

Material Use and Life Cycle Impact of Crystalline Silicon PV Modules Over Time

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Abstract—Most life cycle assessment (LCA) of crystalline silicon photovoltaics (c-Si PV) modules are based on public life cycle inventory (LCI) datasets with limited use of actual manufacturing data. We collect and calculate the amount of material used for production of different PV modules installed in the U.S. to analyze the trend in material intensity over and compare the numbers among various tier manufacturers and module reliability. Furthermore, results of LCA models using the public LCI data and the actual manufacturing material (specifically aluminum) data are compared to investigate the impact of material use on the life-cycle impact assessment of c-Si PV modules. Results show a trend of material use decrease over time and indicate a potential connection between material usage and the manufacturer tier – better manufacturers tend to use more materials for modules production which may lead to higher quality performance. Additional work will complete the life cycle assessment, explore more materials, and fill the data gap of PV modules produced by different manufacturer tiers in different years.

Keywords—*c-Si PV, Aluminum, Life cycle assessment, Trend analysis, Manufacturer tier comparison*

I. INTRODUCTION

As the end of 2020, the cumulative photovoltaics (PV) capacity installed worldwide reached nearly 714 GW, and 127 GW was installed within the year [1]. In the U.S., the cumulative PV capacity exceeded 113 GW in 2021 and the number keeps increasing – 300 GW of new PV capacity will be installed in the next ten years [2]. Among the installed PV capacity in the U.S. in Q3, 2021, residential PV accounts for almost 25%, and the rest is commercial or utility-scale [3]. The most common type of PV modules is crystalline silicon (c-Si), which account for 96.4% of the global PV production in 2020 [4]. The application of PV systems can reduce environmental impacts compared to conventional fuels. However, the production phase of PV modules can impose negative impacts on the environment.

Life cycle assessment (LCA) is a common tool or method to analyze the environmental impacts of PV systems from a holistic perspective. Most LCA study of PV systems has been based on two life cycle inventory (LCI) datasets. The first one is Ecoinvent PV dataset [5], which reflects the status of c-Si PV technology production in 2005. The second one is IEA PVPS 2015 dataset [6], reflecting the status of c-Si PV technology in year 2011. In 2020, PVPS published the up-to-date LCI data describing the status for c-Si PV technology in year 2018 (except for some manufacturing data in 2011) [7]. However, the

site-specific inventory data are often not available to compare the performance of various PV modules.

Among the life cycle inventory data, materials used for PV module production are an important category and a small difference in material usage amount can lead to a significant difference in environmental impacts. As the technology mature it is expected that PV modules will use less and less materials such as aluminum and glass. For example, ITRPV forecasted a mass reduction for module frame and a thickness reduction of the front side glass from 3mm to 2mm between 2013 to 2029 [8][9]. From the 2015 to 2020 IEA PVPS LCI reports, the material intensity for aluminum and glass has remained constant [6][7], which may not really reflect technology status of the PV industry.

This study collects and calculates the amount of material used for production of different PV modules to get some insights of the trend of material intensity over time and to compare the numbers among various tier manufacturers and module reliability. The hypothesis we are testing are: 1) the material intensity of PV modules has been decreasing over time, 2) PV modules produced by Tier 1 manufacturers have higher material intensity than non-Tier 1, and 3) modules with better quality and reliability performance have higher material intensity than those with lower performance. Based on the material data collected, LCA models of PV modules are built. The LCA results are compared between using the LCI datasets mentioned above and using the actual module data. We choose aluminum since it contributes to 8% of the total mass of framed c-Si PV module [10] but 10% of the carbon footprint. Quantifying the amount of aluminum used in frame is also important to plan for PV module recycling since it is one of the most materials recycled in a module [10].

II. METHODS

The scope of this study is limited to silicon PV modules commonly installed in residential applications in the U.S. The material investigated is aluminum but additional data on glass will be collected using a similar method. Most modules selected for this study were commonly installed in California in 2019. To make sure representative samples are collected for the analysis, modules produced by certain manufacturer tiers or with certain years stated in the specification sheet were added.

A. Material data collection and calculation

The amount of aluminum and other materials used for PV modules are rarely disclosed by manufacturers or suppliers.

