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Commentary

# Design changes for improved circularity of silicon solar modules

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https://doi.org/10.1016/j.oneear.2024.01.020

**While recycling technologies are being developed for silicon solar modules, design changes to improve module circularity have been rarely explored. This commentary discusses several cost-effective design changes that could alleviate some of the challenges in silicon module recycling to reduce recycling cost, improve material recovery, and minimize environmental hazard.**

Since the inception of the solar industry, the focus of the manufacturers has been almost exclusively on cost, efficiency, and reliability of their modules.[1] Their laser-sharp focus is credited for the rapid growth of the industry over the last 40 years, with an average annual growth rate of 35% in the last 20 years.[2] In 2022, the global installation of new solar modules reached 239 gigawatts peak (GWp). Solar modules are designed to last 25 years. That is, we would see 239 GWp of, or roughly 14 megatonnes of, end-of-life solar modules in 2047. This number does not include all the balance-of-system waste including power converters, mounting components, electrical wires, and storage batteries.

The lack of attention to circularity has created several barriers to a circular economy in the solar industry that include toxic and scarce materials used in solar modules as well as difficulties in module delamination.[3] Moreover, the current research efforts to create a circular solar industry tend to emphasize recycling technologies for solar modules over design changes to improve module circularity.[4] This unbalanced emphasis is evident in the large number of publications on recycling technologies in contrast to the small number of publications on design for circularity. Without design changes, current recycling technologies reclaim only 10%–15% of the materials in silicon modules by weight (wt %) for reuse in new modules.[3] The small percentage includes mainly the aluminum frame and copper wires in the junction box. The remaining 85–90 wt % of the materials are either landfilled or downcycled for less demanding applications such as concrete aggregate or sandblasting.

While innovations in recycling technologies are needed to improve material recovery rates, this commentary proposes several design changes to alleviate some of the challenges in silicon module recycling and achieve a 90–95 wt % circularity, i.e., 90–95 wt % of the materials are recovered for reuse in solar and similar applications. These cost-effective design changes include:

(1) Lead-free modules to eliminate environmental hazard of silicon modules.
(2) Silver-free modules to control recycling cost in light of diminishing silver content.
(3) A new encapsulant for easy separation and exposure of silicon cells from modules.
(4) An effective recycling technology or a new encapsulant for dual-glass modules.
(5) Traceability of module information to facilitate effective reuse and recycling.

## Lead-free modules

Today, all silicon modules contain toxic lead at 10–15 g/module. It presents an environmental hazard if it is not removed from recycling sludge before landfilling. As shown in Figure 1, the first step in silicon module production is to electrically interconnect silicon solar cells by soldering copper wires between them. The solder is made of roughly 60% tin and 40% lead. However, few recyclers talk about lead recovery today. This is because reclaiming lead does not generate revenue but incurs significant cost. As shown in Table 1, all the lead contained in a 60-cell aluminum back-surface field (BSF) or passivated emitter rear contact (PERC) module is worth only 4¢/module.[5] In stark contrast, the cost to extract lead for safe disposal is estimated to be about 100 times higher at a few dollars per module.

There are some efforts to remove lead from end-of-life modules and recover it as metallic lead for reuse in new solder.[6] Recyclers could impose a fee on module owners, say $5/module, to cover the cost of lead recovery, but switching to a lead-free solder might present a more economic and environmentally friendly alternative. This switch would eliminate any chance of accidents during lead recovery. Lead-free solders have been commercially available for decades.[7] A popular lead-free solder is an alloy of approximately 96% tin, 3% silver, and 1% copper. All the metals in this solder can be recovered through recycling. The additional cost for the lead-free solder is below $0.35/module over the current leaded solder. One of the challenges in adopting a lead-free solder is its higher melting point, 217°C, versus 183°C for

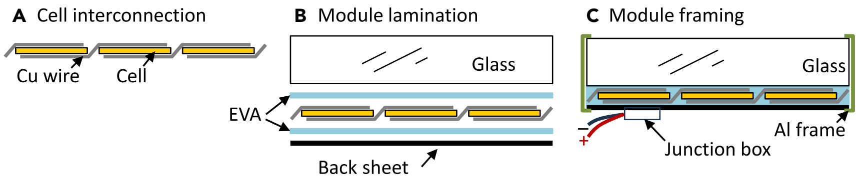


**Figure 1. Today's prevalent production process for silicon modules**
(A) Interconnection of silicon cells by soldering.
(B) Lamination of silicon cells through EVA with glass and back sheet.
(C) Attachment of aluminum frame and junction box.

the leaded solder. This creates more thermal stress, thus likely more wafer breakage and a lower yield, for manufacturers. The lower yield might be a price we have to pay for improved module circularity.

