Material Intensity and Carbon Footprint of Crystalline Silicon Module Assembly Over Time

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Highlights

- Evaluated the temporal variation in glass and aluminum content in silicon modules using specification sheets.
- Life cycle impact analysis of silicon module manufacturing, taking into account module designs, manufacturing years, and manufacturing locations.
- The aluminum intensity in the module frame decreased by 30% from 2010 to 2021, while the solar glass thickness remained relatively constant.
- Local electricity mixes significantly impact the carbon footprint of photovoltaic manufacturing.

Abstract

The growing solar photovoltaics (PV) installation has raised concerns about the life cycle carbon impact of PV manufacturing. While silicon PV modules share a similar framed glass-back sheet structure, the material consumption varies depending on module design, manufacturer, and manufacturing year, leading to varying carbon emissions. However, current life cycle assessment (LCA) studies and public inventory databases of silicon PVs lack an assessment of the variability in commercialized solar module designs and their potential impact on module reliability and carbon footprint. The present study aims to address this research gap by providing a temporal analysis of aluminum and glass intensity in crystalline silicon modules produced from 2006 to 2021. The material inventory data is obtained from specification sheets of 167 crystalline silicon modules produced by 31 manufacturers. Subsequently, we use the collected material inventory to estimate the carbon footprint of manufacturing silicon modules in multiple countries over the past decade. The results reveal a 30% reduction in the aluminum intensity used for frames from 2010 to 2021, while the solar glass thickness remains relatively constant. Additionally, the comparison among manufacturer tiers indicates that more reliable modules tend to use more materials for module production. Moreover, the comparative life cycle assessment of modules manufactured in various countries demonstrates a significant impact of local electricity mixes on the carbon footprint of module manufacturing. Modules manufactured in China exhibit the highest carbon emissions, followed by Malaysia (4-9% lower than China), South Korea (15-16% lower than China), the US (17-18% lower than China), Thailand (19-21% lower than China), Turkey (18-21% lower than China), and Vietnam (25-30% lower than China). Overall, the present study highlights the importance of up-to-date data on material inventory and local electricity mixes in evaluating the environmental impacts associated with PV manufacturing. Lastly, we advocate for integrating the variability of module designs and manufacturing locations within low-carbon solar module criteria and guidelines, recognizing the importance of adaptability in achieving sustainable solar manufacturing.

Keywords:

Crystalline silicon, Solar photovoltaics, Material use, Life cycle assessment.

1. Introduction

The solar photovoltaics (PV) market has been booming to meet the global energy demand and to reduce the carbon emissions from energy production. Among all the PV technologies, monocrystalline (mono-Si) and multicrystalline (multi-Si) silicon PVs are the most widely installed and have the highest global market share (95% in 2021) (Pastuszak and Węgierek, 2022). Regardless of the cell technology, silicon modules have a similar design (Figure 1) where silicon-based cells are sandwiched in between encapsulant (ethyl vinyl acetate) layers, with tempered glass as the top layer and a polymer-based back sheet (Peplow, 2022). These different layers are usually enclosed in an aluminum (Al) frame (aluminum alloys, $AlMg_3$). The general composition of a typical crystalline silicon module is 75% glass, 12% polymers, 9% aluminum, 3% silicon, and 1% copper (Peplow, 2022). However, the actual material composition of solar PVs varies by various parameters such as module design, manufacturing year, and solar manufacturer. No study has investigated the variability in commercialized solar module designs as per these parameters and their associated environmental impact.

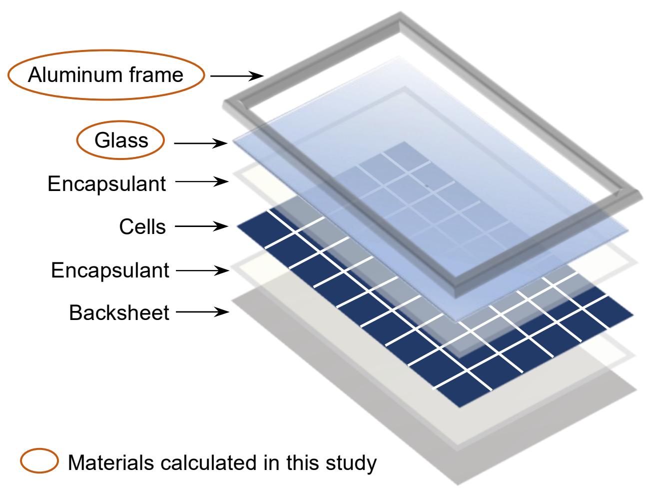

Figure 1. Structure of framed silicon solar module

Over the years, solar modules have become lighter with steadily decreasing mass and optimized module designs (Weckend et al., 2016) to lower manufacturing and transporting costs (Aleo Solar, 2017; PV TECH, 2022; VDMA, 2022, 2014). However, a thorough evaluation of module designs' historical evolution is lacking to better understand their impact and potential for further improvement. Meanwhile, analyzing variations in material intensity and module designs is essential for accurate PV waste volumes and materials forecasts. Investigating material intensity changes over time can direct recycling and end-of-life management decisions. Existing literature on material demand quantification and waste generation forecasting for solar technologies has not addressed the intricacies of such variations (Liang et al., 2022; Prabhu et al., 2022; Song et al., 2023). Thus, this study aims to address the gap by providing insights into material variation over time and across diverse manufacturers. A module's material intensity can affect module durability. For instance, larger and heavier module frames have shown better mechanical stability (Tummalieh et al., 2022). Although it is commonly assumed that manufacturers producing higher-quality modules would use more materials to improve product quality, no study has tested this hypothesis. Comparing the material usage in modules produced by various manufacturers is essential to provide solar purchasers with a reference for selecting solar modules that align with their performance and sustainability criteria. Even for the modules produced by the same manufacturer, no study has examined if they follow the same design or material intensity or if it changes with time. This study aims to fill this knowledge gap by examining the relationship between material intensity and the manufacturer's public ranking. We use the PV Evolution Labs (PVEL) Top Performers List (PVEL, 2022) and Bloomberg New Energy Finance (BNEF) PV Module Tier List (BloombergNEF, 2022), The PVEL list, established through their Production Qualification Program, evaluates manufacturers based on module performance and reliability. On the other hand, the BNEF list classifies manufacturers' tiers based on their bankability, given the preferences of banks and financial organizations for loans to implement large-scale solar projects (BloombergNEF, 2020).

