Cradle to cradle Recycling of Perovskite Solar Cells

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***Abstract* — Cradle-to-cradle recycling plays an important role in resolving one of the major upcoming challenges for photovoltaics in the energy transition – resource management. As photovoltaic production continues to grow, it absorbs a vast amount of resources. Cradle-to-cradle recycling is essential to keep these resources available perpetually and minimize waste generation. To achieve this, a new design paradigm for solar panels that puts recycling in its center is needed. In this study, we show first results of a perovskite solar cell that was created using such a design paradigm. We created a device with 18.1% efficiency and an architecture that facilitates disassembly of the functional layers. We show that the absorber material, $MaPbI_3$ was used for the test device, can be recycled without causing a loss of solar cell efficiency.**

I. INTRODUCTION

Cradle-to-cradle (C2C) recycling becomes inevitable for photovoltaic technology at the terawatt (TW) scale. On the one hand, one terawatt of today's silicon solar panels has a mass of roughly 50 million tons, and will create waste accordingly. On the other hand, solar panel production will become a major consumer of every material involved in its production. The photovoltaic industry is already a major consumer of silicon, flat glass, silver, aluminum and certain polymers, and scaling todays manufacturing capacity by, following Verlinden [1], a factor of about ten, will cement the industries dominant consumer role. Hence, resource and supply chain management will be among the greatest upcoming challenges for PV. C2C recycling has the potential to alleviate waste- as well as resource management greatly, especially once PV installations have reached the end of their growth phase.

Assuming no recycling at all, one TW of today's silicon solar panels (350W, 1 x 1.67 m², 40mm thick, 18kg mass) equals roughly 50 million tons of waste with a volume, assuming panels are stacked, of approximately 200 million m³. Verlinden suggests a global annual production of 3TW in 2040, meaning that maybe twice this amount - there will be improvements in the power per mass ratio of modules- would become waste, probably in the early 2070s. This compares to an annual global landfill generation of 500 million tons in 2022, estimated by the World Bank. Hence, if all solar panels were dumped they would constitute a notable share of global landfill waste, and a significant fraction of electronic waste. While managing such an amount of waste would not be impossible, it would mean a significant and unnecessary loss of resources.

Today, the PV industry consumes about 10% of globally mined silver [2], and a similar amount of flat glass [3]. Scaling capacities by a factor of ten will entail massive transitions for the way the PV industry works. When the industry became the dominant market for silicon and started to overtake information technology, new polysilicon factories were tailored entirely to solar cell production. Today, photovoltaics is the dominant consumer for silicon, and the silicon for PV supply chain is entirely linked to solar cell production. A similar trend is already observable for glass. New photovoltaic production lines, like the ones of First Solar [4], are constructed alongside glass manufacturing. As PV glass is already a specialized product, we expect to see stronger links between glass and module manufacturing. While for silicon and glass, resource availability is not a principle issue; the situation is different for silver. Competition with other consumers and rising prices are bound to become a challenge for the PV industry, motivating strong efforts to reduce or replace silver [2].

As we continue to scale PV capacity, we have to invest the resources needed to achieve the targeted 50 to 80 TW [1]. During this time, recycling can aid to reduce material demand and help reduce waste. Yet, by the time the target capacity is installed, C2C recycling has to be in place to minimize the need for additional material to maintain this capacity. The sheer amount will likely make mining end-of-life panels the most attractive option for new materials. Yet, to be able to do this, a paradigm shift is needed that includes recyclability into PV module design. The new design should have the goal to make resources perpetually usable (see Figure 1). In this work, we introduce first results of our attempt to create a completely cradle-to-cradle recyclable module, using perovskite technology.

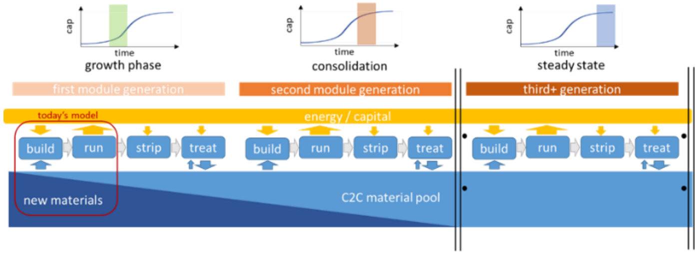

Fig. 1. Vision for a fully cradle-to-cradle recyclable solar panel. Rather than designing a device with a focus on a single operation period only, we want to develop a design that enables a perpetual use of all involved components.

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II. SOLAR CELL DESIGN AND CONSTRUCTION

Our choice to use perovskites was motivated by the fact that all functional layers of this solar cell are deposited using solution processing, which enables the use of solvents with complementary solubility for subsequent layers. Our initial goal was to construct a solar cell using a reversible sequence of processing steps, materials, and solvents so that this cell could be disassembled in the same way as it was produced. Our first test structure consisted of an ITO glass substrate with SnO_2 electron transport layer, a $MaPbI_3$ absorber layer deposited using DMF and NMP, and a hole transport layer made of PDCBT deposited using 1,2-dichlorobenzene coupled with a layer of PTAA-BCF. The test stricter employs contacts of evaporated gold. Image, structure, and performance of this test structure are displayed in Figure 2. Shown is the result for a champion cell out of a batch of 18 with an efficiency of 18.1%.

