

Remanufacturing Perovskite Solar Cells and Modules – a Holistic Case Study

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Remanufacturing Perovskite Solar Cells and Modules

– a Holistic Case Study

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Abstract

While perovskite photovoltaic (PV) devices are on the verge of their commercialization, promising methods to recycle or remanufacture fully-encapsulated perovskite solar cells (PSCs) and modules are still missing. Through detailed life-cycle assessment shown in this work, we identify that the majority of the greenhouse gas emissions can be reduced by re-using the glass substrate and parts of the PV cells. Based on these analytical findings, we develop a novel thermally-assisted mechanochemical approach to remove the encapsulants, the electrode and the perovskite absorber, allowing to re-use most of the device constituents for remanufacturing PSCs, which recovered nearly 90% of their initial performance. This remanufacturing strategy allows to save up to 33% of the module's global warming potential. Finally, we demonstrate that the CO₂-footprint of these remanufactured devices can become less than 30g/kWh, which is the value for state-of-the-art c-Si PV modules and can even reach 15g/kWh assuming a similar lifetime.

Introduction

To comply with the climate goals of the Paris Agreement, the global installed photovoltaic (PV) capacity is projected to enter the multi-terawatts scale in the forthcoming years.¹⁻⁴ Despite PV's potential to be an environmentally friendly alternative to fossil fuel energy sources, emissions associated with PV are non-negligible^{4,5} and the projected increase in PV installations is estimated to lead to 78 million tons of waste cumulatively by 2050.⁶ Recycling could mitigate the amount of PV related waste and has become one of the central discussions in the PV sector.⁷⁻⁹

However, recent studies have shown that bulk recycling is not necessarily more environmentally friendly than technologically simpler End-of-life (EoL) treatments such as landfill disposal or incineration¹⁰ due to the energy intensive separation of PV module materials at their EoL and processing of recycled materials. The re-use of entire modules or parts thereof could offer an environmentally friendly alternative to such methods. This could be particularly viable for PV modules compatible with solution-based processing techniques, such as perovskites. Here, the active components of the solar cell can potentially be washed off to

directly re-use bulk materials with high environmental impact such as glass. In such case when a combination of re-used, recycled, repaired or replaced parts serves to manufacture a new product, the term remanufacturing is normally employed.

Perovskite photoabsorbers have a high absorption coefficient, requiring significantly less material for building a PV module, in comparison to silicon devices and, therefore, have the potential to reduce the mass in PV-associated waste streams.¹¹ In addition, their solution-based processing – a unique feature for such well-performing semiconductors – allows for tremendous reduction in the energy demand not only during fabrication but also for recycling or remanufacturing.¹² Methods for perovskite recycling or remanufacturing should be considered and evaluated before such devices are introduced to the market, so that their widespread adoption could already substantially reduce PV related waste streams and greenhouse gas emissions.

Several works have demonstrated recycling approaches of perovskite solar cells (PSCs), showing almost no performance loss, even after multiple recycling cycles.^{13,14} To our knowledge, however, previously published reports only developed processes for recycling PV cells and no real case studies on encapsulated devices have been performed. Yet, to produce modules with lifetimes suitable for actual commercial deployment (>25 years), perovskite solar modules (PSMs) need to be equipped with additional barriers to limit environmental degradation (e.g. from moisture and air), such as encapsulation materials and a back sheet glass.^{5,15} which could also ideally be complemented by lead-sequestering materials embedded into the modules.^{16–18} Thus, the practical applications for recycling unencapsulated PSCs are limited without suitable methods to cleanly get rid of the encapsulant material.

In this work, we demonstrate for the first time a remanufacturing strategy for glass-glass encapsulated perovskite solar cells.^{19–23} Our study presents a facile experimental method to remove the edge-sealant, encapsulant, back electrode and degraded perovskite, allowing to re-use the device constituents with the highest global warming potential – glass substrate and back-sheet. By performing a life cycle assessment, we show that directly re-using the glass substrate, is a more environmentally favorable option than recycling, which can lead to a strong reduction of the PV module's global warming potential. By definition, recycling implies the disintegration of the waste material into a recyclate (i.e. small constituents of the waste material), which is then re-processed for the production of a new object. In contrast, remanufacturing implies that parts of the waste product can be reused – utilized in a new product directly without additional energy spent on creation of recyclate and its re-processing. Although in this study we utilize

PSCs with carbon-based electrodes (CPSCs) due to their promising commercialization potential and device stability, the herein developed remanufacturing approach is also applicable to other PSC architectures, especially n-i-p based ones. This remarkable strategy paves a new way to strongly reduce the global warming potential of PV modules and tremendously reduce their waste streams, which is essential for the terawatt-scale PV installations of the future.

