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EUROPEAN SOLAR PV INDUSTRY ALLIANCE

RECOMMENDATIONS PAPER SERIES II

Addressing uncertain antimony content in solar glass for recycling

1. EXECUTIVE SUMMARY:

The rapid growth of end-of-life waste from photovoltaic (PV) modules in Europe presents a significant challenge. Current estimates suggest that over 200,000 tons of discarded PV panels are generated annually, with projections indicating a potential increase to over 400,000 tons by 2030. Approximately 60% to 70% of this waste consists of high-transparency solar glass. Effectively managing this waste stream requires an efficient collection system and suitable recycling processes.

Glass accounts for a significant proportion of PV module weight, making glass recycling an environmentally beneficial process due to reduced CO2 emissions and energy savings. However, the composition of solar glass varies, particularly in terms of antimony content, depending on the production method. Antimony is used to enhance the performance of patterned solar glass but poses environmental and health risks, complicating recycling efforts.

While float glass, commonly used in Europe, can be easily recycled within the EU due to its consistent composition, recycling imported patterned glass — through the import of modules — with variable antimony content is challenging and economically inefficient. Antimony-containing glass can lead to undesirable interactions with the manufacturing process, impacting quality and emissions.

To address these challenges, the EU should consider making it mandatory within the upcoming EcoDesign PV module manufacturers to disclose the composition and manufacturing process of solar glass, including additives like antimony compounds. This information should be included in the European Product Registry for Energy Labelling (EPREL) or through other accessible means. Implementing such a measure will provide recyclers with the information needed to process solar glass effectively and economically, encouraging glass recycling within the EU and contributing to a more sustainable circular economy.

2. THE PV MODULE END-OF-LIFE WASTE CHALLENGE

There is a challenge with the rapidly growing end-of-life waste of photovoltaic (PV) modules in Europe. The estimated annual volume of discarded PV panels is already 200,000 tons, and it is projected to exceed 400,000 tons by 2030, [1], see Figure 1. About 60% to 70% of this waste is comprised of high-transparency solar glass. To manage this volume effectively, an efficient collection system is necessary, along with proper downstream users for recycling the glass cullets.

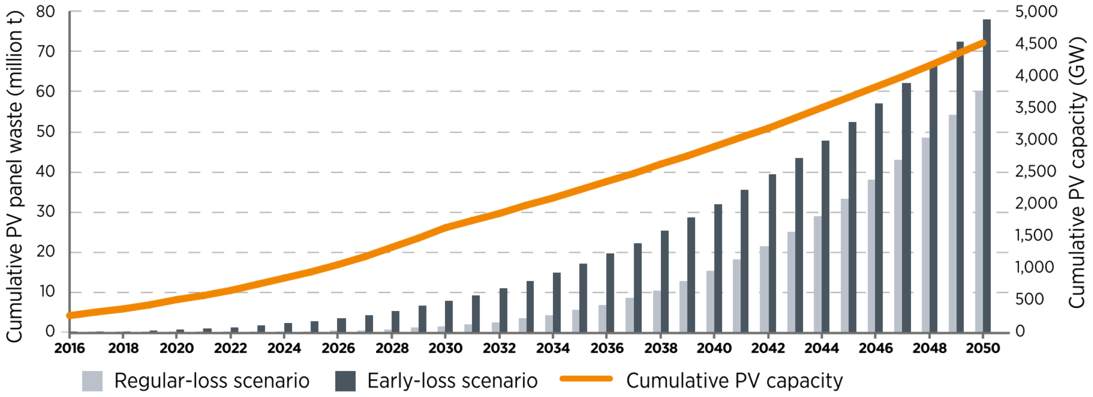

Figure 1. Estimated cumulative global waste volumes (million t) of end-of-life PV panels [1].

PV modules are classified as category 4 "large equipment" in the directive on the waste of electrical and electronic equipment (WEEE). Member States are obligated to meet annual collection targets for this category.

Since 2019, the collection target stands at 65% of the average weight of EEE placed on the market (POM) in the preceding three years in the respective Member State, or 85% of WEEE generated within that Member State.

The EU circular economy framework aims to revolutionize product design, promote circular economy practices, encourage sustainable consumption, and ensure waste prevention, while maximizing resource retention within the EU economy. Recycled glass derived from solar panels can be a precious resource in this context.

