Technologies to Improve the Profitability of Silicon PV Module Recycling

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With today's technology, the cost for recycling Si PV modules far exceeds the revenue from recycling. This paper examines two recycling scenarios which can improve the profitability of Si module recycling: 1) module reuse and 2) material extraction and reuse. The process sequences for the two scenarios are outlined, along with the potential revenues, the recycling technologies needed, and the major challenges for each scenario. Material extraction and reuse is the ultimate solution for module recycling. A two-stage recycling process is proposed for this scenario. The first stage is module recycling which can be done locally to recover and recycle ~95% of the module weight. The second stage is cell recycling which is carried out in centralized facilities involving chemical processing. Several module trends which negatively impact module recyclability are discussed including dual-glass modules and reduced Ag consumption in modules.

1. Introduction

While the need to recycle PV modules is widely recognized, it is seldom practiced due to the high recycling cost. In the US, the recycling cost is $20–25/module excluding the costs to decommission, package, and ship waste modules, while the recovered materials from the modules by today's technology are worth at best $3/module [1]. Therefore, research is needed for new technologies which either maximize the revenue from and/or minimize the cost for recycling, in order to promote PV module recycling.

Out of all the module technologies on the market, Si modules have always been the dominant technology with a market share hovering around 90% for decades. In 2019, Si modules accounted for ~95% of the PV market [2], so their recycling represents a pressing need. In this paper two recycling scenarios are proposed and analyzed for the purpose of improving the profitability of Si module recycling: module reuse and material extraction/reuse. Module recyclability is also discussed in light of recent module trends.

2. Today's Recycling Technology

Fig. 1 shows the structure of the most common Si modules today excluding the junction box. It contains an Al frame with a silicone sealant, a junction box which has a plastic case containing Cu wiring and silicone potting, a glass pane, Si solar cells which are interconnected with Cu ribbons and Pb-based solder, two layers of ethylene vinyl acetate (EVA) as the encapsulant, and a backsheet made of polyethylene terephthalate (PET) and polyvinyl fluoride (PVF) or polyvinylidene fluoride (PVDF).

Today's recycling process recovers only the bulky materials in Si modules including Al, glass, and Cu. The process is all mechanical (Fig. 2): 1) remove the junction box for Cu; 2) extract Cu from the junction box; 3) remove the Al frame; and 4) shred the remaining modules for glass. The glass recovered by this process contains fluoropolymer and Si cells, so it is low-quality glass cullet and there are few buyers for it. Some recyclers skip junction box removal or even Al frame removal. They shred the modules as a construction material. If the Al and Cu are recovered and a buyer can be found for the glass cullet, each module can in principle generate ~$3/module by today's technology (Table 1).

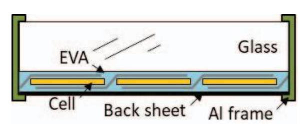

Fig. 1. Schematic structure of today's most common Si modules.

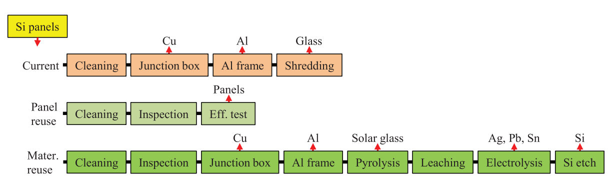

Fig. 2. Current and proposed recycling processes for Si modules.

Table 1: Revenue by today's technology for Si modules as of 02/14/2021.

Material	Weight (kg)	Price ($/kg)	Value ($/module)
Glass	13.5	0.05	0.68
Al	1.83	0.84	1.53
Cu	0.11	6.79	0.75
Total			2.96

With the recycling revenue far below the cost, it is worth a while to rethink everything about Si module recycling in order to improve the profitability of Si module recycling.

3. Module Reuse

Two possible scenarios to improve the revenue from Si module recycling are shown in Fig. 2. One is module reuse and the other is material extraction and reuse [1].

Many decommissioned modules are still functioning but at lower efficiencies. The manufacturers typically guarantee 80% of the original efficiencies after 25 years. These modules can be in principle sold as a lower-quality product at a lower price than new modules. Fig. 2 shows the steps involved in module reuse: 1) clean the modules; 2) inspect the modules for visual damage; and 3) if no damage, test module efficiency for recertification. Automated module efficiency testers are available, but an automated visual inspection station is yet to be developed. For module cleaning, we can adopt the car wash equipment.

