End-of-life of c-Si solar panels: demonstrating the possibility to reuse the cover glass

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Abstract
The cover glass in a silicon solar panel accounts for about 2/3 of the device’s weight and, at the end of life, these panels are expected to be recycled to reduce the industry’s environmental impact. The recycling methods often require the panel to be smashed, which splint the cover glass in low-value fragments. Here we demonstrated that the cover glass could be recovered unbroken through a mechanical process. Due to its chemical and mechanical strength, this glass would be ready to be reused without the need to melt it again, bringing by this way important savings of its energy content and carbon emission related to its production. The material would be ready to be used as cover glass in another solar panel or, still, as architecture material or another application. Besides that, we have utilized Fourier-transform infrared, Raman, and energy-dispersive spectroscopies to confirm the composition of the remaining components, as well as to identify aging. We confirmed that our study-case panel has a composition similar to most Silicon solar panels in the market, and the results indicated that it would be feasible to recover the glass in most of these devices and by this way reduce the carbon emissions of the photovoltaic industry by more than 2 million tonnes every year.

Keywords: Minimization, reuse, cover glass, photovoltaics

1. Introduction

Crystalline silicon photovoltaic (c-Si) technology has been developed since the 1950’s (Pearson, 1957), but it was only after the 2008 economic crisis that it took the stage worldwide, promising to be a “clean and affordable” alternative to fossil fuel-based energy. In the 2010s the photovoltaic (PV) installed capacity worldwide was multiplied by roughly 20 and it is expected to reach the terawatt scale in the next few years (Haegel et al., 2019). The market share of c-Si is about 95% (Fischer et al., 2021), and even though many other technologies have been developed in the last few decades (Nayak et al., 2019) none could rival c-Si production capacity. However, some scarce minerals such as silver may impose constraints (Lo Piano et al., 2019) to c-Si production growth soon (Haegel et al., 2019). Alternative materials and technologies to reduce the raw material consumption of this technology are

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needed, such as efficient recycling (Feltrin and Freundlich, 2008; Tao et al., 2011; Graedel et al., 2015; Davidsson and Höök, 2017).

On the other hand, the life-cycle of c-Si panels should be enhanced to reduce environmental impacts and Carbon emissions contributing further to our carbon budget and the related climate goals (Bhandari et al., 2015; Pickard, 2017; Zhou and Carbajales-Dale, 2018; Peters et al., 2020). To reduce costs the industry has pursued to reduce materials volume, waste, and replace expensive minerals with cheaper alternatives (Fischer et al., 2021), which often contributes to reducing the environmental impacts, even though this was not the primary goal. Besides that, expanding c-Si panels production is itself pressuring other industries to scale up their production capacity.

By volume, the cover glass is the main component of most c-Si solar panels. At an average thickness of 3 mm (Fischer et al., 2021) it accounts for about 7.5 kg/m² in weight, which demands massive industrial infrastructure to produce millions of panels per day (Burrows and Fthenakis, 2015). Still, bifacial c-Si panels (Gu et al., 2020) are being widely deployed worldwide and are expected to dominate the market in the next decade (Fischer et al., 2021), in such a way that it will boost the demand for flat glass production. Glass industry already consumes a lot of energy and emits significant amounts of Carbon in the atmosphere. In Europe, for example, Schmitz et al. (Schmitz et al., 2011) have accounted for an average emission of 0.74 tons of CO₂ per ton of flat-glass produced. Such value may change drastically from one plant to another due to the use of different sources of heat, however the direct energy demand and carbon emissions in any flat-glass production line will be about the same. In this way, to produce 1 kg of glass one may expect an energy demand between 2-3 kWh, due to the high melting temperatures (1500-1600°C), and direct carbon emissions of about 0.2 kg due to the carbonates used as raw materials.

