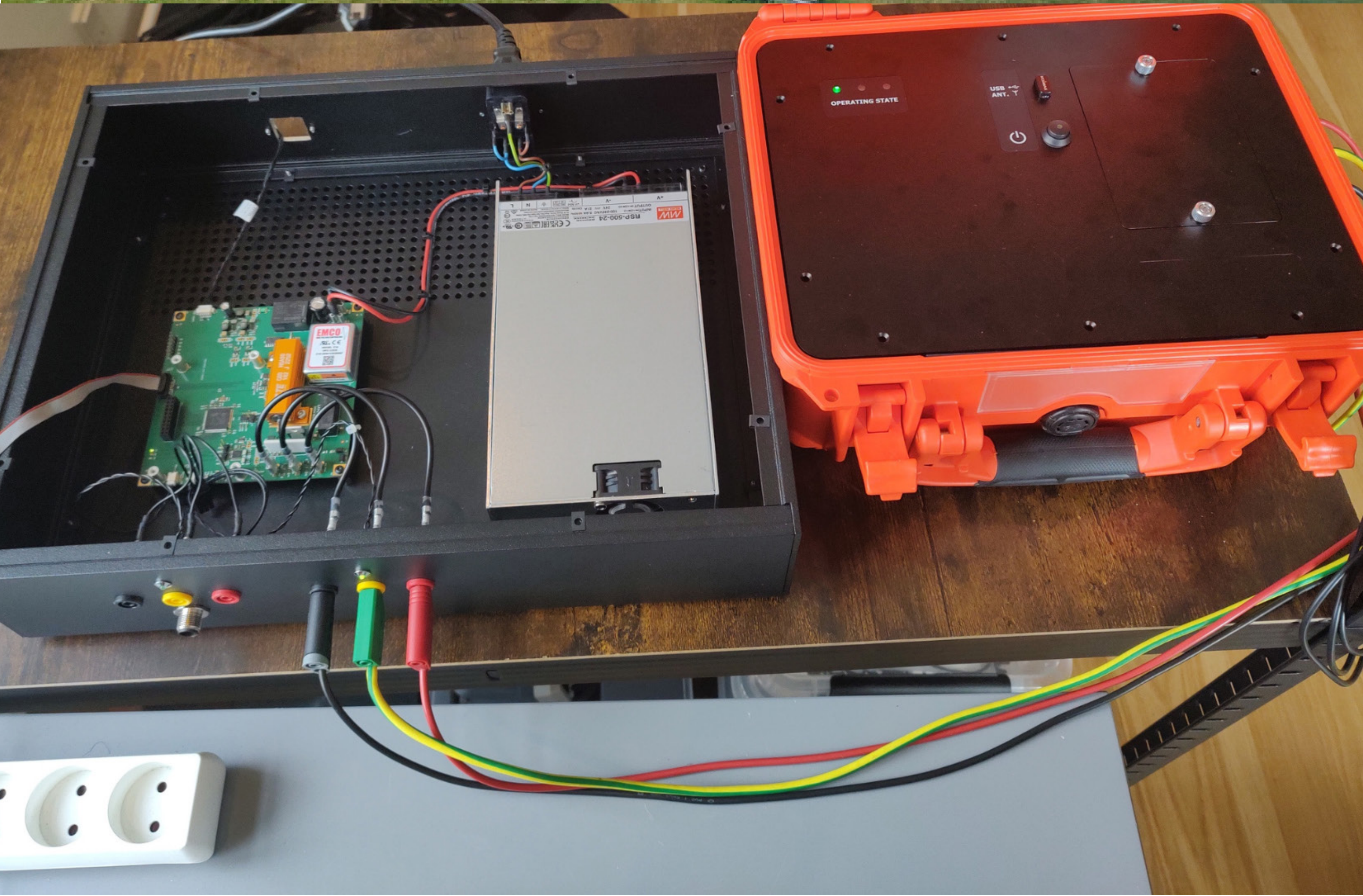
64021-2082 DIGITAL PV
DIGITALISATION OF PV OPERATIONS

Final report
June 2024



1. Project details

Project title	DigitalPV - Digitalisation of PV operations
File no.	64021-2082
Name of the funding scheme	EUDP
Project managing company / institution	European Energy A/S
CVR number (central business register)	18351331
Project partners	DTU Electro emazys ApS Micro Technic A/S
Submission date	01 July 2024

2. Summary

2.1 Project summary

The purpose of the project

The DigitalPV project aimed to address the growing need for advanced maintenance solutions for modern photovoltaic (PV) systems. The project focused on developing and demonstrating digital tools to enhance the performance and reliability of high-power, high-current PV modules.