## Silver-free modules

Silver is the second most expensive material in silicon cells behind the silicon wafer. It is a significant source of revenue in recycling, accounting for over 40% of the total revenue as shown in Table 1. Today, a PERC cell of 166 × 166 $mm^2$ produces about 6 Wp under standard test conditions (AM1.5 and 25°C). Each PERC cell requires about 0.1 g, or 15.4 mg/Wp,[8] of silver for the front finger electrode and the back soldering pads. This amount of silver costs about 7.5¢/cell at the current price of silver. More advanced cell structures require more silver. The tunnel oxide passivated contact cell and silicon heterojunction cell require 65% and 120% more silver than the PERC cell, respectively,[8] which translates into $2.93/module and $5.32/module in additional silver cost. The rapid growth of the silicon solar industry may one day strain the silver supply, leading to price hikes for silver and making these advanced cell structures less attractive.

To contain cost, manufacturers have been making consistent efforts to reduce the silver content per cell or per watt peak. Over the last decade, there has been a 4-fold reduction in silver content on a per-watt-peak basis, and another 2-fold reduction is projected by 2030.[8] This trend poses a dilemma for recyclers. At 8.5 mg/Wp of silver by 2030, all the silver in a 60-cell PERC module is worth only $2.45/module, which is likely below the cost of running the silver recovery process. At this point, the only way for recyclers to recover silver is to charge the extra cost to module owners, leading to a higher recycling fee.

Because the diminishing silver content would deter recyclers from recovering silver, it is desirable to scrap silver altogether and substitute it with copper instead of reducing silver content. There would be no revenue from silver, but no cost for silver recovery either, so recyclers would break even on silver. As an alternative, copper electrodes, by electroplating, have been demonstrated in place of silver on silicon cells.[9] However, the industry has not adopted electroplated copper due to the significant upfront investment for the electroplating and associated tools and the significant process cost due to the extra patterning step for the front electrode. A copper paste would overcome these barriers, as it works the same way as the current silver paste in the industry, utilizing the same screen-printing tool without the need for patterning.[10] The main challenge with a copper paste is to make sure that it does not impact the cell efficiency, as copper is known to kill cell efficiency once it diffuses into silicon. Moreover, copper is more prone to oxidation than silver. Despite all the advantages of copper, including lower cost and more abundant resource, manufacturers must overcome copper oxidation and diffusion during high-temperature firing and over a 25-year lifespan.

## New encapsulant

The biggest barrier to silicon module recycling today is delamination.[3] The module production process involves encapsulating silicon solar cells with a polymer, typically ethylene vinyl acetate (EVA), which binds them to glass and a back sheet (Figure 1). This durable, crosslinked polymer is hard to break apart, preventing easy separation of silicon cells from glass and back sheet. NPC Inc. has developed a hot knife tool that cuts through the encapsulant between silicon cells and glass, allowing clean separation of cells from glass,[11] but there is currently no commercial tool to separate the back sheet from silicon cells. For metal leaching, the residual EVA on separated silicon cells must be removed. The only practical option for EVA removal today is thermal decomposition above 500°C in a furnace. However, the back sheet still attached to the silicon cells is a fluoropolymer. It would release a nasty fluorine exhaust during thermal decomposition of EVA. This is why most recyclers stop after aluminum frame and copper wires, leading to a 10–15 wt % circularity for silicon modules.

There are efforts to develop an alternative encapsulant material, although the motivation has not been module circularity. For easy delamination, new polymer encapsulant materials that are of interest are not covalently crosslinked like EVA. One example is thermoplastic polyolefins (TPOs).[12] Their crosslinking is through van der Waals bonding, so they undergo reversible thermophysical softening and

**Table 1. Potential revenue from a 60-cell aluminum back surface field or passivated emitter rear contact module**

| Material | Weight | Price ($/kg) | Value | % Total Revenue |
|---|---|---|---|---|
| Glass | 13.5 kg | 0.10 | $1.35 | 13.3 |
| Aluminum | 1.83 kg | 1.15 | $2.10 | 20.7 |
| Polymers | 1.18 kg | N/A | 0 | 0 |
| Silicon | 0.62 kg | 1.50 | $0.93 | 9.2 |
| Silver | 6 g | 738.81 | $4.43 | 43.7 |
| Copper | 0.11 kg | 6.72 | $0.74 | 7.3 |
| Lead | 18.3 g | 2.17 | $0.04 | 0.4 |
| Tin | 21.9 g | 24.56 | $0.54 | 5.3 |
| Total | N/A | N/A | $10.13 | 100 |

Prices are current as of October 24, 2023 assuming 100% material recovery.[4]

hardening upon heating and cooling. They could also be recovered for reuse many times. TPOs have a good balance of cost and mechanical properties along with improved degradation resistance over EVA. However, TPOs are more prone to moisture permeability than EVA, and in some cases, their adhesion to silicon cells is not as strong.

