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Investigating the Remanufacturing Potential of Dye-Sensitized Solar Cells

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Abstract: Resources are becoming more expensive and less accessible, for instance construction wood or semiconductors. In addition, climate change requires the conversion of the energy system to 100% renewable energy. Therefore, we need resources to prevent the climate crisis from worsening, but at the same time, we are suffering from a worsening resource crisis. State-of-the-art technologies, such as silicon-based photovoltaic or wind power plants, are harnessing renewable energy but causing problems and resource losses at the end of their useful life. This alarming situation must be addressed with renewable energy technologies that can be used longer, repaired and remanufactured, and properly recycled at the end of their useful life. An emerging technology that can complement the established systems is dye-sensitized solar cells (DSSCs). Their production is less energy intensive and they can be manufactured without toxic materials. In line with the concept of the circular economy, the service life of all products must be improved in order to reduce resource consumption. Therefore, we investigated the potential for remanufacturing DSSCs by taking apart old DSSCs, cleaning the components, and building new DSSCs from the remanufactured components. The remanufactured DSSCs have the same or higher efficiencies and can be remanufactured multiple times.

Keywords: circular economy; remanufacturing; dye-sensitized solar cell; sustainability

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1. Introduction

In addition to the climate crisis, society faces another global challenge, namely the depletion of resources [1]. Recent developments in resource scarcity include the rise in timber prices and the shortage of semiconductors [2,3]. These problems have a variety of causes, but the main cause is the linear economy [4]. The processes in a linear economy are usually described as "take, make, waste", meaning that resources are extracted, processed, used, and then disposed of [4]. Some parts are already recycled, but the quality of recycled products is low and most valuable resources are discarded or incinerated [5]. That is why it is particularly important for resource-poor countries, such as Germany or Japan, to close material loops and work on circular economy concepts. In a circular economy, a product's lifetime should be extended by repairing, refurbishing, remanufacturing and ultimately recycling of the product [4]. Material loops are closed and the material is reused.

The climate crisis makes it necessary to invest in renewable energy technologies to transform the energy sector and achieve a climate-neutral energy supply [6]. However, the resources to build renewable energy technologies are currently running through a linear economy.

The main problem of crystalline silicon photovoltaics (c-Si PV) is the composite material of glass, silicon and various plastics. This composite material is difficult to take apart, and the recycled glass is contaminated with plastic or metal parts, resulting in an inferior end product and downcycling [7]. In a normal glass recycling process, it has not yet been possible to recover any high-quality material. Furthermore, there are no established and standardized strategies of how modules could be repaired or upgraded [8]. Initial repair services for individual module components are already being offered in practice [9,10]. However, business models for the implementation of complete repair and reuse processes are still the subject of research [11]. Accordingly, c-Si PV modules are not designed for repair, remanufacturing or recycling.

For this reason, interest in alternative, more sustainable technologies is rising. One promising technology is dye-sensitized solar cells (DSSC) [12,13]. DSSCs can potentially be made from non-toxic material and the production process is less complex and energy consuming than c-Si PVs [14–17]. This low-tech option of using renewable energy is easy to manufacture and could potentially be produced in rural areas [18]. The areas of application are areas with low light intensity, for example indoors or at twilight [19]. DSSCs probably cannot replace c-Si PV yet, but they complement the state of the art in renewables and can be used in facades, cars or devices for the Internet of Things [20,21].

The following is a brief description of the functional mechanisms of a DSSC: the main components are two glass plates coated with fluorine-doped tin oxide (FTO), which gives the glass conductive properties. A semiconductor material, usually TiO_2, is deposited on the FTO layer of the front electrode. The TiO_2 layer is porous and the dye, the photoactive material in the cell, is incorporated into this layer. Graphite or platinum is applied to the FTO layer of the counter electrode as a catalyst. Both electrodes are connected by an electrolyte. Light can excite electrons in the dye, which are then transported through the TiO_2 layer into an external circuit. There, the electricity can be used. Through the counter electrode of the DSSC, the electrons can re-enter the system and combine with the acceptors of the electrolyte. In this way, the electrolyte is reduced and the charge can be transported back to the dye. The catalyst layer on the counter electrode, graphite or platinum, allows the electrons to move through the electrolyte to the TiO_2 layer and complete the circuit [22,23].

DSSCs are not yet produced on an industrial scale, as efficiency and long-term stability still need to be improved. Efficiencies of over 14% are achieved on a laboratory scale using toxic or scarce materials, such as platinum, silver and ruthenium dyes [24–27]. DSSCs even work in ambient light, and a power conversion efficiency (PCE) of 28.9% was achieved [28]. DSSCs based on non-toxic components, such as plant-based dyes and graphite, as a catalyst achieve PCEs below 1% [29–31]. Another problem is the long-term stability of DSSCs. For DSSCs with liquid electrolyte, the PCE value decreases rapidly with the evaporation of the electrolyte. When the electrolyte is refilled, those DSSCs can be used for at least four months [32]. To improve the long-term stability of DSSCs, solid-state and gel electrolytes have been researched [16,33,34]. DSSCs with gel electrolytes are stable for at least 140 days [35]. Further research on long-term stability is needed to bring competitive DSSCs to the mass market. For realistic applications in wearable technologies, a lifetime of up to 5 years, and for applications in the construction environment, a lifetime of up to 25 years is required to be competitive [36,37].

Other upcoming technologies that researchers are focusing on are perovskite solar cells and organic solar cells [38,39]. Perovskite solar cells are promising, due to their high performance and low production costs, with PCEs of 25.5% reported in 2020 [40]. However, perovskite solar cells contain lead, which can potentially harm the environment. Lead-free perovskite cells are currently being researched, but do not achieve the same efficiency and long-term stability as cells with lead [41]. Organic solar cells, similar to DSSCs, have lower production costs and are, therefore, potentially economically efficient [42]. Recent advances in research have resulted in organic solar cells with a PCE of over 18% [39]. However, long-term stability remains a major problem for organic solar cells [42].

Concerning the resource crisis, it is necessary to design sustainable renewable energy technologies. Since already large amounts of c-SI PV modules are on the market, one could learn from the recycling and remanufacturing problems that occur and do better with DSSCs.