Results, conclusions and perspective

The DigitalPV project has successfully developed and demonstrated advanced digital tools for the operation and maintenance (O&M) of modern photovoltaic (PV) systems. Key accomplishments include the development of a digital interface for I-V curve scanning, implementation of Electrical Impedance Spectroscopy (EIS) for detailed diagnostics, introduction of predictive maintenance tools utilizing machine learning and big data approaches, and the creation of a diagnostic string combiner box capable of impedance testing PV module strings up to 1500V DC.

These technologies have significantly improved the reliability and efficiency of PV systems, facilitating early fault detection and optimizing performance. The next steps for the developed technology include further refinement of calibration routines for impedance measurements, expanded deployment of the digital interface and EIS tools across more PV installations, integration of these technologies into commercial PV projects by European Energy and emazys, continued development of the diagnostic string combiner box for broader market application, and ongoing research and field testing to enhance the precision and applicability of the developed tools.

The project results are expected to have a significant impact on the future development of PV technology by enhancing the performance and reliability of PV systems through advanced digital monitoring and diagnostics, reducing maintenance costs and increasing the return on investment for PV system owners, supporting the transition to a more sustainable energy grid by improving the efficiency and uptime of renewable energy sources, and contributing to national and international renewable energy targets. The successful outcomes of the DigitalPV project will likely pave the way for wider adoption of these advanced technologies, setting new standards for PV system maintenance and performance optimization from a Danish perspective.

2.2 Projektresumé

Formålet med projektet

DigitalPV-projektet havde til formål at imødekomme det stigende behov for avancerede vedligeholdelsesløsninger til moderne solcelleanlæg. Projektet fokuserede på at udvikle og demonstrere digitale værktøjer til at forbedre ydeevnen og pålideligheden af højtydende, højeffektive PV-moduler**.**

Resultater, konklusioner og perspektiv

DigitalPV-projektet har med succes udviklet og demonstreret avancerede digitale værktøjer til drift og vedligeholdelse (O&M) af moderne solcelleanlæg (PV-systemer). Vigtige resultater inkluderer udviklingen af et digitalt interface til I-V-kurve scanning, implementering af elektrisk impedansspektroskopi (EIS) til detaljeret diagnostik, introduktion af prædiktive vedligeholdelsesværktøjer ved brug af maskinlæring og big data-tilgange samt skabelsen af en smart combinerbox, der kan teste PV-modulstrenge op til 1500V DC. Disse teknologier har væsentligt forbedret pålideligheden og effektiviteten af PV-systemer, hvilket muliggør tidlig fejldetektion og optimering af ydeevnen.

De næste skridt for den udviklede teknologi omfatter yderligere finjustering af kalibreringsrutiner for impedansmålinger, udvidet implementering af det digitale interface og EIS-værktøjer i flere PV-installationer, integration af disse teknologier i kommercielle PV-projekter af European Energy og emazys, fortsat udvikling af den diagnostiske smart combinerbox til bredere markedsanvendelse samt løbende forskning og feltprøvning for at forbedre nøjagtigheden og anvendeligheden af de udviklede værktøjer.

Projektets resultater forventes at have en betydelig indflydelse på fremtidig udvikling af PV-teknologi ved at forbedre ydeevnen og pålideligheden af PV-systemer gennem avanceret digital overvågning og diagnostik, reducere vedligeholdelsesomkostninger og øge afkastet af investeringen for ejere af PV-systemer, støtte overgangen til et mere bæredygtigt energinet ved at forbedre effektiviteten og oppetiden af vedvarende energikilder samt bidrage til nationale og internationale mål for vedvarende energi. De succesfulde resultater af DigitalPV-projektet vil sandsynligvis bane vejen for bredere adoption af disse avancerede teknologier og sætte nye standarder for vedligeholdelse og optimering af PV-systemers ydeevne i et dansk perspektiv.