Although PV technologies are crucial for grid decarbonization, they are still responsible for carbon emissions during material extraction, component production, module assembly, and end-of-life management (Tawalbeh et al., 2021). Life cycle assessment (LCA) is a method used to evaluate the potential environmental impacts of products or services throughout their entire life cycle (ISO, 2006). Conducting a comprehensive LCA study is difficult due to a lack of life cycle inventory based on production data (Kumar et al., 2020). Most of the available LCA studies on silicon PVs are based on two life cycle inventory (LCI) datasets: the Ecoinvent PV dataset (Ecoinvent, 2021) and the International Energy Agency (IEA) Photovoltaic Power Systems (PVPS) dataset (Frischknecht et al., 2020, 2015; Fthenakis et al., 2011). The Ecoinvent dataset (Ecoinvent, 2021) is based on IEA PVPS 2011 and reflects the silicon PV technology production status in 2005 and 2006. The second one, the IEA PVPS 2015 dataset, reflects the production status of silicon PV technology in 2011. In 2020, PVPS published updated LCI data corresponding to silicon PV manufacturing in 2018 (Frischknecht et al., 2020). The disparities between newer and older versions of PVPS LCI data primarily reflect technological advancements that have improved material and energy consumption (Fthenakis and Leccisi, 2021). However, it is noteworthy that certain inventory data, specifically materials like aluminum alloy and solar glass used for module assembly, have not undergone updates to represent more recent developments. Additional information is available in Table A.1 in Appendix A. Thus, using existing public inventory in LCA will likely not reflect recently produced modules' technology status and environmental impacts (Müller et al., 2021).

Furthermore, the current LCI datasets are based on the production of an average module, which does not account for the variability in design and material consumption of current modules available on the market. The quantity of materials used for PV production is an important part of life cycle inventory data, and a slight variation can affect the results. For example, a study showed that a 1.4 mm reduction in glass thickness could lower the overall life cycle environmental impacts by 2.77%, and a 30% reduction in aluminum frame mass resulted in a 2.1% lower impact (Jia et al., 2020). Another study proposed alternative frame designs by reducing frame weight and showed an up to 12% reduction in carbon emissions (Tummalieh et al., 2022). Thus, it is crucial to understand manufacturer- or module-specific module designs and material inventory to better estimate the environmental impact. Existing literature gives more attention to variations of silicon consumption instead of materials used for module assembly, such as aluminum and glass (Gazbour et al., 2018; Jia et al., 2021; Tannous et al., 2019). A study investigating material consumption in diverse designs of existing solar modules and their corresponding environmental impact is required.

The PV industry has been advocating for sustainable solar manufacturing, with the release of criteria for low-carbon solar modules worldwide (Global Electronics Council, 2023; Ultra Low-Carbon Solar Alliance, 2021a, 2021b). The manufacturing phase of a module has the most significant impact in terms of carbon footprint along the entire life cycle, which is highly dependent on the manufacturing locations (Müller et al., 2021). So, evaluating the electricity mix of the location or country where the module is manufactured is also an important factor in estimating the overall environmental impacts of solar PV. At present, the global solar supply chain is dominated by China, followed by Southeast Asian Nations (ASEAN) and North America (IEA, 2022). However, coal-fired power plants contribute to China's large share of consumed electricity for PV manufacturing, which is not the case in North America and the European Union. Thus, incorporating the PV manufacturing location's electricity grid while analyzing the PV environmental impacts is an essential aspect that needs to be investigated. Meanwhile, the variation in this electricity grid over time is another critical aspect. China has committed to achieving carbon neutrality before 2060 (IEA, 2021), which may lead to a decarbonized electricity grid and, thus, the decreased carbon footprint of manufactured modules (Fthenakis and Leccisi, 2021). Thus, it is essential to analyze the carbon footprint of silicon modules manufactured in China over time, considering the changes in electricity generation structure and investigating the influence of manufacturing locations.

The novelty of this study lies in its approach of considering the manufacturer's module specification sheets for the first time to assess the temporal changes in aluminum and glass intensity for silicon PVs and, further, its integration with manufacturer rankings by PVEL and BNEF. To the authors' knowledge, this is the first research to incorporate these rankings and analyze manufacturers' relationships with material intensity in PV modules. The inventory results are used to calculate silicon PVs' life cycle global warming potential and compare it with the PVPS inventories. Additionally, for modules with multiple manufacturing countries, the carbon footprint of its manufacturing in different locations is estimated and compared. This research comprehensively examines the module's material intensity and variability, including how different module designs, manufacturers, and manufacturing year impacts the material use and carbon emissions of module manufacturing.

2. Methodology

2.1. Selection of PV manufacturers and modules

To evaluate the material usage and its variation, manufacturers are selected from two ranking lists, namely, PVEL and BNEF. Later, the module specification sheets are collected to compile information on the aluminum frame's module measurements, glass thickness, and structural design. Manufacturers not publishing this information are screened out during the selection process. The final list of selected manufacturers and their manufacturing locations is provided in Table A.2.
To ensure that selected modules represent the historical module installations in the US, we used the California Net Energy Metering database (NEM database) [26], which provides information about the PV model number, manufacturer, and quantity of modules interconnected in California. For each manufacturer identified in Table A.2, installed mono-Si or multi-Si modules are selected from the NEM database. The publication year of the module's specification sheet is considered the module's production year. If the year is not mentioned in the specification sheet, the earliest installation year of the module from the NEM database is considered the module's production year. Crystalline silicon modules produced between 2006 and 2021 are considered. To account for the exponential increase in PV manufacturers and modules in the last decade, more modules have been selected for recent years (2016-2020) than for earlier years (2006-2015). Additionally, fewer modules are selected for 2021 due to the unavailability of published specification sheets. Modules from 2006 to 2013 are not classified into tiers because the PVEL list started from 2014 onward. Beginning in 2014, the same number of PVEL Tier 1 and non-Tier 1 modules are selected each year to compare material usage between various manufacturer tiers.

2.2. Data collection and material calculation

The present study considers two abundant materials used in silicon PVs, aluminum, and glass, to analyze the material's temporal trend of modules produced by various tier manufacturers. PV manufacturers/producers/suppliers rarely disclose the product's material inventory. Thus, the aluminum frame weight is calculated using the specified datasheet's measurements. The provided frame figures in the datasheets are used to calculate the cross-section area using an area calculator tool, "SketchAndCalc" (Dobbs, 2011). Then, the area is multiplied by the module height and aluminum density to determine the frame weight (Eq.1). The second material considered in the present study is glass, which is used in silicon modules as a flat top sheet. It is assumed that the area of the glass sheet is 99% of the module area based on the measurements of frame cross-sections provided in the specification sheets (Eq.2). The normalized material weight is calculated as per the weight per square meter of the module (Eq.3). The considered densities for the aluminum frame and the glass sheet are 2.7g/m^3 and 2.53g/m^3, respectively.

$$\text{Al frame weight} = \text{Frame cross section area} \times \text{Module height} \times \text{Al } density \quad (1)$$

$$\text{Glass sheet weight} = \text{Module area} \times 99\% \times \text{Glass thickness} \times \text{Glass } density \quad (2)$$

$$\text{Normalized material weight} = \text{Material weight} / Module\ area \quad (3)$$

2.3. Life cycle assessment

2.3.1. LCA goal & scope

This study aims to assess the differences in carbon footprint between diverse designs of silicon solar modules over time for various PV manufacturing countries of the selected manufacturers. The LCA is conducted using SimaPro Analyst v9.3 (PRé Sustainability, 2021). A temporal analysis and life cycle assessment of modules manufactured in China over time is conducted. Based on the manufacturing locations (Table A.2), modules made by manufacturers with production facilities located in China are selected for LCA. Further, if the module's manufacturer has a production facility located in another country, LCA is carried out accordingly, and the impact is compared with that in China.

