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Assessing the long-term stability of laser enhanced contact optimization (LECO) treated PERC cells in PV modules by extended indoor and outdoor durability tests

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Abstract. It was previously shown that the Laser Enhanced Contact Optimization (LECO) Process is a promising boost for PERC and TOPCon cell manufacturing enhancement. In this contribution, a method is developed to assess the long-term stability of industrial LECO treated PERC cells in a module compound. Therefore, extended accelerated aging tests as well as outdoor measurements were performed on modules comprising LECO treated cells as well as untreated references. It is described, how data can be evaluated to separate typical, known aging and degradation effects from presumable LECO specific effects. The results of this work show that test modules comprising LECO treated cells did not show a different behavior in the accelerated aging or degradation compared to the reference. The same conclusion was found for thermal cycling and damp heat tests, both far in excess of IEC requirements, as well as in a sequential test sequence. In addition, their outdoor performance with local and integral measurements has been evaluated. We can conclude that for the tested PERC cells, aging and degradation effects appeared, but none of them could be attributed to the LECO process. Hence, improvements in the efficiency and/or yield on cell level due to LECO can be translated to the module or even system level considering typical aging and degradation behavior, independently of a prior LECO process.

Keywords: Laser enhanced contact optimization / accelerated aging tests / outdoor tests / passivated emitter and rear cells / module stability

1 Introduction

Adding a production step into a cell line must enable an increase of efficiency or it must improve the overall process stability. Laser enhanced contact optimization (LECO) is a downstream production step for optimizing metal semiconductor-contacts on finished solar cells and provides both mentioned positive impacts at the same time. When analysing the LECO treatment in detail, it can be noticed, that next to increasing the efficiency potential, also the off-spec share of cells in a production line is minimized [1,2]. Furthermore, it can be found, that the highest benefits arise, if the cell process is adapted in a way, that Current-Fired-Contacts [3] are the dominant contacting mechanism [4]. The LECO process on PERC cells was introduced in 2019 [1] and its effectiveness on improving lower efficient cells was shown in 2020 [2]. In 2021 the first evaluation of the impact of LECO on the module output in industrial scale and on the module-reliability was presented [5] – where shorter-term effects have been analysed. In autumn 2022 also results of LECO on TOPCon cells have been shown [6].

For the first time, this contribution presents a larger amount of data that was collected through extended accelerated aging indoor tests and outdoors over the time of ~1 year to validate the LECO treated cell stability. We built 12 standard modules with LECO treated and non-treated solar cells from the same producer in three different efficiency classes and two other producers. The approach of this work is divided to:

– Reliability and durability:
  - extended thermal-cycling (TC) > 600 cycles,
  - damp-heat (DH) > 2000 h, and
  - a combined stress test sequence containing DH, aging under ultraviolet lamps (UV), TC and high frequency (HF).

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– Power and energy yield:
- Outdoor measurement at Fraunhofer CSP roof facility
- P_{mpp}-tracking with regular IV-curve sweeps.

2 Methodology

2.1 Samples

In the first step, the cell optimization process, in total, over 1000 solar cells from different manufacturers and with different initial quality (all standard process, standard pastes, but by manufacturer scrapped due to low power or optical properties) were treated by the LECO-process. Initial results have been shown in [5] and are reproduced in Figure 1, comparing the cells power before and after the LECO treatment. For the reliability study, modules have been manufactured where always 20 cells from each cell category, as defined in Figure 2, are interconnected in series. With the 20-cell approach, different types of solar cells mentioned can be studied simultaneously in a single module and easily compared. After manufacturing, all modules were characterized by a sun simulator to determine the module power.

2.2 Indoor tests

Various established standard tests (potential induced degradation (PID), TCT and DH) and a sequential test (DH200 + UV15 + TC50 + HF10 [7]) were performed to investigate the reliability. As shown in our previous publication [5] some of the cells show particular high susceptibility to boron-oxigen (BO) degradation, which leads to additional challenges in the analysis of the reliability tests. Good PID resistance was already demonstrated, with only 3% power loss after extended PID exposure (384 h 85 °C, 85%rh, 1.000 V) [5].