3. SOLAR GLASS RECYCLING INTRODUCTION

Glass represents 65% to over 95% of the weight of PV modules. Glass recycling has great environmental benefits: the use of cullet in glass melting processes avoids CO_2 emissions as it requires less energy to melt, and replaces carbonated raw materials. From a sustainability policy standpoint, it makes sense that products aimed at providing renewable sources of energy are properly recycled in a closed loop or at least not downcycled.

- Recycling 1 ton of cullet saves 1.2 tons of raw materials.

- Using cullet enables significant energy savings. +10% cullet usage in new glass products results in -2.5% energy consumption.
- This implies that recycling 1 ton of cullet prevents the emission of approximately 300 kg of CO_2 (Scope 1: Energy & Raw mat Carbon) or 700 kg of CO_2 (direct and indirect emissions), contributing to a decrease in greenhouse gas emissions.

4. PATTERNED GLASS VS. FLOAT GLASS

Most solar glass produced in China, and therefore the world, is produced by the rolled glass process and is termed patterned (or textured, or cast) glass, see Figure 2 for the estimated future market shares. Nearly all PV manufacturers (except thin film PV manufacturers) use low iron solar patterned rolled glass. The patterned glass is produced in a different way than the float glass that goes into most flat glass products. Solar glass can be either low-iron patterned glass or low-iron float glass. Both can be recycled if the quality is acceptable, but this depends on the glass composition and the end product to be produced.

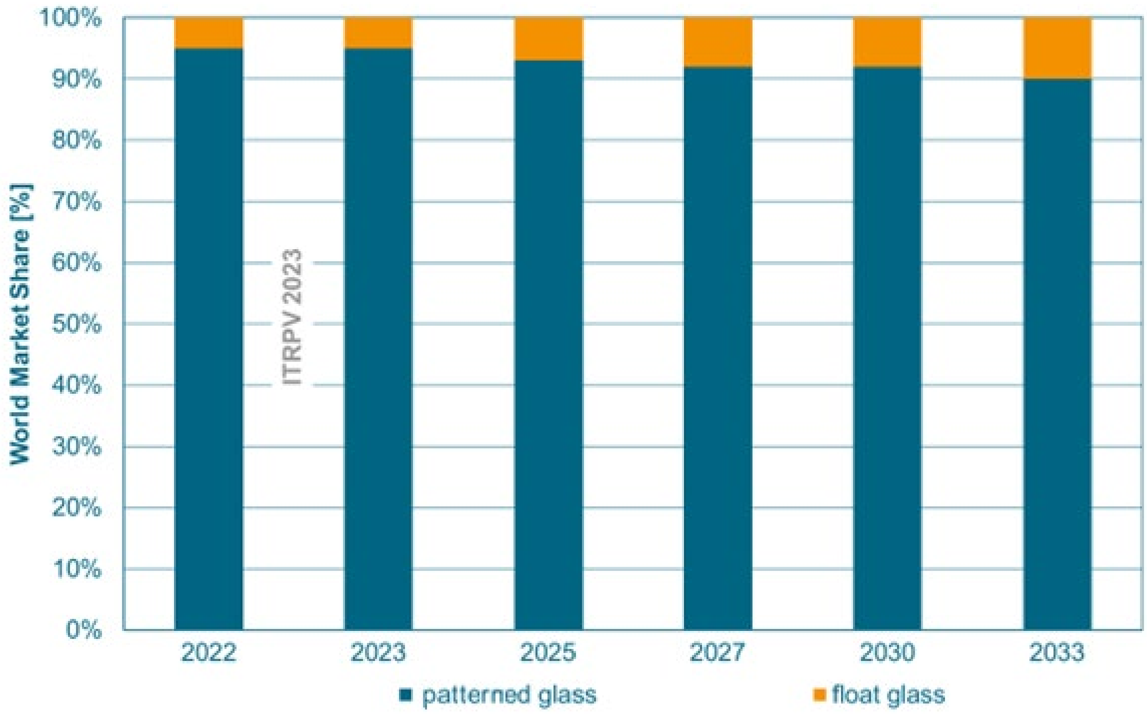

Figure 2. World Market Share of different glass manufacturing process for front side [2].

The vast majority of flat glass produced in the EU is made via the float glass process, and over the last decades, the European flat glass sector has increased the share of cullet in its batch from 20 to 26% to replace virgin raw material [3].

When it comes to performance, the transmission of a glass results from (1) the reflection and (2) the absorption in the glass.

