

Reversing LeTID in PV power plants: a feasibility study

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Received: 28 June 2024 / Accepted: 28 November 2024

Abstract. Light and elevated Temperature Induced Degradation (LeTID) is likely causing strong yield losses in a significant number of photovoltaic (PV) power plants which were commissioned in the late 2010s. In this work, a procedure for an in-field recovery using overnight current injection to trigger temporary recovery of LeTID is presented. The general feasibility of such a procedure is first demonstrated by climatic chamber experiments on strongly degraded mc-Si PERC PV modules. Within the screened test conditions, a temporary recovery procedure with high currents and low module temperatures is most promising for an economic application in PV power plants. An outdoor experiment with current injection during nights and MPP tracking during days confirmed the possibility to recover LeTID in PV power plants. By injecting a pulsed current, the heating of the modules caused by the current injection was strongly reduced compared to the heating at constant current injection. Recommendations for the application of a procedure in PV power plants are given based on the required energy expenditure and cost.

Keywords: LeTID / recovery / power plant / degradation / monitoring / outdoor characterization

1 Introduction

Light and elevated Temperature Induced Degradation (LeTID) was discovered in 2012, when light soaking at elevated temperature resulted in unexpectedly high efficiency losses for multicrystalline silicon (mc-Si) passivated emitter and rear cells (PERC) [1]. LeTID is a carrier-induced degradation mechanism that can cause efficiency losses due to defect formation in the bulk. In addition to mc-Si PERC, various other cell technologies have been observed to exhibit LeTID, including Czochralski-based silicon (Cz-Si), float-zone silicon (Fz-Si) [2], aluminum back-surface field (Al-BSF) [1], or n-type Cz-Si solar cells [3]. In addition to boron-doped silicon [4], gallium-doped material can also be affected [1,5,6].

Experimental studies have demonstrated that efficiency losses due to LeTID can reach more than 10% in laboratory conditions [7–9]. Furthermore, results from PV power plants [10,11] and outdoor experiments [12,13] have indicated that similar efficiency losses are likely to occur in the field under adverse climatic conditions.

A decade of extensive research has led to a better understanding of the factors influencing LeTID [14–16] and the optimization of the fabrication processes by solar cell manufacturers, resulting in significantly less LeTID-sensitive PV modules on the market. In addition, the development of module quality tests and, in particular, the publication of IEC TS 63342 [17], have significantly reduced the risk for investors to purchase PV modules with high LeTID susceptibility.

While the risk of yield losses due to LeTID is greatly reduced for recently installed PV power plants, significant yield losses are possible for power plants that were commissioned in the late 2010s. Considering the test results on PERC PV modules published in 2018 and 2019 [8,9] and the global market share of PERC-like structures, which exceeded 20% in 2017 [18] and 65% in 2018 [19], a large number of PV modules installed during this period were likely susceptible to LeTID.

Yield losses due to LeTID are strongly dependent on the local climatic conditions and especially on the module temperature [13,20]. The formation of LeTID defects (“degradation”) is accelerated by the cell temperature and the number of excess minority charge carriers Δn (also referred to as the “injection level”). Therefore, degradation

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Table 1. Overview of the modules and experimental conditions in the indoor experiment and the outdoor experiment. The initial power deviation of all modules is given as a relative deviation from the nominal power. The injected current was defined relative to the nominal I_{SC} (deviation between the two power classes $< 1\%$).

Module designation	Experiment	Nominal power	History	Initial power deviation	Temperature (Indoor experiment)	Injected current
Ind_1_10C_1.0xIsc	Indoor	340 W	Power Plant	-8.4%	10 (+2.6/-3.8) °C	I_{SC} , pulsed
Ind_2_11C_1.25xIsc	Indoor	340 W	Power Plant	-8.5%	11 (+1.5/-4) °C	1.25 x I_{SC} , pulsed
Ind_3_22C_0.5xIsc	Indoor	340 W	Power Plant	-9.1%	22 (+/-2.5) °C	0.5 x I_{SC} , pulsed
Ind_4_23C_0.5xIsc	Indoor	335 W	LeTID Test	-6.4%	23 (+/-3) °C	0.5 x I_{SC} , pulsed
Ind_5_21C_0.75xIsc	Indoor	340 W	Power Plant	-9.1%	21 (+1.5/-2.5) °C	0.75 x I_{SC} , pulsed
Ind_6_21C_1.0xIsc	Indoor	340 W	Power Plant	-9.4%	21 (+5.5/-3.5) °C	I_{SC} , pulsed
Ind_7_21C_1.0xIsc	Indoor	335 W	LeTID Test	-9.8%	21 (+/-3) °C	I_{SC} , pulsed
Ind_8_23C_1.0xIsc	Indoor	340 W	Power Plant	-8.0%	23 (+4/-6.5) °C	I_{SC} , constant
Ind_9_20C_1.25xIsc	Indoor	340 W	Power Plant	-9.4%	20 (+3/-2.5) °C	1.25 x I_{SC} , pulsed
Ind_10_40C_1.0xIsc	Indoor	340 W	Power Plant	-8.5%	40 (+1.5/-4.5) °C	I_{SC} , pulsed
Outd_1_Ref	Outdoor	340 W	Power Plant	-7.7%	-	-
Outd_2_Ref	Outdoor	340 W	Power Plant	-8.4%	-	-
Outd_3_1.0xIsc_p	Outdoor	340 W	Power Plant	-9.5%	-	I_{SC} , pulsed
Outd_4_1.25xIsc_p	Outdoor	340 W	Power Plant	-10.0%	-	1.25 I_{SC} , pulsed
Outd_5_1.0xIsc_c	Outdoor	335 W	Power Plant	-8.3%	-	I_{SC} , constant
Outd_6_1.25xIsc_c	Outdoor	335 W	Power Plant	-8.4%	-	1.25 I_{SC} , constant

is mainly observed under irradiation or forward bias at elevated temperature. After a certain period of time, an increase in module efficiency can typically be observed under the same conditions that previously caused degradation. This increase in efficiency is caused by “regeneration”, a concurrent reaction that is accelerated by the same influencing factors as the degradation reaction, but at lower reaction rates under typical operating conditions. Compared to other carrier-induced degradation mechanisms, such as Boron-Oxygen Light Induced Degradation (BO-LID), LeTID and its regeneration evolve under comparatively long time scales: Under typical operating conditions, it can take years to reach the maximum power loss due to LeTID [10,13,20] and decades to complete the regeneration process [20].

A third reaction known to influence the evolution of LeTID in the field is called “temporary recovery” [21]. Temporary recovery is the reverse reaction of LeTID and is typically observed at temperatures below the typical degradation temperatures (e.g. 25 °C [12,21]). Under realistic operating conditions, temporary recovery can increase the efficiency during cold seasons, reducing overall degradation in countries with temperate climates such as Germany. Compared to the other known LeTID state transitions, temporary recovery is the least investigated LeTID reaction with currently only one known kinetic study [21]. The reaction rate of temporary recovery is highly dependent on the injection level, which has an approximately exponential dependence on the voltage [22] under forward bias or irradiance, leading to a roughly linear

dependence on the current under forward bias [23]. At 25 °C and forward bias, with an injected current in the range of the short-circuit current I_{SC} of a module, full temporary recovery can be achieved within days [12,13,24,25].