Results

Environmental potential of recycling and remanufacturing encapsulated perovskite PV devices

The solar cell stack includes a fluorine-doped tin oxide (FTO) front electrode, compact and mesoporous titanium dioxide (c-TiO₂ and m-TiO₂, respectively), zirconium dioxide (ZrO₂) and a carbon-based back electrode (Fig. 1a). After infiltration and crystallization of the perovskite inside the mesoscopic scaffold, the cells were encapsulated with thermoplastic olefins (TPO) and polyisobutylene (PIB)-based edge seal (photographs in Fig. 1a). The justification of the encapsulation method selection can be found in the Supplementary Note 1. Statistics of the device power conversion efficiency (PCE) in Fig. 1b demonstrates high reproducibility of this encapsulation approach with an average PCE in reverse-scan of 14.5% and 13.7% before and after encapsulation, respectively. However, we also note an increase in hysteresis upon encapsulation. The complementary performance statistics can be found in Fig. S1.

From an environmental perspective, the focus of any waste reduction route should be to recover and re-use those materials with high associated environmental impacts. To identify these environmental hotspots, a life cycle analysis (LCA) was conducted on the PSMs with carbon-based electrodes (CPSMs) reviewed in this study (details of which can be found in the Supporting Information and Fig. S2). For the assessment we consider a CPSM with a PCE of 13.2%, based on the current-voltage (*IV*) measurement of a module we manufactured (Fig. S3). In this work we focused primarily on the global warming potential (GWP), expressed in kg of CO₂-equivalent per kWp of generated power, as this quality is the most direct link between the energy generation system and its greenhouse gas emissions. Figure 1c presents two distribution charts of individual contributions of device constituents to the total GWP.