Module characterization was done using a class AAA solar simulator. The repeatability of the system is better than 0.3% for maximum power determination. Flash measurements were done at STC conditions and 200 W/m^2. Electroluminescence images were taken in a commercial EL system with a cooled CCD camera.

Climate chamber tests (TC, DH, HF) were carried out in appropriate chambers by applying the procedure defined in IEC 61215-2. The UV exposure was performed in a class CBB high intensity UV exposure system with metal halide lamps also according to IEC 61215-2.

2.3 Outdoor tests

After current induced degradation (CID) pre-conditioning one module of each group is mounted on the roof of Fraunhofer CSP for long-term outdoor exposure. The setup is shown in Figures 3a and 3b. Each of the strings is monitored individually and every 5 min an IV curve sweep is conducted. Between measurements the modules are kept at P_{mpp}-conditions. Besides the electrical data of the modules the string temperature is measured at a representative position on the module back side. Irradiation measured by a reference cell in module plane and a pyranometer. The ambient conditions (temperature, wind speed, wind direction) are recorded by a weather station.

Besides the online measurements the modules were taken of the roof after specific times for indoor characterization.

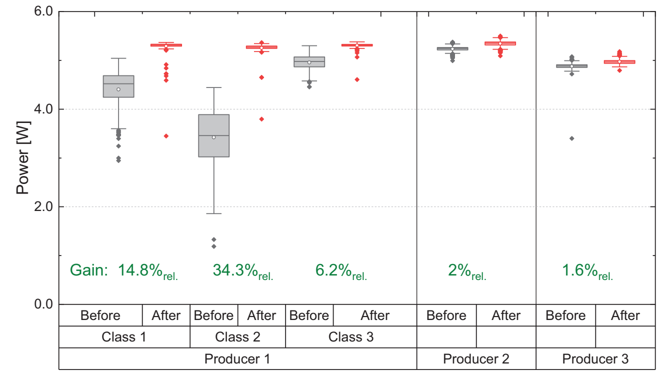

Fig. 1. Efficiency gains for the different used cell classes (taken from [5]).

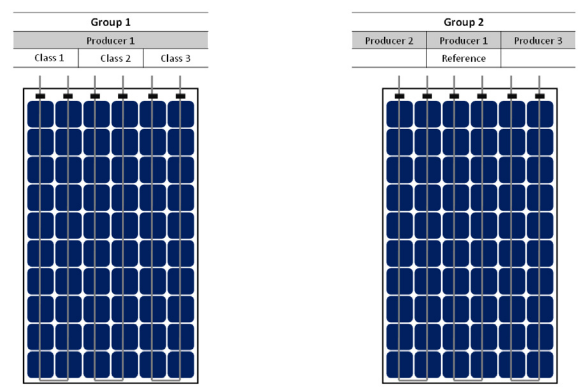

Fig. 2. Layout of the PV modules for the used LECO-Optimized solar cells (taken from [5]).

3 Results

3.1 Reliability and durability

Results of thermal cycling show a comparable stability of the LECO treated cells compared to the reference. Here we also see that the cells of producer 1, class 1, which were initially severely degraded in the BO test, show almost complete regeneration in the first 50 cycles due to the current injection. The degradation trend is very similar for all strings and lies between 1% and 2.5 % after the standard 200 cycles (see Fig. 4), which is in reasonable range. The extension to now 800 cycles (4× IEC) does not reveal any deviations between the investigated treated and untreated cells. The power degradation is at a good level of 4–6% with respect to the test duration.