In this study, we explore the possibility of recovering LeTID in PV power plants by overnight current injection. In a climatic chamber experiment, we have investigated the influence of the module temperature and the current level on the energy required to achieve significant temporary recovery. The results from climatic chamber experiments were utilized to identify promising parameters for the current injection. An outdoor experiment with daily MPP tracking and nightly current injection demonstrated the feasibility of recovering LeTID under realistic environmental conditions. In light of the experimental findings, theoretical considerations on the economic efficiency are discussed and recommendations for the application of a LeTID recovery procedure in PV power plants are given.

2 Materials and methods

2.1 PV modules used in the experiments

The experiments were conducted on 16 commercial multi-crystalline silicon (mc-Si) PERC PV modules from the same manufacturer and product line, but from two different power classes (see Tab. 1).

Two of the PV modules (Ind_4 and Ind_7) were characterized and subjected to a potential-induced degradation (PID) test at TestLab PV Modules, Fraunhofer ISE,

as part of module quality testing in 2018. The test resulted in a minor power loss of 0.4% to 0.6%. After completion of the PID test, the modules were subjected to a long-term LeTID experiment at 75 °C and I_{SC} - I_{MPP} (see [8]) for at least 1134 h (Ind_4). The LeTID experiment resulted in a power loss of up to 9.3% and a deviation to the label value of 9.8% (Ind_7, after 1782 h of LeTID testing). The results of the first 808 h of LeTID testing were included into a previous publication [8] (type “Multi-PERC G”). The long timescales for degradation of Ind_4 and Ind_7 are in agreement with other studies on LeTID (e.g. [7,26]).

The other PV modules were installed in a power plant in Southern Spain in 2018 and operated for four years, including an open-circuit period of several months before the power plant was commissioned. After the aforementioned period of operation, a significant degradation in the performance of the PV power plant was observed and 14 PV modules of the power plant were characterized at CalLab PV Modules, Fraunhofer ISE, where negative deviations from the nominal (label) power of up to 10% were measured. Subsequently, the modules were subjected to the experiments as shown in Table 1.

Since no initial (before outdoor exposure) I - V curve measurements were available for the modules from the power plant, the initial power deviations from the nominal power are given in Table 1 for all modules in the experiment as an indicator of the possible degradation caused by LeTID. It should be noted that slight deviations from the nameplate values are common, even for unaged PV modules [27–29].

2.2 Indoor experiment: LeTID recovery under controlled conditions

In an indoor experiment, the modules Ind_1 to Ind_10 were tested under controlled conditions in a climatic chamber (see Tab. 1). The purpose of the experiment was (a) to demonstrate the general feasibility of temporarily recovering heavily degraded PV modules from LeTID by current injection and (b) to investigate the effect of different experimental conditions on the recovery speed and amount of energy required. During the experiment, a current between $0.5 \times I_{SC}$ and $1.25 \times I_{SC}$ was injected into each module, where I_{SC} was defined by the nameplate short-circuit current of each individual module (two different power classes). With the exception of module Ind_8, all modules were tested with a pulsed current, where one minute of current injection was followed by two or three minutes without current injection (2 min for tests at lower current). The pulsed current was chosen to reduce the heating caused by the current injection and thus reduce the temperature difference between the cooling air in the climatic chamber and the module. The climate chamber was controlled to maintain the temperatures shown in Table 1.

The progress of the temporary recovery of LeTID was tracked through regular interim characterization: I - V curve measurements under standard test conditions (STC) were taken at CalLab PV Modules with an overall

measurement uncertainty of 1.8% and a long-term reproducibility of less than $\pm 0.5\%$. Electroluminescence (EL) images were taken at a current of $0.1 \times I_{SC}$ and $1.0 \times I_{SC}$, respectively.

The cumulative energy applied prior to each interim measurement was calculated based on the current and voltage readings of the power source utilized for the current injection.

2.3 Outdoor experiment: LeTID recovery under realistic conditions

Modules Outd_1 to Outd_6 (see Tab. 1) were studied under realistic outdoor conditions in the Fraunhofer ISE Outdoor Performance Lab. The purpose of the experiment was (a) to demonstrate the general feasibility of temporary recovery of LeTID in PV power plants by overnight current injection and (b) to investigate the influence of the selected current injection conditions on the module temperature during injection and on the effectiveness of the temporary recovery of LeTID.

The experiment was conducted from August 31, 2023, to September 25, 2023 on a rooftop at Fraunhofer ISE in Freiburg, Germany. The modules were mounted on an open rack system. During the day, all modules were operated in their individual maximum power point (MPP) by electronic loads. During the nights, four different current injection conditions were applied to the modules Outd_3 to Outd_6 as specified in Table 1 (constant or pulsed injection of $1.0 \times I_{SC}$ or $1.25 \times I_{SC}$). When pulsed current injection was used, 1 min of current injection was followed by 3 min without current injection. In order to compare the effectiveness of the different injection conditions, the cumulative energy applied to each module during the experimental period was limited to approximately 22 kWh and each module was aimed to receive the same energy dose per night. During most of the nights, approximately 1 kWh were applied to each module with injection intervals starting at 9 pm (pulsed current) or at 2 am (constant current). During the first night of current injection (starting August 31, 2023), a higher energy dose (3.7 kWh for Outd_5 and 4.7 kWh for Outd_6) was inadvertently applied to the modules subjected to constant current injection. The current injection for these modules was therefore paused during the subsequent three (Outd_5) and four (Outd_6) following nights to achieve a similar energy dose for all PV modules during the rest of the experiment. The modules subjected to pulsed current received approximately 1 kWh per night during the whole experiment. The actual amount of energy applied to the modules was 22.5 kWh (Outd_3), 22.3 kWh (Outd_4), 21.7 kWh (Outd_5) and 21.1 kWh (Outd_6). Modules Outd_1 and Outd_2 were used as reference modules in the experiments and did not receive any external current.

While outdoors, the modules were connected to a monitoring system: during daytime a full I - V curve was measured every 5 min; MPP tracking data was logged in-between. During nighttime, current and voltage were monitored. Module temperature (one Pt100 sensor

attached to the rear side of each module behind a centrally located cell), in-plane irradiance and other ambient conditions were monitored alongside day and night.

Before and after the experiment, the modules were characterized by means of I - V curve measurements at STC and EL measurements (see Sect. 2.2).

Due to the multitude of different ambient conditions and influencing factors, data validation and filtering is an integral part of outdoor data analysis. For the given case, a minimum filter set was used comprising mainly irradiance fluctuation during measurements ($<1\%$) and the exclusion of irradiance conditions below 200 W/m^2 due to higher non-linear effects.

The subsequent time-series analysis of the filtered outdoor data was done comparatively. In a first step, the extracted characteristic points of the IV curve were normalized to their initial STC values. This excludes previously existing differences like power class and module history and hence creates a normalized starting point from which to follow the process of improvement. These values were then compared to (divided by) the same values of the reference modules, then aggregated to daily averages (arithmetic mean) and their development was analyzed over time. As the reference modules remained approximately stable (which was confirmed by the indoor STC measurements), these were used as a baseline. The following equation illustrates the calculation of the normalized power at MPP as an example for the normalization of I - V curve parameters:

$$P_{\text{MPP,normalized}} = \frac{\frac{P_{\text{MPP,Outd}}}{P_{\text{MPP,STC}}}}{\frac{P_{\text{MPP,Ref,Outd}}}{P_{\text{MPP,Ref,STC}}}}. \quad (1)$$

The temperature rise of a module due to current injection was estimated by the temperature difference to average the temperature of the reference modules at the time of each measurement:

$$\Delta T_{\text{Module}}(t) = T_{\text{Module}}(t) - \frac{T_{\text{Outd}_1\text{Ref}}(t) + T_{\text{Outd}_2\text{Ref}}(t)}{2}. \quad (2)$$

3 Results and discussion

3.1 Temporary recovery of LeTID under controlled conditions (indoor experiment)

In the climatic chamber experiment, temporary recovery of LeTID was observed under all applied conditions. Figure 1 depicts the relative deviations of the I - V parameters from the interim measurements: P_{MPP} , V_{OC} , I_{SC} and FF to the nameplate values of each module are given as a function of cumulative energy.