The analysis considers two types of crystalline silicon modules: mono-Si and multi-Si. Modules that have both aluminum and glass intensity available are further screened from the modules selected in Section 2.1 for the life cycle impact assessment. The calculated aluminum and glass inventory based on module specification sheets is used to assess the carbon footprint of module manufacturing. Reference LCA models are created using IEA PVPS LCIs (2015 and 2020) (Frischknecht et al., 2020, 2015), and the inventory is adjusted with the calculated material intensity (results from Section 2.2) of aluminum and glass. The resulting findings are interpreted and compared as per two approaches, the IEA PVPS LCIs and production data based on module specification sheets. This attributional LCA follows the IEA PV LCA guidelines (Frischknecht et al., 2016). Additionally, given the role of PV technologies in the transition to low-carbon energy systems, the impact category global warming potential (GWP) is assessed in this work using the IPCC 2021 method.

2.3.2. Functional unit and system boundary

The functional unit (FU) of this study is twofold: (i) production of 1 m^2 of a mono-Si or multi-Si PV module and (ii) 1 kW_p of nominal module power. The system boundaries are shown in Figure 2, illustrating the manufacturing stages of crystalline silicon modules. It is assumed that all components' production and modules' assembly occur in the same country. The installation, operation, and end-of-life treatment are excluded. Transportation is also excluded because it has negligible influence on the overall impact (<5%) (Liu and van den Bergh, 2020; Müller et al., 2021), especially under the assumption of no cross-country shipment.

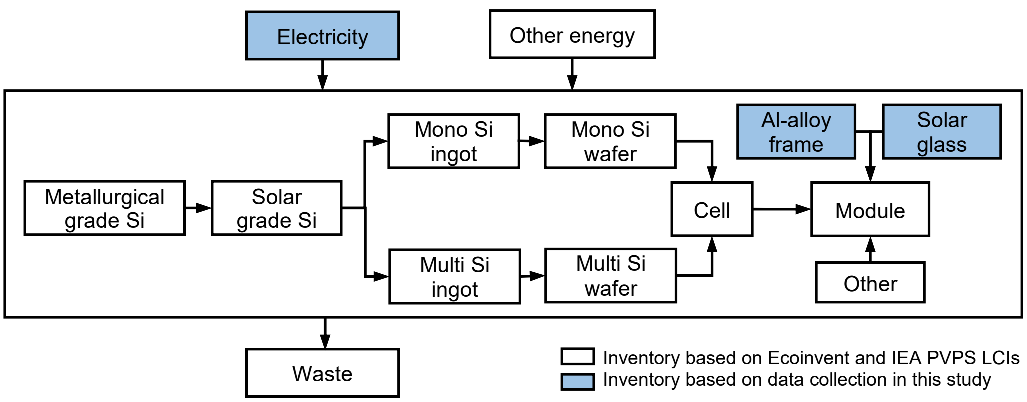

Figure 2. System boundary of this study

2.3.3. Life cycle inventory

In this study, the LCI of background processes is based on Ecoinvent 3.8 (Ecoinvent, 2021) and DATASMART 2021 (LTS, n.d.), whereas IEA PVPS LCIs (Frischknecht et al., 2020, 2015) are considered for foreground processes. Material inventory data (collected in Section 2.2) incorporates such variation and its effect on the module's carbon footprint. One of the reference LCA models is chosen for each module based on the module's production year (as per Table 1). The referenced LCI is modified for aluminum and glass inventory to reflect the actual module production data (Table A.3).

Table 1. References of LCA models

Referenced LCI	Production status	Production year of selected PV modules
PVPS 2015 (Frischknecht et al., 2015)	2011	2011 - 2015
PVPS 2020 (Frischknecht et al., 2020)	2018	2016 - 2021

In the IEA PVPS 2015 report (Frischknecht et al., 2015), the accounting of recycled silicon in ingot and wafer production is incorrect (Fthenakis and Leccisi, 2021), where zero energy and environmental burdens are allocated to the recycled silicon from wafer cutting losses. The IEA PVPS 2020 report corrects these allocations in the updated inventory, and the same is corrected in the present study for the reference LCA model built upon the PVPS 2015 report, as detailed in Section A.3 of Appendix A.

2.4. Electricity for PV module manufacturing

This section considers electricity mixes of different manufacturing locations to develop a regional life cycle inventory of PV module manufacturing. The electricity mixes in Ecoinvent 3.8 (Ecoinvent, 2021) are based on 2012 for China, 2019 for the US, and 2018 for other countries. A spatial-temporal analysis is performed to investigate the electricity generation of various countries by year. Grid mixes for China and the US are derived from EIA (EIA, 2022), whereas grid mixes for other countries are based on public statistics (Ember, 2022). Source-based production mixes are modified based on the electricity process in the LCI database of DATASMART 2021 and Ecoinvent 3.8 for the US and other countries, respectively.

3. Results and Discussions

3.1. Modules selection

The material inventory data for this study is obtained from specification sheets of 167 crystalline silicon modules produced by 31 manufacturers. The selection of modules for material intensity analysis is contingent on data accessibility and the availability of material-related information, as outlined in Section 2.1. Figure 3 provides an overview of the selected modules, indicating the number of selected modules for each year and their distribution among manufacturers. Due to limited data availability, only one module with the frame cross-section information is found for 2006 and 2007, and no module is found for 2009. The number of modules with available data increased in subsequent years, with two modules found for 2008 and three for 2010. The number of modules with available information on material usage varied for other years, thus, resulting in the uneven selection of module numbers in different years (as shown in Figure 3). Overall, most selected modules are from LG (18 modules), followed by Canadian Solar (17 modules) and Trina Solar (17 modules).