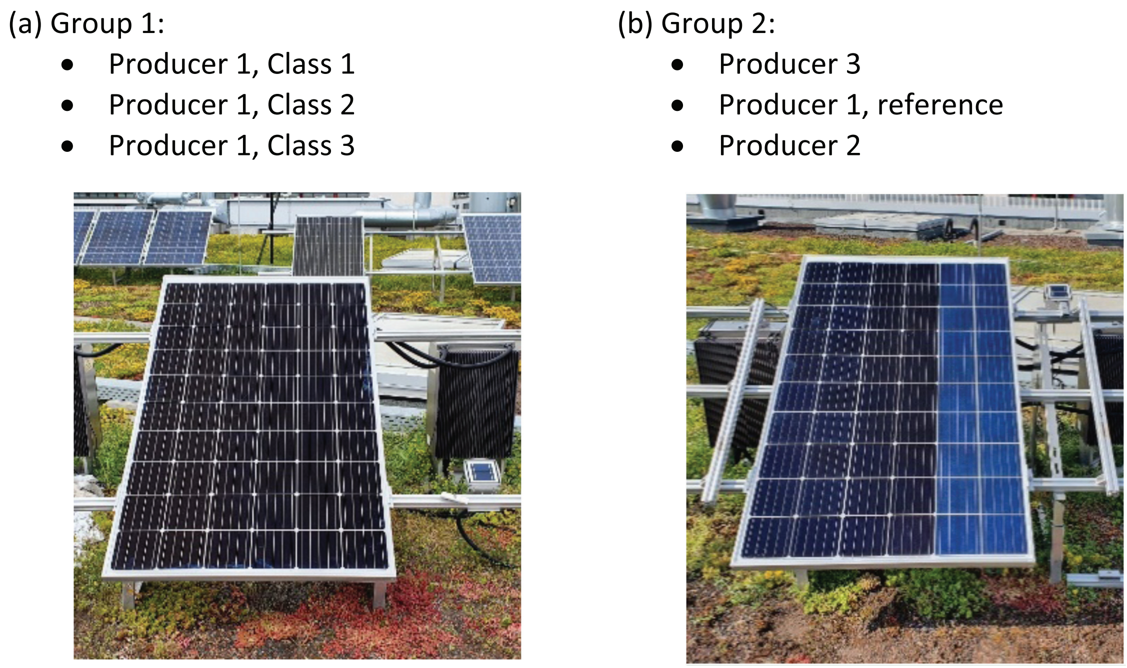

Fig. 3. Photo of outdoor test setup on Fraunhofer CSP rooftop: (a) group 1, (b) group 2.

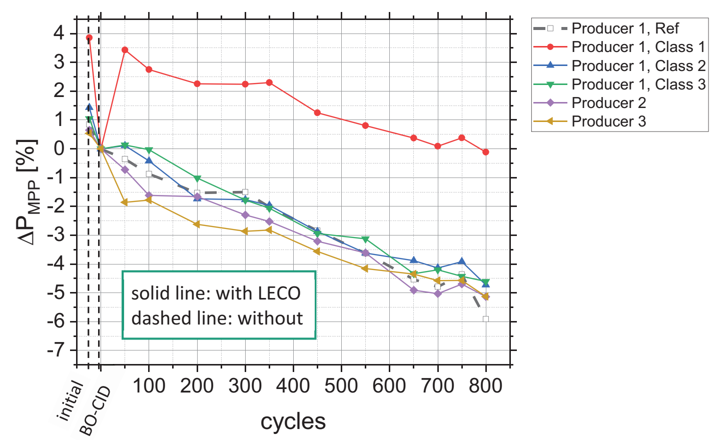

Fig. 4. Degradation of STC power of LECO modules in extended thermal cycling test; please note: the values before 0 are the initial measured data and at 0 are after BO-pre-treatment.

During the long-term DH, there is a reduction in performance between 3 and 4.5% after 1000 h, except for Producer 1, Class 2, which shows 6% power loss (see Fig. 5). However, as this sample shows a high initial degradation, it is likely that part of the degradation could be recovered by light soaking or recovery by dark current injection. After the 3000 h DH and a final recovery step, most samples are at a degradation level between 8 and 10%. Only Producer 1 Class 2 remains at more than 16% power loss. From the detailed IV curves (provided in the 'additional information' section), one can see that a recovery also takes place here, but there is an additional series resistance problem.

The EL images (see Fig. 6) show the normal damp heat degradation pattern ("bleeding" near the busbars) after 2300 h. The corrosion contributes to the reduction of the short-circuit current and to the reduction of the fill factor. For Producer 1 Class 2 there is an internal mismatch of the series-connected cells, which leads to an unfavorable operating point.