Life cycle analyses (LCA) of DSSCs show that the production of the transparent conductive oxide (TCO) glass is the most critical component regarding the impact on the environment [37,43,44]. However, these LCAs assume a cradle-to-grave scenario for the TCO glass. Various scenarios can be applied in a life cycle assessment. Cradle-to-grave means that the environmental impact of a product or material is recorded from the extraction of the raw material through processing, the use phase and disposal. If a recycling process is added, the energy consumption in the production of TCO glass is reduced and a cradle-to-cradle scenario could be applied in the life cycle assessment [45]. Another option is a remanufacturing process; it would add even greater benefits to the life cycle of a DSSC. In remanufacturing, the product is disassembled and parts of the product are cleaned, refurbished, subjected to testing and made to appear new again. New products are manufactured with these improved or upgraded parts [46]. Refurbished products have the same or even better quality and functionality compared to new products because there are fewer teething problems and the known problem parts have been replaced or improved [47]. One design approach to improving the remanufacturability of a product is to use a modular design so that the product can be easily disassembled and certain parts can be replaced or upgraded [48,49].

Around 70% of the environmental impact of a product is predetermined in the design phase of a product [50]. Because DSSCs have not yet been commercialized on an industrial scale, there is now an opportunity to research and develop DSSCs that are repairable, remanufacturable and recyclable. For non-toxic glass-based DSSCs, the FTO coated glass has the highest environmental impact [51]. Therefore, the highest potential is to reuse the coated glass for building new DSSCs in the remanufacturing process. In this experiment, we investigated how the TCO glass and TiO_2 from old DSSCs can be reused to build new DSSCs and what impact this has on the PCE. Therefore, we discussed the results of three experimental setups, explained in Section 2, how TiO_2 can be recovered in the process, what remanufacturing technologies exist for c-Si photovoltaics, and how they can be useful for remanufacturing DSSCs.

2. Materials and Methods

The fabrication of DSSCs mainly involves the preparation of the electrodes with dye and graphite, the assembly and hydration with the electrolyte. To prepare the electrodes, fluorine-doped tin oxide (FTO) coated glasses (Man Solar, Petten, The Netherlands) were used. The counter electrodes were prepared by coating the FTO glasses with a 9B graphite pencil (Faber-Castell, Stein, Germany) to obtain a catalyst layer. Front electrodes for the samples G1.1–G1.6 were purchased with an additional TiO_2 coating. However, the front electrodes used for the samples T1.1–T1.12 were recovered for remanufacturing. Figure 1 visualizes the process of remanufacturing.

The DSSCs used in previous experiments were disassembled and the electrodes were cleaned with ethanol and fully desalinated water. To clean the front electrodes, the TiO_2 layer had to be carefully rubbed off with a rubber glove under running water. Then, a new layer of TiO_2 was applied using TiO_2 paste (Man Solar, Petten, The Netherlands) and the doctor blade technique. The thickness of the TiO_2 layer was approx. 30 μm. The TiO_2 layer was then sintered at 500 °C for 2 h in an oven (Nabertherm, Lilienthal/Bremen, Germany).

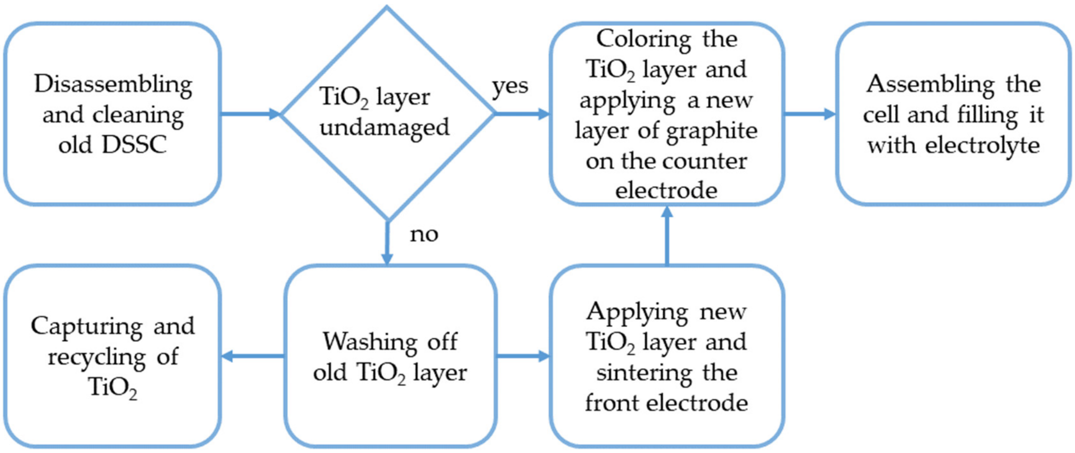


Figure 1. Visualized process of remanufacturing DSSCs.

Hibiscus flowers were used for the dye. The dye solution was prepared from 2.5 g of hibiscus flowers, 22.5 g of distilled water and 7.5 g of ethanol. The dye was then extracted by stirring the mixture at room temperature for 20 min. After filtration, the front electrodes were placed in the filtrate for 20 min, rinsed with ethanol, and dried at ambient conditions. The counter and front electrodes were then assembled, fixed with adhesive tape (tesa SE, Norderstedt, Germany) and filled with two drops of electrolyte (iodine/potassium iodide, Man Solar, Petten, The Netherlands), resulting in an active energy conversion area of 6 cm^2.

The prepared DSSCs were contacted with alligator clips and the current–voltage curves were measured at room temperature against a black background with a Keithley 2450 source meter (Tektronix Inc., Beaverton, USA). For this, the DSSCs were illuminated with 100 mW/cm^2 by an LS0500 solar simulator with 1.5 G spectrum (LOT-Quantum Design GmbH, Darmstadt, Germany). Although the alligator clips damaged the glasses with every measurement, it did not seem to have much impact on the FTO layer or the PCE. The damaged glasses were investigated with a light microscope, Axio Observer 7 materials (Carl Zeiss Microscopy GmbH, Göttingen, Germany). The data from the Keithley measurements were used to calculate the efficiency of the DSSCs. After the efficiency dropped to a low level, some samples were remanufactured. For this purpose, the DSSCs were disassembled, and the electrodes were cleaned with ethanol. The front electrodes were placed in a new dye solution as described above for 20 min and dried at ambient conditions. The counter electrodes were coated with a new graphite layer. The electrodes were then reassembled as mentioned earlier. Other samples, however, were rehydrated by refilling them with two drops of electrolyte (iodine/potassium iodide, Man Solar, Petten, The Netherlands).