As the lifespan of most solar panels ranges between 20-30 years, the fast growth of this sector in the last decade means that in the 2030s massive quantities of c-Si solar panels will reach their end-of-life (EOL). Researchers worldwide have been addressing this imminent challenge of recycling these materials (Tao and Yu, 2015; Sica et al., 2018; Xu et al., 2018a; Deng et al., 2019; Mahmoudi et al., 2019; Chowdhury et al., 2020), which seems fundamental to recover scarce minerals and enable multi-terawatt deployment of c-Si, while it could reduce energy demand, carbon emissions, and raw material extraction, contributing to more sustainable development.

In this contribution, we propose a route to drastically minimize the amount of waste from c-Si products. But before discussing that we present in the next section a brief review on today’s management of c-Si waste.

2. The state of the art of PVs waste management

From top to rear commercial c-Si panels are composed of glass, encapsulation material, c-Si cells (including interconnections), another sheet of encapsulation material, and a plastic back sheet (Fischer et al., 2021) (typically made of Tedlar-Pet-Tedlar, or TPT). An aluminum frame is often the last part to finish the panel, though some frameless panels are already in the market. The most common encapsulation material by far is ethylene-vinyl acetate (EVA), though alternatives such as polyolefins have been proposed (López-Escalante et al., 2016).
and their market share is expected to grow significantly in the next few years (Fischer et al., 2021).

It is quite easy to remove the aluminum frame, and this component can be easily recycled. However, all the other components are laminated together, resulting in a sealing that is fundamental to the panels to withstand the environmental conditions for several decades. Additionally, even though some high-value materials are present, such as Silver or polycrystalline Silicon, most of the panel weight is plastics, aluminum, and glass, which makes alone about 60-70% of the total weight (Xu et al., 2018b).

Researchers, governments, and industries are concerned about the proper management of this growing stream of EOL solar panels. The exact volume worldwide is not precisely known (Mahmoudi et al., 2019), and Europe is the only continent with dedicated PVs recycling facilities in operation (Heath et al., 2020). Among the several routes available to process these products some are good enough to allow the reuse of silicon solar cells, however, this method has been discouraged due to several drawbacks, such as unavoidable cracked wafers and the interest of industry in produce refurbished panels (Heath et al., 2020).

Several delamination processes are available. The choice relies on several factors and may vary in some regions as the cost of inputs, such as energy, may be very different. In general, one may classify these methods as chemical, thermal or mechanical delamination (Deng et al., 2019), while in some routes, these processes can be combined and applied at the same time (Chen et al., 2019; Lovato et al., 2021). Every method has its positive and negative aspects, which may include high energy demand or the consumption and production of toxic chemicals (Chowdhury et al., 2020).

We have pursued a practical and convenient method to minimize the challenges imposed by EOL c-Si panels. Initially, we investigated chemical delamination with solvents such as Acetone, Acetic Acid Glacial, Hexane, Ethanol, Methyl isobutyl ketone, Isopropyl Alcohol, and Tetrahydrofurane, under room temperature and pressure, with and without stirring. Nevertheless, it was required to cut the solar panel into pieces (2x2cm), and delamination was successfully only with Tetrahydrofurane and just after stirring by a few hours. In fact, with various solvents, it is well-known that dissolution of the EVA encapsulant increases significantly with temperature (Chen et al., 2019; Lovato et al., 2021) however, our goal had been to find an alternative method that did not require such an approach.

Mechanical delamination often requires crushing, cutting, and smashing the panel (Tao and Yu, 2015; Guo et al., 2021). As a result, small pieces of the panel, which are mostly composed of glass are submitted to other steps to decompose the EVA and separate the materials. In this work, we report some results on our attempt to recover a c-Si cover glass unbroken, enabling several benefits due to its reuse and reduction in demand for new cover glass, while safely eliminating approximately 2/3 of the PV waste volume. Next, we describe our experiment.

