

Failure mode analysis of Austria’s first road-integrated photovoltaic system

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Abstract. The exploration of traffic areas as a novel photovoltaic integration opportunity within the traffic sector, specifically in road surfaces, has been demonstrated in various projects. Limited data and publications about the performance and failure modes of these innovative road-integrated modules highlights the need for a comprehensive failure analysis. This study focuses on first time assessing failure modes of road-integrated photovoltaic modules installed at Austria’s first road-integrated PV system in Teesdorf. A comprehensive failure mode analysis is conducted at the 100 m² PV parking place using a combination of quantitative and qualitative methods. These methods include regular visual inspections, I-V-curve measurements at both string- and module-levels (with a simplified STC correction), electroluminescence- and dark-I-V-curve measurements, and the use of monitoring data. The PV parking place produced 10.2 MWh in its first operation year, 27.18% less than the estimated yield. Visual inspections reveal various failure modes, including detachment of the module top layer, delamination, and broken module edges. In the analysed monitoring data continuous power losses are observed over the systems operation time. String-level power losses of up to 47.8% (mean: 33.5%) are calculated for the first year of operation. For the second year of operation the power losses reach a up to of 77.5% (mean: 56.2%). Cell cracks as the main cause of these power losses, attributed to vehicle loads, are identified through electroluminescence images. Out of 16 analysed strings with dark I-V-curve measurements three showed at least one bypass diode malfunctions. The combination of quantitative and qualitative methods identified multiple failure modes and their main causes. As a conclusion, the study highlights the challenges of integrating PV modules into road surfaces, emphasizing the need for standardisation and quality assurance in the field of road-integrated PV applications.

Keywords: Road-integrated photovoltaics / maintenance / reliability / failure mode analysis / I-V curve measurements / dark I-V curve / electroluminescence

1 Introduction

The yearly installed photovoltaic (PV) capacities of the past two years show high two-digit growth rates in the European market, with 42% in 2022 and 43 % in 2023 [1]. In the Austria market more than half of the cumulative capacity in 2023 were installed in those two years [2]. With the first time achieving 1 GWp of added capacity in 2022 and the highest growth rate in Europe in 2023 (+157.96%), Austria is on track to achieve the Renewable Energy Act goal of 13 TWh electricity from PV ahead of the 2030 target [3], although new studies for Austria show that in order to reach climate neutrality by 2040 21 TWh of PV are necessary by 2030. The high installation capacities challenge not only the aspect of grid integration. It further saturates the predominant rooftop market in Austria (84% in 2022 and 86% in

2023 [2]). For yearly PV installations in the range of 1-2 GWp new potentials need to be tapped. Besides the ground-mounted PV systems where the social acceptance in Austria is lower (54% [4]) than for roof-top and building-integrated PV (BIPV) systems (81%), other PV potentials and system types must be considered. Compared to other renewable energy technologies PV modules can be integrated into existing structures, facilitating a synergistic and combined area utilization for new PV potentials. Key integration options include building-integrated PV, Agri-PV, and floating PV. The exploration of traffic areas as a novel integration opportunity within the traffic sector, especially in road surfaces, bike- and walkways, has been demonstrated in various projects worldwide since 2006 [5–10] and discussed in the literature [10–13]. Beside prototypes [14–17] and experimental research approaches [9,18,19], companies, such as Solar Roadways, Wattway by Colas, SolaRoad, Platío Solar, developed products for the broad application of this PV integration type. Although

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some publications focus on the durability and robustness of these products and prototypes, limited data on failure modes are available. In Coutu et al. [20] the durability and robustness of the Solar Roadways module was evaluated without analysing the influence of the applied load cycles on the electrical performance. The research in Ma et al. [15] is a further example for this. For demonstrations projects constructed with SolaRoad modules the results of visual inspections are discussed in [21]. In Klerks et al. [22] the yield and the performance of the first solar bike ways in the Netherlands is analysed. Although different failure modes such as delamination or degradation of the anti-skid layer and the improvement of the used product versions are discussed, no further failure analysis methods (e.g. current-voltage (I-V) curve measurement, electroluminescence (EL), etc.) are applied. In the “Rolling Solar” project [23] crystalline silicon and thin-film module (copper indium gallium selenide – CIGS) were analysed in an controlled environment with mechanical stress of passing cars. The efficiency losses were calculated and validated with accelerated lab tests, but no further methods to analyse possible cell cracks in the field (e.g. with EL or UV fluorescence) were conducted. EL was used in Colberts et al. [24] for the feasibility assessment of thin-film PV laminates for road integration in an laboratory environment, where smaller samples were used for the testing approach. In general all publication stating yield values of road-integrated PV systems [22,23] show that there are power losses over the course of the operating time that are higher than the usual degradation rates and can therefore be attributed to failure and degradation modes.

The mentioned publications show the lack of data on failure modes of road-integrated modules (RIPV), or in general traffic area-integrated modules, in the field. Those results would be especially valuable for the scientific community to develop improvements for RIPV applications and for planners and stakeholders to evaluate the technology in terms of its market maturity.

In this paper, the focus is on assessing the failure modes of RIPV modules installed at Austria’s first RIPV system in Teesdorf. The PV parking place undergoes a comprehensive failure analysis using a combination of quantitative and qualitative methods. These methods include regular visual inspections, I-V curve measurements at string- and module-levels, EL and dark-I-V-curve measurements, and the use of monitoring data. The comprehensive approach allows the identification of failure modes, the quantification of their performance impact, and determines or narrows down the causes. Through the participation in the planning phase, a distinction can be made between causes of errors due to system planning problems and product errors. Finally, possible improvements for the analysed PV module are formulated and the suggestions for the whole field of RIPV are derived from the results.

2 Material and methods

In this section, first an overview of the analysed RIPV system in Teesdorf is given, including the construction of the systems. Afterwards, the measurements setups, the data processing and analysis steps are described.

2.1 PV parking place Teesdorf

The PV parking place in Teesdorf (Austria) was commissioned in May 2022 on an already existing parking place in front of the community centre in Teesdorf (see Figs. 1a and 1b). The location was chosen due to the fact that the parking lot for the public building is mainly used in the evening when different kinds of events take place. During daytime, the parking lot is only used rarely and allows the area to be utilised for photovoltaic power generation during that time. From a research point of view, this is an attractive constellation as the performance during daytime and the vehicle loads during nighttime can be investigated at one location.

For the construction of the site, the existing pavement, together with the substructure, was removed and replaced by a concrete foundation. Plastic profiles were then mounted on the foundation, and the PV modules were placed on top of them (see Fig. 1c). The profiles were mounted with according spacing, so that every module had contact with three profiles (one on each edge and one in the middle) for a better load transfer to the concrete foundation. This allowed an easier cable management and enables the placement of sensors below the modules after commissioning.

The whole systems consist of 780 commercially available four cell RIPV modules, with a load capacity of two tonnes according to the manufacturer. Each module has a nominal power of 21.52 Wp and consists of a glass-foil assembly on the top and a polymer composite substructure. Further module data is presented in Table 1. The module does not have a certification according to IEC 61215. To reach the operating voltage range of the used IQ7+ Enphase[®] microinverters [25] the modules were connected to strings of 18 to 20 modules. In the layout of the string plan factors such as shading due to nearby buildings and possible parking cars, the inverter input parameters and safety parameters (OVE E 8101 [26]) were considered. The connection of the modules in the strings was made through 3MTM ScotchlokTM MGC connectors. Each of the 42 strings is connected to one IQ7+ microinverter. Figure 1d shows the string layout with the labelling of the strings and the number of modules in one string.

The production of the RIPV system is used in the nearby community centre and the surplus is fed into the public grid. Besides the inverter monitoring no further continuous monitoring of the strings is carried out. To differentiate between mechanical and weather induced material degradations a reference string of 20 modules is placed on the roof of the community centre. Further there is a datalogger on the community centres roof to log weather data (irradiation, air temperature, relative humidity and wind speed) and measure the backsheets temperature of three RIPV modules. The backsheets temperature is used for analysing the temperature behaviour of the RIPV module under test. The reference string and datalogger are in operation since October 2023, due to problems with the logger hardware. Further details about the PV parking place in Teesdorf are described in [27].

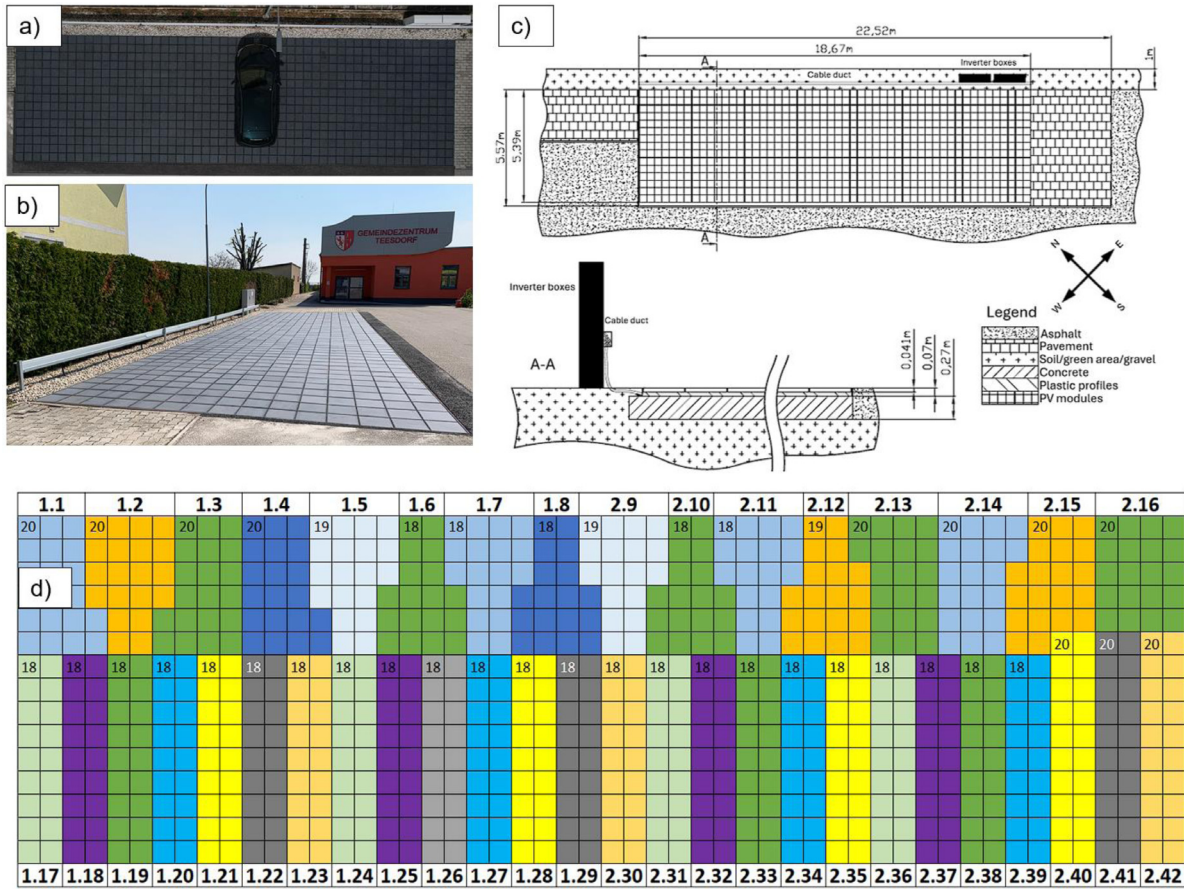


Fig. 1. PV parking place in Teesdorf (Austria); (a) top view of the PV parking place, (b) side view with the community centre Teesdorf in the back, (c) dimensions and layer structure and (d) string layout of the RIPV system with string labelling (The first digit in the labelling code referees to the inverter boxes, which each contain 21 microinverters, and the last two digits are the sequential numbering of the strings).