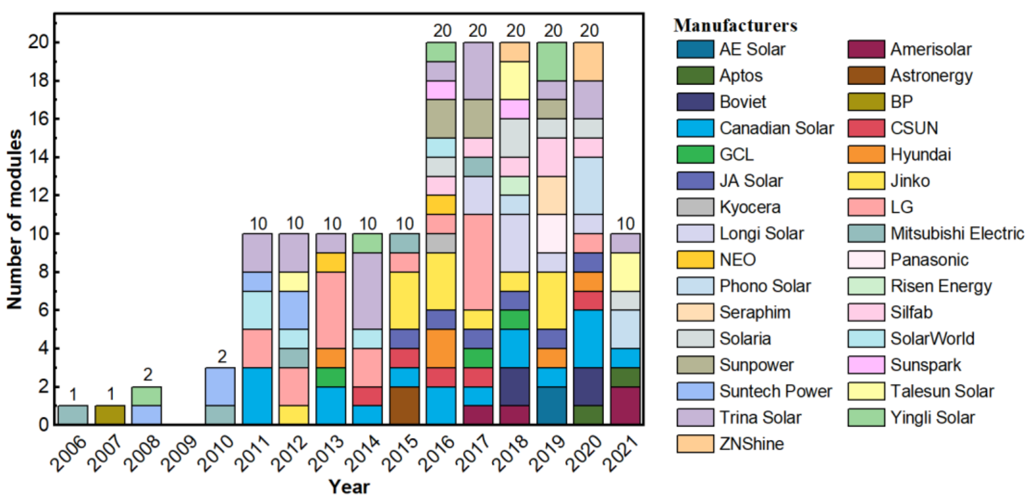

Figure 3. Number of selected modules by the manufacturer for each year

3.2. Material intensity analysis

3.2.1. Temporal analysis of material intensity for crystalline PV modules

The temporal material intensity is investigated based on data compiled for 167 modules, and the results showed significant variations in material consumption associated with module designs.

Figure 4 shows three different designs of aluminum frame cross-sections. Example (a) is the most common design with straight edges, while (b) and (c) are customized designs with curved edges.

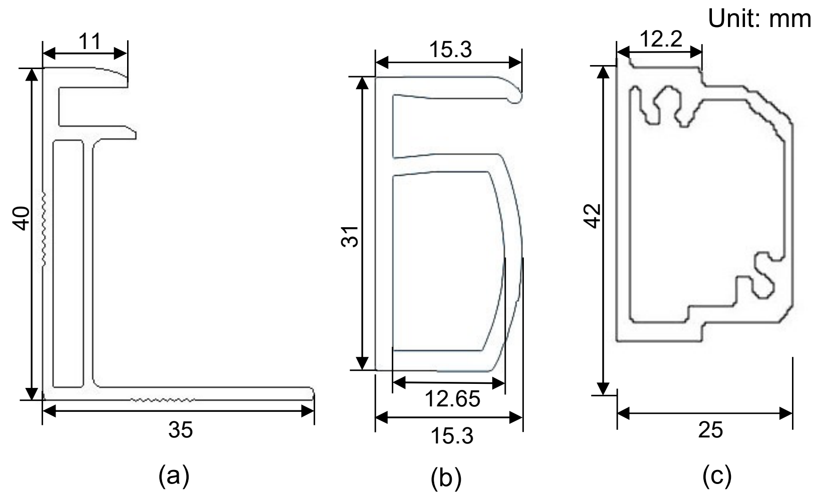

Figure 4. Examples of silicon module frame design

(a) Module #CS6K-275M (Canadian Solar, 2015), (b) Module #SW240-Mono (LG, 2011), (c) Module #LG235M1C-G2 (Solar World, 2011)

A comparison (Figure 5) of material intensity data collected in this study to the IEA PVPS LCIs (Table A.1) indicates that the most used inventories overestimate the material intensity of PV production. In particular, the most recent PVPS 2020 LCI (Frischknecht et al., 2020) uses outdated data on the usage of aluminum frame and glass per m^2 of a module from the PVPS 2015 LCI (Frischknecht et al., 2015). This sets the need for research action on including many module designs in material inventories. Also, LCA practitioners should regularly evaluate and update published inventories (Gazbour et al., 2018).

The analysis in the present study observed a notable decline in the material intensity of aluminum within the module frames from 2008 to 2021 (illustrated in Figure 5a). This trend is aligned with the projections outlined in the ITRPV forecast (VDMA, 2022, 2014). The decrease is primarily due to thinner modules, simplified frame designs, and larger module sizes. The thickness of PV modules over time is presented in Figure A.1 and is positively correlated with the observed trend in aluminum intensity. Before 2010, solar modules typically featured thicknesses ranging from 40 to 50 mm. In contrast, the module thickness currently falls within the 30-40 mm range. This reduction in module thickness can be attributed to the continuous advancement in material science and processing methods, which decreased wafer and cell thickness to reduce production costs (S. Pingel et al., 2009; VDMA, 2023, 2014).

An overview (Appendix B) of module frame cross-section structures shows that older modules have more intricate designs to incorporate multiple layers into the aluminum frame than current designs. Furthermore, the increasing market share of large-sized PV modules, with more cell numbers and larger cell sizes (IEA, 2023; VDMA, 2023), has decreased the normalized aluminum mass (kg/m^2). For example, two Trina Solar modules, TSM-330DD06M (say M1) and TSM-410DE15H (say M2), differ in size irrespective of the same thickness (35 mm) and area (136 mm^2), i.e., M1:1690*996 (mm) and M2: 2015*996 (mm). The resulting normalized Al weight for M1 and M2 is 1.38 kg/m^2 and 1.31 kg/m^2, respectively, showing that larger-sized modules have lower normalized Al weight [18]. However, notable decreases in 2008 aluminum intensity were observed, mainly due to the simplified frame design adopted by the manufacturers (Suntech and Yingli) (Appendix B). A substantial reduction from 2010 to 2011 is attributable to the reduction in module thickness due to technological improvement in PV manufacturing and the resulting wafer thickness reduction (VDMA, 2012). In 2013, one extremely high aluminum-intensive module was observed, which could be related to the manufacturer's (GCL) production strategy of increasing material usage in response to the cost reduction caused by the oversupply in the PV market (VDMA, 2014). From 2014 to 2015, the aluminum consumption in module frames increased, resulting from the increased thickness of some modules (Figure A.1). Moreover, a consistent rise in aluminum intensity has been noted from 2019 to 2021. This was driven by adopting more intricate frame designs characterized by larger cross-section areas with higher aluminum consumption (Figure A.4).