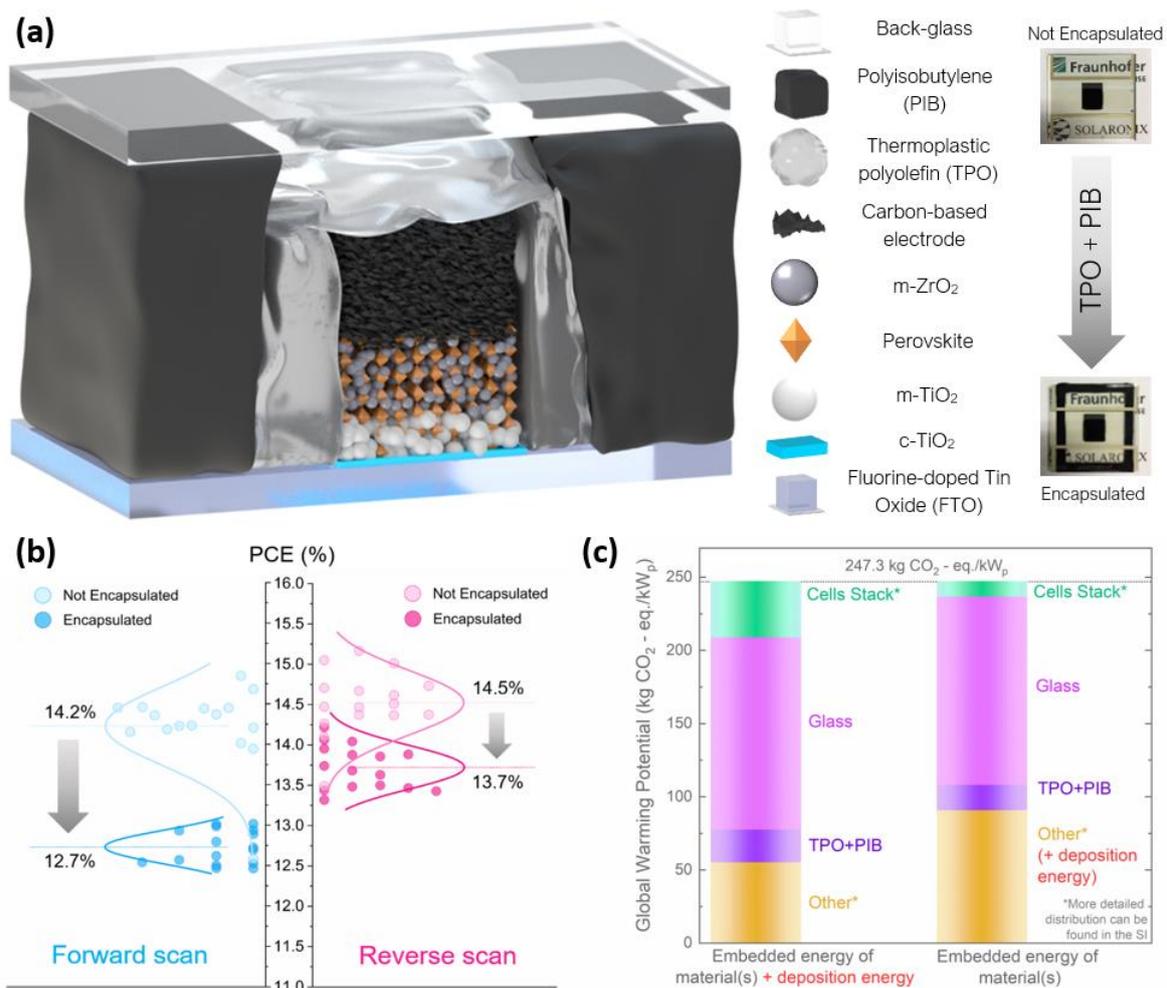


Figure 1: (a) Illustration of device stack of the encapsulated photovoltaic perovskite solar cells and modules with carbon-based electrodes employed in this study, with photographs (right) of the cells prior and after the encapsulation with TPO and PIB. (b) Power conversion efficiency of the cells before and after their encapsulation. (c) Global warming potential obtained from an LCA of a module based on the device structure shown in (a).

The chart on the left side shows the amount of kg CO₂-eq. emitted during the full processing of each module component (including the energy needed to deposit the layers, e.g. for screen-printing and sintering). Thus, this graph shows the potential GWP reduction per layer that can be achieved if layers are re-used without re-processing after EoL. The chart on the right side visualizes the embedded GWP per deployed material itself and has a separate part included in the “Other” contribution to account for all the energy and solvents used to fully process the layers (and overhead energy). More detailed distribution of individual contributions (e.g. cell layers, junction box, bus bars) to the total GWP (and other environmental impact categories) can be found in the Figs. S4 and S5. We highlight that during this LCA, we deliberately made conservative assumptions (such as a total glass thickness of 5.2 mm, which can be further

reduced, and conservative estimates of overhead electricity), to avoid portraying an ideal case and showcase a more realistic scenario of the potential GWP upon commercial production. Nevertheless, we note that the total GWP of encapsulated CPSMs was estimated to be 247.3 kg CO₂-eq./kW_p, which is one of the lowest GWPs reported for perovskite PV modules (Fig. S6), according to our knowledge. However, the LCAs of perovskite PV devices in literature often linearly extrapolate the known values of energy consumption of lab-scale production to manufacturing processes of ~m² modules, resulting in an assumption of an energy inefficient production and overestimation of the required resources. More importantly, the evaporation techniques required for metal electrode deposition, which are typically used as back-contacts in conventional PSCs are highly energy-intensive steps (not to mention the very negative environmental impact of gold), limiting the potential of perovskite PV to reach low GWPs.²⁴

The second chart depicts that only a small part of the GWP contribution of the cell stack comes from the materials itself (5%), while the majority originates from the energy and solvents used to deposit these layers. Thus, for the cell stack, possible GWP reduction can primarily be achieved by re-using the components in layer form (as they were originally deposited), which should be the initial aim of PSM remanufacturing schemes. Contrarily, the GWP mitigation potential for the recovery and subsequent reprocessing of the cell stack materials is limited.

In this study we do not consider module components such as the junction box, as these are typically separated before PV module recycling/remanufacturing and sent to designated electronic waste recycling plants.²⁵ Besides the materials and energy used directly for the fabrication of PSMs, GWP impact comes from indirect processes such as overhead electricity, infrastructure and packaging (included in “other” in Fig. 1c), which are not module components that can be recycled. Recycling the TPO and the PIB-based edge seal is relatively complicated because they both contain additives (necessary to obtain desirable encapsulation traits). The presence of such additives may lead to degradation during melting and re-extrusion or cause catalyst deactivation in thermal recycling processes, thereby reducing the quality of the material.²⁶ High-quality recycling of the encapsulant and edge seal would require processes and installations outside the scope of this project and is thus not considered here.

Both charts clearly demonstrate that the main GWP reduction can be achieved by re-using or recycling the glass (front and back), which can potentially reduce the GWP of PSMs by up to 53% and 52%, respectively. However, glass recycling comes with additional transport and energy to produce glass cullet and subsequently melt this into recycled glass. Due to these added efforts, glass recycling would likely bring little to no environmental impact reduction in respect

to GWP (Figs. S7 and S8). Correspondingly, our main aim was to design a remanufacturing process that allows the direct re-use of glass and as many PSC layers as possible, since this can potentially provide a substantial decrease in GWP impact.

Development of the resource separation process

Among all the cell components presented in Fig. 1a, perovskite is the one most likely to deteriorate in the shortest time, meaning that in order to replace it at least the PIB, TPO and back-glass have to be removed. Given that PIB is a rubber elastomer with glass transition temperature below room temperature, additional heating induces softening, allowing an easier mechanical separation of the back-sheet glass from the FTO (with cell stack). However, we note that heating the encapsulated cell above 160°C would melt the TPO due to presence of polypropylene (with melting point at 160°C), which then strongly adheres to the FTO surface. Therefore, we identified the ideal processing window for glass substrate separation (FTO and back-glass) to be between 120-140°C. The separation was assisted by making incision through the PIB rubber with a blade, which can also be done with a thin metallic wire on larger scale, since the gap between the glass substrates is around 400-500 µm, as can be seen from the SEM image in Fig. S9. After separation (Fig. S10) the glass substrates were left to cool down to room temperature before the encapsulant removal step.