Table 1. Module data of the analysed RIPV module.

Technical data	Dimension (H × W × D)	353 × 353 × 41 mm
	Glass thicknesses/module structure	• 6 mm tempered glass (anti-slip – R12) • Encapsulant-Cell-Encapsulant-Backsheet
	Weight	6.5 kg
	Number of bypass diodes / Cells	1/4 × monocrystalline cells
	Material of the module substructure	Recycled polymer composite; LDPE and HDPE copolymer with matrix-forming material
Electrical data	Maximum load (wheel load)	2000 kg
	MPP power P_{MPP}	21.52 Wp
	MPP voltage U_{MPP}	2.29 V
	MPP current I_{MPP}	9.39 A
	Open circuit voltage U_{oc}	2.68 V
	Short-circuit current I_{sc}	9.85 A
	Temperature coefficients P_{MPP} , U_{oc} , I_{sc}	-0.38%/°C, -0.32%/°C, 0.05%/°C
	Connection cable	2.5 mm ² (blank without plug)

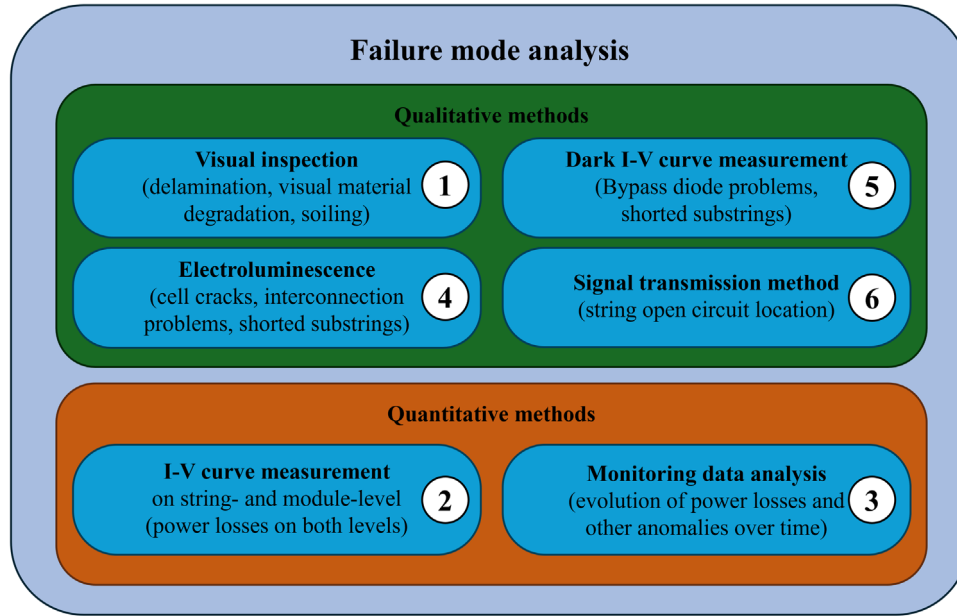


Fig. 2. Overview of the applied failure mode analysis methods and their detectable failure modes or analysis parameter (quantitative methods). The numbering of the individual methods represents the order in which they are described in the methodology and results sections.

2.2 Failure mode analysis

The comprehensive failure modes analysis of this study uses quantitative and qualitative methods, which are well described in the literature [28–30]. This combination of methods enables the quantification and location of failure modes. Figure 2 provides an overview of the methods used and the possible types of failure modes that can be detected.

Qualitative methods are referred to in this study as analysis methods where no information about the electrical state or behaviour of the analysed modules or strings are obtained. Visual inspection (see Sect. 2.2.1), electroluminescence (EL) (see Sect. 2.3), the measurement of the dark I-V curve (see Sect. 2.3.1) and the signal transmission method (see Sect. 2.3.2) are used as qualitative methods in this study. As mentioned in IEC TS 60904-13 [31] and demonstrated in Kropp et al. [32] EL can be used as a qualitative method as well. The same applies to the measurement of the dark I-V curve, where the resistances and the other parameters of the one- or two-diode-model can be determined by analytical evaluation [30].

To quantify the influence of the detected failure modes the following quantitative methods are used: I-V curve measurements on module- and string-level (see Sect. 2.2.2) and the analysis of the monitoring data (see Sect. 2.2.3).

In the following subsections, each conducted methodology of the above-mentioned failure mode analysis methods is described, covering the measurement setup and measurement procedure through to data preparation and analysis. The analysis period of the failure mode analysis ranges from May 2022 to June 2024.

Thermography is not used for the analysis, as captured thermography images were too blurred for a proper analysis, due to the glass thickness of 6 mm (see Tab. 1).

Further, EL is an alternative (detecting the same and more failure modes) for field thermography, although with the cost of longer setup times and the need of more equipment (DC supply, camera, laptop). UV fluorescence is not used in this study, because due to the short timespan between commissioning and a test measurement in October 2023 no useable UV fluorescence was found, as the method would require more UV exposure during the day [33].

2.2.1 Visual inspection

Visual inspections at the PV parking place in Teesdorf are carried out at regular intervals (2-3 months) or in response to messages from the monitoring system. Anomalies and defects are documented using visual images and the module position in the system. Inspection checklists, as the one developed in Köntges et al. [28], are not used, as they are for normal PV modules and considering the number of modules (780) the data that can be gathered using a checklist is not in reasonable proportion to the time required. Inspections carried out by the system owner (municipality of Teesdorf) are also included in the analysis.

The recorded image material is analysed together with the module position in the system to be able to assign visually detected faults to local or material-related causes. Furthermore, in combination with the quantitative methods, it is also analysed whether the detected failure modes have an influence on the performance of the modules and the string or are purely material degradations.

2.2.2 I-V curve measurements

To quantify changes in module performance, the I-V curves of selected modules were measured after the systems commission in May 2022 and after the first year of

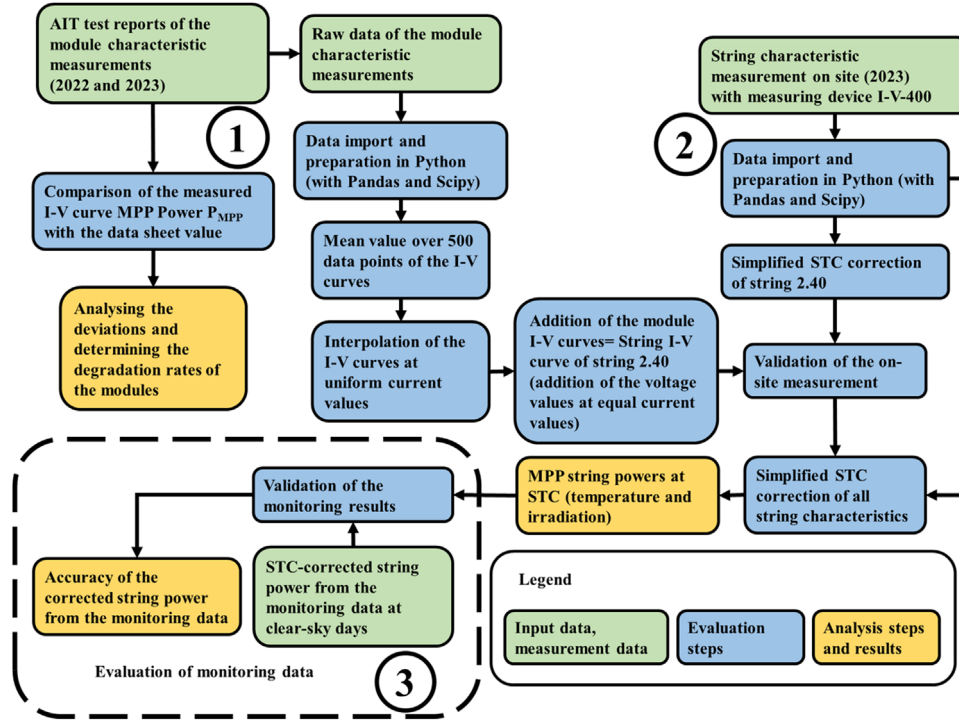


Fig. 3. Flow chart of the data processing and evaluation steps of the I-V curve measurements. The numbering corresponds to the order the steps are carried out.

operation in May 2023. As the voltage range (up to 2.6 V) of modules (see parameters in Tab. 1) is too low for conventional I-V curve measurement devices, the modules of a string are measured in accordance with IEC 60904-1 Ed.3.0 under standard test conditions (STC) conditions in a flasher at the Austrian Institute of Technology (AIT) in Vienna. The selected string is string 2.40, as it is assumed that it will be exposed to frequent vehicle loads during its operating time due to its location close to the community centre entrance. The measurements are carried out in a pulsed sun simulator (multiple flash method) of class A+A+A+ [34–36]. The initial characterisation of string 2.40 and the reference modules of the roof system took place on 4th May and 5th May 2022. After the first year of operation the characterisation of the string 2.40 modules took place on 23rd May 2023. The reference string modules were not measured as the rooftop system had not yet been installed at this time and were therefore not exposed to any weather-related influences.