The reflection per surface is almost the same for all glasses, which is at ~4%. The surface of patterned glass leads to a diffuse scattering of the reflected light, which gives the appearance of it being "matt", but does not change the actual ~4% reflection value. In view of this reduced glare, patterned glass is the preferred type when it comes to solar glass for PV and solar thermal. Both float glass and patterned glass can be coated on one side with an anti-reflective (AR) coating. The AR coatings usually lead to a transmission gain of between 2% and 3%.

With regards to absorption, it is influenced by the iron content, the state of the iron oxide, and of course the glass thickness. Low-iron float glass usually has an iron content of around 100 ppm, compared to patterned glass with around 120 ppm. Heavy metal oxides are used to convert the colorizing ferrous oxide (FeO) into ferric oxide (Fe_2O_3) in patterned glass. The greater the proportion of ferric oxide in the glass, the greater the energy transmission of the solar glass in solar cell specific regions of the spectrum [4]. The chemical refining agents used to increase the proportion of ferric oxide are traditionally arsenic or antimony compounds.

Antimony does not exist in glass making raw materials above the ppm level. Antimony compounds (antimony trioxide, Sb_2O_3, or sodium antimonate $NaSbO_3$) are added to a batch, at the 0.1—1 wt% level, to increase light transmission in patterned solar glass. Antimony exists as an ion within the patterned glass matrix — it is not a separate substance.

Neither arsenic nor antimony oxide refining agents are used in the production of float glass, as these refining agents can lead to unwanted interactions with the liquid tin bath used in the float glass manufacturing process. There is no tin bath in the production of patterned glass, and antimony compounds can therefore be used without hesitation from a process point of view. To compensate for this disadvantage, European float glass manufacturers instead use low-iron raw materials in the production of solar glass. Alternative manufacturing strategies exist to achieve the same light transmission improvement.

The problem with adding antimony trioxide (or sodium antimonate) in the glass process is that it raises sustainability and health concerns due to its toxicity. Antimony compounds are rather volatile and can create toxic emissions after melting. The effects of antimony poisoning are similar to arsenic poisoning and cause respiratory irritation, pneumoconiosis (a group of interstitial lung diseases), antimony spots on the skin and gastrointestinal symptoms. Additionally, antimony trioxide is possibly carcinogenic to humans [7], so is not used in the EU in glass production as it presents health risks for workers. In addition to China, in the last few years, antimony containing solar glass has also been supplied to the EU from other countries/regions like Malaysia, Vietnam, India, Middle East, and Northern Africa.

5. THE SOLAR GLASS RECYCLING CHALLENGE

PV module recyclers face the challenge of finding industrial end-users near their recycling centers since glass cullets have low density and low value, resulting in high transportation costs. The variable antimony content in patterned glass adds a substantial cost to the recycling process, as measuring it is essential to meet quality requirements for end-users of the glass cullets. Reducing these costs is crucial to enhance the reusability of solar glass cullet.

In addition to the toxicity of antimony, and the health risks it poses for the workers in glass factories, the differing compositions of patterned glass compared to low iron patterned glass or conventional float glass make European float line and patterned line operators reluctant to accept recycled cullet from external sources. As explained, when reintroduced in the manufacturing process of float glass, the antimony reacts with the tin in float bath and the antimony in the glass is reduced causing a colouration on the surface, making it unusable.

Furthermore, unwanted contamination could severely impact the yield and lifetime of glass melting furnaces, leading to a negative impact of the CO_2 footprint, which contradicts the carbon reduction objectives of the flat glass sector and the European Union's 2050 climate-neutral goal.

Consequently, float line operators are reluctant in accepting cullet from external sources. Patterned glass manufacturers might have more options to blend the antimony containing glass, provided there are no further impurities present (Fe, organics stones, ceramics etc.). Antimony-containing glass could in principle be recycled to produce new solar glass (antimony-containing) via the rolled process. However, the challenge is that the composition of the glass produced outside the EU still remains unknown[1] and the EU currently does not have the capacity to consume all the potentially available supply, as we currently are not aware of a European patterned glass manufacturer that wants to work with glass cullets containing antimony.

Very low concentrations of antimony could theoretically be reintroduced in European glass production lines. However, the lack of knowledge about the amount of antimony in solar glass produced in countries/regions like China, Malaysia, Vietnam, India, Middle East, and Northern Africa inhibits solar glass recycling.