3. Project objectives

The primary objective of the DigitalPV project was to develop and demonstrate advanced digital tools for the Operation and Maintenance (O&M) of modern photovoltaic (PV) systems. Specifically, the project aimed to enhance the performance and reliability of new high-power, high-current PV modules by leveraging digitalization and advanced monitoring techniques. This involved the creation of updated O&M tools that could handle the increased complexity and scale of contemporary PV technologies, ensuring optimal operation and minimizing the risk of failure.

The specific goals of the project included:

- Developing an updated performance indicator that describes both the overall performance of the PV park and the performance of individual electrical strings within the park.
- Automating the collection and analysis of I-V curve measurements from all electrical strings in the park, using new inverter features to generate detailed performance data.
- Introducing and applying Electrical Impedance Spectroscopy (EIS) to obtain detailed health status information for each PV module in a string.
- Identifying and mitigating unknown risk factors in the newly developed PV module technology by analysing and addressing any detected anomalies.

The DigitalPV project focused on several cutting-edge energy technologies within the photovoltaic sector:

1. **High-Power PV Modules**: The project involved the deployment and monitoring of bifacial, glass-glass, large wafer, and high-current PV modules. These modules represent the latest advancements in solar cell technology, offering higher efficiency and power output compared to traditional modules.
2. **Digital I-V Curve Analysis**: Development and implementation of a digital interface for automatically triggering I-V curve scans and acquiring measurements from PV inverters. This technology allows for detailed monitoring and analysis of the performance of individual PV strings, facilitating early fault detection and performance optimization.
3. **Electrical Impedance Spectroscopy (EIS)**: Integration of EIS into the O&M toolkit to provide detailed diagnostics of PV module health, capable of identifying specific failures such as diode issues, ground faults, and cracked cells. This technology complements traditional I-V curve analysis by offering a more nuanced understanding of module performance and failure modes.
4. **Predictive Maintenance Tools**: The use of machine learning and big data approaches to analyze the vast amounts of performance data collected, enabling predictive maintenance strategies that anticipate and prevent major faults before they lead to significant power loss.

Through these technologies, the project aimed to demonstrate a comprehensive and advanced approach to PV system maintenance, significantly improving the reliability and efficiency of solar power plants.

4. Project implementation

The project evolved well with only a minor change to the project plan extending the project for 6 months to achieve realizing and testing the smart combiner box the project set out to develop and test. The project partner knew each others from pervious project making the project execution efficient from the start.

We achieved the goal of building functional electronics appropriate for installation in a combiner box environment, that can perform impedance measurements even with string voltages ranging from 1000-1500V. This has not been done before, so it is an achievement for the consortium, and it will likely bring many new opportunities and applications with it.

The impedance data we were able to harvest during field demonstrations in 2024 still require work to interpret in depth, and we still need to fully develop the calibration routines for the impedance measurements – but the hardware is working.

A challenging aspect has been to deal with the high efficiency (HE) modules. High efficiency modules have high capacitance which can cause errors when measuring currents and switching strings in and out of inverters and combiner boxes. The capacitance can also cause a large in-rush current which can pose challenges for electronics associated with the PV system.

In addition to producing the commonly known DC current, PV modules also have AC or dynamic characteristics (diffusion layer capacitance). There exists a modest amount of parallel plate-type junction capacitance in addition to a much higher capacitance associated with excited electrons in the body of the semiconductor layers. This is known as diffusion layer capacitance, and it increases with cell voltage and with irradiance, and it also increases rapidly with cell efficiency.

The magnitude of diffusion capacitance can reach the microfarad range for high efficiency modules.