After the first year of operation, I-V curve measurements for all strings are carried out on the test site on 22nd May 2023. The I-V curve measuring device HT I-V-400 is used for this purpose. An on-site measurement after commissioning was not possible as the device was in repair and calibration at the time. As the module rear side temperature cannot be measured due to the module design, the temperature on the front side of the module is recorded. The PT100 sensor is attached to a module from string 2.16 for the I-V curve measurements (a module from string 2.15

was used to measure string 2.16). The PT100 is shielded from direct sunlight to prevent a temperature increase caused by the irradiation.

Where results from both I-V curve measurements are shown (flasher and on-site), the reference to indoor and outdoor measurement are added to enable a better differentiation.

Figure 3 shows the evaluation steps for the I-V curve measurements, including input data and analysis steps. The test reports of the measurements at the AIT are evaluated with regards to the Maximum-Power-Point (MPP) power of the modules, compared with the data sheet value and the deviations are analysed. Based on the change in module output, the degradation rates of the measured modules in the first year of operation are calculated. Furthermore, the module's I-V data, provided by the AIT, is imported and processed in Python. The raw measurement current-voltage data is averaged over 500 data points, new curve points at uniform current values are calculated for all module I-V curves using interpolation. The module I-V curves of string 2.40 are combined to string I-V curves for the years 2022 and 2023 with the addition of the module voltage values at the same current value. This enables a qualitative analysis of the string I-V curves and the calculation of the degradation rate of string 2.40.

The string characteristics measured with the HT I-V 400 (excel file) are processed as well in Python. In the first step a simplified STC correction is performed for the string I-V

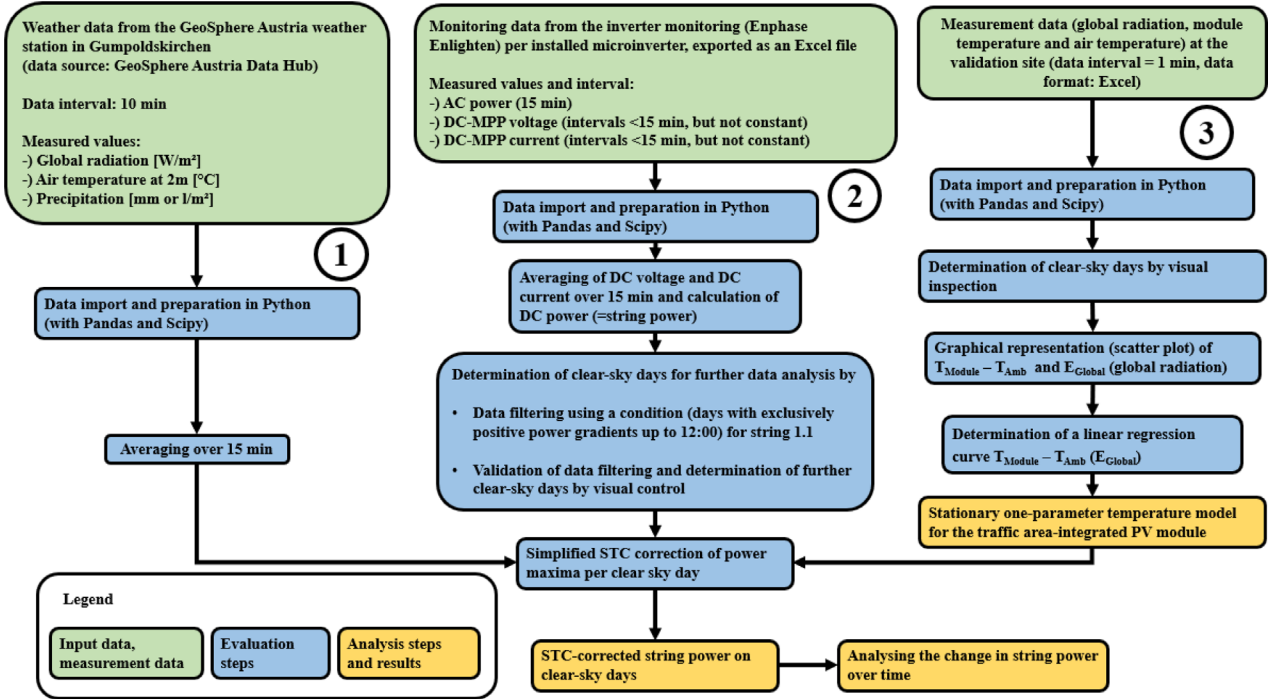


Fig. 4. Flow chart of monitoring data analysis. The numbering corresponds to the order the steps are carried out.

curve of string 2.40 and graphically validated with the string I-V curve of the AIT measurement for the year 2023. The STC correction applied is described in the following Section 2.2.2.1. After validation of the simplified correction method, the STC correction of all measured string I-V curves is performed. This is then used to validate the simplified STC correction applied to the monitoring data.

2.2.2.1 I-V curve measurements at the PV parking place and simplified STC correction

As the correction methods described in IEC 60891 [36]^{*} cannot be used for the STC correction, a simplified STC correction of the measured string I-V curves is carried out based on the influencing factors on the I-V curve given by (1) and (2). It considers the temperature dependency of the module's voltage and the linear influence of irradiation on the current. The corrected voltage values U_{n_C} are calculated with the voltage values of the measured I-V curve U_{n_M} , the temperature coefficient of the open circuit voltage α , the measured module temperature T and the STC temperature T_{STC} . For the calculation of the corrected current values I_{n_C} the measured current values I_{n_M} , the short-circuit current of the measured I-V curve I_{SC_M} , the measured irradiation E_M and the STC irradiation E_{STC} are used. If the short-circuit current were replaced by the term of the respective current value I_{n_M} , the correction would not consider the irradiation

dependence of the voltage. The influence of temperature on the current is neglected. Finally, the MPP of the respective string is determined using the STC-corrected string I-V curve.

$$U_{n_C} = \frac{U_{n_M}}{(1 + \alpha \cdot (T - T_{STC}))} \quad (1)$$

$$I_{n_C} = I_{SC_M} \cdot \left[\left(\frac{E_{STC}}{E_M} \right) - 1 \right] + I_{n_M} \quad (2)$$

2.2.3 Monitoring data analysis

The monitoring data analysis is carried out in several steps and uses further data sources in addition to the inverter monitoring (Enphase[®] Enlighten[®]). The process is shown in Figure 4.

First, the necessary meteorological data for the analysis is collected and processed in Python. As no weather station was installed at the car park in Teesdorf at the time the system was commissioned, weather data (global radiation, air temperature) from the GeoSphere Austria weather station closest to the system location is used. The data of the weather station in Gumpoldskirchen (~10 km distance to the RIPV system) is exported from the GeoSphere Austria Data Hub [37].

In the second step the data of the inverter monitoring is exported, collected and processed for all 42 strings in the period from 12th April 2022 to 30th June 2024. As the DC parameters do not have constant recording intervals (less than 15 min) average values over 15 min are calculated and

^{*} The correction parameters for methods 1, 2 and 4 are not known and cannot be calculated due to only one recorded I-V curve per string. Method 3 requires the measurement of several I-V curves and is therefore also not applicable for this work.

used to determine the DC power. The DC parameters correspond to the MPP parameters (MPP current and MPP voltage) of the strings. Then clear-sky days are selected in the observation period. These are needed for the trend analysis of the string power values over time and the application of the STC correction. The selection is made by filtering the power data – days with exclusively positive power gradients up to 12:00 p.m. – and validated via visual data inspection. The string used for this filtering is 1.1, as this has the least shading in the winter months and little shading from vehicles is assumed. The performance of all strings on the clear sky days is then analysed for deviations and anomalies.

As it is expected that RIPV modules have a different temperature behaviour than standard PV modules (slower behaviour due to higher heat capacity and no rear ventilation) and no backsheet temperature for the parking place modules are recorded, a stationary one-parameter temperature model is developed. Measurement data from the validation period of the measurement hardware is used for this. The measurement setups and the used hardware components are described in [27]. The measurement data (global radiation E_{Global} , module backside temperature T_{Module} and air temperature T_{Amb}) is exported from the data logger and imported into Python for data processing. The observation period is the month of September 2023. As with the monitoring data, clear-sky days are determined based on the global radiation for the next evaluation steps by visual data inspection. The selected days are then displayed graphically in a scatter plot ($T_{\text{Module}} - T_{\text{Amb}}$ on the ordinate and E_{Global} on the abscissa). A linear regression curve is determined for a specified period of the day (at least until 12:00). The parameters (slope k and offset d) of the regression curve are used to create a radiation-dependent stationary temperature model according to (3).

$$T_{\text{Module}} = T_{\text{Amb}} + k \cdot E_{\text{Global}} + d. \quad (3)$$

With the created temperature model, the GeoSphere Austria weather data and the monitoring data, an STC correction of the power maxima on the determined monitoring clear-sky days is carried out according to (4). It should also be noted that the global radiation maximum E_{M_max} is not calculated at the same time as the MPP power maximum P_{MPP_M} , as local differences (distance between GeoSphere Austria weather station and car park) can result in deviations (local shading by clouds, etc.). The temperature coefficient of the MPP power γ is shown in Table 1.

$$P_{MPP_STC} = \frac{P_{MPP_M} \cdot \left(\frac{E_{STC}}{E_{M_max}} \right)}{(1 + \gamma \cdot (T_{\text{Module}} - T_{STC}))}. \quad (4)$$

The STC-corrected string power values are then validated with the power values of the STC-corrected string I-V curves and power values of the calculated string I-V curve of string 2.40 (based on the AIT module measurements). The last step is the analysis of the evolution of the string powers over the analysis period.

2.3 Electroluminescence

Night-time electroluminescence (EL) measurements are carried out on 9th May 2022, 15th May 2023 and 2nd October 2023 to analyse possible cell cracks and contacting problems at the RIPV modules and to determine short-circuited bypass diodes. The MBJ Mobile EL from MBJ Solutions is used as the measuring system for this. The system consists of a camera (silicon detector) with a frame, a power supply unit and a laptop with a control and analysis software. The voltage and current range of the power supply is 0 to 60 V and 0 to 25 A.