Since aluminum is mainly used for the frame, we calculate the module frame weight using frame dimensions from the specification data sheet published by the manufacturer of the PV module product. With the assistance of an area calculator tool called “SketchAndCalc” [11], the frame cross section area is measured, which then multiplies the depth or height of the frame to calculate the total volume. The density is kept constant at 2.7g/m^3 . Normalized material weight is calculated as weight per square meter of the module:

$$\text{Normalized weight} = \text{Weight} / (\text{length} \times \text{width}) \quad (1)$$

Examples of PV frame cross section are shown in Fig. 1. In addition, publication year of the specification sheet is collected to better understand the trend of material use for PV modules.

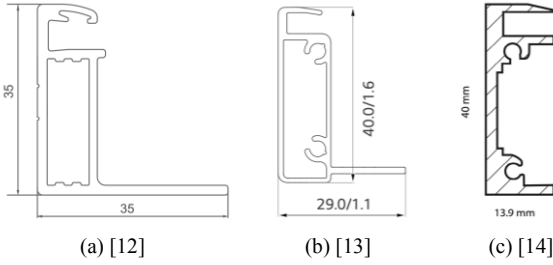


Fig. 1. Examples of PV module frame cross section.

B. Manufacturer tiers

This study refers to two Tier 1 lists to further analyze and compare the material use and environmental impacts of PV module products among different manufacturers and tiers. The first list is Bloomberg PV Module Tier 1 List, Q3 2021 [15], which divides the PV market into tiers based on manufacturers' financial situations. And the second one is PVEL 2021 Top Performers [16], which is based on the product quality and reliability through the PVEL's Production Qualification Program.

C. Life cycle assessment

For the selected PV module, two different LCA models are built for comparison. One uses a commonly used LCI dataset (Ecoinvent PV dataset, IEA PVPS 2015 dataset, or IEA PVPS 2020 dataset) depending on the year stated in the specification sheet. Another one uses the actual production data which is the aluminum amount calculated by the author. Results of these two models are interpreted and compared.

III. RESULTS AND DISCUSSIONS

In total, specification sheets of 64 PV modules produced by 14 different manufacturers are collected. A summary of the manufactures' tiers is listed in TABLE I.

TABLE I. SUMMARY OF MODULES BY MANUFACTURER TIERS

Bloomberg Tiers, Q3 2021	PVEL Tiers, 2021		Total
	Tier 1	Non-Tier 1	
Tier 1	34	7	41
Non-Tier 1	7	16	23

Bloomberg Tiers, Q3 2021	PVEL Tiers, 2021		Total
	Tier 1	Non-Tier 1	
Total	41	23	64

A. Trend of aluminum amount used for PV modules over time

Based on the 64 modules collected, trend of material weight over time is presented in Fig. 2. The aluminum weight for PV module frames is decreasing over time which is what was expected [8][9]. In IEA PVPS 2015 and 2020 datasets, the inventory data of aluminum used for PV module production is 2.13 kg/m^2 , which is higher than the numbers presented in Fig. 2. Additional analysis will be performed to understand the increase seen for 2013 modules and 2016 which is probably associated with change in module design. In 2013 and 2016, certain modules have frames with more complicated structure or larger dimensions.

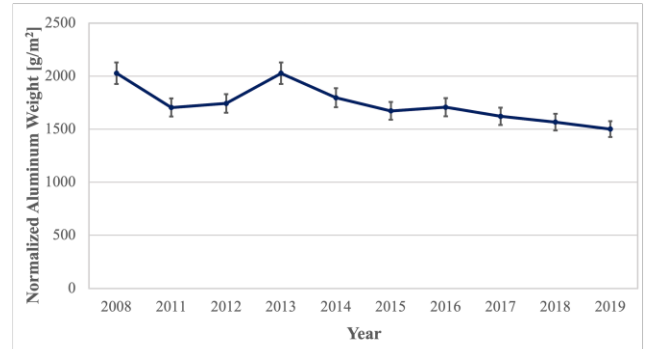


Fig. 2. Average normalized aluminum weight by year.

When looking at specific manufacturers, as Fig. 3 shows, the trend is not obvious. However, it can still be noted that some manufacturers, e.g., Suniva, Hyundai, and JA Solar, are using less and less aluminum for the module frames. While some manufacturers, e.g., Astronergy and Trina Solar, are using more materials for their frames than the previous year.