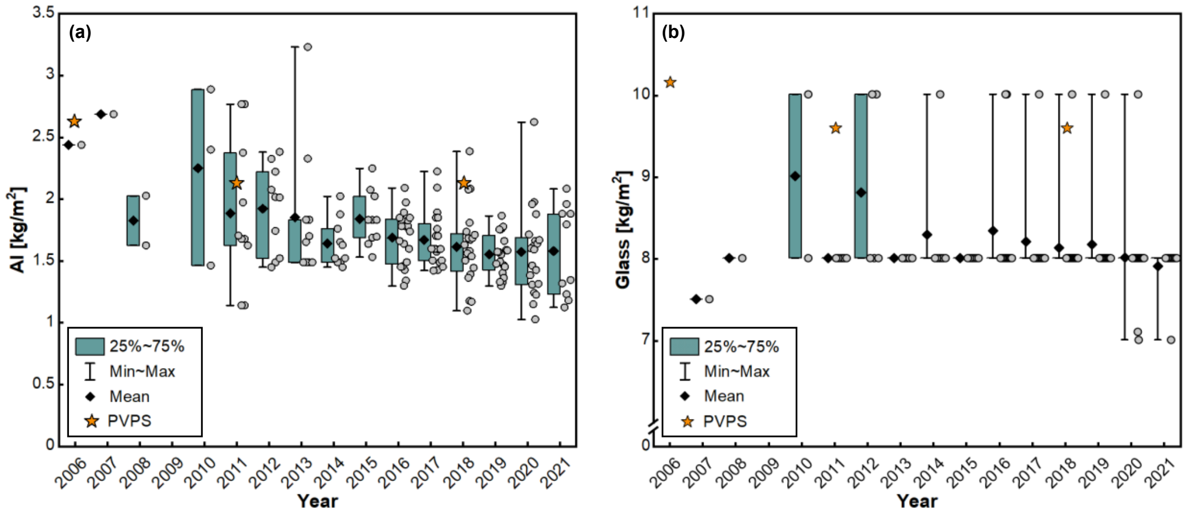

Figure 5. Intensity of (a) aluminum and (b) glass over time

Concerning glass, it can be seen from Figure 5(b) that the glass intensity has remained constant from 2008 to 2021. As previously discussed in Section 2.2, it is assumed that the glass sheet area equals 99% of the module area, making the glass intensity (kg/m^2) dependent on its thickness only. Currently, 3.2 mm tempered glass dominates the market with a small share of 4 mm tempered glass (Solar Frame, 2020). Meanwhile, there has been a recent trend towards thinner glass sheets, particularly for bifacial modules (Solar Frame, 2020). Figure 5 demonstrates the temporal intensity of glass usage in solar PVs based on the available glass thickness in the module specification sheets. However, the transition towards thinner glass appears to be progressing more slowly than initially anticipated. Most PV modules have consistently used 3.2 mm tempered glass, with some using 4 mm from 2007 to 2021. Furthermore, several modules manufactured after 2020 use tempered glass with 2.8 mm or 2.84 mm thickness. This gradual shift towards thinner glass can be attributed to several factors, such as the perceived risk of reduced mechanical strength or durability, and the availability and cost of thinner glass (PV TECH, 2017).

In 2022, the world market share of bifacial modules reached 30%, which is expected to continue to increase in the next few years (IEA, 2023; VDMA, 2023). Thus, it can be predicted that the thickness of the solar glass sheet would decrease, but the overall intensity of glass used for a silicon module would increase due to the bifacial application. The aluminum frame thickness and usage will also increase in correspondence to the increased total laminated thickness. Despite the constant thickness of solar glass, its transmission rate has improved from 93.5% to 94.5% over the past decade, which enables module efficiency improvement (VDMA, 2022, 2014). In the next decade, the transmission rate is expected to reach 95% (VDMA, 2023, 2022).

3.2.2. Comparison of Tier 1 vs. Non-Tier 1 manufacturers

This section compares the material intensity of modules produced by manufacturers in different tiers. As per Section 2.1, manufacturers are classified into tiers based on PVEL (PVEL, 2022) and BNEF (BloombergNEF, 2022) ranking lists, reflecting module reliability and business bankability, respectively. Since the PVEL list started in 2014, the tier classification only covers the period 2014 - 2021. Table 2 shows the number of modules analyzed for each tier.

Table 2. Summary of modules by manufacturer tiers from 2014 to 2021

BNEF Tiers	**PVEL Tiers**		***Total***
	Tier 1	***Non-Tier 1***	
Tier 1	39	33	72
Non-Tier 1	24	34	58
Total	63	67	130

The material intensity of PV modules produced by different tier manufacturers is presented in Figure 6. Regarding PVEL rankings, Tier 1 manufacturers generally use more aluminum than non-Tier 1 in five out of eight years. The disparity between different tiers in aluminum intensity was minimal in 2017 and 2018. The only year with non-Tier 1 observed to show significantly higher Al intensity than Tier 1 was 2020. The Al intensity by non-Tier 1 dropped significantly in the following year. Regarding glass, it can be observed that PVEL tier 1 manufacturers use more glass per m^2 module than non-tier 1 in four out of eight years, and both tiers have similar glass intensity in two out of eight years (2015 and 2016). This suggests that our hypothesis was correct and that more reliable modules use more aluminum and glass.