Due to the mounting frame and field of view of the camera only four to six of the PV modules are captured in one EL image. This means that up to four individual images are required to capture an entire string EL image. The reverse current is not selected in accordance with IEC TS 60904-13 [31] (reverse current with I_{SC} and $0.1 \times I_{SC}$), as it is not possible to set this current value for strings with long cable lengths due to the voltage limitation of the power supply unit. Instead, the reverse currents are set individually. The same thing applies to the exposure time, which is determined separately on each measurement day using test images and is adjusted during the individual recordings.

For the evaluation, the individual EL images are combined in the GIMP image processing software to create string and complete system EL images. In the final step, the EL images are analysed qualitatively (occurrence of cell cracks and their development over time, interconnection problems at the solder connections and identification of short-circuited bypass diodes).

2.3.1 Dark I-V curve measurements

A self-built measurement setup consisting of a current sensor (LEM CKSR 15-NP [38]), a voltage sensor (LEM DVC 1000-P [39]) and a measuring device (MonoDAQ-U-X [40]) is used to measure the dark I-V curves. The DewesoftX software (installed on a laptop) is used for data acquisition. The string under test is connected with the measurement box and a regular laboratory DC power supply. The DC supply used has a voltage and current range of 0 to 60 V and 0 to 5 A.

The dark I-V curve measurement was carried out together with the last EL measurement on 2nd October 2023. The dark I-V curve is recorded from the reverse bias quadrant to forward bias quadrant by manually changing the voltage value on the power supply unit.

The measurement data is recorded at a sampling rate of 10 kHz and averaged over one second for evaluation. In the next step, the I-V curve data is exported as an excel file. Afterwards the files are then imported into Python, displayed graphically and analysed qualitatively. Possible bypass diode faults are identified by higher reverse voltages with the same reverse current in a relative comparison to the other strings. Short-circuited bypass diodes can be detected by lower voltages in the forward bias quadrant.

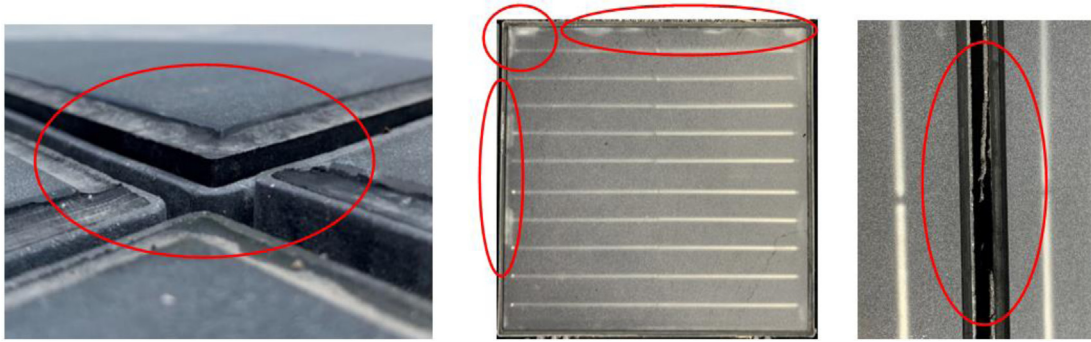


Fig. 5. Main material degradations found during visual inspections: Detachment of the top layer (glass-foil-module) from the base structure (left), delamination at the module glass edges (middle) and broken module edges (right).

2.3.2 Signal transmission method

If open circuit problems occur during the analysis period the signal transmission device pvTector from photovoltaikbuero [41] is used for locating the open circuit position. The method works with two different frequency signals [30] injected in the open circuit string at both poles in reference to ground. With a receiver the injected signals are converted to audio signals. Then the string under test is examined with the receiver. Where the audio signal switches frequency the open circuit position is found.

3 Results

This section describes the results of the failure mode analysis. The failure modes determined by the applied analysis methods are explained and assigned to their possible causes. The results of the quantitative methods (I-V curve measurement and analysis of the monitoring data) are used to quantify the effects of failure modes in terms of power losses. Based on the results of the qualitative methods (visual inspection, EL and dark I-V curve measurement) the causes or possible causes of all detected failure modes are described.

3.1 Visual inspection and signal transmission method

The main failure modes found through visual inspection are presented in Figure 5. Three months after the systems commissioning, at some glass-foil modules detachments from the module substructure and break outs at the module edges were observed. This allowed water to enter the room between the glass-foil module and the substructure. The observed material degradations are not linked to a decrease in system or string power for the first year of operation. However, a connection with power losses due to module and cell short circuits was found in the second year (see Sect. 3.4). In addition to the detachment of the glass-foil modules and the broken edges, visually flawless modules also showed water ingress between the module glass and the module edges, as the seals on the module edges had come loose (only visible under very close inspection). These water ingresses were detected by a person walking over the modules.

As the inspections progressed, an increased occurrence of delamination at the module edges were detected. In conjunction with the material defects described above, this led to the replacement of 34 modules on 9th August 2022. Two modules of string 2.40 were replaced in this process as well.

On 7th February 2023, two modules with broken glass were detected by the municipality of Teesdorf. No correlation between the modules position in the system and the defect type were found. Vandalism was assumed to be the cause of the two glass breakage modules. A surveillance camera had not yet been installed at the parking place at this point. However, due to the renewed occurrence of the failure mode in January 2024, a temperature-related cause in connection with the ingress of water – freezing and subsequent vehicle loading – could not be ruled out. Due to a camera malfunction renewed vandalism must also be considered.

In addition to the increasing number of modules with edge delamination, modules with already existing edge delamination showed an increase in the delaminated module area. Recognisable delamination above the cell surfaces (see Fig. 5.) indicates that the delamination is between the glass and the encapsulation. The delamination can be attributed to several possible causes. Firstly (1), delamination is favoured or caused by not optimally selected lamination parameters (temperature and pressure) [42]. Secondly (2), delamination could be favoured by the detachment of the glass-foil module from the module substructure – possible connection between the delamination at the module edges and the adhesive points. The third (3) possible cause is the stress caused by the vehicles during acceleration and braking. As these forces are not absorbed directly by the module frame and transferred to the module substructure via the glue point, the possible displacement of the module layers can reduce the adhesion to the neighbouring materials (cell, glass or backsheets) and cause delamination.

The breaking off of the module edges is primarily attributable to insufficient material thickness. In addition, the UV resistance of the substructure's copolymer material and missing expansion joints must not be disregarded as a further cause or accelerating influence. The latter mentioned is due to a planning error where the thermal expansion of the modules was not considered.



Fig. 6. Detected open-circuit positions at string 2.42 (left) and string 2.41 (right) with the signal transmission method.

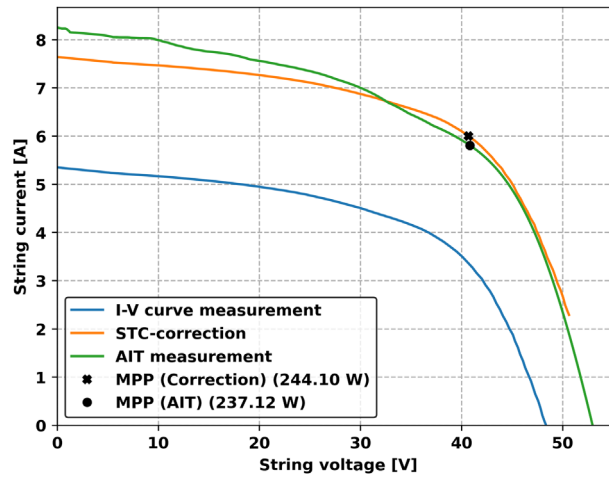


Fig. 7. Validation of the simplified STC correction of the string I-V curve measurement (outdoor) of string 2.40 with the calculated string I-V curve from the AIT module measurements (indoor).

As already mentioned, the material degradations progressed further or even accumulated in some modules (detachment, edge breakage and delamination). In June 2024, modules were discovered in which the mechanical and electrical connection to the substructure was interrupted and the modules were therefore no longer connected to the strings. These modules had broken edges in common and the most plausible cause of disconnection of the electrical wiring is due to horizontal vehicle forces (e.g. braking or acceleration).

During the operation time of the system two strings (2.42 and 2.41) went out of operation and an open circuit problem was identified as the cause of the failure. Through the signal transmission method, it was possible to locate the open circuit positions (Fig. 6). Crushed cables caused the open circuit due to either wrong installation or the thermal movement of the PV modules over time.

3.2 I-V curve measurements

Figure 7 shows the measured outdoor I-V curve, the STC corrected string I-V curve and the calculated string I-V curve based on the AIT measurements in 2023 of string 2.40

(indoor). The MPP power of the STC corrected string I-V curve is 244.10 W and deviates 2.94% from the MPP power of the AIT string characteristic curve (237.12 W). The qualitative comparison of the two STC curves shows a match of the characteristic curve in the MPP range, whereby the STC corrected I-V curve lies above the AIT I-V curve. Since the deviation of the MPP power is in the range of the measurement uncertainty of the I-V-400, the simplified STC correction was applied to all measured string characteristics.

The deviation of the AIT I-V curve from the STC corrected string I-V curve at lower string voltages, which does not affect performance, can be explained by faulty bypass diodes in the modules of string 2.40. As a result, the weakest module limits the string power at lower voltage values. This was not considered when creating the I-V curve based on the AIT measurements. No extrapolation was carried out for the STC-corrected characteristic curve in the open-circuit voltage range, as this was not required for validation.

Figure 8 shows the validation of the monitoring data STC correction with the STC-corrected MPP powers of the string I-V curve measurement (outdoor). For this purpose,

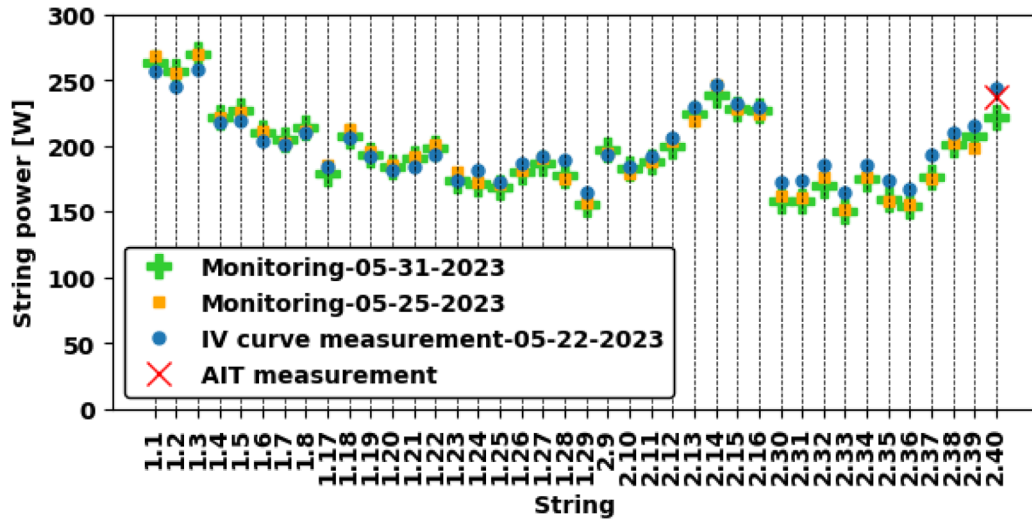


Fig. 8. Validation of the STC corrected monitoring data with the STC corrected string I-V measurements (outdoor) and the AIT measurement (combined string I-V curve; indoor) based on the string MPP powers.