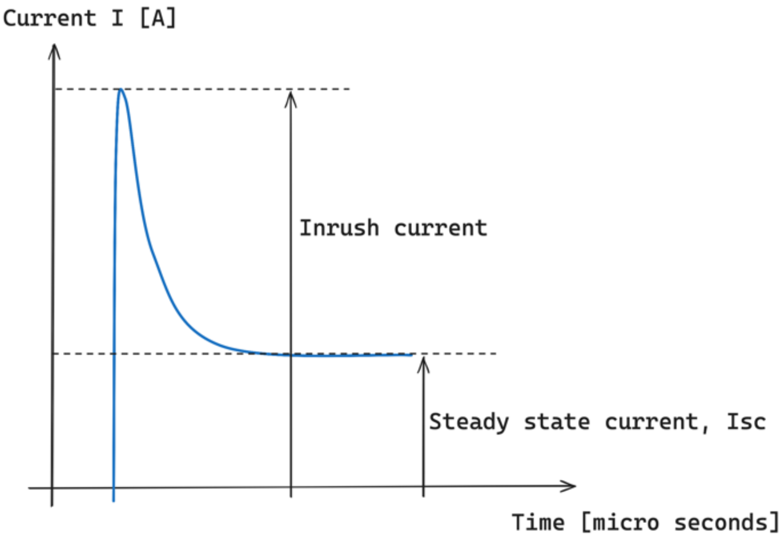
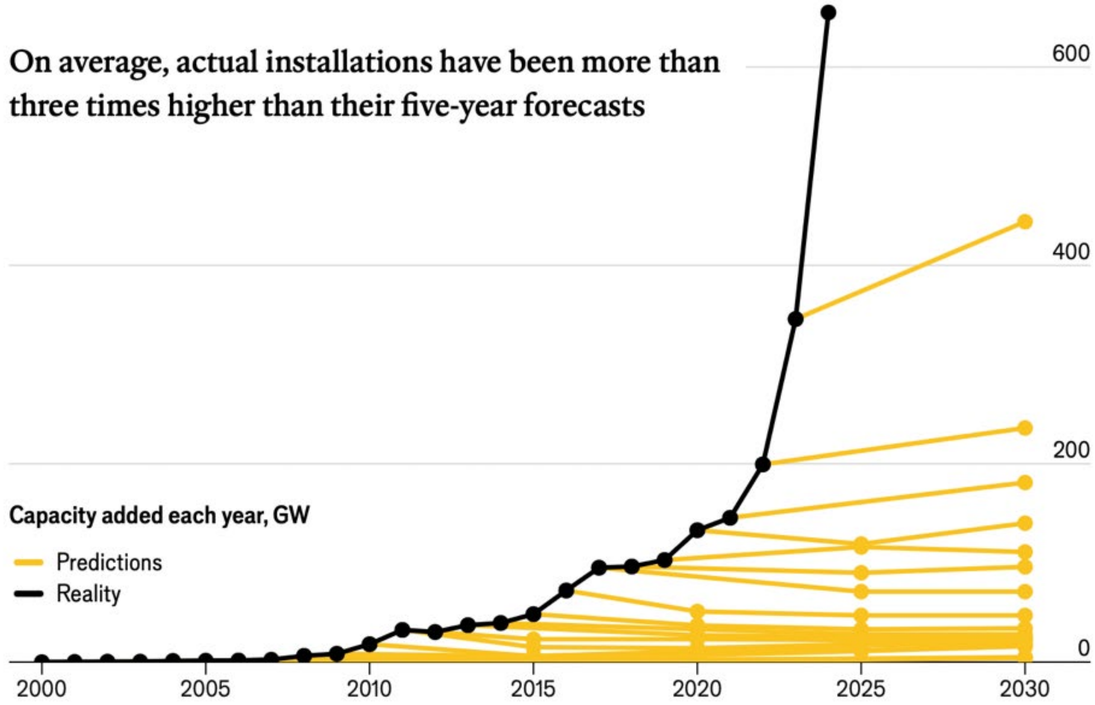


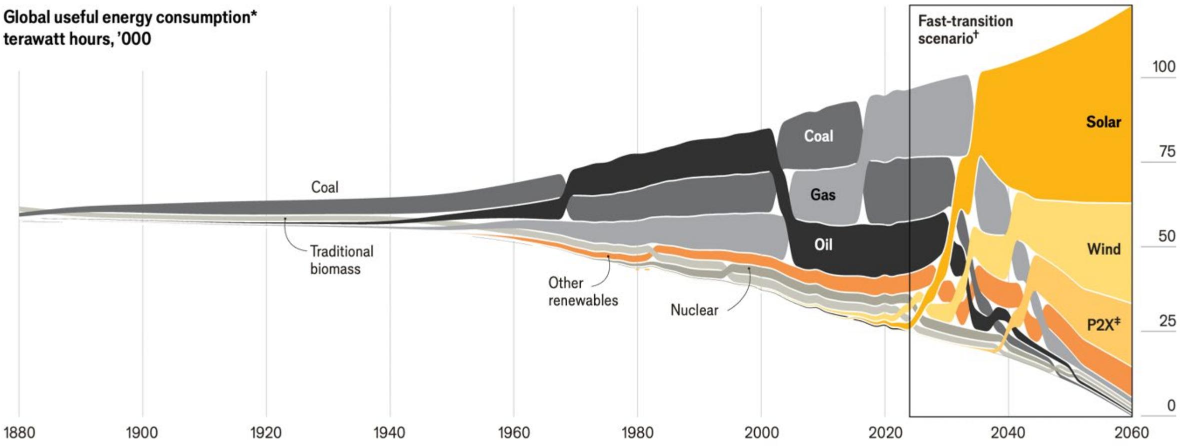
Figure 1 Simple illustration of a PV module inrush current. Due to a high capacitance in the high efficiency modules, there often is an inrush current during the first short time interval, when e.g. a current test is carried out. This inrush current can severely damage such components as the msr_engine if it is not properly protected.