3. Materials and methods

A small solar panel, model KS20T (Kyocera Solar) measuring 520x352 mm (0.18m²), was used to provide power for illumination in an external area in our university during the last five years and was selected to be mechanically delaminated. In figure 1 one can see some photos of the panel and the beginning of the delamination process.
We begin by removing the aluminum frames, which was the easiest step. Next, beginning in the border of the panel, we manually pulled the laminated layer containing the back sheet, Silicon, and the interconnections. Thanks to the strength of the back sheet and the adhesion provided by the EVA lamination, we could separate the cover glass. In the end, it still had some spots of EVA encapsulant, which could include some points containing small quantities of Silicon. In figure 2 one can see a picture of the recovered glass and in table 1 the weight of the parts which were separated.

About 12-13% of the weight is ascribed as “others” in table 1. It consists of a sheet composed mainly of the back sheet and EVA, besides the metals and the silicon, which are the most valuable parts. FTIR-ATR (Perkin Elmer Frontier), Raman (Bruker Senterra), and MEV/EDS (FEI Quanta-250/Oxford spectrometer model X-Act) were used to confirm the composition of the materials found in this remaining sheet. As one can see in figure 3,

| Component | Weight (g) | Weight/Total |
|-----------|------------|--------------|
| Glass     | 1714       | 0.715        |
| Frame     | 372        | 0.155        |
| Others    | 308        | 0.128        |
| Total     | 2394       | 1.000        |

Table 1: Weight of the solar panel used in this work.
FTIR-ATR measurements could identify several bands that are characteristic of the EVA.

![FTIR-ATR spectrum of the EVA from the KS20T panel](image)

Figure 3: FTIR-ATR spectrum of the EVA from the KS20T panel, showing some characteristic lines (Marcilla et al., 2005; Jentsch et al., 2015).

Raman spectroscopy was performed under 532 nm pumping, and as one can see in figure 4 it also shows some characteristic lines from EVA. In addition, one can see an intense and broad emission that is attributed to the luminescence, as such result is similar to others found in the literature (Schlothauer et al., 2012; Lyu et al., 2017). It is worth mentioning that several UV-blocking substances and other additives can be included in the EVA by the PV industry, and we do not know such details about the original composition of the EVA in the KS20T panel. However, EVA luminescence has been used to quantify the degradation, as both functions of solar radiation dose (Jentsch et al., 2015) or penetration depth (Lyu et al., 2017). As the KS20T panel had been exposed to the sun for several years, such luminescence under 532 nm pumping could be expected.

At this point, we had not investigated the EVA degradation enough, and we cannot say how it may have facilitated our manual delamination process of the KS20T panel. As the encapsulant composition and cross-linking may change from one fabricant to another, our proposed method to recover the cover glass still needs further investigation to confirm if we could apply it to any c-Si panel on the market.

EDS measurements were performed in some pieces of the laminated sheet that remained, after the cover glass separation, to confirm the presence of several key elements. Besides Silicon, we could easily identify Tin, Lead, Copper, and Silver. In figure 5 we show the EDS spectrum of the surface of a Copper interconnection ribbon.

In Europe, lead soldering is not allowed since 2011 in most electronic devices. PV panels are excluded from this restriction but the industry expects that in the 2030s lead-free solar cell technologies will dominate the market (Fischer et al., 2021). Besides that, the reduction in volume/thickness of the materials in PVs are indicating that the value of this remaining
Figure 4: Raman spectrum of the EVA from the KS20T panel. Besides some characteristic lines (Peike et al., 2011), broad bands that we attributed to luminescence due to degradation can be observed (Schlothauer et al., 2012; Lyu et al., 2017).

Figure 5: EDS spectrum of the wiring surface, demonstrating that we have the typical Sn/Pb coating. Another spectrum, not shown here, demonstrates the interconnects are the typical Sn/Pb coated copper.

The manual removal of the cover glass was simple and worked as a proof of a concept. A machine to perform such a task could be developed, providing a pathway to process the massive amounts of PVs that will reach the EOL in the coming decades. As mentioned, it is very delicate to recover Si cells for reuse, and there is no demand for refurbished cells. However, in the case of the cover glass, it may be quite different.

