

DISPOSING END OF LIFE PV MODULES – REUSING, RECYCLING AND UPCYCLING

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ABSTRACT: The exponential growth of photovoltaic (PV) installations is an important and desirable element in the global response to climate change. Increased use of PV panels for energy production would also lead to enormous volumes of PV waste that need to be dealt with in an environmentally responsible manner. Crystalline silicon (c-Si) technology commands more than 95% share of the solar PV industry. The growing amounts of silicon PV panel waste present new environmental and waste management challenges. The issue has been acknowledged and some recycling processes have been developed. However, the complexity of the recycling process is one of the prime reasons hindering their large-scale implementation and growth of the PV panels recycling industry. In this paper we present a review of the existing processes of recycling of end-of-life PV panels and propose a new possible use of recycled silicon from the end-of-life c-Si PV panels.

Keywords: Sustainability, recycling, circular economy, PV panels

1 INTRODUCTION

There has been a rapid growth of photovoltaic (PV) installations in the past decade. Global installed capacity of PV reached 760 GW at the end of 2021 [1] and is expected to reach 8520 GW by 2050 [2]. The exponential growth of the PV installations is an important and desirable element in the global response to climate change. A typical PV module has a lifetime of 20-25 years. However, some will be damaged during production, transportation, handling, or installation, and some will even stop functioning after shorter time, while some would be discarded during testing called as factory reject modules. There is an urgent need to establish efficient measures to deal with the upcoming enormous volumes of PV waste in an environmentally responsible manner. According to the predictions published by International Renewable Energy Agency (IRENA), the cumulative PV module waste could reach 1.7 - 8 million tonnes in 2030 and 60 – 78 million tonnes by 2050 [3] for installed capacity of 4500 GW. Assuming an average panel life of 25 years and the increased production and deployment of PV panels, large amounts of PV wastes are anticipated by early 2030s. It is expected that by 2040, the weight of waste PV panels generated would almost match that of the new installations[3].

The growing amounts of PV panel waste presents new environmental and waste management challenges. However, with proper waste management procedures in place, this challenge could present us with unprecedented opportunities to pursue new technological and economical avenues. Recovery of raw materials from the PV panels could lead to establishment of new solar PV end-of-life industries. In-fact, solar PV recycling would be of paramount importance for the transition into a sustainable and economically viable renewables-based energy future. To unlock the mechanisms and possible advantages of PV panels recycling, it is important to research different avenues of reusing the end-of life PV modules in time to meet the expected surge in the PV panel waste. Hence, it is important to consider the pathways in which the components could be recycled or reused most effectively, minimizing the generation of the pollutants, unusable waste, and contaminated by-products of the module recycling process.

There are several possible ways of handling end-of-

life (EoL) PV panels – repairing, reusing, recycling, and upcycling. Some panels have minor damages which could either be repaired onsite or offsite to extend their serviceable life. In a large-scale commercial PV plant, some PV panels degrade earlier than others and are replaced with new PV panels. These PV panels may not have reached their EoL performance, however, since their slightly lower performance compromises the operation of the plant, they are usually replaced. PV power plants may also decide to change the existing panels with a new improved technology. The slightly degraded yet functional panels could be given a second lease of life for non-critical operations. A small fraction of PV panels that are completely degraded in terms of performance yet maintain their physical appearance and integrity could be upcycled for various domestic applications. Bifacial PV panels could be utilized as a replacement of glass panels for some domestic applications such as garden fences, noise barriers and green tunnels. However, the applicability of such upcycling or repurposing options are rather limited, both in number and opportunities. The upcycling of solar panels would simply delay the disposal of the PV panels, rather than disposing them completely. Hence, upcycling of PV panels could not be considered as one of the prime strategies for handling PV waste. A literature survey of these options is presented later, highlighting the advantages and disadvantages of the existing solutions.