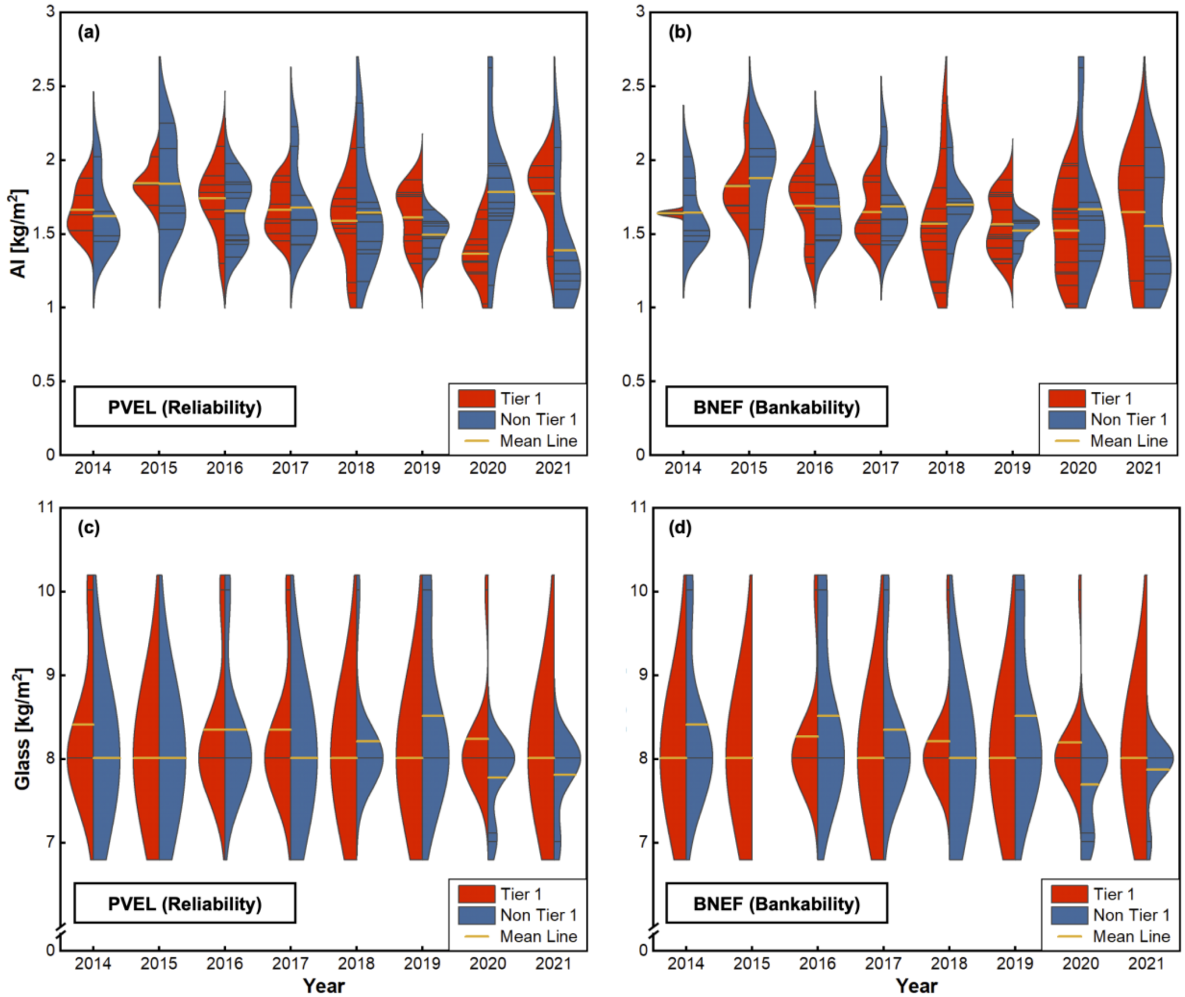

Figure 6. Split violon plot showing material intensity for Tier 1 (red) and Non-Tier 1 (blue) manufacturers. The black lines depict individual data points for modules and the orange lines depict the mean. (a) Aluminum intensity by PVEL tiers, (b) Aluminum intensity by BNEF tiers, (c) Glass intensity by PVEL tiers, and (d) Glass intensity by BNEF tiers.

Overall, the results from this section provide insight into the relationship between material usage and the manufacturer tier. PVEL tier 1 manufacturers generally use more materials, which may result in modules with better reliability. Thus, it is crucial to consider the material intensity of the module while evaluating product quality. A module frame with higher aluminum intensity lowers the risk of delamination and moisture ingress to encapsulated layers (Segbefia et al., 2021).

Similarly, applying thicker glass could avoid early breakage and module failure (Aghaei et al., 2022).

On the other hand, there is no correlation between Tier 1 BNEF tier and higher material usage. Using more materials by PVEL tier 1 manufacturers may result in a higher environmental footprint, especially concerning carbon emissions associated with material production and transportation. However, it is also possible that the higher quality and longer lifespan of PVEL tier 1 modules could result in a reduced environmental impact over the long term, as fewer replacements and repairs would be needed.

3.2.3. *Comparison of materials usage by different manufacturers*

This section presents a detailed materials analysis of modules produced by the top four manufacturers, with most modules selected in the present study. The selected manufacturers are LG, Canadian Solar, Trina Solar, and Jinko. As shown in Figure 7(a)-(d), the aluminum intensity used by these manufacturers exhibits variations in the last decade. LG and Jinko Solar have used aluminum at relatively constant levels, indicating a consistent design approach from 2011 to 2021. In comparison, Canadian Solar and Trina Solar showed notable variations in aluminum intensity, with an overall decrease from 2011 to 2021. This indicates that these manufacturers might have strategies to reduce material use in module assembly and, thus, lower overall manufacturing costs and carbon emissions.

Regarding solar glass, most PV modules produced by these four manufacturers use 3.2 mm standard solar glass, although the thickness can vary due to design changes. For LG (Figure 7(e)), most modules' specification sheets do not specify the glass thickness, except for one module produced in 2020 that uses 2.8 mm thick solar glass. Canadian Solar has maintained a consistent glass thickness of 3.2 mm from 2011 to 2021 (Figure 7(f)). In contrast, Jinko Solar and Trina Solar have used 3.2 mm thick solar glass for most of their module types from 2011 to 2021, but also have used thicker glass sheets, with 4 mm in 2012, 2014, 2017, and 2015, respectively (Figure 7(g) and (h)).

The analysis of aluminum and glass usage among the four manufacturers suggests significant variation in material usage among manufacturers. The consistency in aluminum and glass usage by Jinko Solar may reflect their commitment to design and production standardization. In contrast, other manufacturers' variations in material usage may reflect their adaptive design and production strategies.