In the sequential test, a regeneration step (I_{SC} current injection at 80 °C for 48 h) was performed after the initial BO test (see Fig. 7). The fast regeneration of module power is an additional proof that it is most likely the BO-defect. In the following test the monocrystalline Producer 1 and 2 cells show almost the same behavior with a relatively large drop during the HF10 test. Producer 3 with multi-crystalline cells show a slightly different behavior. The regeneration step after the HF10 resulted in a significant recovery of the performance values for all samples.

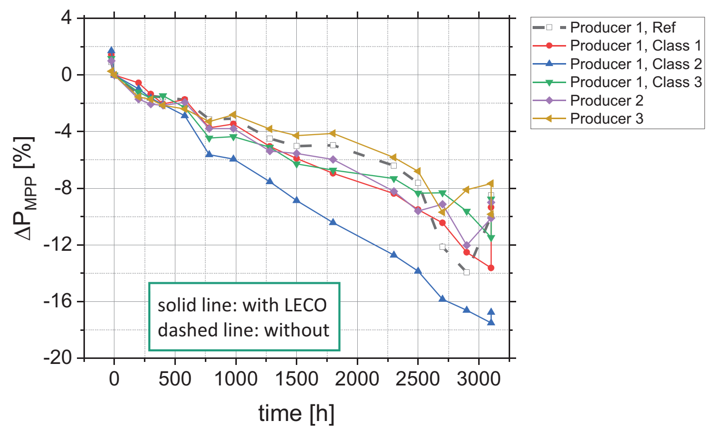

Fig. 5. Degradation of STC power of LECO modules in extended Damp heat test.

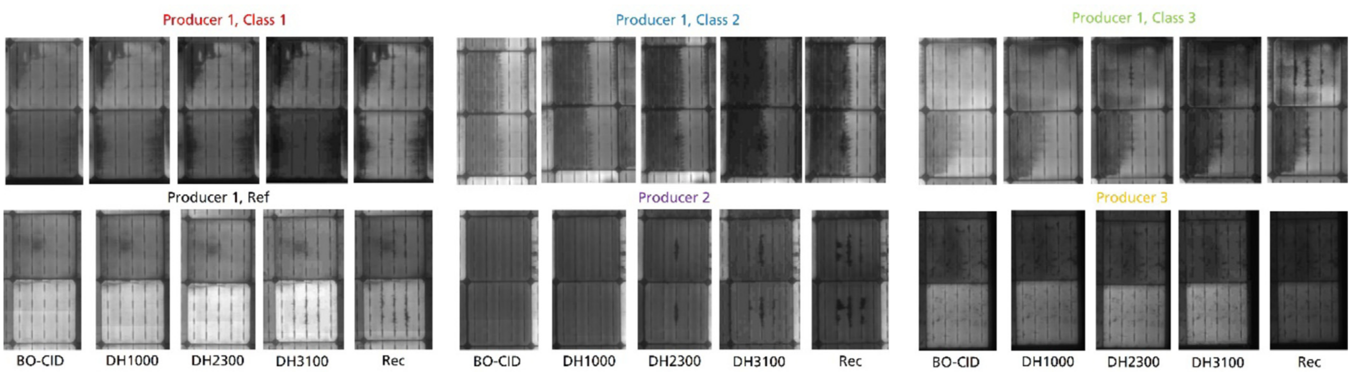

Fig. 6. Selected electroluminescence image sections from the extended damp heat test, $I = 10$ A, 1 s.

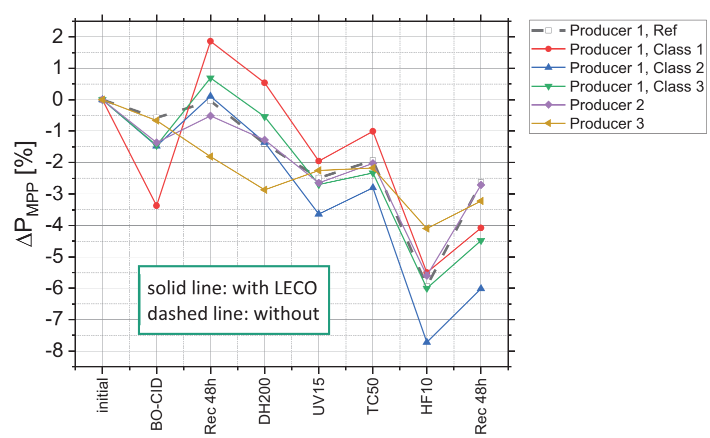

Fig. 7. Degradation of STC power of LECO modules in sequential test.