2.1. Four Generations of Commercially Applied TiO_2 Layers

The front electrodes that had commercially applied TiO_2 layers were used to prepare six DSSCs (G1.1–G1.6). These DSSCs were measured until the efficiency dropped to a low level. After that, the DSSCs were remanufactured as mentioned above. Then, the new generation was measured until the efficiency dropped again, and the procedure was repeated. This way, a second (G2.1–G2.6), third (G3.1–G3.6) and fourth generation (G4.1–G4.6) were measured to investigate the potential of the remanufacturing process.

2.2. Two Generations of Manually Applied TiO_2 Layers

The front electrodes that had manually applied TiO_2 layers were used to prepare 12 DSSCs (T1.1–T1.12). These DSSCs were measured until their efficiency sank to 0.01%. After that, the DSSCs were rehydrated with electrolyte (T1.1rehy–T1.12rehy). The DSSCs were then measured until their efficiency dropped again. Afterwards, six DSSCs were rehydrated (T1.1rehyII–T1.6rehyII), while the other six DSSCs were remanufactured (T2.1–T2.6). These DSSCs were then again measured and compared to investigate the difference between reprocessed and rehydrated DSSCs.

2.3. Remanufactured DSSCs from 2015

In another test series, old DSSCs with manually applied TiO_2 layers from 2015 were investigated. For this, six DSSCs were rehydrated with electrolyte (Reviv1–Reviv6). Six other DSSCs were opened and cleaned, before an additional TiO_2 layer was applied above the existing layer (Over1–Over6). Another six DSSCs were remanufactured as mentioned earlier (New1–New6). These 18 DSSCs were then measured and compared to speculate which remanufacturing process has the most potential.

2.4. Recovering TiO_2 during Remanufacturing

To recover the TiO_2 during the remanufacturing, the DSSCs were disassembled, and the residual dye and electrolyte were washed off with desalinated water. The TiO_2 layer had to be carefully rubbed off with a rubber glove while desalinated water was poured over the front electrode. The water with the TiO_2 was collected in a plastic cup. The water was then evaporated at room temperature. This process took four days.

In another process, the DSSCs were disassembled and cleaned, without rubbing off the TiO_2 layer. Residues of the dye gave the TiO_2 layer a light lilac color. The optical properties of this TiO_2 layer were investigated using a UV–Vis spectrophotometer, Thermo Scientific Genesys 10S (Fisher Scientific GmbH, Schwerte, Germany). The sample was sintered as described above and compared to a pure sintered TiO_2 layer.

3. Results and Discussion

3.1. Four Generations of Commercially Applied TiO_2 Layers

Figure 2 shows the average PCE of six DSSCs with commercially applied TiO_2 layers and Figure 3 shows the average open circuit voltage (Voc) and short circuit current (Jsc).

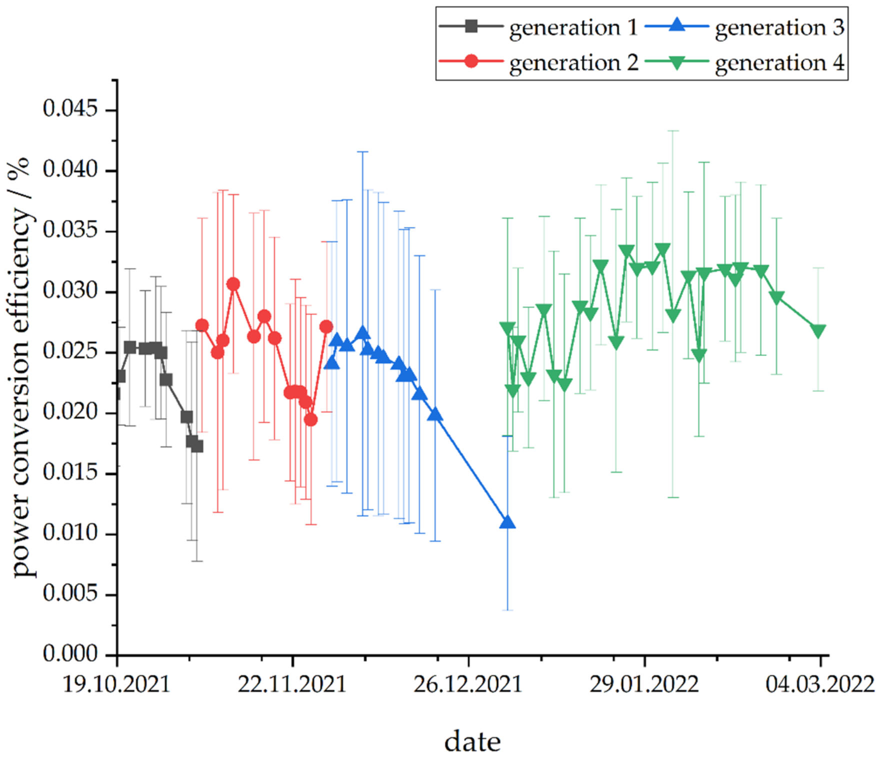


Figure 2. Average PCE of four generations of DSSCs with commercially applied TiO_2 layers.