Recycling the PV panels to recover the materials is one of the most promising ways of dealing with the PV waste. It has been estimated that by 2050, the materials recovered from recycling of PV panels could support production of 2 billion new panels, equivalent to 630 GW by current performance standards [3]. In many countries, stringent guidelines are already in place to deal with Waste Electrical and Electronic Equipment (WEEE) [4], [5]. Especially the EU has published one of the most detailed regulations related to recycling of PV modules. These regulations stipulate a minimum of 80-85% recovery or reuse of materials [4], [6]. Some of the materials such as the external wiring, glass layer and the aluminium frames could be easily extracted and recycled or in some cases reused entirely[7]. In some cases, the metal busbars (usually made of copper could also be easily extracted using either chemical process or a thermal process or a combination of both [8][9]. Then the remaining parts of the module including the glass and c-Si solar cells are just

crushed or milled resulting in glass cullet [10]. In most of the reported module recycling processes, the silicon obtained at the end of the process is metallurgical grade silicon [10]–[12]. Several chemical means could be employed to recover precious metal (usually silver) and solar grade silicon from the mixture which could be recycled [13]–[15]. While chemical treatment to obtain pure silicon appears to be promising and attractive, it has several drawbacks. The process must be tailored for different cell types and architectures. This makes the process extremely complex and prohibitively expensive. Additionally, the chemicals required for this process are highly hazardous and dangerous. The different grades of silicon that can be obtained from a PV module along with the expected revenues are shown in Table 1 [10]. Hence, the end use of the recovered Si from the PV modules would depend on the processing cost of silicon and the value of the product obtained.

Table 1: Revenues from Si of different qualities (value according to Oct-2019) [10]

| Si Quality | Purity (%) | Weight (kg/module) | Price (\$/kg) | Value (\$/module) |
|------------------------|------------|--------------------|---------------|-------------------|
| Ferro-Si | 75 | 0.68 | 0.45 | 0.31 |
| Metallurgical-grade Si | 99 | 0.62 | 1.5 | 0.93 |
| Second-grade Si | 99.99 | 0.56 | 5.5 | 3.09 |
| Solar-grade Si | 99 | 0.56 | 7.6 | 4.24 |

In this paper we review the published methods of recycling silicon obtained from end-of-life c-Si PV panels and propose new routes to use the Si in metallurgical operations.

2 ONSITE/OFFSITE REPAIR OF PV MODULES

The module in service can fail in several ways, failure in interconnection, delamination, cracked glass or backsheets are among the most common failure modes [16], [17]. Other failures could be in the frames, mounting clamps and support structures and associated electronics [18].

2.1 Repair of panels with cracked backsheets or glass.

The backsheets of a PV module protect the solar cells and connectors from degradation due to environmental factors. It also acts as an insulator protecting against electrocution on accidental contact with the underside of the panels. Backsheets available for commercial use could be polyamide (PA), polyvinylidene fluoride (PVDF) or polyethylene terephthalate (PET)-based; comprise multiple stacks laminated together or could be in the form of coextruded foils [19], [20]. Cracking, delamination, and yellowing are the reported to be most commonly occurring backsheets failures [21]–[27]. These defects are mostly visible to naked eye and are the easiest to spot. Modules with defective backsheets compromise the electrical safety of the PV installation and accelerate various PV module degradation modes such as delamination, corrosion, potential induced degradation (PID) or polymer hydrolysis by allowing moisture ingress into the modules [28]–[31]. The maintenance for the backsheets could either be preventive or corrective. Preventive maintenance could be

carried out when the damage to the backsheets is minimal (microcracks) and the electrical performance and physical integrity of the backsheets are not compromised. On the other hand, corrective maintenance strategies would be applied when the backsheets have completely cracked and the electrical insulation is compromised. Certain coatings (epoxy, polyurethane, acrylate, silicone, and rubber) could be used to seal cracks and provide sufficient insulation [32], [33]. Small, near surface cracks in the backsheets could also be covered using certain tapes for small cracks, provided the electrical properties of the module are not compromised. Despite the easy applicability of these solutions, the long-term stability of such solutions is not yet established. Additionally, these solutions appear to work only if the cracks in the module have not caused any further degradation of the modules such as corrosion and delamination [32].

Like backsheets, glass failure in glass-glass modules could also damage the insulation of the encapsulant layer and cause water ingress, severely compromising the performance of the PV module [34]. The glass defects in PV modules could be cracked or broken glass layers, caused by human or extreme weather factors. Human factors may include mishandling during transportation, installation, or maintenance of the modules [35]. Weather factors such as hailstorms, strong wind and heavy snow load may also cause damage to the glass layer [36]. Glass failures accounted for 10% of all module failures within two years of operation which increased to account for 33% of all module failures within eight years of operation [37]. Nevertheless, glass-glass PV modules are more resilient to cell-damage and water ingress related issues, and hence, can endure some glass defects without exhibiting considerable loss in the performance [37]. Hence, information related to the repair of the glass defects in PV module in published literature is limited.