For five of the tested modules, the experiment was conducted until a power deviation of 2% or less was reached (see Fig. 1a). For three of the aforementioned modules (Ind_1, Ind_2 and Ind_9), it is likely that saturation was reached during the experiment. The remaining deviations of the I - V parameters of these modules from the nameplate

values are most likely not caused by LeTID, but rather by other degradation mechanisms due to the previous outdoor exposition, and possible nameplate deviations of the modules after production.

A comparison of the changes in ΔP_{MPP} for modules tested at similar temperatures (e.g. Ind_3 to Ind_9, tested at temperatures between 20°C and 23°C) revealed a clear trend towards a more energy-efficient procedure at higher current. Consequently, current values below the I_{SC} were excluded from the test conditions in the outdoor experiment. A reduction in the module temperature to values around 10°C resulted in a further reduction in the energy required for current injection: Module Ind_2, which was tested at 11°C and $1.25 \times I_{\text{SC}}$, showed saturation after a cumulative energy of 5.5 kWh, which corresponds to a time of 9.3 h. Comparable conditions are therefore relevant for an economic on-field recovery procedure (as discussed in Sect. 3.3). Even at 40°C , a notable degree of temporary recovery was achieved, albeit at a significantly higher energy expense compared to the temporary recovery at lower temperatures. Consequently, temporary recovery at 40°C would be technically feasible, although it is unlikely to be economically viable. These results indicate that – within the temperature and current range investigated in this study – a combination of low temperature and high current is favorable for an on-site LeTID recovery procedure.

Before discussing the changes in the other I - V curve parameters (V_{OC} , I_{SC} and FF), the impact of LeTID and temporary recovery of LeTID on the cells of each module is briefly discussed based on the EL images obtained as interim measurements (Fig. 2). Before the experiment, module Ind_6 exhibited a checkerboard pattern characteristic of LeTID [7,9,30], indicating significant differences in the efficiency loss of the individual cells. As the subsequent EL images demonstrate, not only the extent of efficiency loss, but also the time needed for full temporary recovery varies strongly between cells in the same module. More strongly degraded cells tend to recover more slowly, which can likely be explained by a lower injection level due to the reduced efficiency and a higher number of degraded defects that need to be recovered. This finding is important for the effectiveness of a recovery procedure in different PV power plants: the energy required for the temporary recovery of a PV module is not solely dependent on the recovery conditions, but also on the state of the modules subjected to the procedure.

The discrepancies between cells (i.e. mismatch) are relevant for the interpretation of the changes in the I - V curve parameters. In a PV module with series-connected cells, improvements in V_{OC} of each cell contribute to the overall module V_{OC} . The changes in ΔV_{OC} shown in Figure 1 can thus be seen as average changes in the open-circuit voltages of individual cells. In contrast, the I_{SC} of each cell string, which consists of 24 cells protected by the same bypass diode, is limited by the cell with the lowest I_{SC} . For some modules, one cell string was almost recovered relatively quickly, resulting in a rapid saturation of ΔI_{SC} , while the open-circuit voltage continued to rise. The FF changes are even more significantly influenced by mismatch: In most modules, the initial stages of the temporary

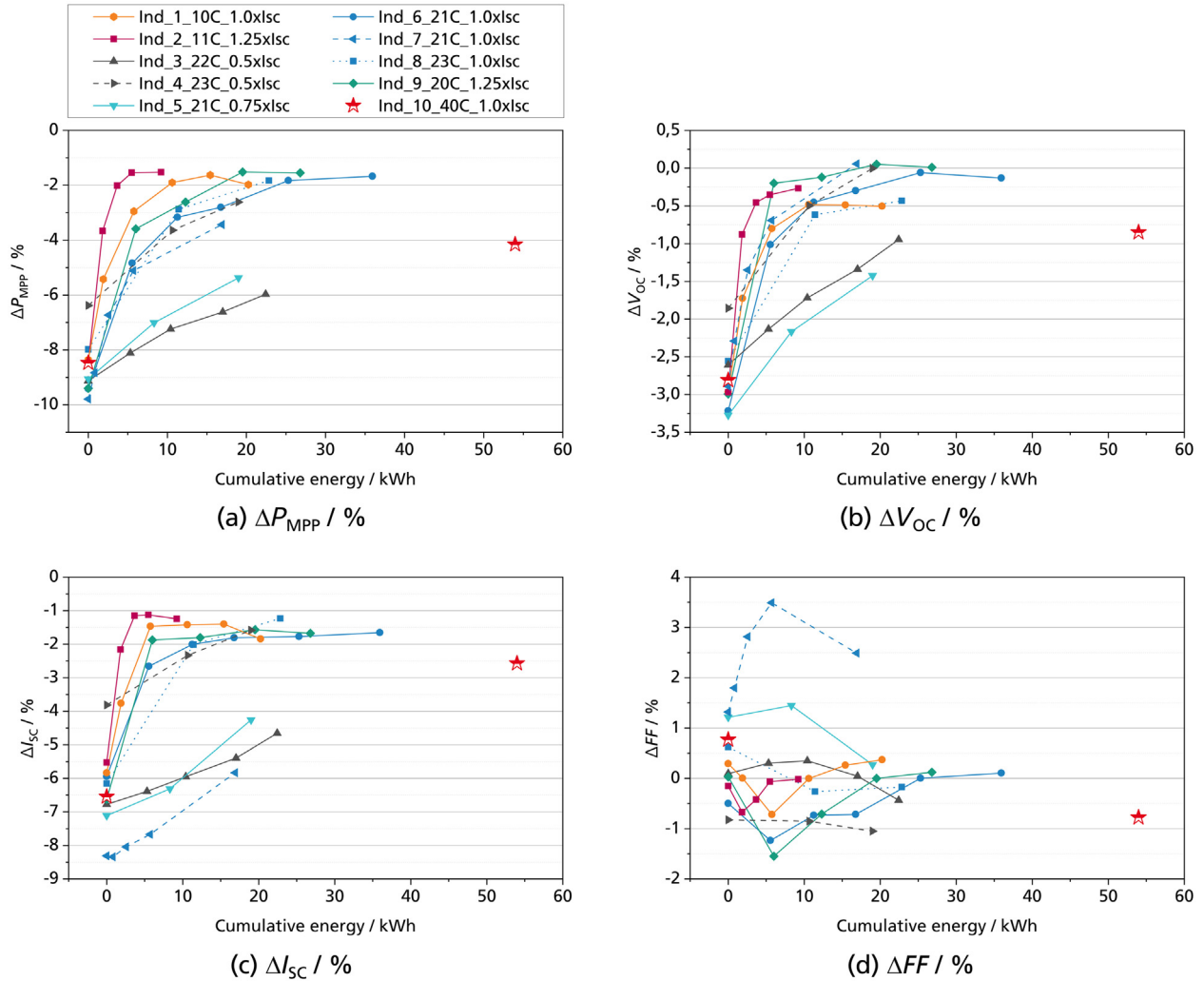


Fig. 1. Relative deviations of the I - V curve parameters at STC over the cumulative energy applied by current injection under different test conditions in the indoor experiment. (a) Relative deviation of P_{MPP} ; (b) relative deviation of V_{OC} ; (c) relative deviation of I_{SC} ; (d) relative deviation of FF .