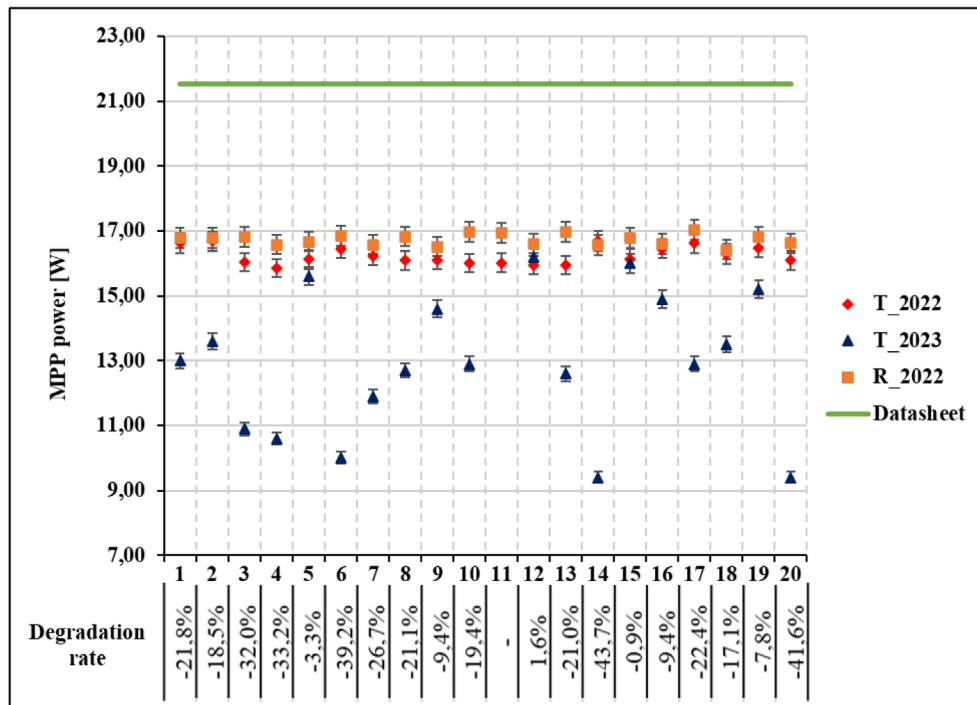


Fig. 9. Measured MPP power of the modules (indoor measurement) of string 2.40 (T_2022 and T_2023) and the reference string modules (R_2022) compared to the data sheet value. Power values with the uncertainty range of the measurement device [35,36].

one clear-sky day before and after the string I-V curve measurement is used. Further the MPP power of the combined string I-V curve from the indoor I-V curve measurements at the AIT is added. With an average deviation (I-V curve vs. monitoring data) of 2.1% (21 May 2023) and 1.5% (25 May 2023), it can be stated that the simplified STC correction is valid. However, it should be noted that there are deviations of up to 9.5% (overestimation) specific to the strings, which must be considered when analysing the results.

The results of the module I-V curve measurement at the AIT are shown in Figure 9 based on the MPP power. After commissioning, the modules of string 2.40 have a maximum output power that deviates from the data sheet (21.52 Wp) with an average of 16.25 Wp (T_2022) and are 24.5% below the manufacturer's specifications. The same can be seen for the modules of the reference system (R_2022) with an average output of 16.74 Wp (-22.2%). The measurements of the string 2.40 modules after one year (T_2023) show a further reduction in output power to an average of

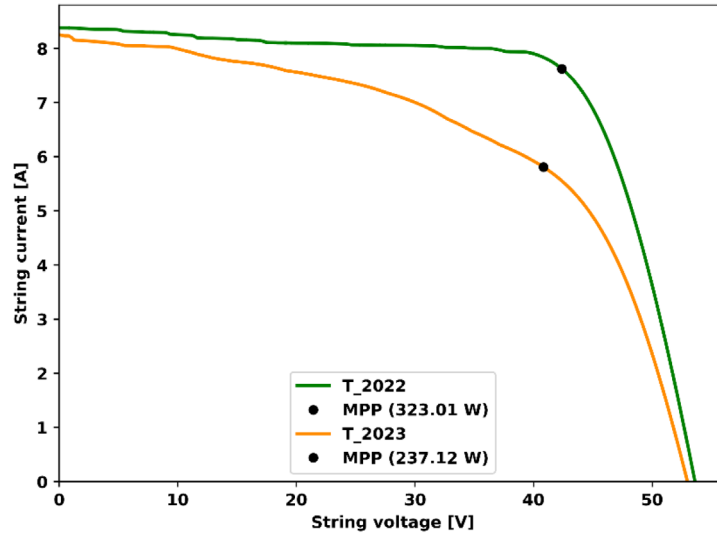


Fig. 10. String I-V curves of string 2.40 (calculated from the module I-V measurements at the AIT) for 2022 and 2023 (both indoor measurements).

12.94 Wp (−39.9% compared to the data sheet value), whereby the outputs are more widely distributed (16.20 Wp to 9.40 Wp). Only three of the modules (5, 12 and 15) show no power losses when the measurement uncertainty is considered. A further analysis of the I-V curves is carried out in [27].

Based on the two measurements in 2022 and 2023, the degradation rate of the string 2.40 modules can be estimated at an average of 20.4% for the first year of operation. The fluctuation range is 1.6% to −43.7%.

Figure 10 shows the string I-V curves of string 2.40, which were calculated from the module I-V curves of the two AIT measurements (2022 and 2023). The string MPP power is 323.01 W after the system commissioning and 237.12 W after one year of operation. This results in a degradation rate at string level of 26.6%. The difference to the average module degradation rate of 20.4% can be explained by the current limitation of the weakest module. Considering the slope of the 2023 I-V curve at I_{SC} and the steps in the region of I_{SC} the drop in the filling factor, compared to the 2022 I-V curve, is attributed to cell cracks (drop of parallel resistance) (see Sect. 3.4) and delamination (see Sect. 3.1). With I-V curve measurements power losses can be calculated, but a clear assignment to failure modes solely on I-V data is not possible for all detected changes in the curves slope. Therefore, I-V curve measurements should be combined with other failure analysis methods (thermography, EL, etc.). For Figure 10, one could assume that failure modes affecting the series resistance, such as solder corrosion, homogeneous soldering disconnections or broken cell interconnect ribbons [28], are present, due to the slight change in the slope at V_{OC} . Although with EL (see Sect. 3.4) and visual inspections those modes can be ruled out. The slight change in the slope at V_{OC} and the reduction of V_{OC} is influenced by a low parallel resistance due to the cell cracks. With increasing cell cracks and inactive areas this change in the I-V curve will increase.

3.3 Monitoring data analysis

In the first year of operation, the yield of the PV parking place is 10.2 MWh (spec. 100 kWh/m²), which corresponds to a deviation of 27.14% from the expected yield of 14 MWh (calculated through simulation in PV*Sol[®] Premium). The reason for this deviation is due to the reduced module power compared to the data sheet value at the time of installation and further power degradations during the first year of operation. Figure 11 shows the increasing deviation of the correlation between irradiation and PV power (AC) in spring 2023. The figure also shows the timestamps of the conducted measurements, failures and module replacements. Due to a power share of 2.5% (based on the number of modules), the failures of string 2.41 and string 2.42 are not visible. The failure causes of string 2.41 and 2.42 were identified through the measurement of the open circuit voltage. As explained in the previous section the open circuit positions were found with the signal transmission device.

The measurement results in the form of the irradiation-related module temperature increase ($T_{Module} - T_{Amb}$) as a function of the global radiation for six September days (clear-sky days) are shown in Figure 12. In addition to the temperature behaviour of the RIPV module, the temperature behaviour of a regular PV module is illustrated. The temperature behaviour of the standard module can be described by a straight line with an origin near the zero point (offset of approx. 2.5°C). The reasons for the deviation of the regression curve from the intersection point at the zero point are the short period for modelling and the scattering of the measurement data due to the cooling influence of the wind.

The temperature behaviour of the RIPV module shows a time-dependent curve compared to the standard module. Further it is shown that the RIPV module has a lower temperature till 650 W/m² due to the higher heat

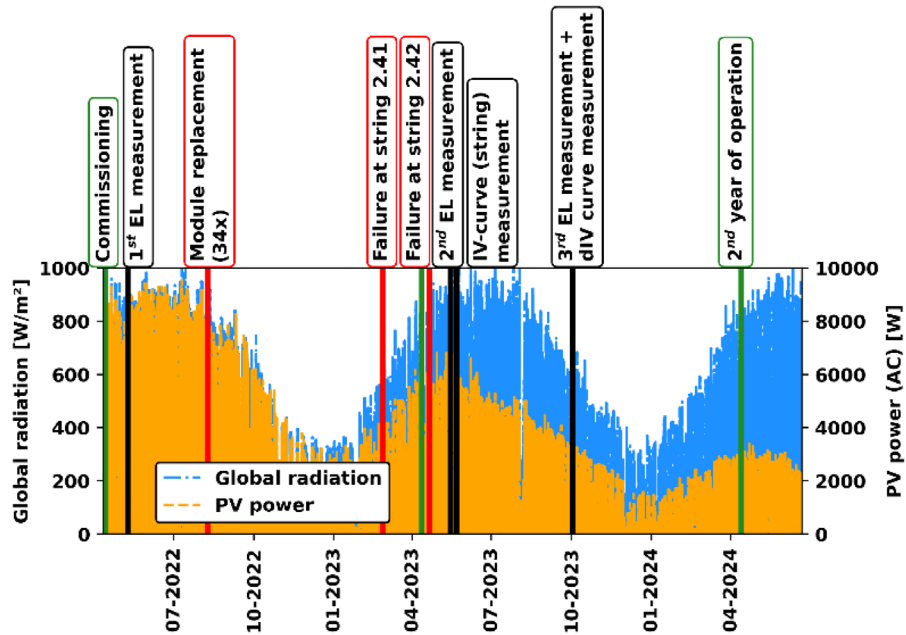


Fig. 11. AC power output of the PV parking place. Global radiation of the weather station in Gumpoldskirchen and marked time events (green = operating time, red = string outages problems, black = measurements).