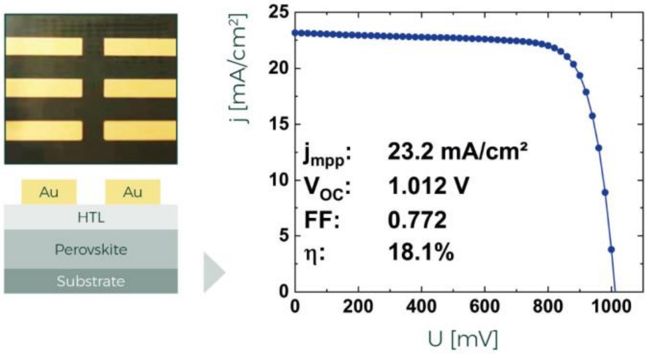

Fig. 2. Structure and current voltage characteristics of the initially produced solar cell. .

III. DISASSEMBLY AND REASSEMBLY

To recover a sufficient amount of material for characterization and treatment, we produced batches of 50 solar cells with matching architecture. On all 50 cells, we peeled of the gold contacts, and used the same solvents as for the deposition to remove the functional layers. When characterizing the recovered $MaPbI_3$, we observed that the recovered material exhibited material- and phase impurities, requiring an additional treatment step to reproduce the initial material quality. This treatment step consisted of i) recycled perovskite solution concentration with rotovap; ii) perovskite crystallization and precipitation with a non-solvent; iii) centrifugation; iv) vacuum drying. The processing and the improvement of material quality during treatment are shown in Figure 3.

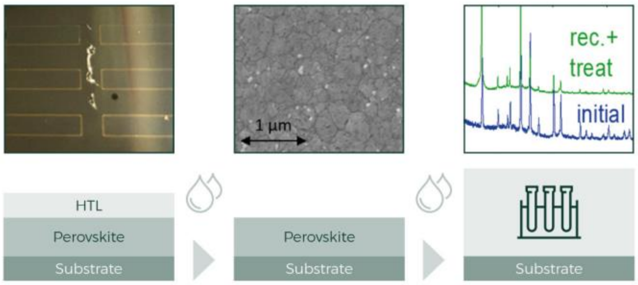

Fig. 3. Disassembly process and recovery of materials.

In a next step, we used the recovered $MaPbI_3$ to fabricate a new solar cell. While we recovered all components of the previous cell, we didn't produce new cells from only recycled materials to investigate the impact of every recycled material on cell efficiency. Hence, the cell with recovered $MaPbI_3$ included a new substrate with ETL, a newly made HTL, and new contacts. For this cell with recycled $MaPbI_3$, we were able to reproduce the same efficiency as with the initial cell. The result is shown in Figure 4, and, again, displays the champion cell of a batch of 18. While there is a variation in the characteristics between the initial cell and the one with recycled $MaPbI_3$, this is within the typical variations we obtain between cell batches. We take the reproduction of the initial efficiency as confirmation that the recycled $MaPbI_3$ does not limit solar cell efficiency differently from the initial cell.

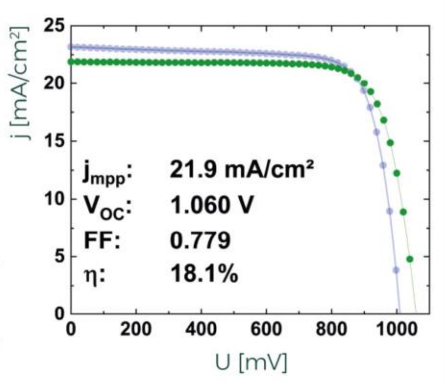

Fig. 4. Current voltage characteristics of the solar cell manufactured with recycled $MaPbI_3$.

In follow-up experiments, we will sequentially replace more and more components with recycled ones until we are able to make a solar cell entirely of recycled materials. The next step will be the creation of a solar cell with recycled substrate and recycled $MaPbI_3$. The challenge in this is not so much achieving a good device performance, but doing so while keeping the amount of energy, capital and new materials to restore the quality of recycled components at a minimum. For this purpose, we track energy and material flows during this process.

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IV. SUMMARY & CONCLUSIONS

To avoid waste and reduce the challenges with providing sufficient resources for PV in the energy transition, we need photovoltaic modules that are C2C recyclable. Current silicon PV modules are produced within a “design for immortality” paradigm, making it challenging to recycle them efficiently. Our aim is to introduce a new “design for circularity” paradigm. In this paradigm, every step during assembly has to be accompanied by a corresponding disassembly step at the end of life. In this way, PV module manufacturing becomes reversible. As a first vehicle to demonstrate this concept, we have chosen perovskite solar cell, because solution processing provides a straightforward way to recover all functional materials that requires designing the use of material stack and solvents. In a first experiment, we designed a solar cell with a reversible assembly sequence, measured its efficiency, disassembled the cell, and used the recovered absorber, $MaPbI_3$, to create a new solar cell. We achieved matching efficiencies for the initial cell and the recycled cell, demonstrating that perovskite based absorbers are capable of circular recycling. The potential to recover perovskites has also been shown, for example, by [5] and [6]. Yet, a full circular recycling of a perovskite PV module is, to the best of our knowledge, still an open task.

Finally, it should be noted that silicon and not perovskite technology will most likely carry the majority of the capacity that will be installed in the next two decades. Neverthelss, developing recycling concepts for perovskites has the potential to impact photovoltaic technology on a larger scale. On the one hand, and directly, perovskite recycling will be relevant for the recycling of perovskite on silicon tandem solar cells, and indirectly, recycling concepts for the module package may be transferable to silicon and CdTe technology.

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