The cracks in the glass can be repaired by using an epoxy resin cured under ultraviolet light source [37]. The technique could be applied at the place of installation and dismantling the panels might not be necessary. Repairing the panels in-situ could be the most cost-effective option for glass-glass panels [37]. However, the effectiveness of the repair process depends on the number and type of the cracks in the glass on the front and the rear. Additionally, some discoloration of the resin might occur over time which may slightly reduce the power output [37].

2.2 Repair of cell interconnection in PV modules

The interconnections in a PV module refer to the soldered joints on the copper or silver ribbons. Corrosion of these interconnections can occur in the presence of moisture and high temperatures [38]–[40]. Ethylene vinyl acetate (EVA) which is used as an encapsulant reacts with moisture under high temperature and could lead to production of acetic acids which causes corrosion of the metal grid on solar cells, soldered joints of the electrodes, and joints between interconnection ribbons and busbars [41]–[44]. These defects are usually identified using electroluminescence or photoluminescence imaging techniques and could be done on-site [45]–[47].

Repairing of the defects in the joint between the bus bars of the solar cells and the interconnecting ribbon have been tried using an induction heater providing local heating to a small area under application [48]. It was shown that duration of heat application was critical to the performance of the repaired module. This method could be applied on site, without the need for dismantling and

transporting the panels. Results regarding long term reliability of this repair technique would further prove its effectiveness.

In some cases, a faulty solar cell could be replaced leading to rejuvenation of the module[49]. However, most of the current modules are not designed for easy solar cells replacement and hence this may not be one of the easiest options for repairing the PV module [18], [50].

The suitability of refurbishing a PV depends on the type and mode of failure and the extent of damage to the PV panel. Additionally, long term reliability of the repaired modules is often misrepresented or misinterpreted. The situation is further complicated due to absence of standard of requalification or re-certification of repaired modules [18].

3 RECYCLING OF PV PANELS

The growing amounts of PV panel waste presents new environmental and waste management challenges. However, with proper waste management procedures in place, this challenge could present us with unprecedented opportunities to pursue new technological and economical avenues. Recovery of raw materials from the PV panels could lead to establishment of new solar PV end-of-life industries [3]. In-fact, solar PV recycling would be of paramount importance for the transition into a sustainable and economically viable renewables-based energy future. To unlock the mechanisms and possible advantages of PV panels recycling, it is important to research different avenues of reusing the end-of life PV modules in time to meet the expected surge in the PV panel waste.

Multiple government, industrial and scientific bodies within EU have funded extensive research to establish methods to recycle crystalline silicon (c-Si) PV panels. A notable example is the LIFE project within which researchers from SASIL SpA and European Commission Joint Research Centre developed a “Full Recovery End of Life Photovoltaic” (FREL P) project to recycle c-Si PV modules [9], [11], [51]. As a result of extensive research on PV module recycling and the growing interest, the world’s first c-Si PV module recycling plant has been established in France by Veolia in 2017[52]. Almost all research activities on module recycling have been focused on c-Si PV modules due to the fact that c-Si technology commands more than 95% of the solar PV industry[53].

Fig.1 shows the mass and value of the materials that could be recovered from a typical c-Si PV panel[11], [54].

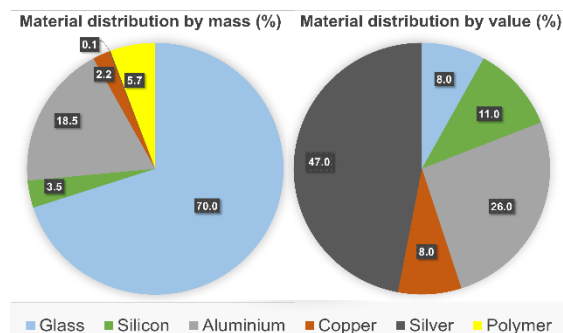


Figure 1: Mass (left) and value (right) of materials recoverable from a c-Si PV module.