An ideal encapsulant material for improved circularity would provide the performance, including moisture resistance, of a covalently crosslinked polymer without requiring high temperature decomposition during recycling. Such a circular encapsulant would delaminate under mild conditions through a triggered response by a stimulus. Stimuli-responsive polymers and self-healing polymers for solar modules have recently reported utilizing reversible crosslinking chemistries.[13] Although these stimuli-responsive and self-healing materials are at an early stage, they point toward a design strategy that could improve encapsulant delamination and ultimately recyclability of silicon modules.

There might be other approaches to delamination. For example, Apollon Solar has developed a new industrial solar cell encapsulation technology that eliminates the encapsulant altogether.[14] Although Apollon Solar is no longer in business, innovations in encapsulant and/or delamination are a high priority for a circular solar industry.

## Dual-glass modules

Dual-glass modules are another example of performance and reliability over circularity. Dual-glass modules have the fluoropolymer back sheet in Figure 1 replaced with a glass back sheet. They have a higher power output than traditional modules with a polymer back sheet, as both sides of the module produce power. They are also more durable, as the glass back sheet is mechanically stronger, less permeable to moisture, and has less degradation than a polymer back sheet. Even the US Government promotes dual-glass modules by exempting them from tariffs imposed on all other silicon modules imported from China.[15]

The problem with dual-glass modules is that there is currently no method to separate the silicon cells from the glass sheets on either side. Existing tools, such as NPC's hot knife tool, do not work for a rigid glass back sheet. This means all the metals in silicon cells are almost impossible to recover, including silver, lead, silicon, tin, and copper. With silicon cells still attached, the glass has to be downcycled, leading to a 10 wt % circularity for dual-glass modules. Before promoting them, the priority should be the development of a recycling technology for them. Alternatively, a new encapsulant that is easy to delaminate may be the answer to recyclable dual-glass modules. Since the back sheet in dual-glass modules is glass, these modules only need to seal the edges, and the encapsulant could be more prone to moisture permeability, allowing TPOs in these modules.

Recyclable dual-glass modules would provide another advantage over traditional modules with a fluoropolymer back sheet. As discussed above, thermal decomposition of flouroploymer releases a fluorine exhaust. Therefore, the only option for fluoropolymer waste is landfilling. This means about 3 wt % of the module is landfilled, and landfilled fluoropolymer will last forever without decomposition. With a glass back sheet, there would be no fluoropolymer back sheet to deal with if the modules are otherwise recyclable.

## Module traceability

After 25 years in the field, the labels on end-of-life modules are often unreadable, product specifications are unavailable, and the manufacturer may no longer be in business. For effective recycling, recyclers must then investigate or guess the design, construction, and constituent materials of the modules, including the presence of toxic materials. With the numerous different types of silicon cells and modules out there, this investigation would be time consuming, costly, and would often miss low-content materials. Remember that silver, lead, and tin each account for less than 0.1 wt % of a silicon module,[5] and their distributions in modules are not uniform.

This problem can be solved with industry standard unique identifiers (IDs) applied by manufacturers with smart tag technology, such as quick-response codes. The unique ID enables module traceability and links to a standardized data model that includes ratings, specifications, and constituent materials. Recyclers and other stakeholders along the supply chain can scan the smart tag to retrieve the unique ID and obtain module attributes 25 years later. The unique ID standards and supporting technology are being developed with funding from the US Department of Energy.[16]

There are more benefits for traceable modules. For example, if a module contains lead, recyclers could charge an extra, say $5/module, over lead-free modules to cover the cost of lead recovery, while a lead-free solder adds only $0.35/module upfront. This way, recyclers may be able to push for lead-free modules and eliminate the environmental hazard of silicon modules. Moreover, the smart tag would facilitate module reuse. To find matched modules, one could narrow down the pool, through the smart tag and unique ID, to those modules with the same design (cell type, cell count, module construction, weight, dimension), the same original performance (voltage, current, power, efficiency, degradation rate), and even the same batch. There are far fewer modules to test and match.

## Outlook

Advances in both recycling technologies and module designs are required to achieve a 90–95 wt % circularity for silicon modules. While lead-free solders are available for adoption by the solar industry, the research community must work with the industry to provide cost-effective technologies for circular silicon modules, including copper electrodes, recyclable encapsulant, and traceable modules.

## ACKNOWLEDGMENTS

This material is based upon work supported by the US Department of Energy's Office of Energy Efficiency and Renewable Energy under award no. DE-EE0007897 awarded to the REMADE Institute, a division of Sustainable Manufacturing Innovation Alliance Corp.

## DECLARATION OF INTERESTS

T.D. has a pending patent related to this work, "Pastes for Solar Cells, Solar Cells, and Methods of Making Same," United States Patent Application No. US20220320357A1, (2022).

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