After recovery, most samples show a power loss between 2.5% and 4.5%, which is comparable to the results of other modules [7]. The IV curves (details provided in the 'additional information' section) show that the power reductions after the HF are caused by a reduction of the short-circuit current and the open-circuit voltage. These can be partially regenerated by the recovery step. Yet, there is a permanent I_{SC} loss or the time for regeneration is too short which indicates defects whose kinetics have longer time scales like Light-elevated Temperature Induced Degradation (LETID). Here the regeneration takes 3–4 weeks with a current injection level of I_{SC} at 85 °C [8]. The slope of the curves also shows an increased series resistance. From the EL images, it can be deduced that the defects are due to the material, as clear areal changes in brightness can be seen (see Fig. 8) which is consistent with the losses in I_{SC} and V_{OC}. Contact problems of the metallisation improved by the LECO process, on the other hand, are not visible.

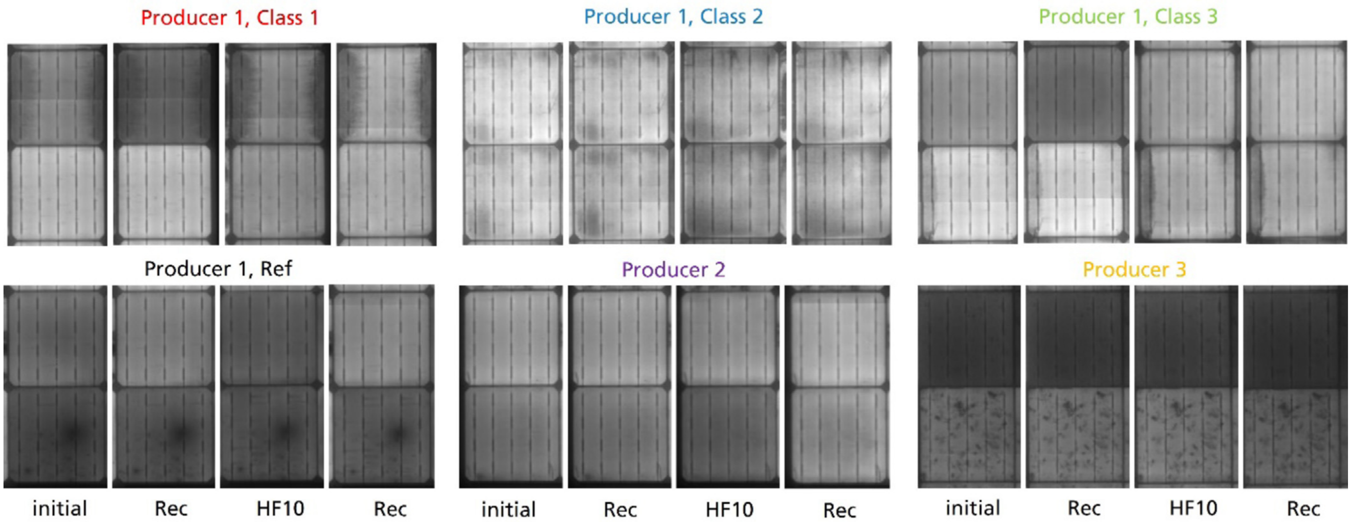

Fig. 8. Selected electroluminescence image sections from the sequential test, $I = 10$ A, 1 s.