recovery experiment resulted in a reduction in FF while the I_{SC} increased notably. This can be explained by the temporary recovery of single cell-strings within the PV module, which enhances the module I_{SC} . However, the current within one or two cell strings remains constrained by a few number of severely degraded cells, limiting the module's I_{MPP} . Modules Ind_4, Ind_5 and Ind_7 show a contrary behavior: they show an initial increase in FF , followed by a subsequent decrease. Their I_{SC} , on the other hand, increases more slowly compared to the other modules. This disparate behavior is linked to the distribution of severely degraded cells within the modules, resulting in a prolonged limitation of current in all cell strings relative to the other tested modules. It can be concluded that the distribution of cells exhibiting disparate LeTID behavior within a module has an influence on the module's temporary recovery behavior. This finding is pertinent to the interpretation of the results of the outdoor experiment.

3.2 Temporary recovery of LeTID under realistic outdoor conditions

3.2.1 Injection conditions and module temperature

The current injection conditions and their effect on the module temperature are demonstrated in Figure 3 for the night from September 8 to September 9, 2023 in the outdoor experiment. In order to achieve a cumulated energy of 1 kWh for each module, the pulsed current injection was started at 9 pm, while for the constant current injection, a time interval starting from 2 am was selected. In the case of the Outd_4 module, the desired set current of $1.25 \times I_{SC}$ was not achieved for the majority of the experiment due to a technical issue. In contrast, the injected current exhibited fluctuations between $1.0 \times I_{SC}$ and $1.25 \times I_{SC}$. Figure 3b illustrates the temperature increase of each module in comparison to the temperature of the two reference modules (mean value of the two modules), which were not subjected to current injection.

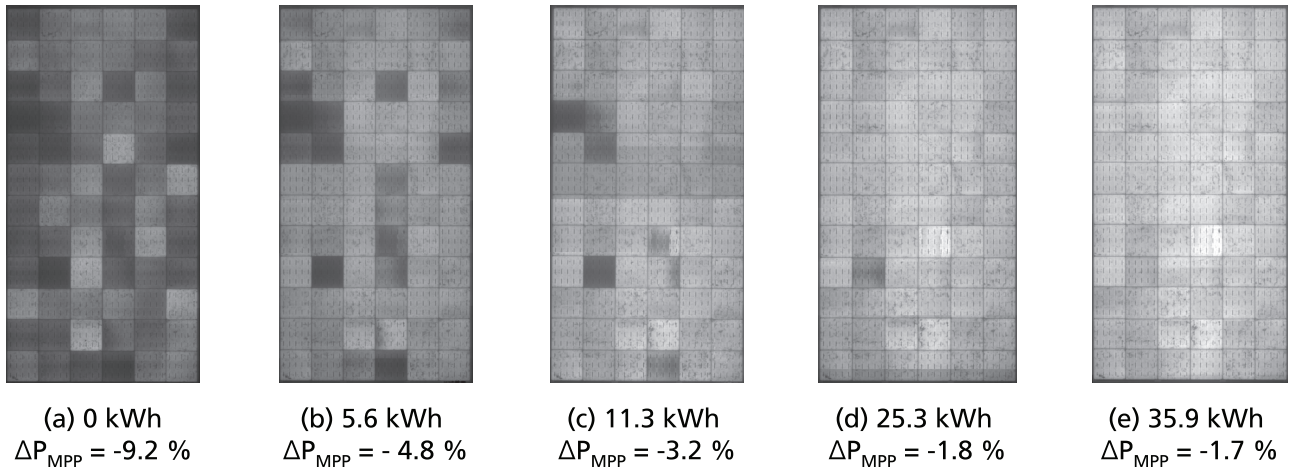


Fig. 2. Electroluminescence images of module Ind_6_21C_1.0xIsc during the interim measurements conducted within the indoor temporary recovery experiment at 21 °C and (nominal) I_{SC} . The images were captured at nominal I_{SC} . The cumulative energy applied in the experiment prior to each image acquisition is provided in the captions of the subfigures.

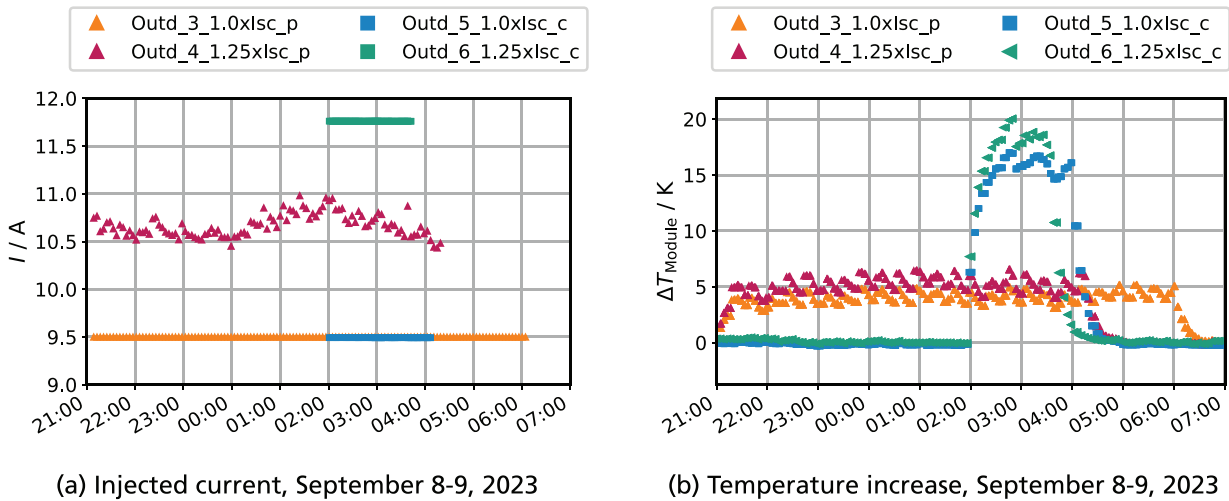


Fig. 3. Measured (a) injected current and (b) module temperature increase due to current injection compared to the temperature of the reference modules during a representative night (September 8–September 9, 2023).

The temperature increase remained below 7 K when a pulsed current was used, while a temperature increase of up to 20 K was observed when constant current injection was employed. The temperature increase observed can be attributed to the average electrical power applied to each module during current injection. The application of a pulsed current can result in a notable reduction in the heating experienced during the procedure. By modifying the pulse ratio, it is possible to achieve further improvements in module temperature. During the outdoor experiment, the modules exhibited average temperatures of 21.4 °C (Outd_3) and 22.7 °C (Outd_4) under pulsed current injection and average module temperatures of 30.6 °C (Outd_5) and 32.4 °C (Outd_6) under constant current injection. For comparison: The average ambient temperature during the times of current injection was between 20.0 °C (periods with constant current injection to Outd_6) and 21.8 °C (periods with pulsed current injection to Outd_4).

