. The average annual worldwide flat glass manufacturing capacity is estimated to be 88 million MT; Of which, U.S. share is 12 million MT [11]. Fig. 2 shows that cumulative glass installations are expected to reach 95.6 million MT and in-use stocks to be 36.8 million MT by 2100 to meet the projected electricity demand. Cumulative glass waste from the use phase alone could reach ~59.3 million MT by 2100 if current practices are continued. This result is in line with IRENA report estimations.

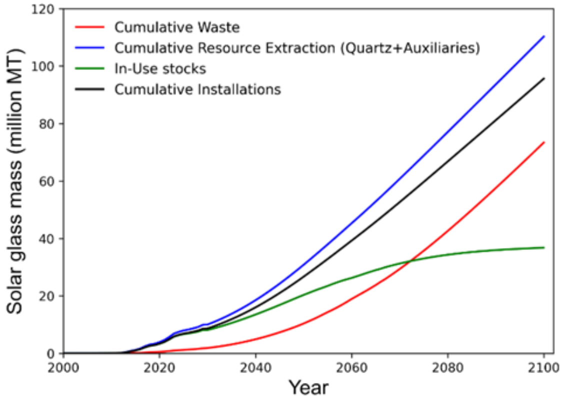


Fig. 2. Baseline scenario cumulative waste, resource extraction (Quartz), in-use stocks and cumulative installations for solar glass in the period 2000-2100.

iii) *Aluminum*

Aluminum frames represent ~10% of panel weight and ~26% of module value and are made of extruded aluminum 6063 alloy. Our results show that cumulative aluminum installations could reach ~12.1 million MT by 2100. In-use aluminum stocks could reach ~4.5 million MT. The rate of increase in aluminum installations is relatively slow due to expected growing shares of frameless modules and manufacturing lighter and thinner frames in recent years. The cumulative life cycle aluminum waste is projected to be ~11.1 million MT by 2100; of which, 7.7 million MT comes as waste from the use phase alone. We calculated the average primary aluminum production share of U.S. consumption to be about 14%. The rest of consumption needs come from secondary production and other imports. Cumulative U.S. primary aluminum production is estimated to be 39.4 million MT in the period 2000-2019 as estimated by USGS reports.

IV. SENSITIVITY OF WASTE GENERATION TO PV PARAMETERS, CIRCULARITY PRACTICES, AND TECHNOLOGY DESIGN SHIFTS

A. *Sensitivity of Selected PV Parameters*

We examined the impacts of a wide range of operational and design parameters on cumulative solar glass and aluminum waste by 2100. We only show the most influential parameters here for solar glass waste because it is the material of most supply concern recently. Fig. 3 shows that factors pertaining to initial deployment seem to be the most influential on waste generation, particularly the first lifetime, module efficiency, and annual degradation.

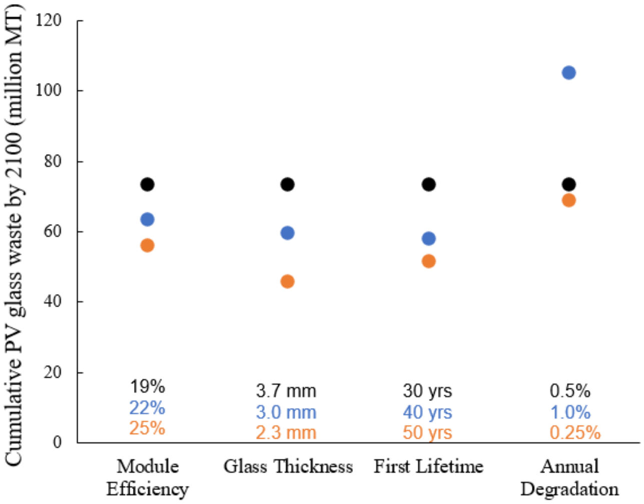


Fig. 3. Sensitivity of selected PV parameters on projected cumulative solar glass waste in 2100. Black dots represent the baseline scenario.