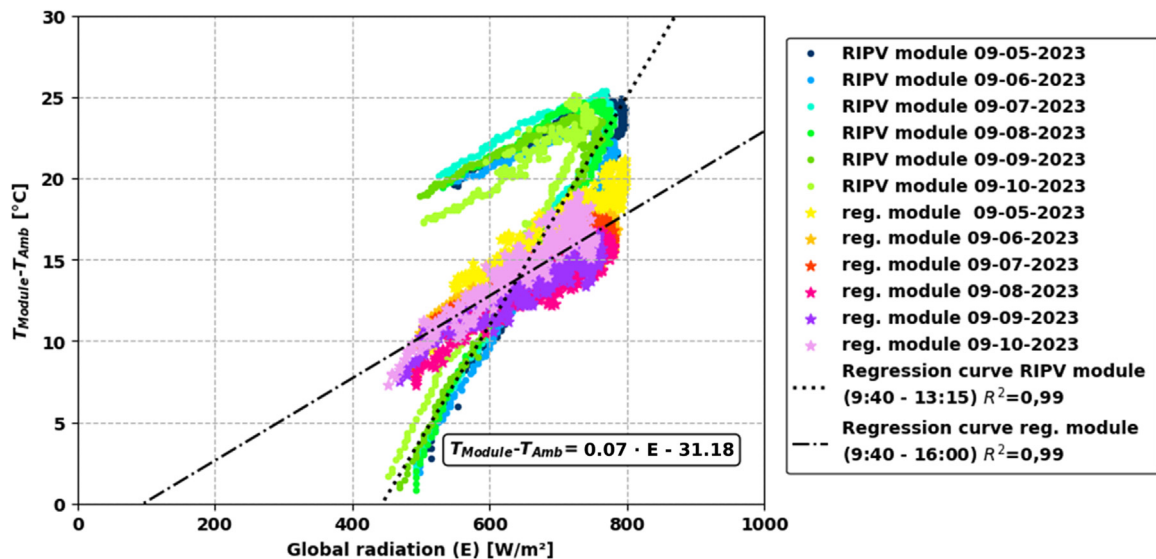


Fig. 12. Temperature behaviour of the analysed road-integrated PV module (RIPV) and a regular (reg.) module from 09:40 to 16:00. Regression curves for both modules and the regression parameters of the temperature model for the RIPV module.

capacity. At over 650 W/m^2 , the temperature of the RIPV module rises above the temperature of the regular module as there is no rear ventilation. The temperature rise of the RIPV module in the morning shows a higher gradient than the temperature decline in the afternoon. This indicates that the heat capacity of the module must be considered when developing a temperature model for an annual simulation of RIPV systems. However, as the temperature model in this work is only used for the simplified STC correction, the temperature behaviour in the afternoon is not considered further.

A linear regression curve was calculated for the period from 9:40 to 13:15. The calculated parameters of the regression curve were used to create the temperature model. As the curve does not originate at the zero point, it is assumed that the module temperature corresponds to the air temperature for radiation values below 450 W/m^2 .

Figure 13 illustrates the development of the STC-corrected module-normalised power (string power per module) over the RIPV systems operation time. The use of the module-normalised power is necessary to make the string powers comparable due to the different string lengths.

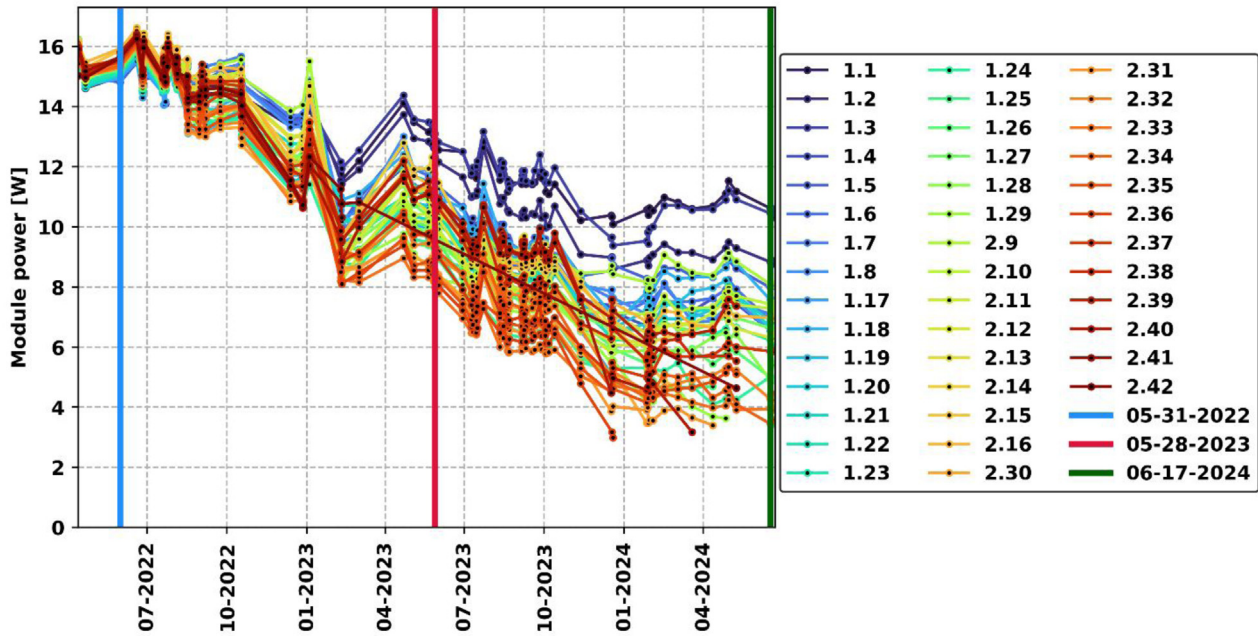


Fig. 13. Evolution of the STC corrected string powers (shown as module-normalised power) on the selected clear-sky days.

Furthermore, string values with module-normalized power below 2 W are not shown for better clarity, as strings with these values can be considered non-functioning at that time.

In comparison to Figure 11, a reduction in power can already be seen in September 2022, which continues until the end of the observation period. The string powers show an increasing spread over the operating time. The correlation between string position in the system and power reduction is also recognisable here – strings that are in middle of the systems or closer to the municipality centre degrade faster as more cars park there. The fluctuations and outliers in the power curves are due to soiling, self-cleaning by rain and the developed temperature model. Based on the monitoring data, the average power losses of the strings in the first year of operation (comparison of 31st May 2022 with 28th May 2023) are 33.5% with a spread of 13.8% to 47.8%. For the second year of system operation (comparison of 31st May 2022 with 16th June 2024) average power losses of 56.2% with a spread of 29.2% to 77.5%. However, 18 strings were no longer in operation on 16th June 2024, as the string voltage was below the starting and operating voltage of the inverters.

3.4 Electroluminescence

The EL images of the on-site measurements carried out in May 2022, May 2023 and October 2023 are shown in Figure 14. For a detailed analysis, the EL images of string 2.40 are presented in Figure 15. It must be stated that a comparison between the strings (e.g. comparison of the local series resistances) is not possible due to the different reverse currents [27]. For the classification of cell cracks the modes explained in Köntges et al. [43] and IEC TS 60904-13 [31] are used.

In the EL image of 2022, the modules show differences in the local series resistance – evident through the contrast differences in the module and string. These contrast differences are due to contacting problems at the soldering points (modules 2, 3, 5, 9, 12, 15 in Fig. 15). Furthermore, cell cracks of type A are visible (modules 3, 4, 5 and 8 in Fig. 15). As the first EL image was taken approximately one month after commissioning, the cell cracks may have occurred either during module production or in the first month of operation.

The EL image of May 2023 confirms cell cracks and cell fractures as the main cause of the power losses. A comparison of the images (May 2022 with May 2023) shows a significant increase in cell cracks and cell fractures. Most cell cracks can be classified as type B and type C, with type C cell cracks being the most frequent. Modules with cell cracks or cell fractures show almost the same fracture or crack pattern – diagonal cracks with active cell areas at the outer cell edges. Based on the repeating patterns, the cause of the cell cracks and cell fractures are attributed to the vehicle load and the inadequate support of the glass-foil module by the substructure of the analysed module. In addition to modules where all four PV cells show diagonal cracks, there are also modules with only one to three affected cells. The reason for this could be a difference in wafer/cell quality [44] or an asymmetrical load on the modules (e.g. vehicle tyres only apply load to the edge of the module).

The possible development of the cell cracks over time can be seen in module 5 in string 2.40: Starting from a semi-circular continuous crack at the outer cell corner, finer cell cracks and cell fractures occur over time, which move towards the centre of the module.

In addition to the cell cracks, short-circuited cells in strings 1.2, 1.27 and 2.38 and short-circuited modules in strings 1.28 and 2.38 are seen (October 2023) in Figure 14.