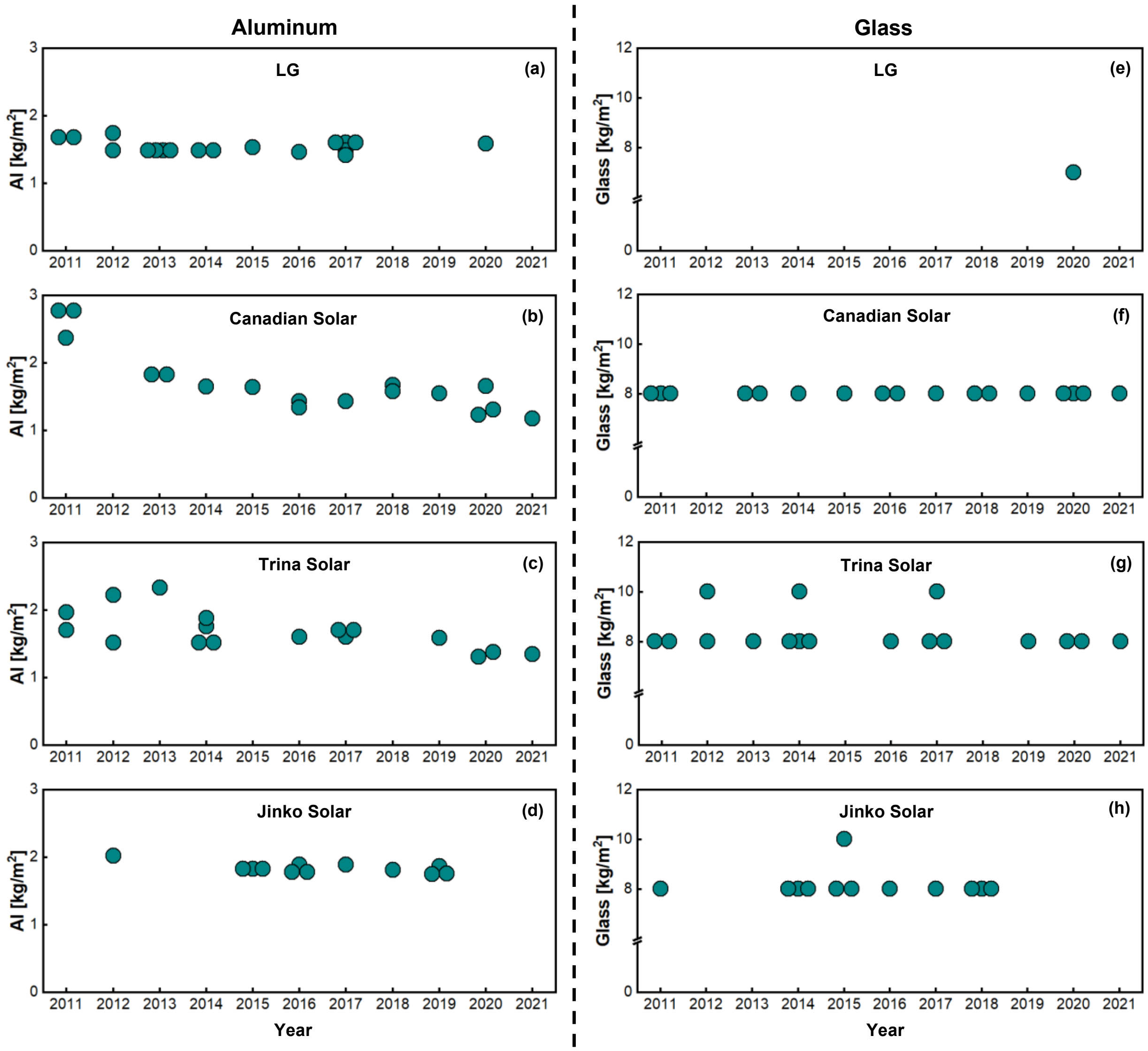

Figure 7. Aluminum intensity in PV modules manufactured by (a) LG (b) Canadian Solar (c) Trina Solar (d) Jinko and glass intensity by (e) LG (f) Canadian Solar (g) Trina Solar (h) Jinko

3.3. Environmental impacts of PV modules

3.3.1. Electricity mixes in PV manufacturing countries

Table A.4 summarizes the electricity generation by source in considered countries. In China, coal has been the primary source. In Malaysia, South Korea, Thailand, Turkey, the US, and Vietnam, fossil fuels such as coal and natural gas have been the primary sources of electricity generation. The Global Warming Potential (GWP) of the local grids is also calculated and listed in Table A.4. Even within the same country, the grid mix has changed over time, reflecting shifts in energy policy and technological advances (McKinsey Sustainability, 2019). For example, in China, the GWP of the national average grid has decreased from 1.05 kg CO_2eq/kWh in 2011 to 0.87 CO_2eq/kWh in 2021. In general, the carbon footprint of the electricity grid in different countries has decreased over time (Table A.4) due to the shift toward cleaner and more sustainable energy.

3.3.2. Carbon footprint of silicon PV manufacturing in China over time

This section selected 24 mono-Si and 31 multi-Si China-based modules from 2011 to 2021 for LCA analysis. The carbon footprint results for the PV module during the manufacturing stage are interpreted per m^2 (Figure 8(a)) and per kW_p (Figure 8(b)), considering the module efficiency. A comparison of the LCA results from the present study to the PVPS LCIs (Figure 8(a)) indicates that the PVPS inventories tend to overestimate the overall environmental impacts of PV manufacturing. This may be because the present study used module-specific data instead of overestimated material intensity for the aluminum frame and glass. As shown in Figure 8(b), for both mono- and multi-Si modules, the GWP decreased significantly after 2015 since two different LCIs were considered for the reference LCA models. The earlier IEA PVPS 2015 is updated to PVPS 2020 with lower material and energy consumption, thus explaining the GWP decrease observed after 2015 in the present study. Apart from this, a decreasing trend of GWP in the manufacturing phase of PV modules is observed. This reduction can be attributed to several factors, including the ongoing grid decarbonization, the aluminum reduction in frames, and the improved module efficiency. These combined factors contributed to a less carbon-intensive manufacturing process of silicon PV modules. Additionally, it is noted that there is a diminishing disparity in GWP per kW_p between mono- and multi-crystalline Si modules because of the higher efficiency of mono-Si modules (Figure A.5). This underlines the critical role of improving module efficiency in reducing the environmental impact of PV technologies.

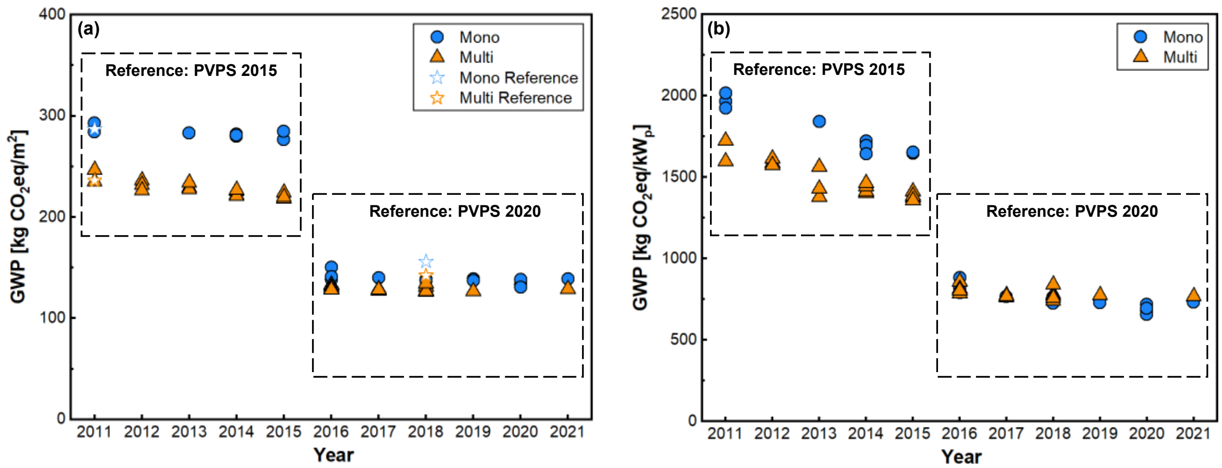

Figure 8. GWP of silicon PV manufacturing in China (a) per m^2 (b) per kW_p

3.3.3. Impact of manufacturing location on the carbon footprint of silicon PV

This section compares the carbon footprint of manufacturing silicon modules in different countries where the manufacturer has facilities to produce the module. A total of 22 silicon modules, including 11 mono-Si and 11 multi-Si modules, are selected. Figure 9 shows that PV manufacturing in China has the highest environmental impact on GWP due to its high dependence on coal. Module production emits the least carbon in Vietnam (25%-30% less than China), followed by Turkey (18%-21% less than China), Thailand (19%-21% less than China), the US (17%-18% less than China), South Korea (15%-16% less than China), and Malaysia (4%-9% less than China).