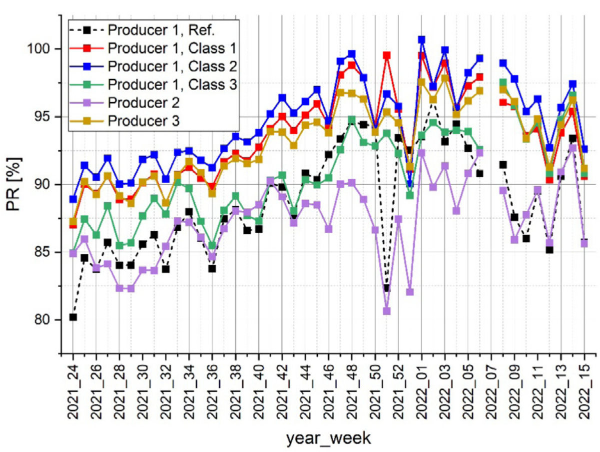

Fig. 9. Weekly performance ratio (PR) of the different strings per group for the period from week 24 of 2021 to week 15 of 2022; there are problems with data availability in calendar week 51 in 2021 (2021_51); for week 7 in 2022 (2022_07) there are no data shown due to deinstallation of the modules for indoor characterization.

3.2 Power and energy yield

The measurements were started in June 2021 and a period until April 2022 has been considered for evaluation.

3.2.1 Performance ratio (PR)

The performance ratio (PR) for the module strings was determined, see Figure 9. A closer look shows small deviations between the individual strings. Producer 1, Class 2 consistently shows the best PR. Followed by Producer 3 and Producer 1, Class 1, which had very similar values at the beginning of the measurements. In the lower half, there are Producer 1, Class 3, Producer 1, Reference, which get better over time, as well as Producer 2. This order suggests that modules with LECO processed cells achieve better performances than without LECO treatment. However, there are still module-specific changes in the weekly PR values, mainly between reference and Class 3 of Producer 1. Based on the findings of the changes in fill factor in the indoor studies, a more detailed analysis is made.

3.2.2 Fill factor (FF)

In order to better understand the changes in PR, the weekly mean FF was evaluated. Also here, calendar week 2021_51 and 2022_07 are again affected by data availability issues.

It can be seen in Figure 10 that the FF of Class 1 and 2 of Producer 1 behave equally over time. The remaining module strings have a lower FF. Furthermore, the reference becomes better from week 39 in 2021 compared to Class 3. From week 8 in 2022, the picture turns, as Class 3 jumps to the level of Class 1 and 2.

Based on these results, it can be concluded that for high irradiances, the FF for LECO treated modules remains stable over time. A look at the other electrical parameters shows, that the lower FF for Class 3 resulted from a reduced power (P_{mpp}), caused from a reduced V_{mpp} and I_{mpp}. On the other side, V_{OC} and I_{SC} for Class 3 are unchanged, see Figure E in the 'additional information' section. The sudden increase for Class 3 beginning in week 8 of 2022 (i.e. an increase in V_{mpp} and I_{mpp}) is still subject of current research.

3.2.3 Indoor characterization

Two indoor measurements were done after approximately 0.7 years and 1 year. The indoor power measurements show a significant loss in open circuit voltage (2–2.3%) and short circuit current (~1%) for Producer 1, Class 1, 2 and 3, resulting in power changes of 3.3–3.9%. Producer 1, Ref, Producer 2 and 3 also show a change in short circuit current but the open circuit voltage remains stable. The power change here is lower (~1%). Comparable to the indoor tests,

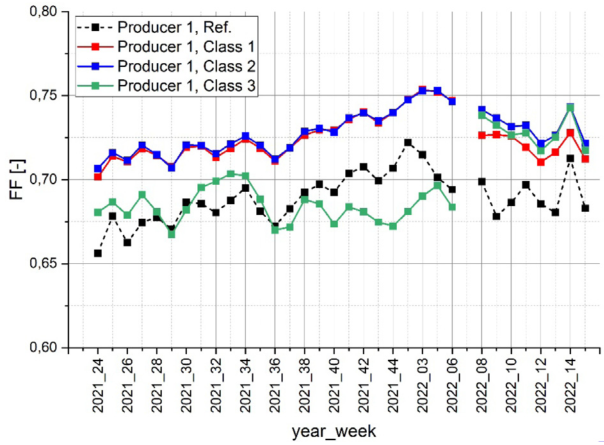

Fig. 10. Weekly mean fill factor (FF) per string group for high irradiance classes (800–1000 W/m^2); for week 7 in 2022 (2022_07) there are no data shown due to deinstallation of the modules for indoor characterization.