While it is more or less standard to use antimony compounds in the production of patterned solar glass outside of Europe, solar float glass and pattern glass produced within Europe does not contain any deliberately added antimony.

When it comes to recycling, float glass is more suitable and can be used 100% as an important raw material in all flat glass plants in Europe. Short transport routes are therefore guaranteed. The recycling of float glass shards leads to a double CO_2 saving. Fewer raw material-related emissions and less melting energy.

The antimony-free European solar glass is thus easily recyclable in the existing European glass industry. **Hence, there is a potential to produce new solar glass sheets in the EU for the PV module industry from end-of-life modules if the original solar glass is antimony trioxide-free**. The European glass industry is taking action to recover and recycle the glass that they manufactured themselves, thanks to their knowledge of the exact composition of the cullet. This is a key unique selling point vis-à-vis imported solar glass, which cannot be returned to the original solar glass producer as they usually are unknown, or the transportation is too long.

To summarize, recycling glass from solar panels produced in China and installed in the EU poses a huge challenge to fulfil the EU circular economy framework. **The presence of**

[1] The unknown composition of the solar glass is something that potentially could be solved by in-line material characterisation methods before recycling of the PV modules. Though it will still require some more research.

antimony in the Chinese patterned glass, hinders viable recycling in European float glass or antimony-free patterned glass furnaces.

6. HOW TO ENSURE SOLAR GLASS RECYCLING?

As explained, antimony-free glass can be used in production of PV modules. However, the use of this type of solar glass is not yet significant in volume. As there is no regulation on the use of PV module glass, manufacturers can produce and sell both antimony-free as well as antimony-containing solar glass. Creating closed-loop recycling schemes with adequate traceability could ensure that glass containing antimony is recycled in rolled glass facilities accepting antimony, while antimony free glass is recycled in float lines or rolled glass (patterned) facilities that do not use antimony compounds for their products.

Utilisation of existing material, usually with unknown composition, in recycling would require the development of a rapid analysis method to detect antimony in the glass and then sort it appropriately. Existing methods are both costly and time consuming.

7. WHAT CAN EU DO?

The composition of the solar glass put on the EU market by European flat or patterned glass manufacturers is well known. The solar glass sector is ready to take back the European manufactured high-quality cullet at the end-of-life stage of PV panels and use it to produce new solar glass for the European solar PV industry. The flat glass industry has historically benefited from the availability of abundant high-quality silica sand in Europe, which is the greatest volume of raw material entering in the flat glass composition [3]. This facilitates the manufacture of high-quality solar glass.

EU should favour locally produced products that can be recycled in a closed loop cycle. As for solar glass produced outside the EU, recyclers should be able to access the composition of the glass used in imported solar panels. New solar glass can hence be produced by recycled glass cullet if they are antimony-free in an economically attractive way if the recycling plant is close to the glass factory. If the distance between the two sites is too far it is neither economical nor environmentally relevant to transport the recycled cullets. So, a key factor is to reduce the distance between the recycling site and glass factory, to balance the environmental and the economic benefits linked to transportation.

8. APPROPRIATE REGULATORY FRAMEWORK

The upcoming EcoDesign legislation for PV modules[2] has been identified as an appropriate legislation to address the problem. The EcoDesign legislation aims to *"foster module and inverter designs that have improved long-term energy yield, circularity and smart readiness"* and to *"take products off the market that are of a low quality and that have higher life cycle costs"*. I.e., improving the recyclability of PV products are one of the mail goals of the up-coming legislation.

Through the EcoDesign legislation, PV modules should be accompanied by a carbon footprint declaration when placed on the market. Furthermore, in the case of crystalline silicon PV modules, representing the vast majority of the market, the declared carbon footprint will not be allowed to exceed a maximum threshold in the EcoDesign legislation.

The carbon footprint declaration and threshold are suggested to work as conceptual references for (1) a similar mandatory declaration about the composition and the manufacturing process of the solar glass in the PV modules, and (2) an antimony trioxide threshold for the solar glass that is not allowed to be exceeded.