3.2.2 Outdoor performance

The evolution of the temporary recovery of the modules in the outdoor experiment can be observed in the outdoor performance parameters over time shown in Figures 4a–4c as daily mean values of the relative, normalized characteristic points of the I-V curve, as defined in Section 2.3. Note, that the y-axis is relative to the reference modules, i.e. the average of these is the baseline leading to a symmetrical appearance of their two curves.

To situate the outdoor performance parameters within the present environmental context, the mean daytime temperature, mean daily irradiance, and irradiance variability are depicted in Figure 4d alongside. The irradiance variability is defined here as the standard deviation of the absolute difference between each two consecutive measurement values. Consequently, a clear-sky day is typified by a high irradiance with a low variability, an overcast day by a low irradiance with a low variability, and a day with flying clouds by an intermediate

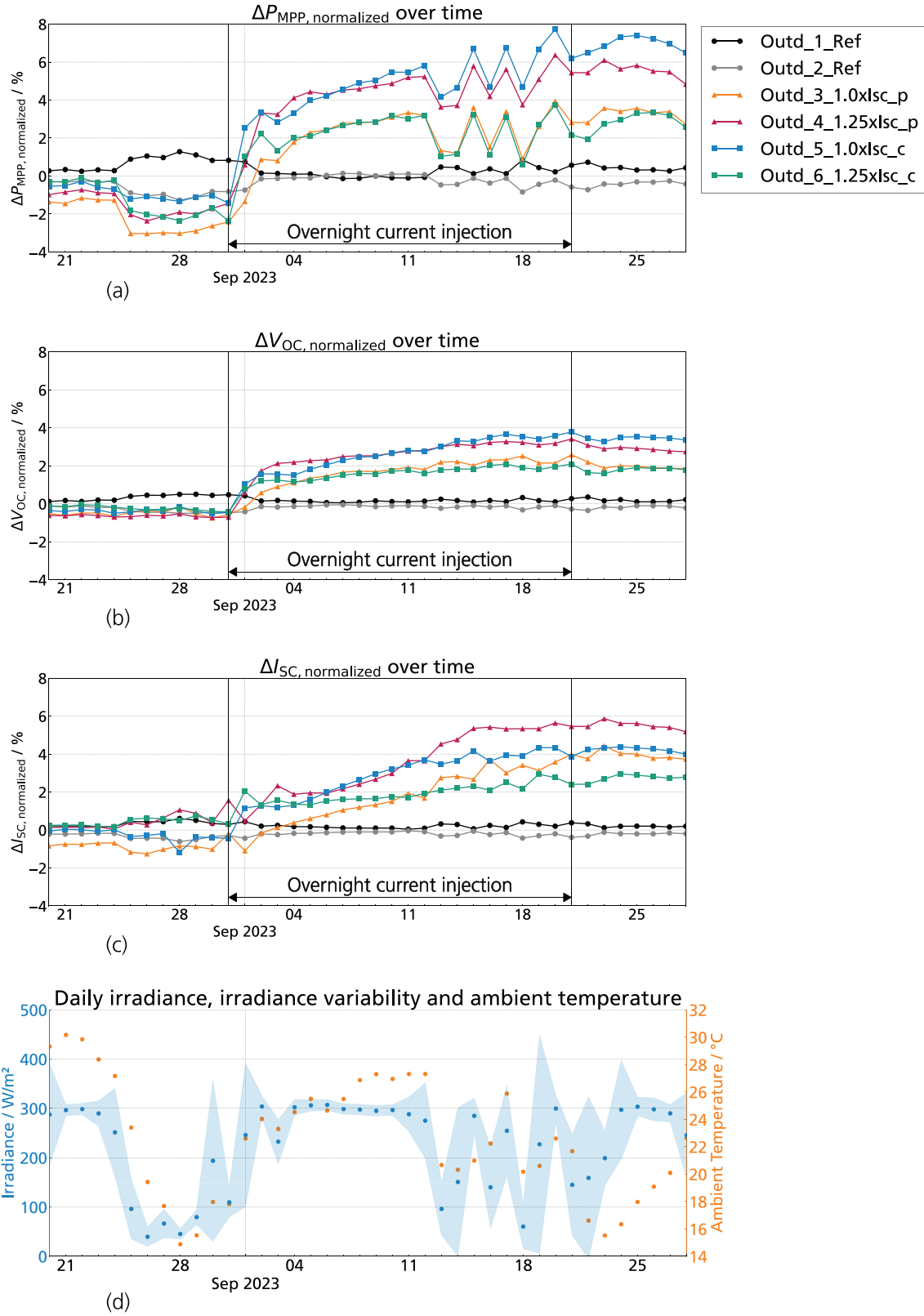


Fig. 4. Evolution of the daily average values of the normalized performance parameters (a) $\Delta P_{MPP,normalized}$, (b) $\Delta V_{OC,normalized}$ and (c) $\Delta I_{SC,normalized}$ as well as (d) the mean daily irradiance, the irradiance variability and the mean daily ambient temperature over the period of the outdoor experiment.

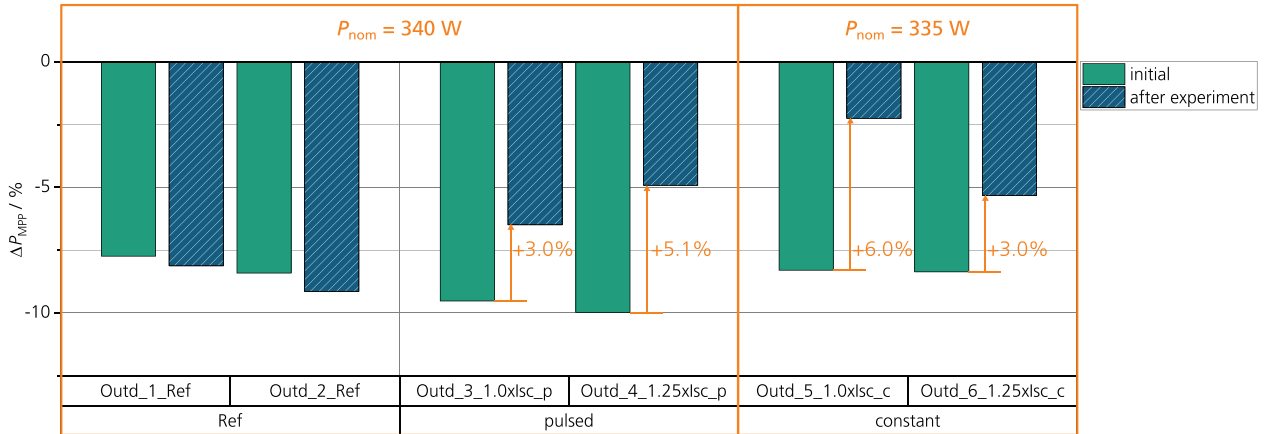


Fig. 5. Relative deviation of P_{MPP} at STC from the nominal value of each module measured before and after the outdoor experiment.

irradiance with a high variability. As Figure 4d is intended to provide a general environmental context, its mean values are arithmetic averages of unfiltered irradiance and temperature data covering the full 24 hours of each day, unlike Figures 4a-4c which analyze pre-filtered module data.