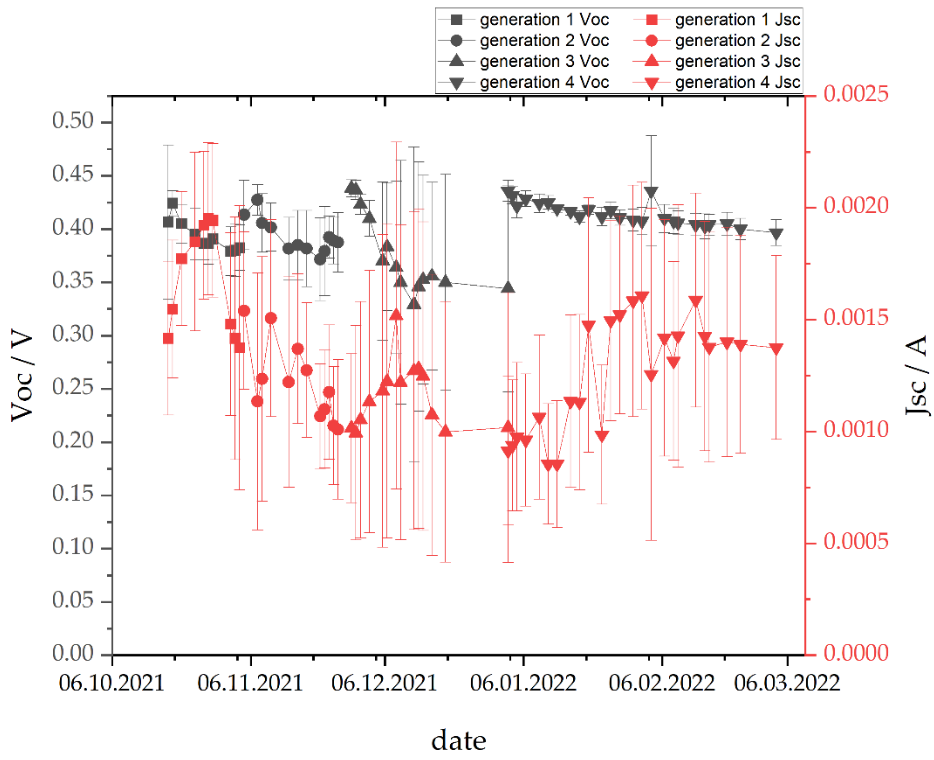
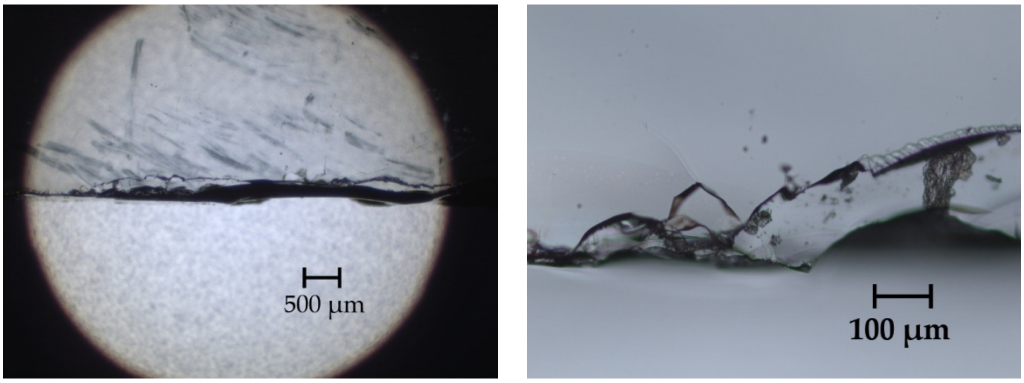


Figure 3. Average Voc and Jsc of four generations of DSSCs with commercially applied TiO_2 layers.

Each color change indicates a remanufacturing process, as described in Section 2. It can be observed that the DSSCs reach similar or even higher efficiencies after the remanufacturing process. It can also be observed that the long-term stability slightly increases. As Figure 3 emphasizes, Voc and Jsc rise after each remanufacturing process. The standard deviation for Voc is comparably small, while the fluctuation of Jsc of the cells is considerably higher. This correlates with the higher fluctuations in the PCE of the last generation. This can be explained by the measurement itself. The DSSCs were contacted with alligator clips and the glass was damaged with each measurement or contact with the alligator clips. Figure 4 shows an example of the damaged glass.



(**a**) (**b**)

Figure 4. Microscope images of glass damaged by alligator clips: (**a**) 1.25 times magnified; (**b**) 10 times magnified.

Small shards of glass were broken out, which might have caused a decrease in conductivity and, thus, lowered the PCE of the cell. In Figure 4a, it can also be observed that the alligator clips caused scratches in the glass. However, the thin FTO layer is important for the conductivity and cannot be visualized with this microscope.

The following observations can explain the large standard deviation:

- In the third generation sample G3.1, the PCE goes to zero after the third measurement.
- Sample G4.2 is difficult to contact and the PCE varies between high values of 0.04% and 0%. This was probably caused by the damaging of the glass.

3.2. Two Generations of Manually Applied TiO_2 Layers

In Figure 5, the average PCE of 12 DSSCs with manually applied TiO_2 layers is visualized. After the PCE sank to 0.01%, all 12 DSSCs were rehydrated with electrolyte. By refilling, the PCE went up again. After the PCE sank to 0%, six DSSCs from the first generation were remanufactured, as described in Section 2. The other six DSSCs were again rehydrated with electrolyte. It can be observed that the remanufacturing process delivers cells that have equally high PCEs. Rehydrating the DSSCs also lifts up the PCE, but the remanufacturing process delivers even higher PCEs. It can also be observed here that the long-term stability slightly increases with each generation. As can be observed in Figure 6, the second generation DSSCs and the DSSCs that were refilled twice have a significantly lower Jsc.

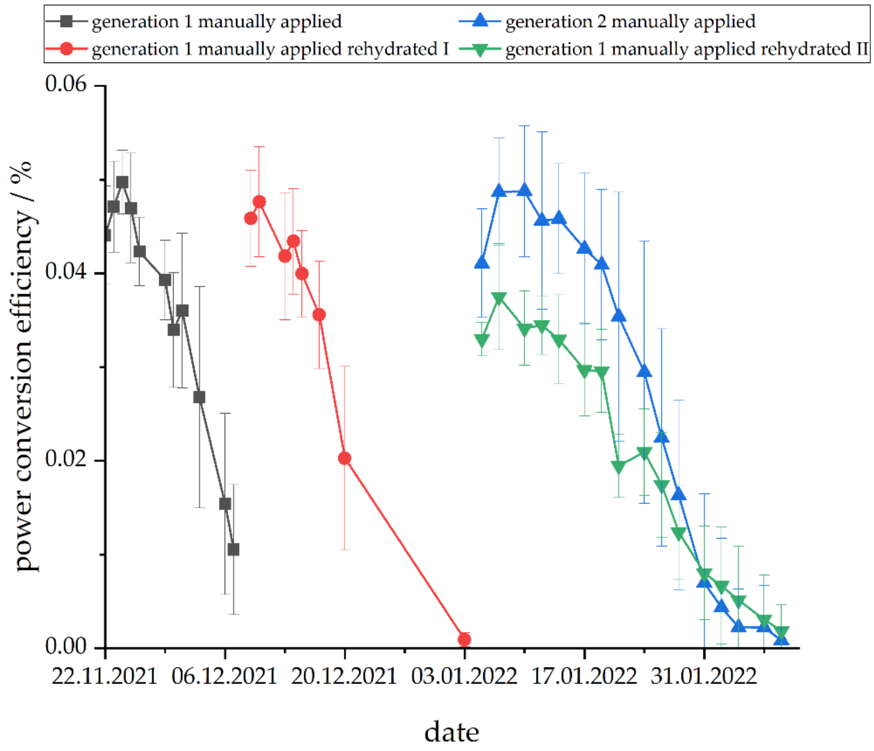


Figure 5. Average PCE of 12 DSSCs with manually applied TiO_2 layers. The third generation was split into six DSSCs that were remanufactured and six DSSCs that were refilled with electrolyte.