9. CONCRETE LEGISLATIVE SUGGESTIONS

To improve the situation and increase the likelihood that the solar glass in PV modules that are put on the EU market can be recycled in the EU in an effective manner, the ESIA suggests that:

(1) A requirement is added to the EcoDesign legislation for PV modules that all solar glass sheets used in PV modules put on the EU market should be obliged to disclose

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[2] Laying down Ecodesign requirements for photovoltaic modules and photovoltaic inverters pursuant to Directive 2009/125/EC of the European Parliament and of the Council.

the composition including additives such as antimony compounds and the manufacturing process of the glass.

a. The amount of impurities/additives in the solar glass, such as antimony, should preferable be measured and declared in weight percentage (wt%).
b. The composition of the solar glass in the PV modules should already from the start be included in the European Product Registry for Energy Labelling (EPREL), so that wholesalers and end customers can check if the PV modules are made by antimony containing glass or not.
c. As an EU digital product passport (DPP) system probably will take a long time to get in place, the information could potentially be demanded to be submitted by some type of barcode/QR-code mark that are stamped/fused into the glass. This will make the information still accessible and readable for the recyclers of PV modules after the 20+ lifetime of modules (when the original glass producer might no longer exist). However, the practicability of this approach needs to be investigated further.

These measures will address the problem of the current unknown composition of glass produced in China (and elsewhere) and increase the economic and environmental benefits of glass recycling in the EU. If the composition of a solar glass entering a recycling factory is known, the extra cost of determining the composition is avoided, and it enables a more educated decision of whether the glass can be recycled into new solar glass sheets or needs to be downcycled. It is currently the potential uptakers of recycled glass cullets that need to pay for the extra cost of a composition analysis in recycling centers. Introducing a *mark* that reveals the composition and the manufacturing process would therefore make it more attractive to recycle solar glass.

In addition, point 1 should be accompanied by:

(2) The introduction of a threshold for antimony in the solar glass of PV modules that are put on the EU market in the up-coming EcoDesign legislation for PV modules. This threshold should be incrementally lowered over time so that antimony in solar glass can be successively phased out of PV modules put on the EU market.

As mentioned earlier, the annual volume of solar glass that needs to be recycled will likely exceed 400 000 tons by 2030, most of it being antimony containing glass (see Figure 1). With such large volumes from discarded PV modules, it is uncertain that there will be enough fields of application for antimony containing glass cullets.

Completely banning imports of PV modules containing solar glass produced with antimony trioxide right now would likely result in an effective stop of imports of modules, which would in turn slow down the energy transition in Europe. By introducing an antimony threshold for solar glass in the EcoDesign legislation of PV modules, and over time decreasing the threshold, the global industry gets the possibility and time to adapt. Hence, a phase out of antimony containing PV modules, without disrupting the deployment of PV, can be achieved.

The actual initial threshold for antimony in solar glass needs to be investigated thoroughly. Standard X-ray fluorescence (XRF) measurements usually have a detection limit of 0.0002 wt% of impurities and contaminations of antimony can be around 0.0004 wt% if no antimony trioxide have been added on purpose. Some preliminary information is that typical antimony levels when the substance have been added intentionally are 0.1 wt% up to 0.25 wt%. A preliminary suggestion from the ESIA is therefore to set the initial threshold at 0.05 wt%. This threshold should, as mentioned before, be decreased in the revision of the Ecodesign legislation for PV modules to achieve an antimony free European PV market in the future.

In case it is practically impossible to include an antimony threshold in the first version of the Ecodesign legislation for PV modules, an alternative solution to measure 2 is:

(2b) A clear communication that an antimony threshold will be evaluated in the upcoming revision of the Ecodesign legislation for PV modules.

   a. When introduced in the revision of the legislation, and not in the first version of it, the threshold should already from the start be set very low (basically antimony-free, e.g., 0.005 wt%), at a level where the antimony would confer no oxidative benefit.

With such a clear communication that the EU plans to ban antimony in solar glass in ~5 years' time, the global industry will have the appropriate time to adapt and adjust their production processes.

10. CLOSING COMMENT ON THE REMAINING CHALLENGE

The currently proposed measures in the Ecodesign legislation fail to effectively tackle the issue stemming from the presence of antimony in the solar glass in the majority of PV modules installed in Europe over the past decade. Neither does it address the problem that the extent of antimony (alongside other impurities) levels within these modules remains largely undisclosed. As a result, the establishment of limits for forthcoming PV modules entering the EU market is poised to provide improvements for the glass recycling predicament only in the distant timeline of approximately 20 to 30 years from now.

To render a more comprehensive solution, the suggested legislative actions outlined in this document should ideally be complemented by robust support for the PV module recycling sector. This support is crucial for fostering the advancement of methodologies and alternatives for recycling the substantial quantities of antimony-containing solar glass that have already found their way into the European Union.

11. REFERENCES

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