If reused modules are sold at 50% of the price for new modules, a 60-cell multicrystalline Al back-surface field (BSF) module can generate ~$20 in revenue at today's module price (Table 2). This is far more than the revenue by today's technology, but still not enough to cover the recycling cost. This highlights the importance of technologies to reduce the recycling cost, along with the ones to increase the recycling revenue.

Table 2: Revenue by module reuse from a 60-cell multicrystalline Al BSF module as of 01/13/2021, ~$20/module.

New Module	EoL Module	Unit Price	Value ($/module)
275 W_p	220 W_p	$0.18/$W_p$	$19.80

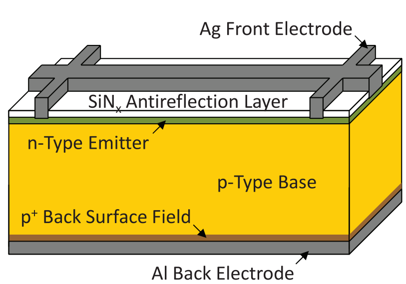

Fig. 3. Schematic structure of the most common Al BSF cell.

The difficulty in module reuse is to find a large and sustained market on the order of hundreds of gigawatts peak every year into the future. Moreover, the spot price for new multicrystalline Al BSF modules is $0.18/$W_p$ today [3], while the price of installed systems is $2.3–3.8/$W_p$ in the US [4]. Cheaper reused modules are financially less attractive considering all the challenges involved with reused modules such as lower efficiencies, shorter lifetimes, unmatched modules, and quality and safety issues [5]. The focus here should be on reducing the price of installed PV systems.

4. Material Extraction and Reuse

This is the ultimate solution as some modules are not reusable. Even reused modules will eventually fail and will need to go through material extraction and reuse.

There are more materials to recover from Si modules than Al, glass, and Cu. These materials include Ag, Si, Pb and Sn from the solder, and Cu from the interconnection, which are all contained in the Si cells (Fig. 3). The Al and SiN_x in the cells are unlikely to be recovered, as they are difficult to recover and they have little value.

To recover Ag, Pb, Sn, Cu, and Si, the Si cells must be separated from the glass first (Fig. 1), which is a critical technology for material extraction and reuse. NPC Incorporated has developed a machine to: 1) remove the junction box from modules; 2) remove the Al frame; and 3) separate the Si cells and the glass [6]. It employs a hot-knife method in which a steel blade heated to about 200˚C slices through the EVA for separation of cells and glass. The glass cullet from the NPC machine contains neither Si cells nor fluoropolymer, so it is solar-quality glass cullet. It can be remelted to make new glass panes for new modules.

With the NPC machine, we can envision a two-stage recycling process for Si modules. The first stage is module recycling and the second stage is cell recycling. Waste Si modules would be sent to a NPC machine and the Al, solar glass, and Cu are recovered from the modules and recycled locally. These three materials account for ~95% of the module weight. The separated Si cells, which are ~5% of the module weight, would be sent to a facility dedicated to Si cell recycling. Cell recycling requires chemical processing [1].

The cells separated from the glass by the NPC machine have EVA and fluoropolymer. The fluoropolymer backsheet should be removed during module recycling and then the EVA can be cleanly removed by pyrolysis. Now we are ready for metal recovery.

Although the technology for metal recovery is still under development, leaching and electrowinning have shown potential to be the simplest and most cost-effective method [1]. Fig. 4 shows a possible process for metal recovery [7]. After pyrolysis (Fig. 4a), the metals (Ag, Pb, Sn, and Cu) are leached from the cells (Fig. 4b). These metals are then electrowon out of the leachate one by one. The next step is to etch off the SiN_x and Al layers and recover the Si wafer (Fig. 4c).

It is possible to further process the Si wafer and extract the p-type base [7]. The 10-µm back-surface field is heavily Al doped and the 0.3-µm emitter heavily P doped. They are out of the specifications for solar-grade Si. The 150-µm base is solar-grade Si with a B doping of ~1×10^{16} cm^{-3}. It can be used as a feedstock for Si ingot growth. The challenges from a recycling prospective include how to clean the recovered Si and how to keep it clean during a “dirty” chemical process. If the recovered Si does not meet the specifications for solar-grade Si, the next grade is metallurgical-grade Si. It is noted the Si wafer is actually much purer than metallurgical-grade Si, 5N’s versus 2N’s. It would be desirable to find a market for 5N Si if not solar-grade Si.