The findings suggest that manufacturing the same silicon solar module in different countries results in different carbon footprints, which is mainly influenced by the carbon intensity of the local electricity grid mix. China is usually considered to have a highly carbon-intensive electricity grid. However, Figure 9 indicates that modules manufactured in Malaysia have a similar carbon footprint to China due to its high share (80%) of fossil fuel. Further, modules produced in Vietnam have the lowest carbon footprint due to a large share (>30%) of hydroelectricity generation (see Table A.4 in Appendix A). This emphasizes the importance of transitioning to cleaner energy sources and investing in renewable energy infrastructure to mitigate the carbon emissions associated with PV module manufacturing. Besides, the results highlight the potential for PV manufacturers to reduce their carbon footprint by selecting manufacturing locations with cleaner grids or increasing renewable electricity sources. This is what is being pursued by many manufacturers. For example, solar manufacturers such as Jinko, Longi, and First Solar, joined RE100 (RE100, 2023) and promised to use 100% renewable energy by 2025, 2028, and 2028, respectively (First Solar, 2020; JinkoSolar, 2019; Longi, 2020). Jinko Solar has built two "RE100 factories" fully powered by renewable energy in China, and one in Malaysia, which reduces annual carbon emissions significantly (JinkoSolar, 2022a, 2022b).

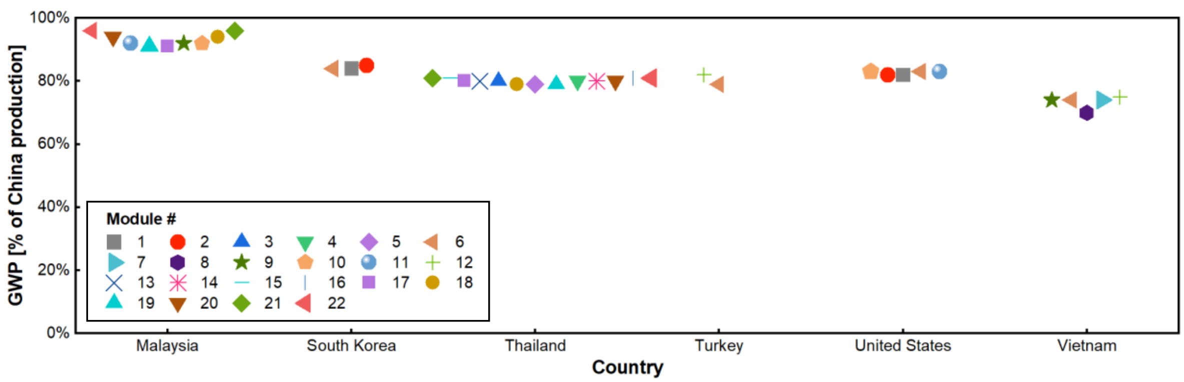

Figure 9. GWP of PV manufacturing in multiple countries where the module's manufacturer has facilities

Overall, the findings from the present LCA study highlighted the importance of up-to-date inventories for material intensity analysis, and electricity mixes specific to production location in LCA analysis. One of the limitations of this study is the exclusion of transportation between manufacturing stages and the assumption that the production processes of all components occur in one country. Although transport has a relatively small contribution to the whole life cycle of PV production (<5%) (Liu and van den Bergh, 2020; Müller et al., 2021), including it can better represent the global PV supply chain. Nevertheless, this study provides a reference for stakeholders to plan for material recycling from the retired PV modules in the coming decades. The same approach that collects material inventory data from the module specification sheet can potentially be applied to other materials, such as cable materials. Based on our data collection process, the authors realized that PV manufacturers rarely disclose detailed material inventories. The available literature also gives little attention to variation in conventional materials like glass and aluminum in the design of crystalline silicon modules. To improve the life cycle environmental assessment of solar modules produced by different manufacturers at different locations, there is a need for more accessible and detailed PV datasheets, public disclosure of manufacturing information, and external review of the bill of materials. The research underlines the need for low-carbon solar module criteria or guidelines that account for module design variations and manufacturing locations. This could pave the way for developing industry standards promoting sustainable solar manufacturing and module design. Further, future studies on the life cycle impact of silicon modules should consider lead and other emerging contaminants like fluorinated compounds, which could pose risks during various life cycle stages. Considering the toxicity impact of these contaminants can provide a better understanding of the environmental impact of solar modules.

4. Conclusions

The present study provides insights into the variation of material usage for crystalline silicon PV modules through a temporal analysis of aluminum and glass usage in 167 modules produced by 31 manufacturers from 2006 to 2021. The selected modules represent products from a diverse range of PV manufacturers, and the results provide a comprehensive overview of the material intensity of crystalline silicon modules over the past decades. An important observation from our study is the correlation between module reliability and material usage, where more reliable modules tend to have higher material intensity for module production. It raises essential questions regarding the trade-offs between sustainability and product quality in the PV industry. Besides, the quantitative data we provided on aluminum frames and glass sheets can serve as a comprehensive resource for estimating material demand, forecasting waste generation of solar PV technologies, and planning material recycling and recovery processes.

The life cycle environmental impacts are also investigated as a function of manufacturing location. Based on the facility locations of the investigated modules' manufacturers, the considered countries include China, the US, Turkey, Malaysia, South Korea, Thailand, and Vietnam. The modules produced in China from 2011 to 2021 reveal a significant carbon footprint reduction in PV module production over the last decade owing to the decarbonization of the grid, the reduction of aluminum intensity for the frame, and the improvement of module efficiency. Additionally, the comparison of actual production data and the commonly used LCIs indicates the need for more comprehensive and higher-quality LCIs that consider a large variety of module designs. The comparison of production in various countries illustrates the significant impact of the local electricity mix on the carbon footprint of PV production. These findings indicate that PV manufacturers can reduce the carbon footprint of solar modules by improving the module design, reducing material usage, or increasing the share of clean energy in production facilities. Global solar manufacturers are encouraged to collaborate and build supply chains with low carbon footprints for each component. Improving the durability and efficiency is also important to ensure a longer module lifetime with more clean electricity generation, so it can reduce the replacement with new modules and compensate more for the carbon footprint associated with module manufacturing.

The present study only focuses on the material intensity analysis of aluminum and glass. Future research could expand upon this approach to analyze a broader range of materials used in PV module manufacturing and investigate how material-use variations affect environmental outcomes. Moreover, in the life cycle assessment performed in this study, stages such as transportation and end-of-life treatment are excluded from the system boundary. Besides, only one impact category, global warming potential or carbon footprint, is considered. Future work could include more stages to evaluate the impact associated with varied material consumption, such as the reduced impact of transportation caused by decreased module mass. Last but not least, to gain a holistic understanding of the environmental impact of solar PV modules, the toxicity impact of contaminants such as lead and fluorinated compounds can be considered.

Overall, this study has important implications for policymakers and industry stakeholders to consider variations of module design and manufacturing locations in low-carbon solar module criteria or guidelines. Meanwhile, it highlights the need for a transparent data reporting and availability platform for accurate environmental impact assessment. The novel approach of collecting aluminum and glass consumption data in the present study can be potentially used for other PV components (e.g., encapsulant and back sheet) to create a more comprehensive material inventory database of solar modules.

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Appendix A. Supporting Information

Appendix B. Raw data

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