In general, clear-sky days are optimal for data analysis as they provide stable, steady-state conditions with a multitude of data points where the module behavior is not significantly influenced by non-linear effects. In this context, the fluctuations observed in the normalized P_{MPP} (also observed in FF , but not shown) are strongly correlated with suboptimal conditions and a dependence of FF on irradiance (R_S leads to higher voltage drops at higher currents). This irradiance dependence varies from module to module. Therefore, the deviation of the FF of each module from the average value of the reference modules is different at different irradiance levels, causing the fluctuations in the normalized P_{MPP} . As most of the energy is generated at higher irradiances, these data points are more relevant. The effect does not originate from LeTID nor is it specific for this experiment.

During the period with current injection, a notable increase in the normalized performance values of all PV modules except the reference modules was observed, resulting in an overall increase in $P_{MPP,normalized}$ by approximately 3% (Outd_6) to more than 7% (Outd_5). These values were estimated by comparing the values of $\Delta P_{MPP,normalized}$ on clear-sky days before current injection (August 21 to August 23) and after current injection (September 24 to September 26). After ten days, approximately 80% (Outd_5) or more of the overall power increase observed after the 21 days with overnight current injection was reached.

A comparison of the increase in $P_{MPP,normalized}$ of the different modules reveals no clear correlation between the injection conditions and the recovery speed. The module exhibiting the highest power increase, Module Outd_5, was subjected to constant current injection at a current level of I_{SC} , whereas the module with the second highest power increase, Module Outd_6, was subjected to a pulsed current between I_{SC} and $1.25 \times I_{SC}$. The possible reasons for this outcome are discussed in Section 3.2.3.

As observed in the indoor experiment, the normalized V_{OC} , representing the average change across all cells of a module, exhibited the greatest increase during the initial period of current injection (see Fig. 4b). By the end of the experiment, the saturation point was nearly reached. The differences in the evolution of $V_{OC,normalized}$ between the modules investigated under constant and pulsed current injection during the first nights can be explained by the different energy amounts applied. As mentioned in Section 2.3, a higher energy amount was inadvertently injected into the modules tested at constant current injection during the first night, followed in omission of current injection during the following nights, until a comparable energy expense was reached.

In comparison to the evolution of the normalized V_{OC} , the values of $I_{SC,normalized}$ exhibited a slower increase during the initial two-thirds of the period with current injection, indicating that in all cell strings of each module, at least one cell with higher degradation was limiting the current during this time. During the final third of the period with current injection, saturation of $I_{SC,normalized}$ was reached for the modules Outd_4 and Outd_5 due to the nearly full temporary recovery of at least one cell string.

3.2.3 Final characterization

The results of the final characterization, namely the $I-V$ curve measurements at STC and the EL measurements, are in accordance with the observed trends in the outdoor performance parameters (Fig. 5). The experiment resulted in a notable temporary recovery of P_{MPP} for all PV modules investigated under current injection, with a range of 3.0–6.0% relative to the initial power. Given that the experiment was conducted in September in southern Germany, where nightly temperatures were not optimal, it is likely that higher degree of temporary recovery would have been achieved at lower temperatures during the winter months.

The remaining losses in P_{MPP} after LeTID recovery exhibit the strongest correlation with losses in I_{SC} , which are likely only partially caused by LeTID. Additionally, losses in V_{OC} (negligible for module Outd_5), and losses in FF contribute to the remaining losses.

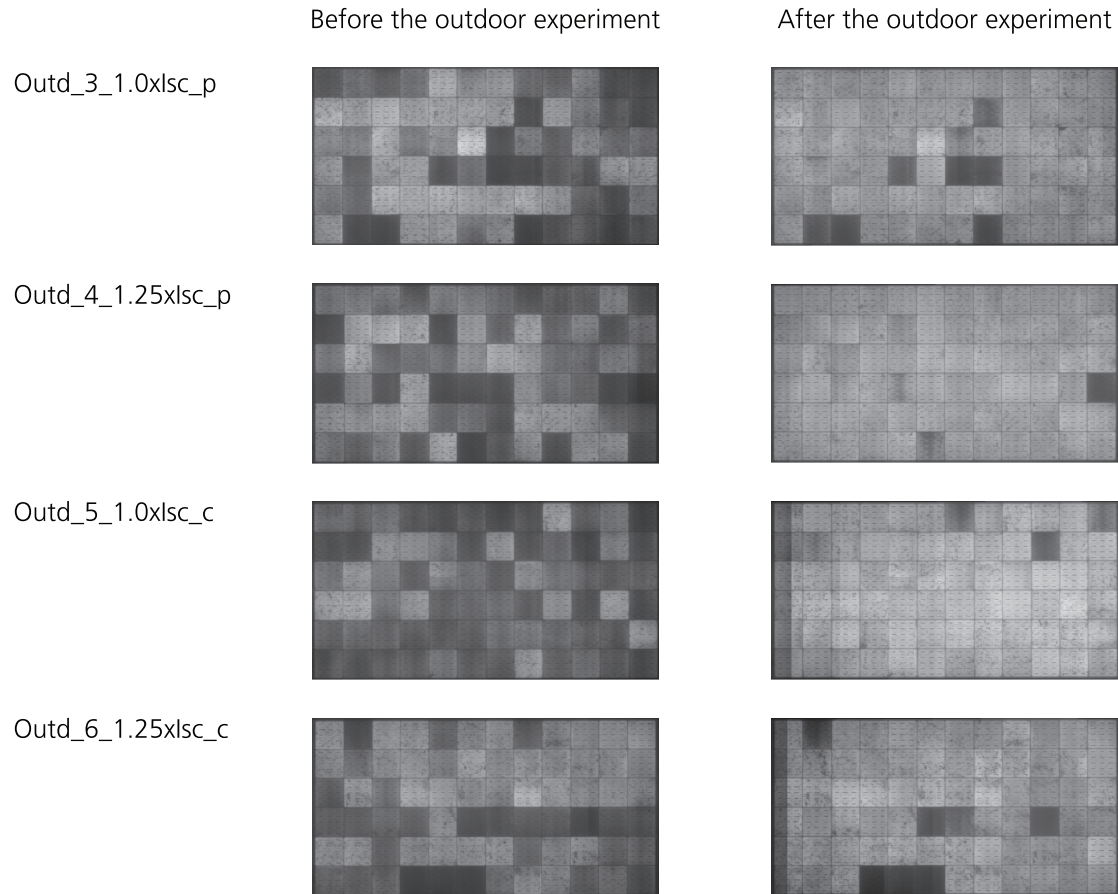


Fig. 6. Electroluminescence images taken before and after the outdoor experiment. The images were taken at I_{SC} .

These remaining efficiency losses due to LeTID are evident in the EL images subsequent to the experiment depicted in Figure 6. While the majority of cells within each module appear to have recovered to a considerable extent, each module exhibits at least one cell that has not fully recovered. This result serves to highlight the significance of cell mismatch with regard to the efficiency of a LeTID recovery procedure.

As observed in the outdoor performance data, the module Outd_5, which was subjected to a constant current of I_{SC} , exhibited the greatest power improvement, followed by the module Outd_4, which was subjected to a pulsed current of $1.25 \times I_{SC}$ (set condition). In contrast to the indoor experiment, the influence of the test conditions does not exhibit any discernible trend. This may seem as an unexpected result, given that a combination of high current and low temperature was identified as the optimal conditions in the indoor experiment, and pulsed current injection was shown to significantly reduce the heating during the outdoor experiment.