Among the screened solvents, which could potentially dissolve PIB and TPO, none of them allowed a complete removal without an intensive additional manual effort (Figs. S11). Therefore, a “one-step” recycling process using a chemical bath with solvent that can dissolve edge-seal, encapsulant and perovskite was not possible for devices encapsulated with TPO and PIB. However, after keeping the substrates with PIB and TPO in acetone for 1 h, both the edge sealant and the encapsulant could be easily peeled off (Fig. 2). Although acetone itself does not dissolve any of the cell layers except perovskite, keeping the cell stack with TPO in acetone for longer times results in partial decomposition of the carbon with perovskite (Figs. S12). The exact composition of the TPO materials can vary, depending on the manufacturer, but typically their main components are various types of polyethylene (PE).²⁷ Since PE can be dissolved in acetone, the loss of TPO adhesion to the FTO is attributed to the partial dissolution of PE in TPO.

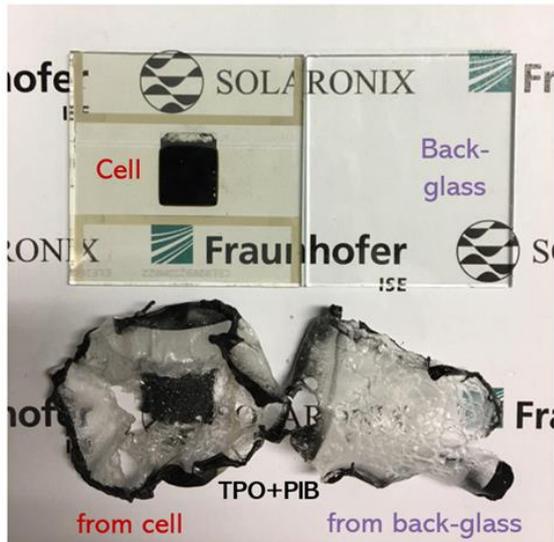


Figure 2: Photographs demonstrating a neat removal of encapsulants (TPO+PIB) and back-glass from the solar cell using the proposed thermally-assisted mechanochemical process, allowing to recycle them to potentially reduce the device GWP.

After the TPO and PIB are peeled off, the devices were dipped into a bath of methylamine (MA^0) and ethanol to liquefy and wash out the perovskite. Among the commonly used solvents such as DMF, DMSO, NMP and GBL, MA^0/EtOH has the lowest boiling point, allowing for its rapid evaporation from the cell stack, after perovskite has been removed.²⁸ Further annealing at 400°C allows to remove perovskite and carbon remnants from the stack, leaving m-TiO_2 and ZrO_2 intact. Cross-sectional SEM images in Fig. S13 demonstrate a comparison between these layers which were “as-deposited” (before the device manufacturing is complete) and the same layers after TPO, PIB, carbon and perovskite have been removed, clearly showing that the layer morphology and thickness are preserved. Therefore, carbon deposition and perovskite solution infiltration, followed by the encapsulation with TPO and PIB can be performed again to complete the remanufacturing loop, depicted in Fig. 3. This remanufacturing route is appealing in terms of solar module EoL due to its simplicity, effective re-use of most of the layers in the cell stack and lack of energy-intensive process steps, such as glass melting.