Glass and aluminium frame together contribute about 85% of the mass of the solar panel, but account for \approx 20%

of the value. Silver is by far the most valuable metal recovered from the module; however, its extraction is usually not straightforward. The silver is present in connecting ribbons, and in the metal grid on the cSi solar cells which is an integral part of the solar cell. In a physical recycling process, such as that used in Veolia plant, the silicon solar cells along with the metal grid (Ag, Al) is usually the product [52]. The materials recovered from the PV panels in the increasing order of complexity could be Aluminium (frame) < glass < copper conductors < silicon/silver.

3.1 Recycling processes of c-Si PV panels

A full-scale recycling plant was operated by Veolia for recycling silicon-based PV modules[52]. In the Veolia process, the modules are shred and grounded into fine grits. The different materials are then separated by using a proprietary mechanical separation process. Although the exact process is not known, it has been known to include sieving, sifting, optical separation steps and an eddy current separator to recover metallic parts. The process claims 95% of materials recovery rate. Aluminium frames and copper wires are completely recovered and recycled. Tempered glass is obtained in the form of glass powder and sold to glass making industries. The recycled Si solar cells are sold to precious metal sectors as silicon cake [10], [52], [55].

Another process that has been tried on pilot scale has been the FREL P process developed by an Italian company SASIL S.p.A [9], [11]. The process is more complicated than the Veolia process. After the removal of the aluminium and the junction box, the panels are heated to 120 °C using an infrared heater. The modules are then passed through a milling machine and a vibrating knife machine which removes the glass from the front side of the module. The glass is recovered by sieving. Contaminated glass (>2% by mass of impurities) is not recycled and is disposed of. The remaining module is further fragmented into smaller pieces and undergo a high temperature pyrolytic process to burn off the polymeric materials. The ash thus obtained is sieved to remove pieces of glass and then treated with nitric acid to leach out the metals (Ag, Cu). The mixture undergoes vacuum filtration process to remove silicon from the leaching solution, and the leachate undergoes electrowinning process, followed by calcium hydroxide treatment to recover the precious metals. Any silicon obtained after this process is low grade [10]. A pilot-scale FREL P facility was set up with a processing capacity of 1300 panels/day. The process does not recover any lead or tin that might be present in the panel.

A process was also developed independently in the US, aims to achieve high value materials [56]. The process could obtain metals such as silver, lead, tin, and copper from silicon solar cells in laboratory scale demonstration. The frames, cables and plastic junction boxes were mechanically separated. Then a thermal combustion process was used to burn off the organic compounds leaving behind separate the silicon solar cells, glass, and residues[57]. The silicon solar cells are treated with nitric acids to leach out the metals. A two-step electrowinning process was used to recover silver, copper, and lead oxide. The silicon wafers were further etched by hydrofluoric acid and sodium hydroxide to remove the metal grid (Al) and passivation layers to recover useable silicon. The metal removed in the final step were not recovered. Intact silicon wafers and glass were reported recovered by the ASU process. However, the purity and physical integrity

of the silicon obtained remains uncertain.

To recover c-Si from end-of-life modules to be used for making solar cells again, all the external impurities need to be removed. These include the Ag and Al metal contacts, the anti-reflection coatings (ARC) deposited on the solar cells (e.g. silicon nitride (SiN_x), silicon oxide (SiO_x), aluminium oxide (AlO_x)), and the heavily doped layers from the front and the rear sides of the solar cells. The bulk metal can be removed by treating a metallized sample with hot HNO₃ (70% wt., 70°C)[58]. The glass interface can be dissolved in hot HF (10% wt. at 50°C), while the embedded crystallites can be removed by dipping the samples again in hot HNO₃ bath[59]–[61]. The ARC could be removed by dipping the cells in hot HF. To remove the heavily doped regions, the silicon thus obtained is further treated with a mixture of HF/HNO₃/CH₃COOH [15], [62]. The concentration and duration of etch could vary. The silicon obtained after his process could be recycled for making c-Si solar cells, albeit with reduced performance[63]. The images from scanning electron microscope (SEM) shown in Fig. 2 highlight the steps in obtaining recycled metal free c-Si wafers from end-of-life solar cells.