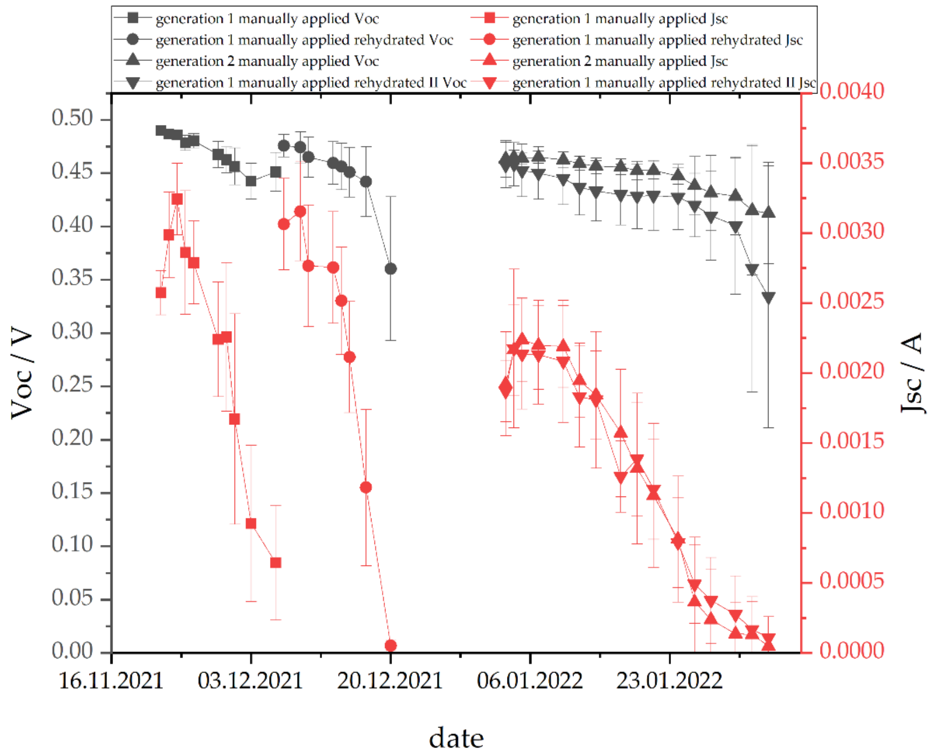


Figure 6. Average Voc and Jsc of 12 DSSCs with manually applied TiO_2 layers. The third generation was split into six DSSCs that were remanufactured and six DSSCs that were refilled with electrolyte.

3.3. Remanufactured DSSCs from 2015

In Figure 7, old DSSCs from 2015 were remanufactured. Six DSSCs were just rehydrated, without any other remanufacturing steps. Only one out of six DSSCs had a measurable PCE of 0.002% over three weeks. The other DSSCs could not be revived by simply rehydrating. The cells were pale; thus, the dye was probably already deteriorated. Six other DSSCs from 2015 were opened, cleaned and an additional TiO_2 layer was applied above the existing layer. Six more DSSCs from 2015 were cleaned and also the old TiO_2 layer was washed off and a new layer was applied. After sintering and dying, new DSSCs were manufactured from the old material. The DSSCs that were cleaned off the old TiO_2 layer delivered higher PCEs; however, for the first 17 days, the standard deviation bars overlapped. Figure 8 shows that the standard deviation increased with time, indicating that the DSSCs exhibit differences in long-term stability and the difference between the Jsc of the DSSCs increases with time. Further research is necessary to identify the best remanufacturing process. The TiO_2 that was washed off can be recovered and reused for building new DSSCs, as described in Section 3.5.

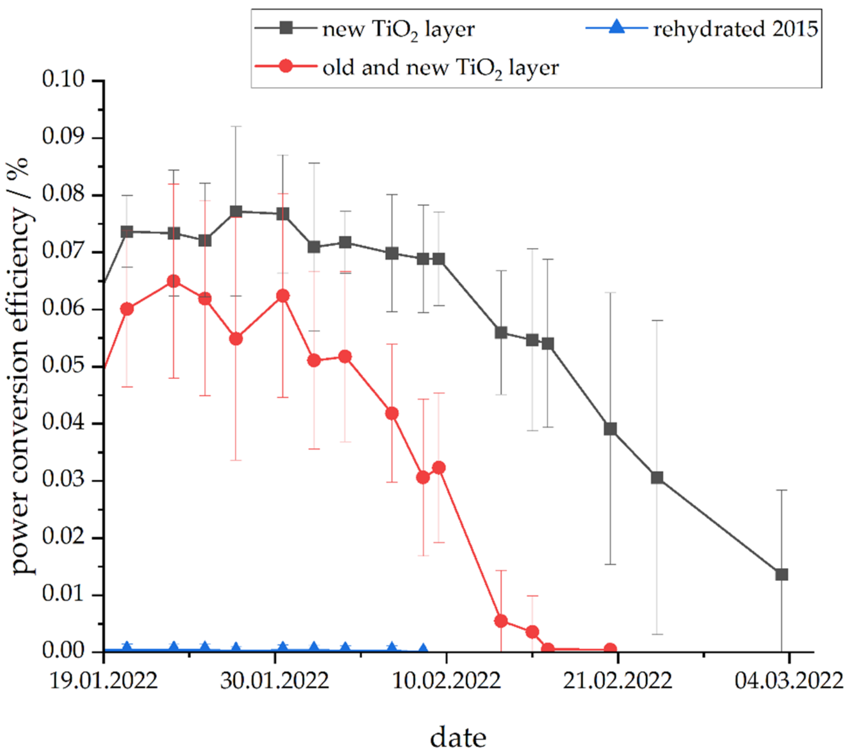


Figure 7. Average PCE of 18 DSSCs from 2015 with manually applied TiO_2 layers. The grey line is the DSSCs with a new TiO_2 layer on cleaned glass, the red line is the DSSCs with new TiO_2 layers on top of the old TiO_2 layer and the blue line is the DSSCs that were rehydrated with electrolyte.