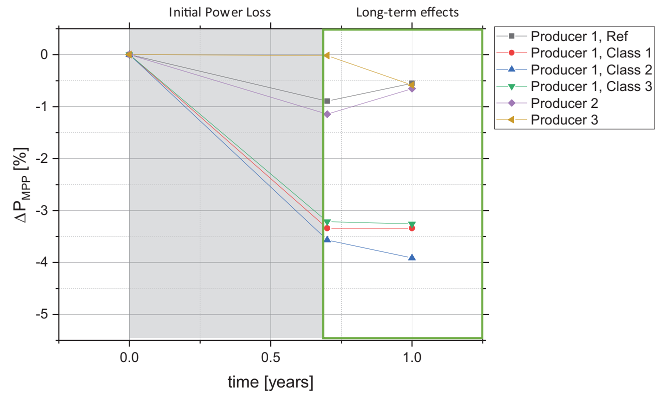

Fig. 11. PMPP changes derived from Interim IV-curves at STC of LECO modules.

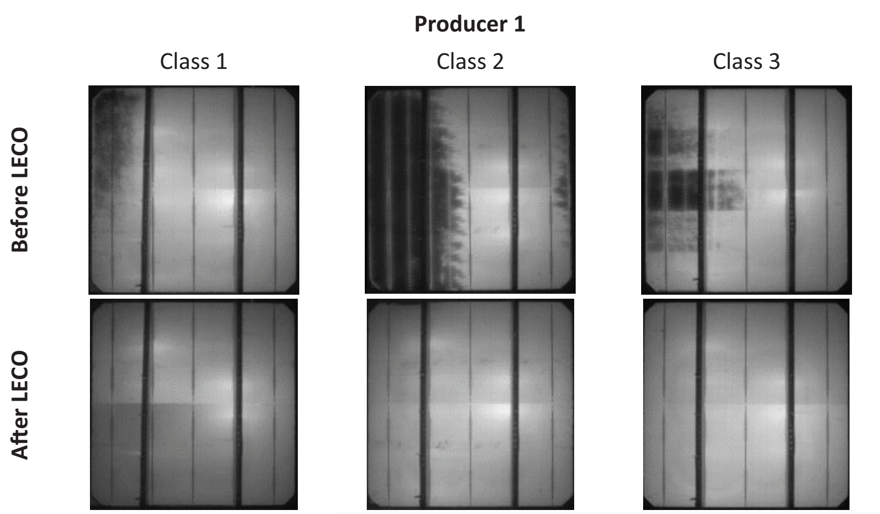

Fig. 12. Electroluminescence image of one representative solar cell of Class 1, Class 2 and Class 3 from Producer 1 before and after LECO treatment (from [5]).

changes in luminescence were also detected, which are in line with the changes in V_{OC} and I_{SC}. The power trend shows that power loss already existed in the first interim measurements.

In respect to outdoor at high irradiance, the indoor STC measurements show a different effect (see Fig. 11). While in outdoor data Producer 1, Class 1 and 2 are stable and only Class 3 shows slight changes (caused by I_{mpp} and V_{mpp}), there are no significant changes for all modules in I_{SC} and V_{OC} in the outdoor data visible. However, since indoor measurements are done under stable and reproducible conditions, small changes can be better measured. In contrast, outdoor measurement data have a higher uncertainty of measurement and depend on constantly changing environmental conditions, such that only the long-term stability under real conditions can be evaluated.

4 Discussion

With the presented analysis, the key question of whether the LECO treatment has an impact on the long-term stability of PV modules was addressed. The used modules showed several effects, especially due to a poor cell quality, but none of them could be attributed to LECO.

In an earlier publication, electroluminescence images of the cells of Producer 1, Classes 1-3 have been shown before vs. after the LECO treatment [5] (see Fig. 12).