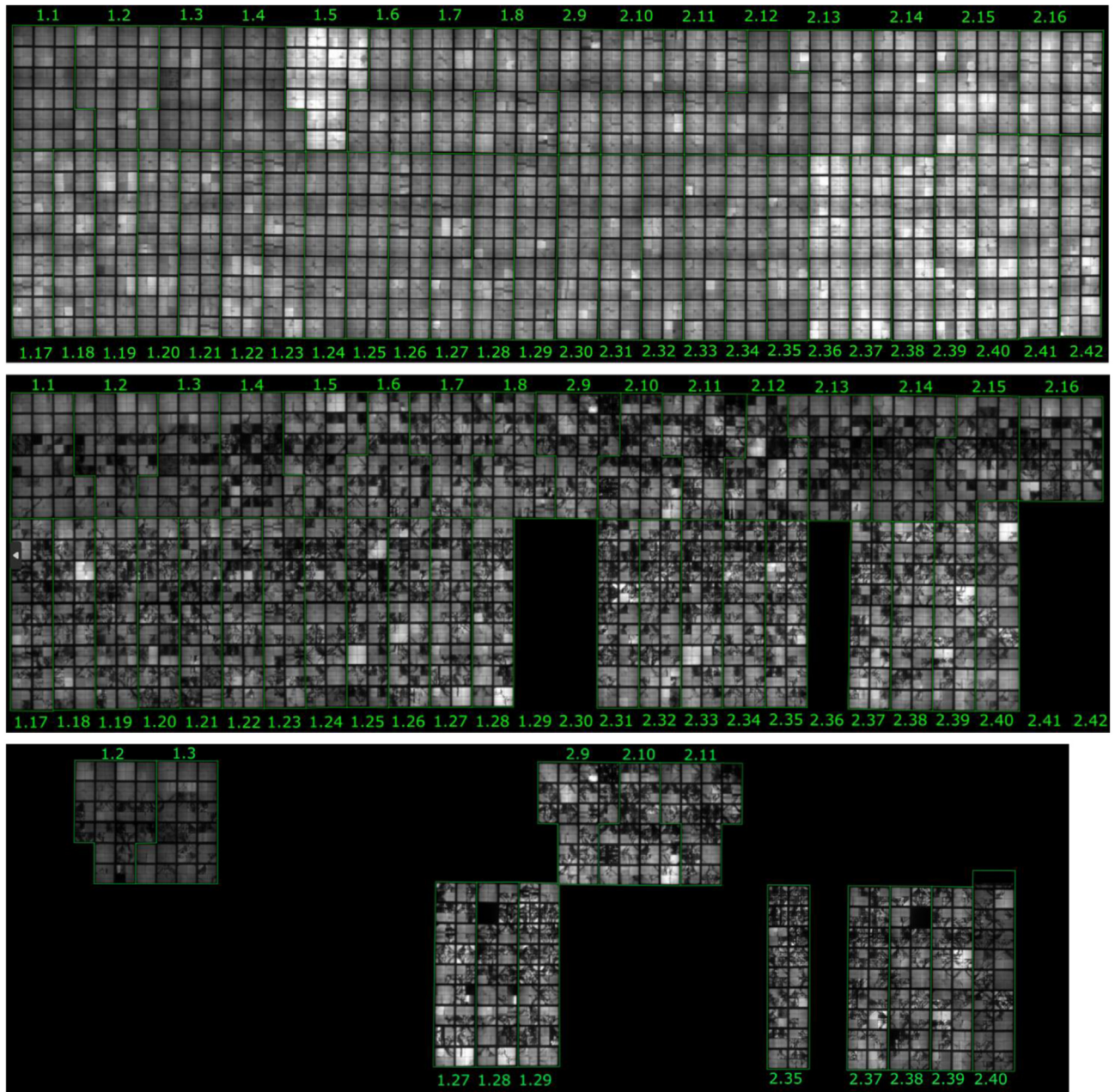


Fig. 14. EL images of the PV parking place in May 2022 (top), May 2023 (middle) and October 2023 (bottom) with string label.

Short-circuited cells occur when both cell poles are short-circuited by moisture due to delamination. At module level, the cause also appears to be due to water ingress between the glass-foil module and the module substructure, where the bypass diode is located. The outage of 18 strings in June 2024, due to too low voltage, shows that the number of short circuits (module or cell) increased in the second year of operation.

The strings with the least cell cracks are string 1.1, 1.2 and 1.3, which are located on the side of the cable ducts and are the furthest away from the entrance to the community centre. It must therefore be assumed that cars were parked less frequently in these parking places compared to other.

The inactive cell areas of the EL image of string 2.40 from May 2023 in [Figure 15](#) show a high correlation with the MPP power data in [Figure 9](#). Two modules (modules 12 and 15) in string 2.40 are noticeable, with no recognisable cell cracks until October 2023. The situation is similar for other strings. A lower mechanical load on these modules can be ruled out with a high degree of certainty due to the cell cracks in the neighbouring modules.

The EL image of string 2.40 ([Fig. 15](#)) shows that there is only a slight increase in cell cracks between May 2023 and October 2023. Modules 2, 3, 6, 7, 11, 14, 16, 17 and 19 of string 2.40 show no or marginal changes in the crack

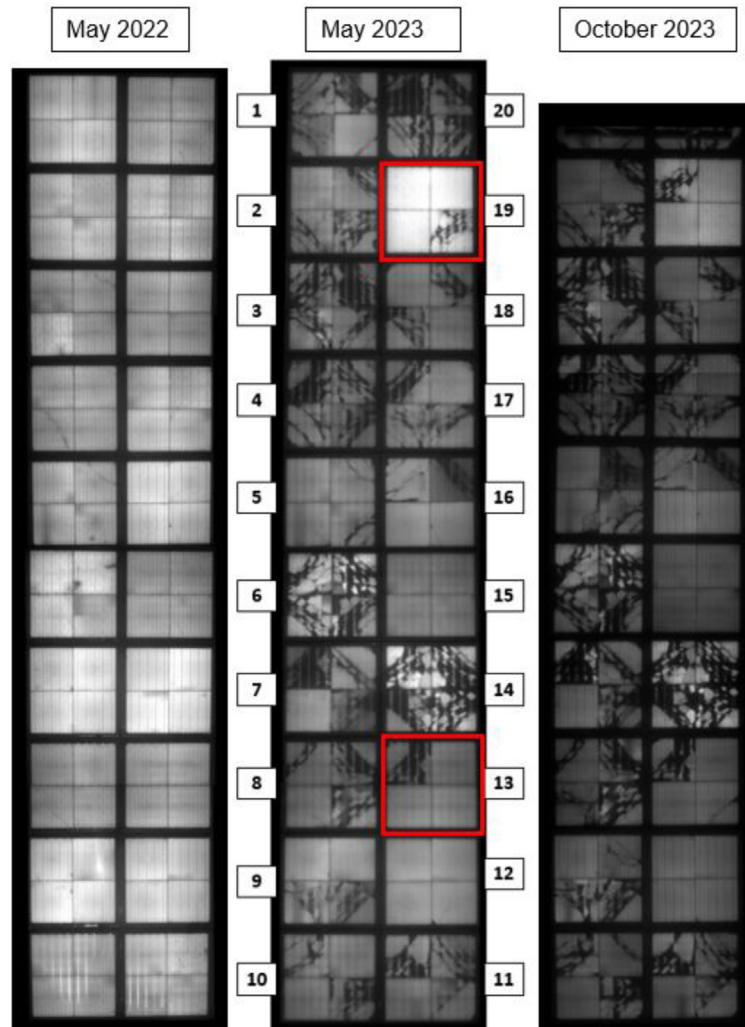


Fig. 15. EL images of string 2.40 in May 2022 (top), May 2023 (centre) and October 2023 (bottom). The numbering corresponds to the module numbers in Figure 9. Replaced modules are marked in red.

pattern. This further indicates that the power losses after October 2023, shown in Figure 13, are due to cell and module short-circuits.

3.5 Dark I-V curve measurement

The dark I-V curves of the measured strings in October 2023 are shown in Figure 16. Out of the 16 strings (reference string excluded), which represent 40% of the strings functioning at this time, two (string 2.36 and 2.30) show no current flow in the forward direction. The reason for this is attributed to temperature-related contacting problems in the modules. No power deviations of the affected strings in relative comparison to the other strings during daytime and the enabling of a current flow due to a mechanical load during the measurement of string 1.28 support this assumption.

Furthermore, faults due to open bypass diode paths are visible in the dark I-V curves. The affected strings 1.2, 2.35 and 2.40 have flatter reverse I-V curve compared to the other strings. The number of modules with an open bypass

diode path per string cannot be calculated due to the unknown reverse I-V curve of the tested modules. For the remaining strings, including string 2.36 and 2.30, no bypass diode fault is detectable. Assuming that all measured modules are installed with functioning bypass diodes, the open bypass diodes are due to water ingress behind the glass-foil module and the electric wiring of the bypass diode. Furthermore, thermal overload due to a lack of rear ventilation cannot be ruled out.

In addition to the string dark I-V curves of PV parking place, the dark I-V curve of the reference string with 20 modules (Ref. string) is shown in Figure 16. In the reverse voltage quadrant, this string shows the diode characteristic of 20 passive bypass diodes (pBD), which have higher voltage drops than the active bypass diodes (aBD) installed in the rest of the RIPV modules.

As Figure 16 shows strings with different numbers of modules and therefore faults in the forward bias quadrant are more difficult to recognise, Figure 17 illustrates strings with 18 modules. A buckle in the dark I-V curve of string 1.28 (orange) is recognisable, which is due to an electric arc.

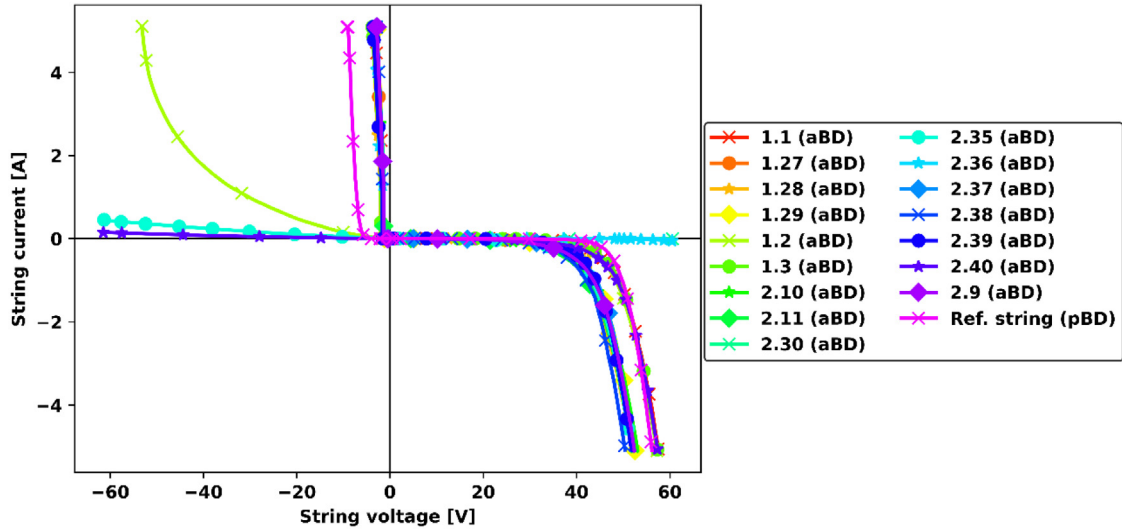


Fig. 16. Dark I-V curves of all measured strings at the PV parking place (x.xx) and reference string (ref. string). The abbreviation in brackets refers classifies the present bypass diode type in the strings (aBD = active bypass diode, pBD = passive bypass diode).