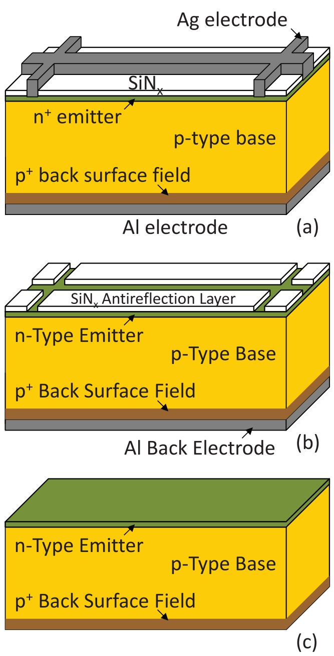

Fig. 4. A possible Si cell recycling process: (a) pyrolysis for clean cells; (b) metals leached; and (c) non-Si layers removed.

Table 3 shows the potential revenue if all the materials are extracted from a 60-cell multicrystalline Al BSF module in their pure, high-value forms as of January 13, 2021. It adds to ~$10/module. The recovered Si is assumed to be metallurgical-grade Si at $1.50/kg. The EVA layers are not recovered, but they can serve as a heat source and reduce the energy needed for pyrolysis of the EVA. The fluoropolymer backsheet is assumed to be removed before pyrolysis. Otherwise a scrubber is needed to capture the fluorine from the pyrolysis exhaust. 100% recovery rates are desirable for all the materials except the polymers.

The most valuable material in Si modules is Ag, accounting for over 50% of the revenue. The Ag price will likely rise in the future, improving the bottom line for recyclers. Al and solar glass each contributes ~15% to the revenue. Pb is a liability which will likely be regulated. The co-existence of Pb and EVA is a bad combination. With moisture, EVA decomposes into acetic acid which is often used to dissolve Pb. This means that Pb leaching is likely when the modules are landfilled. Today’s technology recovers neither Ag nor Pb.

Table 3: Revenue by material extraction from a 60-cell multicrystalline Al BSF module as of 01/13/2021, ~$10/module.

Material	% Recovery	Weight	Price ($/kg)	Value	% Total
Glass	100	13.5 kg	0.10	$1.35	14.1
Al	100	1.83 kg	0.84	$1.53	15.9
Polymers	0	1.18 kg		0	0
Si	100	0.62 kg	1.50	$0.93	9.7
Ag	100	6 g	818.61	$4.91	51.1
Cu	100	0.11 kg	6.79	$0.75	7.8
Pb	100	18.3 g	1.28	$0.02	0.2
Sn	100	21.9 g	4.96	$0.11	1.1
Total				$9.60	100

5. Module Trends and Recyclability

Today’s modules are designed for cost, efficiency, and reliability but seldom for recyclability. This is reflected in several module trends which make them more difficult to recycle.

Ag is the second most expensive component in Si cells behind the Si wafer. There has been a continuous effort in the industry to reduce the Ag consumption per cell. Over the last five years, the Ag amount in each Si cell has come down by a factor of three to ~100 mg/cell [8] and the trend continues. This erodes the financial incentives for the recyclers. A scenario could emerge in which the revenue from the recovered Ag does not cover the cost of the Ag recovery process. For recyclability, the modules should have either a lot of Ag, which is unlikely, or no Ag at all. This means that the solution to expensive Ag must be substitution of Ag with a lower-cost metal, not reduction of Ag consumption.

Another trend with Si modules is the dual-glass bifacial modules. These modules replace the fluoropolymer backsheet with a glass pane, so both sides of the module are covered by glass. These modules produce more power as the backside of the module adds ~10% to the output of the front side. They also improve module reliability as glass is more durable than fluoropolymer and less permeable to moisture. However, there is currently no technology which can extract the Si cells from the dual-glass modules. Until a feasible technology emerges, these dual-glass modules will have to be shredded as a construction material, with Ag and Pb.

6. Conclusions

Two recycling scenarios which can improve the profitability of Si module recycling are proposed and analyzed: 1) module reuse and 2) material extraction and reuse. The process sequences for the two scenarios are outlined, along with the potential revenues, the recycling technologies needed, and the major challenges for each scenario. Module reuse is possible but unlikely to be popular, and material extraction and reuse is the ultimate solution for module recycling. With the critical technology for separation of cells and glass demonstrated, a two-stage recycling process is proposed for material extraction and reuse. The first stage is module recycling which can be done locally to recover and recycle ~95% of the module weight mechanically: Al, solar glass, and Cu. The second stage is cell recycling which is carried out in centralized facilities where the separated cells are sent to. These facilities employ chemical processing as required for cell recycling. Several module trends which negatively impact module recyclability are discussed including dual-glass modules and reduced Ag consumption in modules.

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