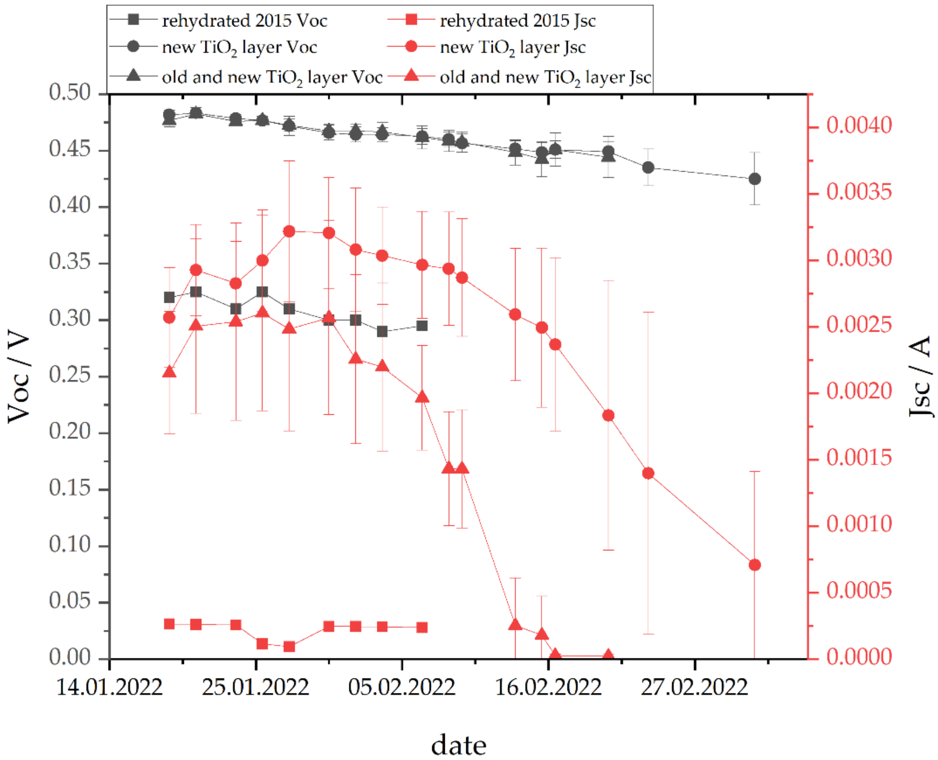


Figure 8. Average Voc and Jsc of 18 DSSCs from 2015 with manually applied TiO_2 layers. The round marks symbolize DSSCs with a new TiO_2 layer on cleaned glass, the triangle marks symbolize DSSCs with new TiO_2 layers on top of the old TiO_2 layer and the square marks symbolize DSSCs that were rehydrated with electrolyte.

3.4. Comparison of the DSSC PCEs

Figure 9 shows a comparison of all the PCEs. The differences in PCEs of the different DSSC batches can be explained by different qualities of glass, TCO and the different methods for applying the TiO_2 layer, either manually or by machine. With machine applied TiO_2 layers, the DSSCs have lower PCEs but longer life span compared to the manually applied TiO_2 layers. Overall, it was shown that remanufacturing of DSSCs is possible and that there are hints for even better performance in the second, third and fourth life of a DSSC. The increased PCE could be explained by the increased density of the dye molecules on the TiO_2 layer [52].

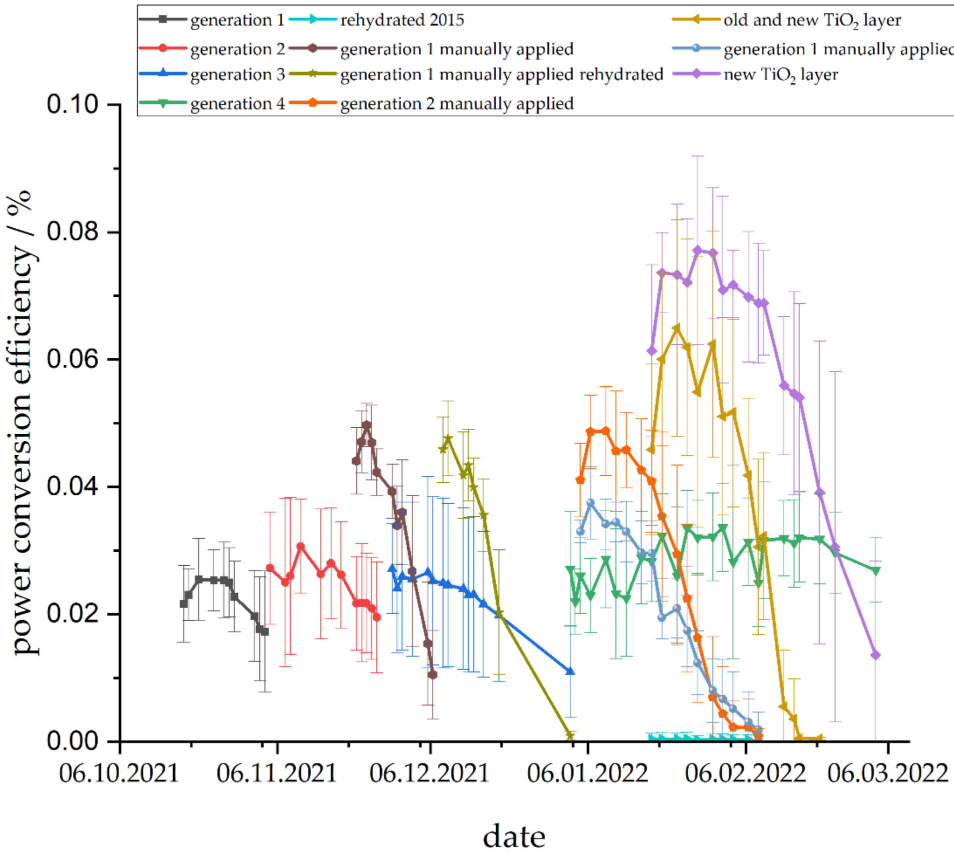


Figure 9. Comparison of all the DSSC PCEs.