However, the fact, that no clear trend regarding the influence of the test conditions on the amount of efficiency increase was identified in the outdoor experiment, is not entirely surprising and may be attributed to a number of potential explanations:

- The PV modules in the outdoor experiment initially exhibited varying degrees of power loss. The modules exhibiting greater deviations from their nominal power (−9.5% to −10%) were subjected to pulsed current injection, while the modules exhibiting lower deviations ($\approx -8.3\%$) were subjected to constant current injection. As previously stated, more strongly degraded cells tend to recover more slowly than less-degraded cells. A module exhibiting higher initial degradation is likely to contain a greater number of degraded cells, or cells exhibiting greater levels of degradation relative to those in a module exhibiting lower initial degradation.
- Mismatch effects play an important role in the efficiency losses due to LeTID. In a series connection of cell strings with bypass diodes, the presence of a cell with lower efficiency due to LeTID results in a reduction of the FF and the I_{MPP} . If each cell string contains one cell with a higher degree of degradation, these cells will reduce the module I_{SC} . Consequently, a relatively small number of degraded cells can exert a considerable influence on the module's overall efficiency. Given that even solar cells from the same ingot can exhibit strong variations in their LeTID susceptibility [7], it is possible that a random distribution of cells with different LeTID characteristics within the test modules may have influenced the observed recovery progress.

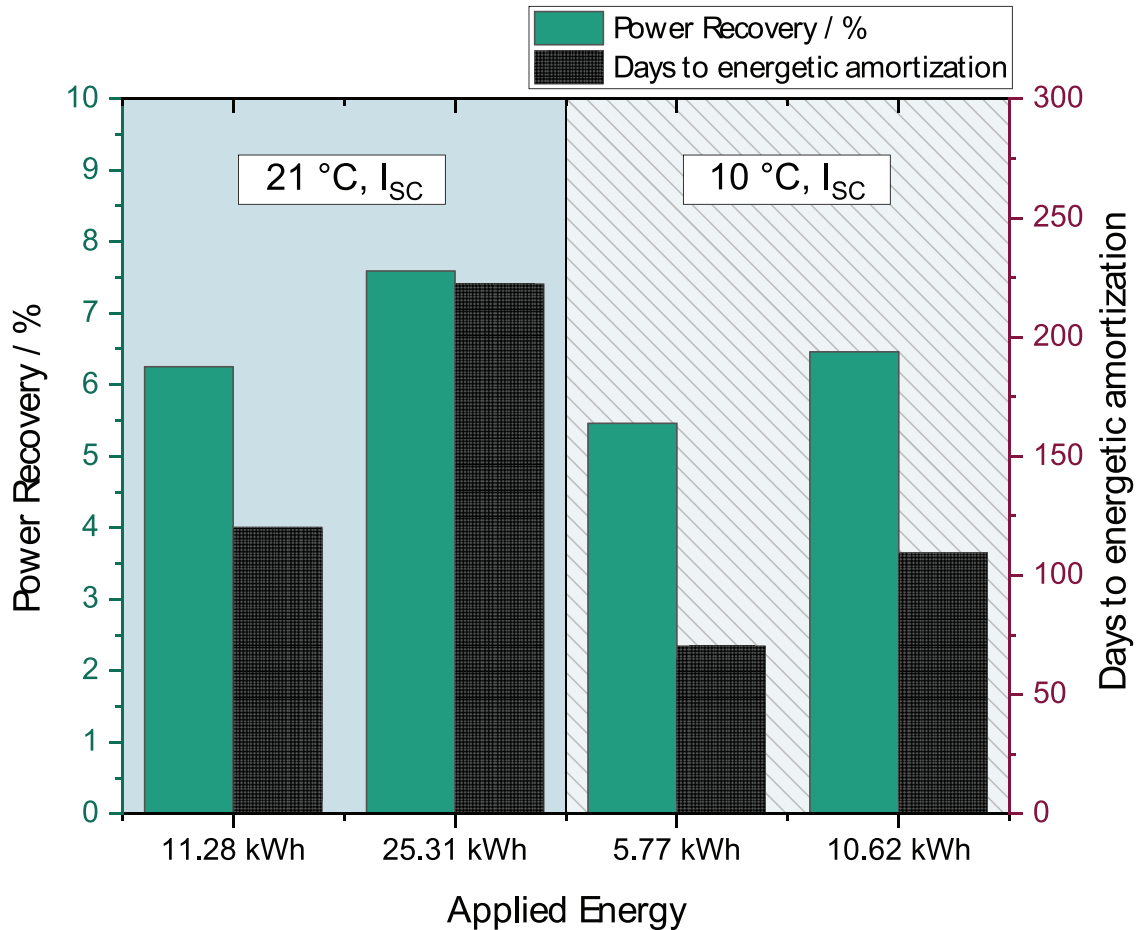


Fig. 7. Power recovery and theoretical energetic amortization time of the modules Ind_6_21C_1.0xI_{sc} and Ind_1_10C_1.0xI_{sc} that were recovered in the indoor experiment at a module temperature of 21 °C or 10 °C and I_{SC} at two different levels of cumulative applied energy. The days to an energetic amortization were estimated for a hypothetical PV power plant in Valencia, Spain, assuming a daily specific yield of 4.413 kWh/kW_P and neglecting re-degradation, electrical losses of the system and other expenses than the energy applied by current injection.

- Despite the fact that the investigated PV modules were produced by the same manufacturer and belong to the same product line, there is a possibility of variations in the production process. The modules may contain cells from different batches with variations in peak temperatures or temperature profiles during production and may in general have a different thermal history, affecting the LeTID susceptibility and kinetics [14,15]. Differences in the production process are even more likely for PV modules of different power classes, as included in our experiment.
- No I - V curve measurements of the non-degraded PV modules (without efficiency losses due to LeTID) were available. Therefore, the deviation of P_{MPP} from the label value of each module was used as an indicator for power loss due to LeTID. Given that deviations of module I - V curve parameters from their label values are common, and that previous exposure of the modules in a PV power plant has likely caused additional degradation besides LeTID, the use of the deviation from the label value may be associated with further uncertainties.
- In contrast to indoor experiments under controlled constant conditions, outdoor experiments are generally subject to greater fluctuations in stress conditions, such as temperature and irradiance. In order to identify clear trends regarding the influence of the test conditions (i.e. current level and pulsed or constant current), a higher number of samples would be required. However, this was not possible in the scope of this study due to limitations in the budget and the available number of modules.

3.3 Theoretical considerations on the efficiency of an on-site LeTID recovery procedure

For an economic recovery procedure in PV power plants, the expenses spent for the temporary recovery of the modules must be recouped by the income from the additional electricity generated within a reasonable time. A detailed cost model would require a consideration of the energy spent for the temporary recovery, the cost for labor and equipment, the price of electricity during nights and

the revenue per kWh sold. Furthermore, yield modeling based on meteorological data, including assumptions for re-degradation of LeTID would be required. Such investigations are beyond the scope of this work.