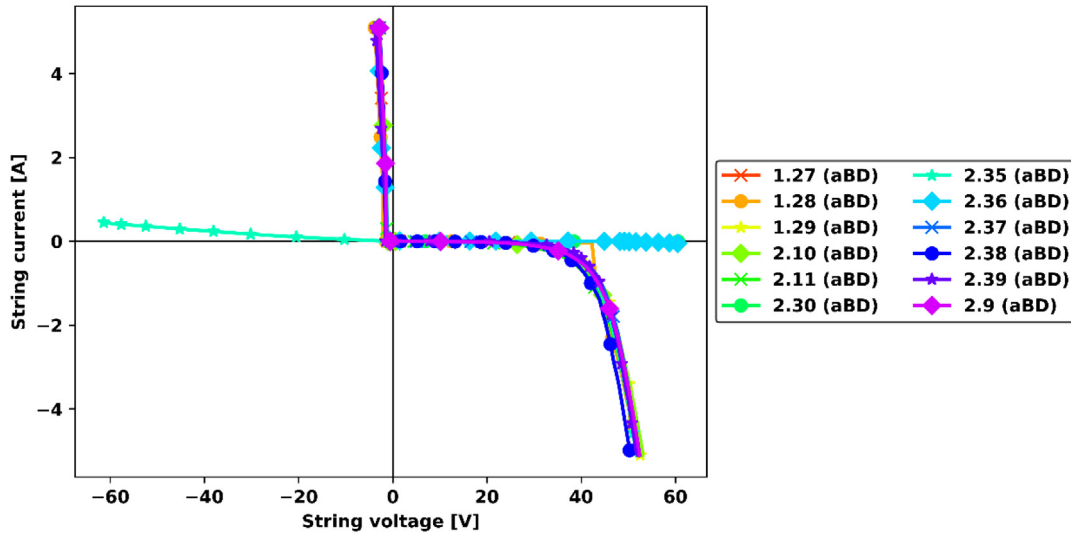


Fig. 17. Dark I-V curves of all measured strings with 18 modules.

The affected module could not be localised as the arc was not visually detectable during the measurement. The affected area in the module is initially non-conductive at low voltages and becomes conductive at higher voltages due to the arc. Second, a voltage difference can be seen at string 2.38 and 1.28 (overlap of the dark I-V curves) compared to the remaining strings with 18 modules. This voltage difference is caused by one short-circuited module in each string. Due to the low open-circuit voltage of the modules and the number of 20 bypass diodes in a string, the exact identification of a module short-circuit is difficult without the inclusion of an EL image.

4 Discussion

The results of the failure mode analysis at the PV parking place in Teesdorf show that several analysis and measurement methods are required for a comprehensive failure mode analysis to quantify the effects of failures and identify the their causes. The I-V curve measurement and the analysis of the monitoring data are suitable as quantitative methods for determining power losses at system, string or module level. By using visual inspections, electroluminescence and dark I-V curve measurements as quantitative methods, it is possible to localise faults and determine the causes of faults.

The visual inspection method has proven to be advantageous compared to data collection using a checklist, as it enables more time-efficient data collection. A disadvantage is the lower level of detail of the information per module compared to a checklist and consistency problems when different parties carry out the inspection. In the case of PV modules for road-integration, however, it can be assumed that faults will occur more frequently due to the module design, the choice of components or the type of installation. These can be analysed more time-efficiently by classifying the fault types. Therefore, the level of detail per module of visual inspections can be kept low at the beginning of application-orientated testing of new PV modules. In the further stages of development, the level of detail should be increased. The combination with other failure analysis methods (I-V curve measurement, EL, etc.) is recommended before increasing the level of detail, as not all types of failure modes can be detected with visual inspection (e.g. cell cracks, bypass diode problems).

Regarding the used quantitative methods, it must be mentioned that the calculated power losses and degradation rates at string level are subject to uncertainties. For example, the simplified STC correction of the string I-V curves and monitoring data represents a possible uncertainty, as not all factors influencing a PV I-V curve were considered. This can be seen from the varying deviation of the string power of both data sources in Figure 8. The short measurement period (one week) of the created temperature model must also be considered as an uncertainty. It is not possible to precisely quantify the uncertainties of the data from the string I-V curve measurement and the monitoring system due to the simplifications made. However, uncertainty quantification would provide little additional benefit due to the extent of the calculated power losses, and as the power degradation of strings progresses over time, the modules no longer fulfil their purpose sufficiently and must be replaced under the manufacturer's warranty.

The EL imaging carried out at the PV parking place made it possible to identify cell cracks and cell fractures as the main cause of the power losses. Regarding the choice of reverse currents for the EL imaging, a standardised return current for all strings would have enabled a string comparison. This should be considered for future measurements at the PV parking place.

The dark I-V curve measurement was used to identify three open bypass diode paths and two short-circuited modules in 16 measured strings. Short-circuited modules are easier to be identify in the dark I-V curve compared to the daylight I-V curve as no temperature differences are present between the modules at night. The low open-circuit voltage of the PV module under test (2.68 V) nevertheless represents a certain scope for misinterpretation compared to a standard PV module. Recording the dark I-V curve with standardised current values could reduce this and would enable software-supported detection.

With open bypass diode paths, there is a risk of hotspots with damaging effects on the cells. This risk increases when close shading by vehicles is considered. As thermography was not used in the failure analysis due to assumed blurred images stemming from the glass thickness, no correlation

between the local heat generation and open bypass diode was analysed in this study. Nevertheless, the local heat generation due to close shading should be analysed in future work on RIPV module and could be helpful in the optimization of shade resistant module designs.

5 Conclusions

The RIPV module used at the parking place in Teesdorf is comparable with other available RIPV modules in terms of cell technology (monocrystalline silicon) and module structure (thickness of the module components, which absorbs the mechanical loads). Differences may arise from the type of integration into the traffic area (adaptation vs. integration), the material of the cover layer (glass vs. synthetic resin). Nevertheless, it can be assumed that the main findings of this work (delamination, cell cracks and bypass diode problems) can be transferred to other RIPV systems, considering the module structure (glass-glass or glass-foil), the module components and the vehicle loads to which the modules are exposed. For validation purposes, the transferability of the results of this work can only be verified based on further comparable analyses on other RIPV systems.

Both material degradation (detachment of the glass-foil module from the module substructure, delamination and module edges breaking away) and power degradation were found at the RIPV system. The material degradations could not be directly linked to the determined performance reductions, but the detachment of the glass-foil module together with the breaking module edges allowed water to enter the module. This water ingress was identified as the main cause of module short circuits and open bypass diode paths. The main cause of the power losses is due to cell cracks and cell fractures (inactive cell areas) caused by the vehicle loads.

Using the example of the modules of string 2.40 (measurement in accordance with IEC 60904-1), it was determined that the modules had an on average 24.5% lower power at the time of commissioning than specified in the manufacturer's data sheet. With the correlation between the indoor and outdoor I-V curve measurements, all installed modules had lower power than specified at the datasheet. Through this finding it can be stated that the manufacturer's quality inspection is inadequate and requires a more comprehensive final inspection. It is therefore recommended that end customers choose RIPV modules with certification or extractable test certificates in accordance with IEC 61215. However, this does not guarantee the quality of every produced module but proves that the modules submitted to the testing institute meet the test requirements. Furthermore, the accelerated ageing tests can detect certain types of failure modes during the test. The delamination problem of the tested RIPV modules could possibly have been detected by the thermal cycles, the heat/humidity and UV tests in accordance with IEC 61215. An adaptation of the IEC test is required for the mechanical load test, as RIPV modules are exposed to higher static and dynamic loads. It should also be considered that the stresses are primarily caused by vehicle

tyres. Compared to wind loads, these tyres have a smaller force area. In addition, braking and acceleration activities cause a further force and direction of force. The inclusion of traffic engineering tests in the test sequence, such as slip resistance tests or other resistance tests for traffic surfaces, should also be considered.

Due to the low number of installations and projects compared to other types of PV integration (BIPV, floating PV or agricultural PV), an international, European or national standard for the component approval of road-integrated PV modules is not foreseeable in the next five to ten years. As the drafting of standards and the development of testing infrastructure are influenced by the demand for the respective products and the size of the product market.

In addition to improving quality control, further suggestions for improving the RIPV module can be formulated based on the findings of this work. To prevent cell cracks and cell breakage, a change in the module design is necessary, as this led to the highest power losses at the solar car park in Teesdorf. If the module design is retained by the manufacturer, the maximum load capacity should be reduced. Changing the module design from a glass-foil module to a glass-glass module would result in better mechanical stability for the PV cells. In addition, the cells would be positioned in the neutral axis in a glass-glass module under bending stress and would therefore be exposed to less mechanical stress. When switching to glass-glass modules, the lamination parameters must also be optimised to prevent delamination due to incompletely cross-linked encapsulation. To improve the temperature behaviour, a filling material other than air is recommended between the RIPV module and the substructure, as this would enable a cooler cell temperature and better module performance. At the same time, the filling material could also improve the force transmission through the module.

A further aspect that could be considered in a possible redesign of the RIPV module is the change in cell technology. Compared to crystalline silicon, thin-film technologies on flexible carrier materials would withstand the mechanical vehicle stresses without cell cracks. This would also enable resource and cost savings (e.g. through lower glass thicknesses).

The results and findings of this paper show that various types of failure modes occur in RIPV or generalised as traffic area-integrated PV systems in the form of material and power degradations. Using the example of the modules examined at the PV parking place in Teesdorf, significant power losses were found, which highlight the challenges of integrating PV modules into road surfaces. Further research on degradations modes and module stability as well as standardisation in module testing are required for the development of RIPV.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author contribution statement

Conceptualization, A.E. and B.G.; Methodology, A.E.; Software, A.E.; Validation, A.E. and B.G.; Formal Analysis, B.G.; Investigation, A.E.; Resources, A.E.; Data Curation, A.E.; Writing – Original Draft Preparation, A.E.; Writing – Review & Editing, B.G.; Visualization, A.E.; Supervision, B.G.; Project Administration, A.E.; Funding Acquisition, A.E. All authors have read and agreed to the published version of the manuscript.

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