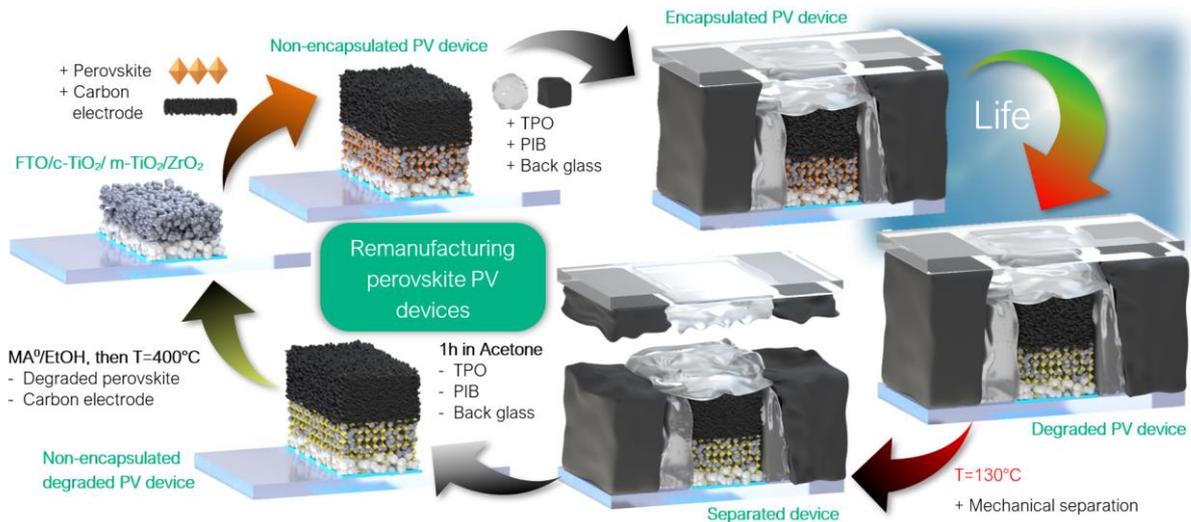


Figure 3: Proposed remanufacturing route for carbon-based perovskite PV modules based on a thermally-assisted mechanochemical method to separate the back-glass, encapsulants, degraded perovskite and carbon layer. This allows to re-use the rest of the layers and to lower the GWP of a perovskite PV module significantly.

The recovery of carbon or perovskite was not considered, since their recycling might be more challenging in terms of processing, translating into additional GWP and reducing the environmental benefit. Especially removal of perovskite and its recovery at high purity to allow for recrystallization in a solar cell might become particularly challenging, since its optoelectronic quality must be high to ensure decent device performance and thus lower GWP. Although methylamine liquefaction and recrystallization has been demonstrated for PSC recycling before, this process requires high content of methylamine to remove perovskite to a reasonable extent, which typically results in creation of pin-holes and defects.^{29,30} Considering that TPO and PIB are nearly intact after their removal from the module, these could possibly be recycled to further reduce PV material waste. However, as mentioned earlier, quality decrease upon recycling limits the utilization of these materials for PV applications, meaning they would be more suitable to produce materials (of lower quality) for other purposes.

Solar cell remanufacturing

The encapsulated CPSCs shown in Fig. 1 were remanufactured according to the developed thermally-assisted mechanochemical approach. The removal of perovskite and carbon, according to the procedure in Fig.3 allows to re-use the metal oxide layers (TiO_2 , ZrO_2) deposited on the FTO (Fig. 4a) in order to re-manufacture encapsulated CPSCs. After remanufacturing, the devices look pristine, without obvious damage to the cell active area (Fig. 4b). To evaluate the efficacy of our proposed remanufacturing route, we have compared the *JV*-

parameters of cells before and after remanufacturing. Fig. 4c demonstrates that while some remanufactured cells have a slightly better PCE than before, the average recovered PCE after remanufacturing is 88% of their initial value. We note that all the cells (virgin and recycled) were always measured 4 days after encapsulation (stored in the dark under 30-40% R.H., room temperature).