So, it can be proposed: if LECO contacts [3] were not stable – the cells after LECO and after the extensive accelerated tests, would appear similarly to the cells before the treatment. During the analysis of the EL images after all accelerated tests, no such structures could be observed.

We can conclude: for the tested PERC cells, improvements in the efficiency and/or yield on cell level due to

LECO can be translated to the module or even system level considering typical aging and degradation behavior, independently of a prior LECO treatment.

4.1 LECO finish

Considering a yield improvement as it is shown in this application case for LECO, where off-spec cells are optimized and can be further used for module manufacturing rather than being scrapped and put into energy intense recycling processes, the highest benefit arises for the cell manufacturer. Nevertheless, the benefit relies heavily on the individual situation of the cell line and output properties and may be very different for different cell manufacturers.

Assuming an off-spec share of around 1% abs. and as rough estimation a share of 10%–50% of these cells are suitable for LECO optimization, the number of in-spec cells can be significantly improved (assuming a throughput of 3600 cells/h/line) approximately up to +18 pcs/h/line. Those cells could not have been used in a PV module without the LECO treatment.

4.2 LECO concept

Several publications showed, that an efficiency increase for PERC and TOPCon cells of 0.17–0.6% abs. [1,2,4,6] can be realized by using LECO on an adapted solar cell. The presented results of this work show: the long-term stability is not influenced by the treatment. Combining both observations, the real benefit for an end-customer can be presumed: considering an efficiency increase potential of +0.6% (abs. for TOPCon – [6]) which is a 2.5% relative gain, a typical private home PV installation of 10 kWp would improve to 10.25 kWp. For typical value of 1.000 kWh/kWp an extra energy of 250 kWh/year can be generated – which can for example be used to power one standard refrigerator for the entire year.

Meanwhile, inline equipment to integrate the LECO treatment in newest high-throughput cell manufacturing lines is commercially available.

5 Summary

In this work, a method for assessing the long-term stability of LECO treated cells in a module compound was developed and applied. In a string-wise arrangement, the modules have been built comprising different groups of LECO treated cells and untreated reference cells. Using these modules, accelerated ageing tests far in excess of IEC requirements have been carried out. The Temperature Cycling test showed no major differences between LECO-treated and the reference cells. Also, long-term DH and a sequence testing showed no changes due to LECO. Nevertheless, significant changes in performance could be observed in the DH as well as the Sequential test. The root cause was found to be changes in the open circuit voltage and in the short circuit current which are attributed to the cell material. It is already described in the literature that a stabilized BO defect in Cz-PERC modules can be destabilized during a DH test [9]. It is concluded that part of the high-power losses are an artifact due to the BO defect. It was demonstrated that there was significant regeneration achieved by a recovery step. Additionally, long-term outdoor exposure tests have been performed. In total, LECO processed modules (here, Producer 1 Class 1 and Class 2) showed the best performance with respect to the reference. In contrast to the indoor measurements, no changes in I_{SC} and V_{OC} could be detected in the outdoor data. However, one LECO treated class (here class 3) showed a slight decrease of the FF, which was found to be caused by I_{mpp} and V_{mpp} decreases.

In the end it can be concluded: LECO treated PERC cells show no significant difference in the long-term behaviour under accelerated aging or real environmental conditions that can be attributed to LECO. Therefore, yield and efficiency improvements on cell level, as have been reported in previous publications, can be directly translated into module or system benefits. Finally, a yield calculation has been carried out, resulting in an additional energy production increase of 2.5% relative enabled by adding the LECO process into the cell production routine.

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Author contribution statement

Experiments were conducted by E. Krassowski, M. Pander, D. Daßler. Data analysis, processing and visualization was done by E. Krassowski, M. Pander, D. Daßler, S. Malik. The supervision of the project was ensured by B. Jäckel. The original draft was written by E. Krassowski and further writing, proof reading and discussion of the results was done by all authors.

Supplementary material

Figures A, B: Additional information to Section 3.1
Figures C–F: Additional information to Section 3.2

The Supplementary Material is available at https://www.epjpv.org/10.1051/epjpv/2023004/olm.

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