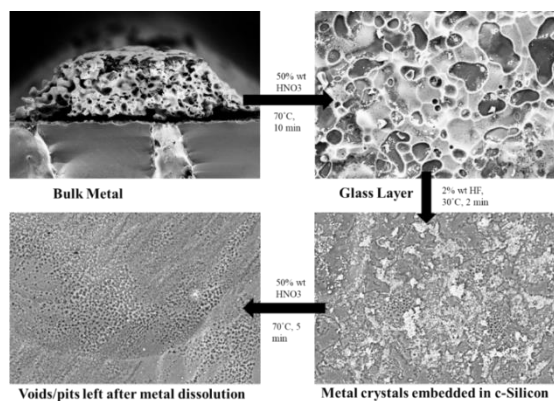


Figure 2: SEM images of the solar cell sample at various stages of etching.

3.2 Alternative uses of glass from recycled PV panels

Reintroducing the materials recovered from the recycled c-Si PV panels into manufacturing supply chain of new PV panels could appear to be the ideal way to achieve circularity. This is referred to as closed loop recycling [54]. However, it might not be always feasible. For example, there may not be a cell/module production facility close to the recycling facility. However, there are several other possible uses of the materials recovered from the EoL c-Si PV panels. These options, referred to as ‘open loop recycling’ options could also result in high, medium or low value products, depending on the recycling effort [54].

Glass obtained from recycled PV panels could have multiple uses. The glass could be used to remanufacture PV glass, which is an example for closed loop recycling. Further the glass could be used as a raw material in the manufacture of bottle glass (high value), glass foam for insulating applications (medium value) and glass for road construction applications (low value) [54]. Moreover, these options could be cascaded providing several cycles of recyclability. For example, glass waste from recycling PV modules could be used for bottle manufacturing, while a small non-usable fraction could be sent for preparation of insulating material. Glass still unusable at this stage

could be used in road construction. A feasibility analysis based on multiple scenarios for such an application was recently published [54].

3.3 Alternative uses of Silicon from recycled PV panels

The Si recovered from all module recycling processes developed so far is metallurgical grade [10]–[12]. This silicon could easily be used in the metallurgical processes. For example, commercial grade ferrosilicon (FeSi) could easily be manufactured from the recycled Si obtained from EoL PV panels by melting it with scrap steel. This could be a simple method of recycling silicon from PV panels as it involves minimum processing steps and eliminates the use of toxic and hazardous chemicals. The FeSi is further used as deoxidizer, or Si carrier in making other metal alloys. We hypothesize that silicon obtained from end-of-life, discarded or non-functional PV panels can be effectively recycled by metallurgical processes to produce useful alloys for metals industry.

Currently, Ferrosilicon (FeSi) is produced using carbothermal process, usually in closed submerged electric arc furnaces. A typical furnace may have the power rating of 25 -100 MVA. Quartzites are used as the silicon source in the production of FeSi. The quartzites lumps are prewashed, crushed and graded. Typical composition of quartzites considered suitable for the production of FeSi contains around 97% SiO₂ and 1.5% Al₂O₃ [64]. Coke (coal or wood) is the primary source of carbon reductant. The iron lowers the partial pressure of SiO required for reduction and forms FeSi solutions that reduce the activity of Si. Hence the process could be carried out at lower temperatures that employed for the production of silicon. This also results in higher Si yield (less of SiO) and lower energy consumption per ton of metal [65], [66].

4 REUSE AND REPURPOSING OF PV MODULES

4.1 Reuse of PV panels

A number of modules from the large-scale PV power plants are decommissioned for various reasons. They could be defective or could be replaced with an improved technology. Reusing these modules, with or without some repairs, could prevent the panels from going to waste and generate clean energy for a longer period. The European Waste Framework Directive emphasizes the importance of avoiding waste disposal and reusing the discarded items.

For a PV module to be reused, it should be severely degraded and there should be no safety concerns. Additionally, the PV panel should have enough usability to justify efforts employed to make it reusable.

The biggest challenge for reusing the PV panels is the economic viability. The PV panels for reuse would not usually carry a warranty. Additionally, they may have lower efficiency and shorter lifetime. Hence, sorting and classifying the panels is necessary to ensure economic viability.