Extending panel service lifetime by 10 years could save ~15 million MT of solar glass waste. About ~3 million MT of glass waste could be reduced for every 1% gain in module efficiency. Reducing annual efficiency degradation to 0.25% could save ~6 million MT of glass. However, if modules experience faster degradation to ~1% per year after initial deployment, net solar glass waste could be ~22 million MT larger than the baseline scenario. Thinning a glass pane by 0.7 mm could save ~20 million MT of cumulative glass waste by 2100 without accounting yet for increased chances of module breakage due to increased module fragility.

B. *Impacts of Circularity Practices*

We evaluated the impacts of several circularity practices on combined PV glass and aluminum material waste streams by 2100. We studied three PV recycling lines: Veolia, FRELP and NEDO FAIS [12][13]. Fig. 4 shows that recycling lines have the highest impact on waste reduction followed by remanufacturing extractable components.

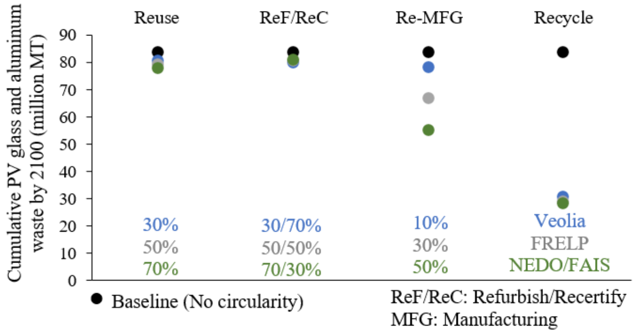


Fig. 4. Impacts of different circularity practices on the cumulative combined glass and aluminum waste by 2100.

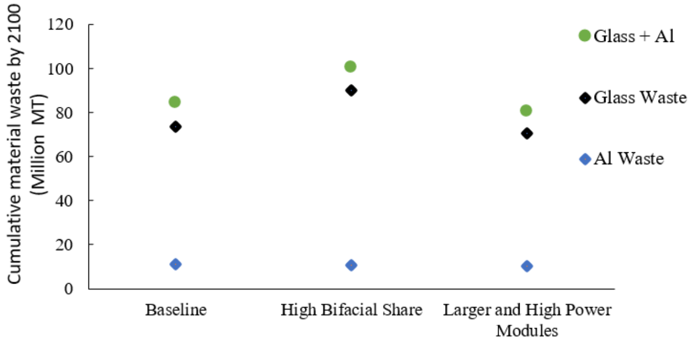
All recycling lines considered have similar waste reduction impacts. NEDO FAIS has a higher scrap yield and recovers glass panes without breakage, which could incentivize closed loop recycling or component remanufacturing in module assembly lines. Veolia and FRELP both recover broken and contaminated glass cullet that may not be further used in PV applications. Aluminum 6063 alloy can retain its quality after multiple recycling if it meets U.S. ISRI scrap specifications. Scrap cleaning and disinfecting increases its selling prices.

Reusing modules, whether refurbished or not, has relatively small effect on waste reduction and does not provide a high electricity generation return in the second life due to considerable degradation in their first life.

C. *Impacts of PV Technology Shifts*

We studied several module design trends, including bifacial modules and deploying modules with thinner glass sheets and lighter frames to maintain weight specifications for larger and high power (>500 W) modules [14]. Fig. 5 shows the waste generation effects of both trends. Our predictions indicate that increasing market share of bifacial panels from 10% in 2020 to ~60% in 2029 could generate an additional ~20 million MT of PV glass waste compared to the baseline scenario.

Large format modules could save 1 million MT of aluminum use and waste. Thinning the glass could save 3 million MT of glass use and waste.



V. CONCLUSIONS

A dynamic material flow analysis framework based on electricity generation is introduced to quantify time-series material flows in the life cycle of silicon solar panels. This framework can be used to quantify life cycle waste generation and resource use for a wide range of design, operational and EOL circular pathway parameters. Module efficiency and reliability are found to be the most influential parameters to resource conservation and waste reduction. Dedicated PV recycling and component remanufacturing were found to be the most effective circularity strategies for waste minimization, while the reuse of old modules had a small effect on the waste stream. PV recycling should emphasize high purity and high value scrap recovery for improved resource efficiency in a circular economy.

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