Glasses already have a high recycling rate in some countries (Jani and Hogland, 2014). But even though a glass bottle has about the same composition as the cover glass in PVs, the latter one has higher purity, transparency and in this way, it would be a loss to mix such high-quality material with colored glass bottles. Virtually all the solar panels in the market today have 60 or 72 Si cells, and their sizes remain in the range between 1.8 m² and 2.2 m² (Fischer et al., 2021). In the near future, an industrial plant separating the cover glass
from these panels would produce a continuous stream of high-quality flat glass, which could be reinserted in the PVs supply chain or, still, in another kind of application.

It is well-known that flat glass can be melted along with other raw materials and reduce consumption and emissions of glass production (Burrows and Fthenakis, 2015). Besides that, waste glass is often proposed to be used by cement and concrete industries (Jani and Hogland, 2014), and it can be recovered from windows and reused in buildings (Nußholz and Whalen, 2019). The possibility to have a stream of high quality flat glass from EOL PVs, with sizes ranging around 2 m$^2$ (and 3 mm thickness) instead of 15 kg of small pieces of it enhances such prospects even further.

Buildings (Pariafsai, 2016) and architecture (Arbab and Finley, 2010) could widely explore such materials, adding value to the cover glass recovered from PVs and providing a pathway towards the development of a circular economy (Eberhardt et al., 2019; Nußholz et al., 2020). To give some picture of the environmental benefits that it could bring to the PV industry, we made some estimates that are shown in table 2 considering a standard solar module, with 144 half-cell M6 (166x166mm$^2$), which has a size of about 2.2 m$^2$ and peak power of $\sim$450 W (Fischer et al., 2021).

| Panels Power (W$_p$) | Weight (kg) | Energy (kWh) | Emissions (t$_{CO_2}$) |
|----------------------|-------------|--------------|------------------------|
| 1                    | 450         | 16.5         | 35.75                  | 9.4$\times$10$^{-3}$ |
| 2.2$\times$10$^6$    | 10$^6$      | 36-10$^6$    | 79.4$\times$10$^6$    | 20.9$\times$10$^3$  |
| 244$\times$10$^6$    | 1.1$\times$10$^8$ | 4-10$^9$   | 8.7$\times$10$^9$     | 2.3$\times$10$^6$   |

Table 2: Quantity of $\sim$2.2 m$^2$ PV panels, average peak power, and an estimate of the total cover glass weight, energy content, and emissions considering the estimates of Schmitz et al (Schmitz et al., 2011) for the European glass industry. The last row corresponds to the total PVs produced in 2020, and the energy content of 8.7 TWh is equivalent to the annual electricity production of a 1 GW coal/nuclear power plant.

As one can see, by recovering the cover glass in EOL PVs we could severely reduce the demand for new cover glass. Considering estimates for the European glass industry, where natural gas accounts for 80% of the fuel consumed (Schmitz et al., 2011), the production of the glass covering the 110 GW$_p$ of PVs delivered last year (Fischer et al., 2021) emitted more than 2 million tonnes of carbon in the atmosphere. Hu et al (Hu et al., 2018) have analyzed the emissions from container glass production in China, and their results indicated that such emissions could be 50% higher than in Europe due to the higher usage of Coal and fuel oil. In this way, the estimates made here may be on the conservative side.

4. Conclusion

In summary, we could recover the cover glass of a 0.18 m$^2$ c-Si solar panel, and it seems feasible to develop some machine that could perform such mechanical delamination. FTIR and Raman measurements could detect some of the main characteristic lines of EVA. Raman under 532 nm pumping demonstrated some luminescence, which has been interpreted as an aging signal. EDS confirmed the presence of several metals commonly found in c-Si panels. Our results indicate that this simple mechanical delamination could be scaled up to recover millions of cover glass sheets from EOL solar panels. Estimated energy conservation could range in the order of 10 TWh due to the avoided demand for new cover glass production.
and, among other benefits, about the equivalent to half the glass weight would be saved in carbon emissions.

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