3.5. Recovering TiO_2 during Remanufacturing

The experiments suggest that the removal of the old TiO_2 layer during the reprocessing process could lead to higher PCEs for the new generation of DSSCs. A new layer only needs to be applied if the old TiO_2 layer is damaged. Since we want to reuse as many components as possible, the washed-off TiO_2 can be recovered and reused for new DSSCs. To recover the TiO_2, the rinse water was collected in a beaker and the water was evaporated at room temperature.

Figure 10 shows the UV–Vis spectra of a pure TiO_2 layer in comparison to a used TiO_2 layer and the same used TiO_2 layer after sintering in the oven, as described in Section 2.

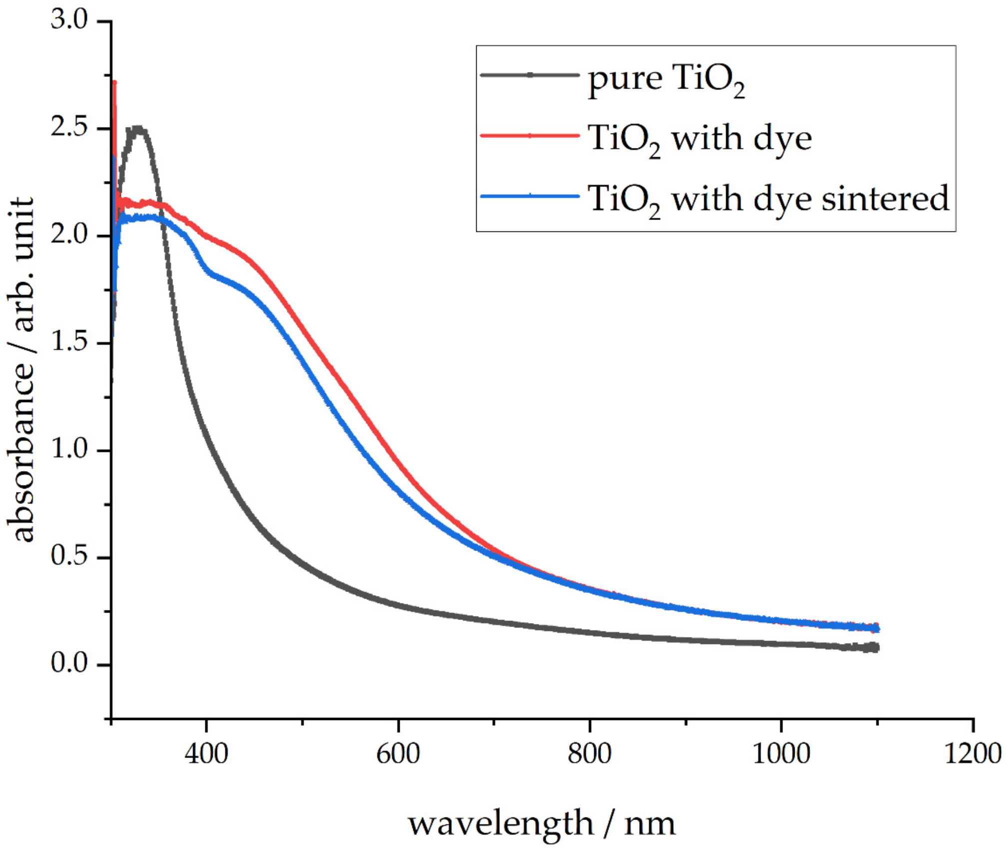


Figure 10. UV–Vis absorption spectra of pure TiO_2, TiO_2 with dye from a used DSSC and a used TiO_2 layer after sintering in the oven.

It can be observed that, even after sintering, the used TiO_2 layer has a significantly different absorption spectrum to the pure TiO_2 layer. Since the reuse of the same TiO_2 layer in the remanufacturing process yielded similar PCEs, it can be concluded that the difference in absorption spectra does not negatively affect the PCE of the DSSCs.

In order to make the recovered TiO_2 usable for other applications, a purification process could be applied. However, in a scenario where the DSSCs are transported to a remanufacturing facility, it is more likely that the recovered TiO_2 will be reused for DSSC application rather than after purification for other purposes.

3.6. Remanufacturing Strategies and Technologies for c-SI and Thin-Film PV

Since c-SI PV is well established, one could learn from the remanufacturing strategies and technologies from this field for other PV applications. Crystalline silicon photovoltaic modules are manufactured on an industrial scale and are well established on the market. A total of 80% of PV waste is caused by defects in the first 4 years. Experts from the CIRCUSOL research project believe that around 45 to 65% of these can be repaired [8]. Therefore, it is technically possible to repair or remanufacture PV modules. However, standardized remanufacturing processes have not yet scaled up to industrial scale, and recycling or even disposal is often preferred.

In connection with the repair and remanufacturing process, fault detection and subsequent testing of the modules plays an important role. In this context, for example, the PV-Rec process was developed. The procedure consists of current–voltage (I–V) characterization under standard test conditions (STC), electroluminescence analysis, infrared imaging measurements, and visual inspection to detect the defects. After reprocessing, a second current–voltage (I–V) characterization is performed to determine the new characteristic values of the modules [11].

The CIRCUSOL project is developing possible standard processes to formalize the second life processes, such as remanufacturing, and to create a regulatory framework [8]. The key component is a product service system for circular business models.

Private companies already offer testing and remanufacturing services. These include pvXchange, Second Sol, Rinovasol and Solar-pur GmbH [9,10,53,54]. However, the service is limited to the repair of defective bypass diodes, junction boxes, module frames, the module back sheet, module cables and solar connectors. In case of broken glass, defective solar cells, delamination or similar defects, repair is not possible [10].

Table 1 shows an overview of a patent search related to remanufacturing and DSSCs, or solar cells.

Table 1. Overview of a patent search related to remanufacturing and DSSCs, or solar cells.

	Solar Cells	DSSC Solar Cells	Solar Cell Materials	Titanium Dioxide TiO_2
remanufacturing	0	0	0	0
recyclable	5	0	1	0
recycling	143	0	30	0
reusing	25	0	1	0

The search for titles of patents using the logical AND conditions gave, for example, 143 hits with the terms ”recycling” and ”solar cells”.