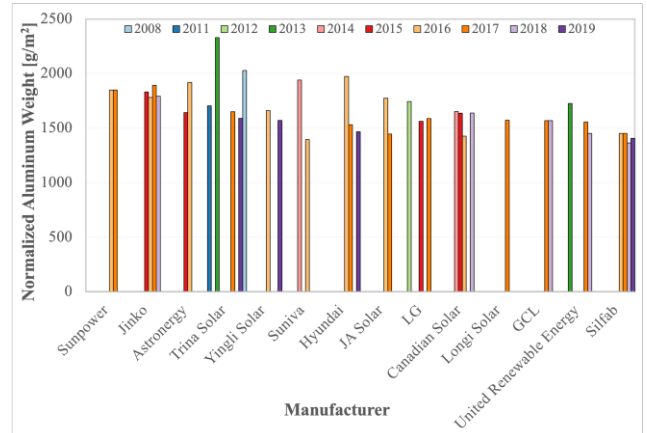


Fig. 3. Average normalized aluminum weight by manufacturer and year.

B. Compare aluminum amount used for PV modules between different manufacturers

Average normalized aluminum weight used for PV modules by different manufacturer tiers is presented in Fig. 4. It indicates

that tier 1 manufacturers are using more aluminum than non-tier 1 on average. The average amount of all these 64 modules is 1653.87 g/m². Fig. 5 shows more specific data by year. In year 2013, 2016, 2018, and 2019, both Bloomberg and PVEL Tier 1 manufacturers have a higher aluminum intensity than non-Tier 1 manufacturers. The results indicate a possible connection between material usage and the manufacturer tier – better manufacturers tend to use more materials for modules production which may lead to higher quality performance. Additional data will be collected for certain years and tiers. There is a data gap that tiers in some years are missing, which will be added in the future work. For example, in Fig. 5, Bloomberg Tier 1 and PVEL Tier 1 are missing in 2008, and Bloomberg Non-Tier 1 and PVEL Non-Tier 1 are missing in 2011.

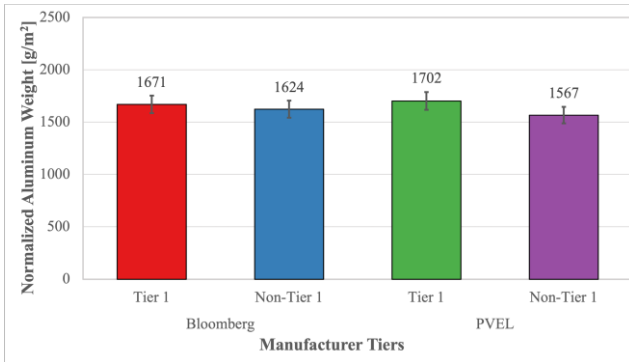


Fig. 4. Average normalized aluminum weight by manufacturer tiers.

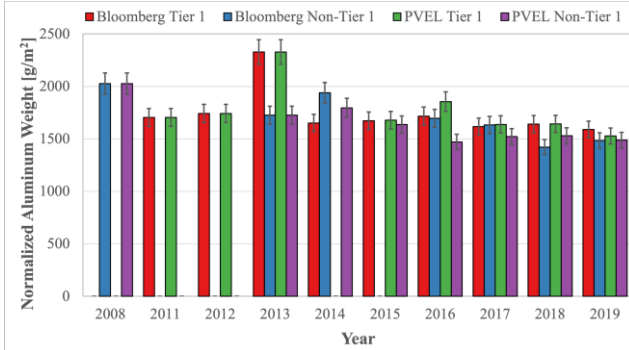


Fig. 5. Average normalized aluminum weight by manufacturer tiers and year.

C. Compare LCA results between using LCI dataset and actual production data

Life cycle assessment is in progress and will be presented at the conference.

IV. CONCLUSION AND FUTURE WORK

Preliminary results show a trend of material use decrease over time for the PV modules installed in the U.S. and indicate a potential connection between material usage and the manufacturer tier – better manufacturers tend to use more materials for modules production which may lead to higher quality performance. Overall, this study demonstrates how the sustainability impacts of PV modules production has been

changing over time and the variability within manufacturers that is currently not considered in life cycle assessment.

Future work will consider additional materials such as glass and plastic. With regards to life cycle inventory data, location-variable data will be considered to build models that consider the manufacturing location (including electricity intensity) and transportation for module installation in the U.S. Finally, we will calculate the life cycle error associated with the use of constant material rather than specific per module data.

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