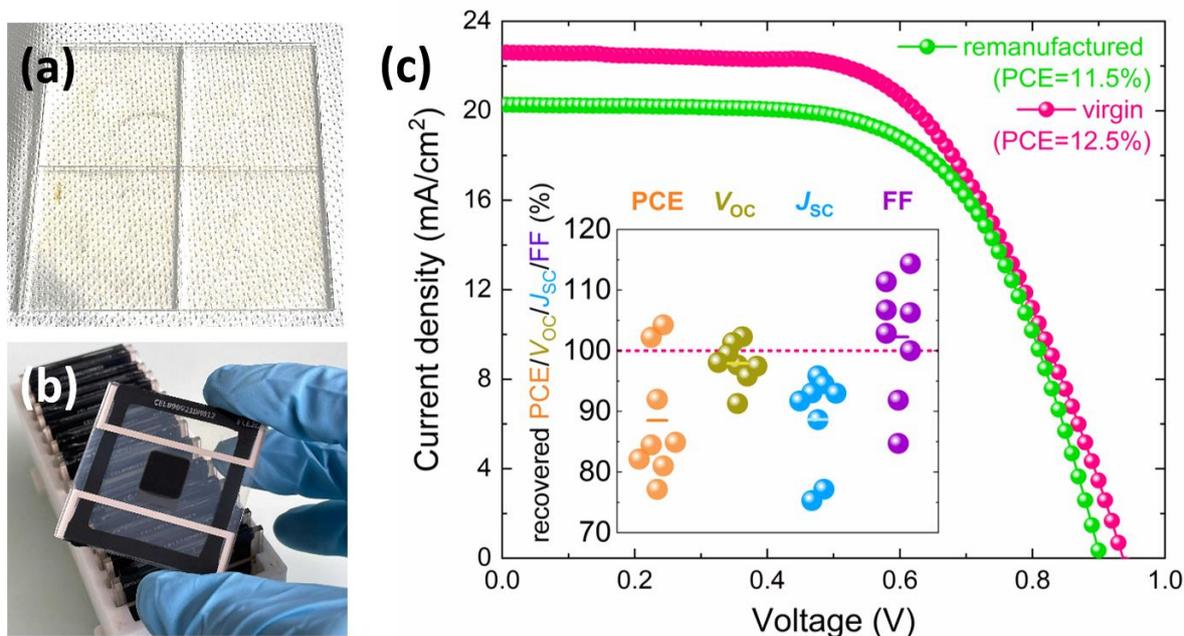


Figure 4: Photographs of recovered (a) FTO/c-TiO₂/m-TiO₂/ZrO₂ and (b) complete encapsulated CPSCs. (c) JV-curves of a representative CPSC before and after recycling with 92% recovered PCE. Device statistics are shown in the inset, demonstrating a change in each individual JV-parameter: PCE, V_{oc}, J_{sc} and FF after recycling relative to the initial (virgin) characteristics.

The PCE loss occurs primarily due to a significant decrease in J_{sc} , suggesting a presence of additional optical or charge extraction losses. We speculate that the surface of the oxide layers could have been modified after the remanufacturing procedure, causing additional optical or charge-extraction losses, or a combination of both. The JV-parameters obtained from forward scans can be found in Fig. S14.

Discussion

The proposed remanufacturing method separates itself from traditional PV (bulk) recycling methods, as most of the device constituents are simply re-used and only perovskite, electrode, encapsulant and edge-seal need to be replaced. As can be seen from Table 1, these constituents

account for only around 15% of the device GWP, while the re-used components represent over 62% of the module GWP (note that some of the GWP, such as from overhead electricity or packaging, is not directly embedded in the module).

Table 1: List of the device constituents, their EoL and corresponding GWP.

	Re-used?	GWP (kg CO ₂ -eq./kW _p)	% of total GWP
Glass	yes	131.3	53.1
FTO	yes	9.4	3.8
c-TiO₂	yes	3.6	1.5
m-TiO₂	yes	5.6	2.2
ZrO₂	yes	4.5	1.8
Perovskite	no	8.2	3.3
Carbon	no	7	2.8
TPO+PIB	no	22.4	9

Next, we evaluate the environmental benefit of remanufacturing modules (1m²) using our newly-developed thermally-assisted mechanochemical approach. A comparison in GWP for virgin, remanufactured with 88% of recovered PCE (based on the mean performance loss of cells shown in Fig. 4c) and “ideal remanufactured” (without any loss of PCE after remanufacturing) are presented in Fig. 5a. A complete environmental profile of the remanufactured modules is shown in Fig. S15. Our findings illustrate how this remanufacturing route could reduce the GWP of CPSMs by 24% or even by 33% if the remanufacturing process is optimized. This could result in 82 kg CO₂-eq./kW_p savings as well as an impact reduction in most other categories. Note that, despite fully re-using parts constituting 62.4% of the GWP, the reduction in GWP (compared to virgin modules) due to remanufacturing is substantially lower. This difference in GWP results from the additional processes required for remanufacturing. Predominantly the chemical treatment in MA⁰/EtOH baths, but also the temperature-assisted mechanical separation of glass substrates and annealing at 400°C result in non-negligible CO₂-eq. emissions.

In Fig. S16 we observe that, with our assumptions, such as linear degradation over lifetime, location of Freiburg, Germany, annual generation of 1429.2 kWh/m²/y etc. (more details are discussed in the SI) a lifetime of over 16 years is required for virgin PSMs to have lower CO₂ emissions per kWh than c-Si modules – 30.8 g CO₂-eq./kWh.³¹ (background parameters adjusted to match this study, see SI). However, this lifetime requirement can be lowered down to 10.7 years when the modules are remanufactured. We also notice that the beneficial effects

of recycling diminish with an increase in lifetime. This is due to the relatively higher impact of Balance of System (BoS) components at higher lifespans because the lifetime of these parts is independent of that of PSMs. Correspondingly, we recommend further research into the efficient reuse and remanufacture of BoS components to decrease the carbon footprints of not only perovskite, but PV power generation as a whole.