The analysis of patent applications refers to the period from 2000 to 2021 and was carried out using the Derwent Innovations Index database. The keywords used for the search are listed in Table 1. The table contains patent applications of categories A and B. The main point of this search was that mainly the innovations from the following areas were protected: reuse of materials used in solar cells and reuse of chemicals used in the manufacturing process of solar cells. Figure 11 shows the patent applications of A and B category by country.

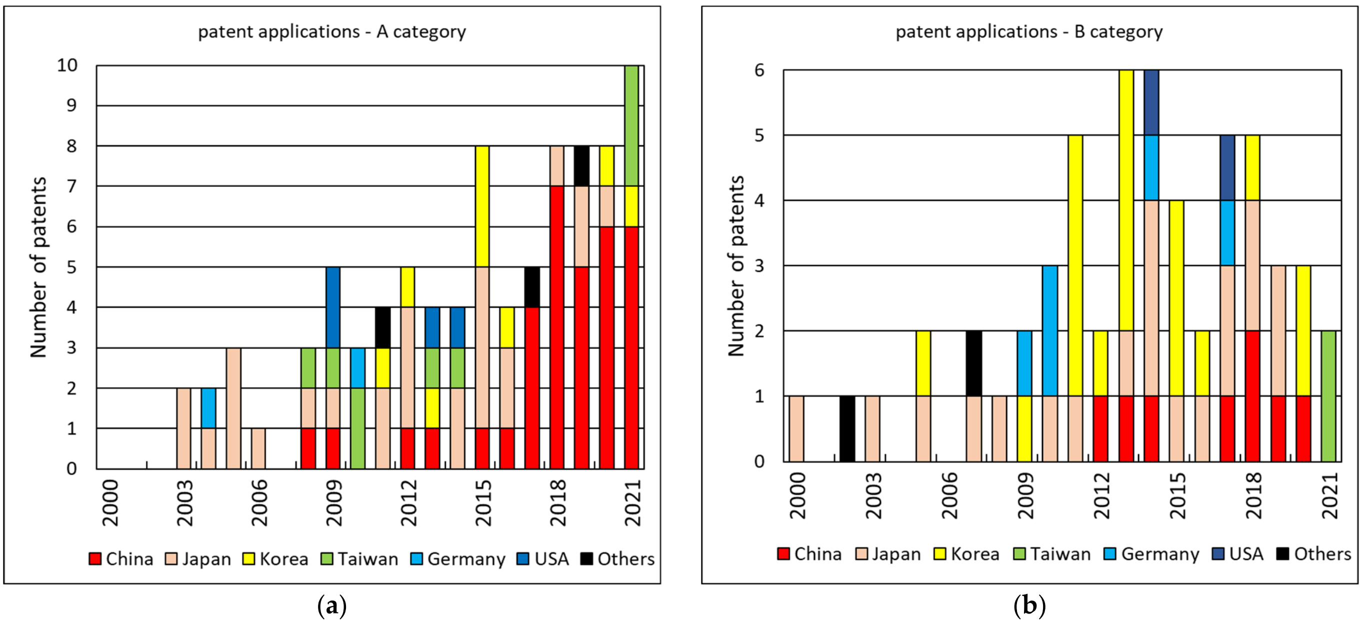


Figure 11. Patent application and distribution of the number of patents by country: (**a**) A category: (the A step of a patent application category): China–34, Japan–26, Korea–9, Taiwan–9, Germany–2, USA–4, others–3. (**b**) B category: (the B step of a patent application process meaning at least publication and preliminary approval): China–8, Japan–19, Korea–18, Taiwan–2, Germany–5, USA–2, others–2.

It can be observed that Asian countries in particular, such as China, Japan and Korea, are the front-runners in patent applications in the field of photovoltaic recycling. Especially in the last four years, China submitted most of the A category patents. Most patents (99%) come from manufacturers trying to incorporate some innovative recycling options into their processes and technologies.

The complete repair of PV modules is currently still the subject of research. Innovative recycling processes that make it possible to delaminate conventional PV modules layer by layer are being developed. In this way, it is possible to separate glass, plastic and solar cells in pure and intact forms. This not only increases the value of recycled modules , but could also expand the possibilities for remanufacturing. One of these innovative recycling processes is the subject of the ReProSolar project [55]. The process involves delamination by high-intensity light pulses and is currently being tested on an industrial scale.

The technologies that are more comparable to DSSCs in terms of low power and low production costs are thin-film PV modules. To date, however, there are no repair or remanufacturing processes, only recycling processes, for thin-film PV applications. Similarly, the lessons learned from recycling thin-film modules can be used to learn about future recycling processes for DSSCs. First Solar is a pioneer in high quality recycling processes for thin-film modules, especially cadmium telluride (CdTe) modules [8]. The concept also includes reverse logistics [56]. Since 2005, several generations of recycling equipment have been developed and continuously optimized. The third generation plant from 2015 can recover 90% of the glass and more than 90% of the semiconductor material. The materials are recovered with a high quality, so that they can be used for the production of new photovoltaic modules or glass production [57,58]. The process is based on a combination of mechanical comminution and wet chemical processing. The high-value recycling requires a high input of resources. However, this is essential in the case of CdTe modules, as otherwise toxic substances are released [57]. All in all, the process of First Solar is not suitable for repair and remanufacturing processes, due to mechanical shredding.

Another approach is an alternative design. In this context, the company Apollon Solar has developed an alternative encapsulation method. The NICE Technology uses neutral gas instead of the plastic encapsulation [59]. The alternative design allows easier high-quality recycling and is also very promising for remanufacturing processes.

4. Conclusions

In this publication, we were able to present solutions for the remanufacturing process for non-toxic DSSCs. The PCE was not negatively affected by the reuse of the FTO glass and TiO_2 layer. The TiO_2 could be recovered and can be reused. Remanufacturing seems to outperform just rehydrating the DSSCs and the long-term stability of DSSCs can also be improved. The state of the art in c-SI PV module remanufacturing is still at the research scale and needs further improvement. For the design of DSSCs, we can learn that not only long-term stability and high PCEs are important, but also a module design that supports repair, remanufacturing and recycling processes.

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