However, in order to get an idea of the possible feasibility of an economical on-site LeTID recovery procedure, simplified theoretical considerations are made based on the temporary recovery of two PV modules under controlled conditions in the indoor experiment, the heating of the tested modules under current input in the outdoor experiment and temperature data from Valencia, Spain, which serves as an example location for a hypothetical PV power plant. In Figure 7, the green bars show the relative power increase of the modules Ind_6 and Ind_1, which were subjected to the indoor experiment. Module Ind_6, which was recovered with a current level of I_{SC} at a module temperature of approximately 21 °C exhibited a relative power recovery of 6.3% (i.e. partial recovery) after a cumulative energy of 11.3 kWh. If a similar result were achieved on a PV module in a power plant in Spain with a daily specific yield of 4.413 kWh/kW_P [31], the spent energy for the temporary recovery would be recouped within 120 average days, assuming no re-degradation during that period and negligible influence of mismatch between modules in the string, and neglecting electrical losses of the system. Temporary recovery of 7.6% of the nominal power (i.e. until saturation is nearly reached) under the same conditions would require the expenditure of more than twice of that energy, resulting in an energy payback time of approximately 220 days. Considering that significant re-degradation is likely during summer [10,13], full temporary recovery of the investigated PV modules at a module temperature of 21 °C would most likely not be economically viable. The assessment of financial viability of partial recovery (e.g. by 6.3%) under these conditions would require a detailed analysis. In Valencia, where a minimum ambient temperature of approximately 7 °C is reached in January [32], injecting a constant current in the range of I_{SC} would likely heat up the modules to a temperature close to 20 °C or higher based on the temperatures reached in our experiment.

It is possible to achieve a notable enhancement in the energetic efficiency of the recovery procedure at a reduced cell temperature. As shown in the outdoor experiment, the heating of the modules caused by current injection can be significantly reduced by using a pulsed current instead of a constant current. Depending on the pulse ratio, applying the recovery procedure at a module temperature close to 10 °C seems therefore possible during the coldest winter nights in Valencia. At a temperature of approximately 10 °C, the module Ind_1 was recovered by 5.5% of its rated power through the application of current injection with a cumulated energy of 5.8 kWh. This would correspond to an energy payback time of approximately 70 days under the same assumptions and simplifications as mentioned before. Re-degradation would likely increase the energy payback time.

Based on these simplified considerations, it can be concluded, that an economic application of a LeTID recovery procedure in a PV power plant may be possible under optimal

conditions. For locations where temperatures below 20 °C are rarely reached, a temporary recovery procedure may, however, not be economically viable. Furthermore, the comparison indicates, that recovering PV modules to a high efficiency level (i.e. with minimal or no remaining degradation) increases the energy payback time of the recovery procedure. It may therefore be reasonable in some cases to cease the recovery process at a point where the remaining power loss is moderate, for economic reasons.

In a real PV power plant, mismatch between PV modules in a string may diminish the economic efficiency, if PV modules recover at disparate rates. The behavior of strings during a LeTID recovery procedure was not a focus of this study and should be considered when applying the procedure on-site. Moreover, it is to be expected that significant re-degradation will occur over time, necessitating a periodic repetition of the recovery procedure (e.g., each winter).

4 Conclusion

A feasibility study was conducted to determine the viability of recovering LeTID in PV power plants through the use of overnight current injection. The procedure is based on the temporary recovery reaction, which is the reverse reaction of LeTID.

In the experiments, we used heavily degraded mc-Si PERC PV modules, which had previously been either operated in a PV power plant in Spain for four years or subjected to LeTID experiments at our laboratory. The results of an indoor experiment conducted under controlled conditions in a climatic chamber demonstrated, that LeTID can generally be fully temporarily recovered under current injection at low temperatures, even for PV modules with high performance losses due to LeTID. The energy expenditure associated with current injection to achieve a specific recovery level depends on the applied conditions. In particular, a low temperature (e.g. 10 °C) combined with a high current (i.e. the nominal I_{SC} or 1.25 times the nominal I_{SC}) allows the most energy-efficient temporary recovery of PV modules. However, due to the lack of data from other temperature and current levels, this conclusion is limited to the ranges included in our experiment. Furthermore, the speed of performance recovery of a PV module is significantly influenced by the initial degree of degradation of the individual cells.

In an outdoor experiment under realistic conditions with an energy of approximately 22 kWh applied to each module under current injection, a significant performance recovery was achieved, demonstrating that LeTID can be temporarily recovered by overnight current injection in PV power plants. In contrast to the indoor experiment, the results from the outdoor experiment revealed no clear trend regarding the influence of the recovery conditions (i.e. current level and module temperature during current injection). This is likely due to differences between the PV modules with regard to the degree of degradation of individual cells, possible differences in the kinetics of LeTID state transitions, and

more complex test conditions in an outdoor experiment compared to experiments conducted under constant conditions.

Simplified theoretical considerations based on the results of our experimental investigation indicate that an economic LeTID recovery procedure in PV power plants may be feasible under certain conditions. For the purpose of implementing this procedure in photovoltaic power plants, we recommend:

- To select a current level of at least the nominal I_{SC} , or, if technically feasible, even higher (e.g. $1.25 \times I_{SC}$).
- To select a period with cold temperature during nights (e.g. winter).
- To use a pulsed current in place of a constant current and modify the pulsing rate in a way, that the heating of the module is reduced to a reasonable extent. In the outdoor experiment, using a pulse rate with one minute of current injection followed by three minutes without current injection resulted in an average temperature increase of approximately 3.3 K at a current level of I_{SC} . The technical implementation of the current injection is beyond the scope of this work. We suggest, however, to inject the current string-wise and investigate the possibilities of using an external power source or a modified inverter to limit the applied energy to a reasonable value, taking into account the extent of degradation of the modules in the PV power plant, the expected cell temperature during current injection, and, if available, indoor test results on the temporary recovery behavior of PV modules from the affected PV power plant. Previously indoor testing of the recovery behavior of a module type with unknown temporary recovery behavior is recommended to confirm, that power losses in the power plant are caused by LeTID and to get information on the recovery speed under certain conditions.
- If the performance in the PV power plant is monitored, the resulting data can be employed to define a stop criterion for the recovery procedure.
- To monitor re-degradation in the PV power plant and repeat the procedure if necessary. It is likely that a lower energy expense will be required when repeating the recovery procedure than was the case with the first recovery, due to a lower degradation degree of the modules.

The influence of mismatch between PV modules in the same inverter string on the effectivity of the recovery procedure was not subject of this study and requires further investigations. Moreover, an investigation of the impact of a temperature reduction to below 10 °C on the temporary recovery behavior would be beneficial for a potential further optimization of the procedure.

Acknowledgments

The authors acknowledge Sandor Stecklum for enabling the pulsed current injection option for the climatic chamber experiments, Georg Mühlhöfer for the laboratory organization, our colleagues at CalLab PV Modules for the I - V curve measurements, and our student assistances for the electroluminescence images. We would also like to thank our industry partners for providing PV modules.

Funding

This research was co-sponsored by an industry partner.

Conflicts of interest

The authors have nothing to disclose.

Data availability statement

Data associated with this article cannot be disclosed due to legal reason.

Author contribution statement

Conceptualization, E.F. and P.G.; Methodology, E.F., A.K., P.G. and C.A.; Software, A.K.; Validation, E.F. and E.S.; Formal Analysis, E.F. and E.S.; Investigation, E.F. and A.K.; Data Curation, E.S.; Writing – Original Draft Preparation, E.F. and E.S.; Writing – Review & Editing, P.G., E.S., A.K., C.A., T.M., V.W., D.P.; Visualization, E.F. and E.S.; Supervision, T.M., V.W. and P.G.; Project Administration, E.F. and P.G.; Funding Acquisition, P.G., D.P.

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Cite this article as: Esther Fokuhl, Paul Gebhardt, Erdmut Schnabel, Alexander Kleinhaus, Cornelius Armbruster, Thomas Mikolajick, Viktor Wesselak, Daniel Philipp, Reversing LeTID in PV power plants: a feasibility study, *EPJ Photovolt.* **16**, 3 (2025)