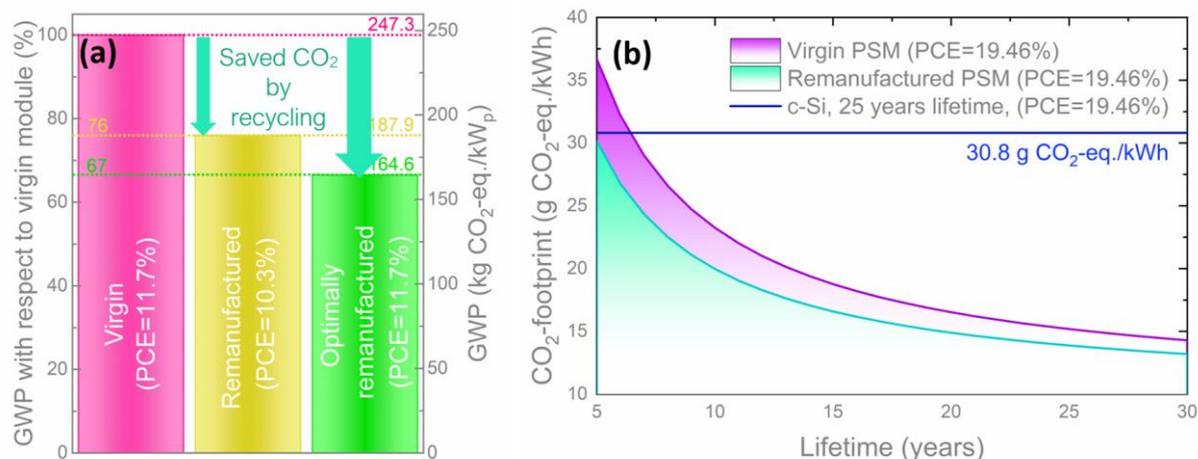


Figure 5: (a) GWP comparison of the virgin CPSMs in comparison to the recycled device with a loss in PCE equivalent to the mean experimentally-obtained value of 12% relative PCE loss in Fig. 4(a), as well as hypothetical case of no performance loss. (b) CO₂-footprint of virgin and remanufactured PSMs as a function of device lifetime in comparison to c-Si modules³¹ currently available on the market (as baseline). Note that in both graphs the PCE over the total area is considered (i.e. a product of PCE on the active area and geometrical FF)

Despite the diminishing results of remanufacturing at increased lifetimes, Fig. 5 shows that module-related emissions of perovskite PV can be substantially reduced by remanufacturing, especially when the PCE loss is kept to a minimum. Additionally, the remanufacturing process described here does not rest on overly optimistic assumptions and can likely still be optimized to further reduce the GWP. For example, we did not consider solvent recycling or re-use (either directly or through distillation) during the remanufacturing process. This could further reduce the GWP of remanufactured PSMs, given that the demand for solvent purity in the described process is rather low and solvents comprise the bulk of the GWP of remanufacturing efforts (Fig.S17). More importantly, this remanufacturing strategy utilizes solvents and treatments that do not decompose inorganic device constituents such as metal oxide layers. Therefore, it can also be applied to more traditional n-i-p architected devices (which currently still hold the last certified PCE world-records among PSCs³²) and some inorganic p-i-n based ones.

It is highly likely that upon eventual market introduction, PSMs should have comparable PCEs with c-Si devices. Fig. 5b presents the CO₂-footprint of high-efficient virgin and

remanufactured PSMs having the same PCE as the state-of-the-art c-Si modules, clearly showing that a further decrease in carbon emissions per kWh could be attained with the proposed production and remanufacturing schemes. If such high performing PSMs were to be produced similarly and remanufactured according to the procedure we describe, their CO₂-footprint would already be lower than that of c-Si modules even after a lifetime of 5 years. With similar lifetimes (25 years), these modules would have a footprint of only 14.4 g CO₂-eq./kWh – less than half of c-Si.

Conclusion

In summary, this holistic study presents a life-cycle assessment of perovskite solar modules and how their remanufacturing may affect their carbon footprint. After identifying the glass substrate as the main contributing factor to the global warming potential of PSMs, we developed an effective approach to re-use the substrate together with most of the cell layers and replace the missing components, thus leading to a development of a perovskite PV device remanufacturing process, for the first time. This thermally-assisted mechanochemical remanufacturing method consists of only a few process steps, does not use toxic solvents like DMF, and produces remanufactured encapsulated devices with a PCE close to 90% of virgin devices. Moreover, this procedure is universally applicable to other perovskite-based devices as well, especially nip-based ones, which utilize inorganic metal oxide layers deposited on glass substrates. Despite the obvious need for perovskite PV devices to be encapsulated, this is, according to our knowledge, the first study that experimentally showcases the remanufacturing of PSCs with a module-like architecture (i.e. including back glass, encapsulant and an edge-seal). We estimate that the GWP of PSM production can be reduced by 24%, or even 33% when the remanufactured modules show no PCE reduction compared to virgin modules through the described remanufacturing method, while also reducing its overall environmental impact. Further, we show that the CO₂-footprint of electricity generated by (remanufactured) PSM systems can become lower than that of c-Si, even at comparatively low lifetime and PCE. Correspondingly, we highlight that a substantial reduction in environmental impact can still be achieved by enhancing device PCE and stability. Overall, this work uniquely combines analytical and experimental methods to assess the sustainability of an emerging perovskite PV technology and to develop efficacious methods to improve it further towards a more environmentally-conscious energy generation system.