The rapid decline in the module costs in the last decade and the continuing trend of lower module costs [53], poses further challenges for the reusability of the modules. The module contributes to approximately 28-30% of the total cost of the PV energy system[67]. Hence, the costs savings from reusing the PV module would not be significant as compared to the balance-of-system (BoS) costs.

It has been suggested that the still functioning PV modules after repair (if necessary), could either be used in small commercial systems, residential PV system or off

grid PV systems in developing countries[68]. However, the transport costs and the recommissioning costs need to be considered for such options to be commercially viable. Reusing PV modules may delay the generation of PV waste and hence reduce the pressure on the recycling/disposing systems. Reusing the panels may also provide sufficient time for the establishment and improvement of the recycling technologies. Developing regulations governing the decommissioning, repair and reuse of the PV modules are also important for the success of re-usable PV market [68].

Social acceptance towards reusing the PV modules is crucial to the success of such interventions. Social behaviour could play an important role in developing and sustaining a second-hand PV module market. It has been known that psychological and behavioural traits can undermine the viability of technical solutions [69]. The success of reusing the PV modules would need coordination and alignment between the PV manufacturers, PV installers, PV system owners and PV repairer/recyclers. Additionally the role of governing bodies and agencies would need to support the efforts by developing suitable regulations. As with most scenarios, increased profitability in terms of lower reuse costs and higher incentives, could be the main drivers of reusing the PV modules [68], [69].

4.2 Repurposing the EoL PV panels.

Another possible way to use the EoL PV modules could be repurposing them after the end of their effective usable periods. The PV panels (especially glass-glass panels) that still maintain their physical integrity could be used for certain applications where glass is used. The EoL PV panels could be used for making noise barriers, garden fences, greenhouse tunnels and car park roofs. Some old PV panels could be repurposed to make benches, tables and animals' shelters. All these applications could also employ good PV panels to generate electricity, however, as mentioned earlier, since PV panels constitute only 30% of the total systems costs, they would need investment. Replacing standard glass with old PV modules could relieve the pressure on the recycling ecosystem while still contributing to reduction of greenhouse gases by offsetting the glass required for such applications. However, commercial viability and social acceptance would still be the deciding factors for repurposing the PV modules.

5 CONCLUSION

Rapid deployment of PV systems is a positive response to combat climate change. However, in the face of exponentially growing PV modules installations, effective management strategies of EoL PV modules are also required. Recycling the PV modules than using them for landfill would prevent contamination and pollution of soil and water. It would also result in the generation of an alternate industry with huge revenue potential.

EoL PV modules could be repaired onsite or off site. Most repairs are concerned with the cracked backsheet or glass. The glass-glass modules are especially resilient to damage and could perform well with minor damages. The repair of cell interconnections is also possible to some extent. It was found that only certain damages to the modules are repairable. However, most repair strategies are at developing stages and more research is required to

assess the long-term reliability of such maintenance strategies.

Recycling the PV modules appears to be the most sustainable and effective option of managing the EoL PV modules. The Al frame, glass, copper wires and metal connectors could be easily recycled with simple physical processes. Together they constitute $\approx 85\%$ of the panel weight. Silicon solar cells including the metal could be more difficult to recycle and require more sophisticated chemical treatment. The recycled materials could be used again for producing PV panels (closed loop recycling) or could be used to manufacture other products (open loop recycling). Some examples of open loop recycling could be using the recycled glass from PV modules in manufacturing bottles or glass fibers and using the Si from the recycled panels in metallurgy industry (e.g. Production of ferrosilicon).

Certain modules that are decommissioned from a PV plant, could be re-used, with or without minor repairs. These modules could be used, for instance, for domestic applications, small stand-alone PV plants or could be exported for use in developing countries. However, these options would be highly governed by the prevailing economic, legislative and social conditions. The modules that have electrically degraded but still maintain their physical integrity and appearance could be repurposed for certain domestic and civil applications replacing glass panels. Some common examples could be noise barriers, fences, greenhouses, and car sheds.

Effective management of EoL PV panels is crucial to maintain the sustainability of the clean energy generation. For a successful ecosystem involving repairing, reusing, or recycling, all stakeholders such as PV manufacturers, PV installers, PV system owners and PV repairer/recyclers will need to collaborate closely to ensure the sustainability of PV energy generation.

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