Methods

Materials

Fluorine-doped tin oxide glass substrates TCO22-7/LI (sheet resistance 7 Ω /sq.), silver paste Elcosil SG/SP, titania paste Ti-Nanoxide T165/SP, zirconia paste Zr-Nanoxide ZT/SP, carbon-graphite paste Elcocarb B/SP and methylammonium lead iodide perovskite solution with 5-ammonium valeric acid additive (5-AVAI) were provided by Solaronix SA. Acetone was purchased from Carl-Roth, ethanol was purchased from Alcosuisse. Titanium diisopropoxide bis (acetylacetonate) (75% in isopropanol), Hellmanex and isopropanol were purchased from Sigma-Aldrich. Thermoplastic polyolefin (TPO) ENLIGHT XUS62250 was obtained from FirstPVM and polyisobutylene (PIB)-based edge seal Solargain Edge Tape was obtained from Quanex.

Fabrication of perovskite solar cells with carbon-based electrodes

Devices were fabricated on 10 x 10 cm² plates of FTO-coated glass. First, a laser pattern defined cathode and anode areas with an automated fiber laser. After that, the substrate was subjected to sequential cleaning steps in 1% aqueous solution of Hellmanex, acetone, and isopropanol respectively (15 min each) in an ultrasonic bath and subsequently dried in air. The thin compact titania layer (c-TiO₂) was grown by spray-pyrolysis on a hot-plate set to 450°C, using a glass mask to protect the contact areas. A volume of 20 mL of titanium diisopropoxide bis (acetylacetonate) diluted in absolute ethanol (1:160) was sprayed with oxygen as a carrier gas, and warming was prolonged for 30 min before allowing the sample to cool down. For the manufacturing of CPSCs, an array of 4 electrodes was subsequently defined by screen-printing silver contacts, m-TiO₂, ZrO₂ and carbon paste using a 100-40, 165-30, 90-48, and 43-80 mesh stencil, respectively (the number of strands is per cm). After printing the wet film, each screen-printed layer was allowed to dwell for 10 min before drying at 120°C for 10 min, followed by a firing step at 500°C (or 400°C for carbon) for 30 min, after a 30 min ramp.

Then, perovskite precursor solution was deposited selectively on the area of interest by inkjet with a 10 pL droplet volume and a spatial resolution tuned to match the desired quantity. The

optimal resolution was determined to be 1200 x 1200 dpi. Same processes were used to manufacture perovskite solar modules with carbon-based electrodes with 12 series-interconnected cells except for the aperture area of the screen-printing mesh and perovskite filling procedure.

The wet samples (cells and modules) were then moved to an oven set to 50°C where they were dried for 10 min, thus forming the perovskite crystals in the porous electrode structure. The resulting devices were submitted to heat and damp treatment at 40°C and 75% R.H. for 150 hours, according to the previously reported method by Hashmi et al.³³ After the damp treatment the devices were encapsulated with TPO and PIB by a home-built vacuum laminator for 10 minutes at 110°C.

Characterization

The current-density and voltage curves of solar cells were measured with a source meter at a scan rate of 5 mV/s using a class A solar simulator providing 100 mW/cm², simulated AM 1.5G illumination, corrected for spectral mismatch. The same equipment was used for obtaining I-V curves of the modules, but the scan rate was set to 100 mV/s in this case. SEM/EDX images were obtained using Zeiss EVO 10 scanning electron microscope.

Life-cycle assessment

The details of the life-cycle-assessment (e.g. scope definition, indicators, assumptions) can be found in the Supporting information.

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Conflicts of interest

P.v.W. is an employee of Energy21 BV, D.Ma., S.N. and A.V. are employees of Solaronix SA, S.S. is a co-founder of Swift Solar.

Author contributions

D.B., P.v.W. and L.W. have generated the concept of this publication. D.B. coordinated the work, analyzed all the measurements, prepared the figures and manuscript together with P.v.W. S.N. and A.V. have manufactured the perovskite solar cells and D.M. prepared the perovskite solar modules with carbon-based electrodes. P.v.W. conducted the complete life-cycle-assessment, evaluated the potential of recycling and re-use of module components, estimated the environmental profile of devices and the CO₂-footprint as function of device lifetime. D.B. conducted IV-, SEM and EDX measurements of manufactured devices. J.L. and P.v.W. have screened possible solvents that can be used for removing the encapsulants. D.B., P.v.W. and S.Z. have developed the thermally-assisted mechanochemical approach for remanufacturing the devices. L.W. initiated the idea of a remanufacturing term and developed it further. M.K., L.W, A.H., S.S. and U.W. have provided important conceptual ideas, contributed to the manuscript preparation and results interpretation. S.G. provided specific insights into the current state of recycling in silicon-PV and thin-film industries, supervised the work and assisted with manuscript preparation. All authors have made valuable comments to the manuscript.

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