During our work with understanding the inrush phenomenon for HE PV modules such as the ones installed at the bifacial site at RISØ/DTU, we realised that the impedance measurement can also but utilised for checking the charging state (capacitance) in the HE PV module string before any measurement is carried out. Depending in the amount of capacitance, the timing of measurements can be adjusted, which means that the reliability of the msr_engine goes up drastically.

In a future scenario, with a doubling of installed capacity PV capacity for each 3 years, the reliability of assets will be essential.


On average, actual installations have been more than three times higher than their five-year forecasts

Installations for 2024 are an estimate from BloombergNEF for direct current solar capacity
Sources: IEA; Energy Institute; BloombergNEF



Sources: Rupert Way; Our World in Data *Primary energy adjusted for waste-heat losses †From Way et al. (2022) ‡Electricity-conversion technologies (eg green hydrogen)

5. Project results

5.1 Digital interface to inverter I-V scanning

One of the first significant results of this project was the development of a digital interface for acquiring current-voltage (I-V) measurements of PV strings connected to Huawei Sun2000 inverters programmatically, which was previously not possible with the software provided by the vendors. This capability opened up the possibility of performing continuous string IV monitoring and fault detection based on IV data for this type of inverter and demonstrated the opportunities for smarter PV fault diagnosis.

Figure 2 shows the digital interface with the communication infrastructure of the DTU Risø PV plant, which was used to implement and demonstrate its operation.

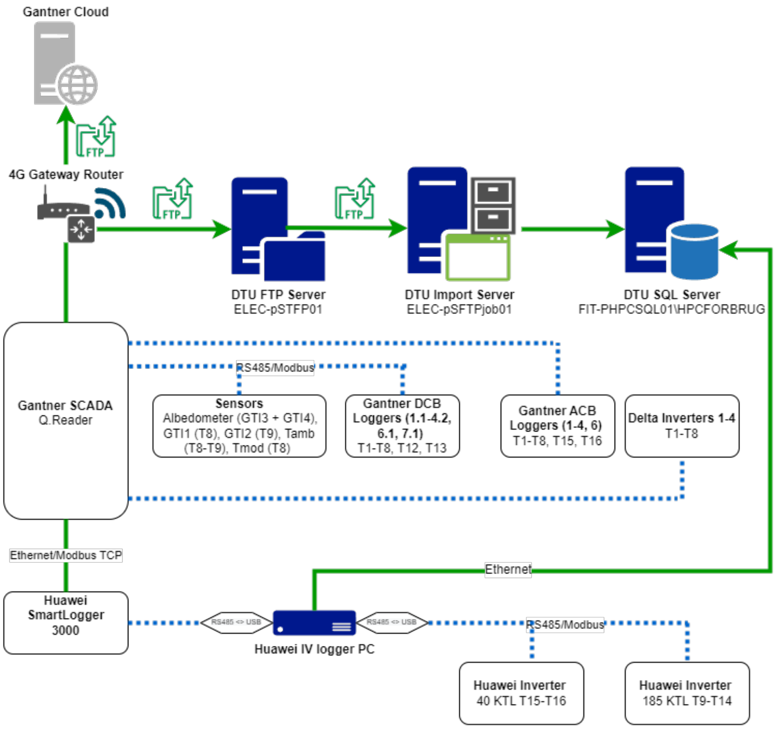
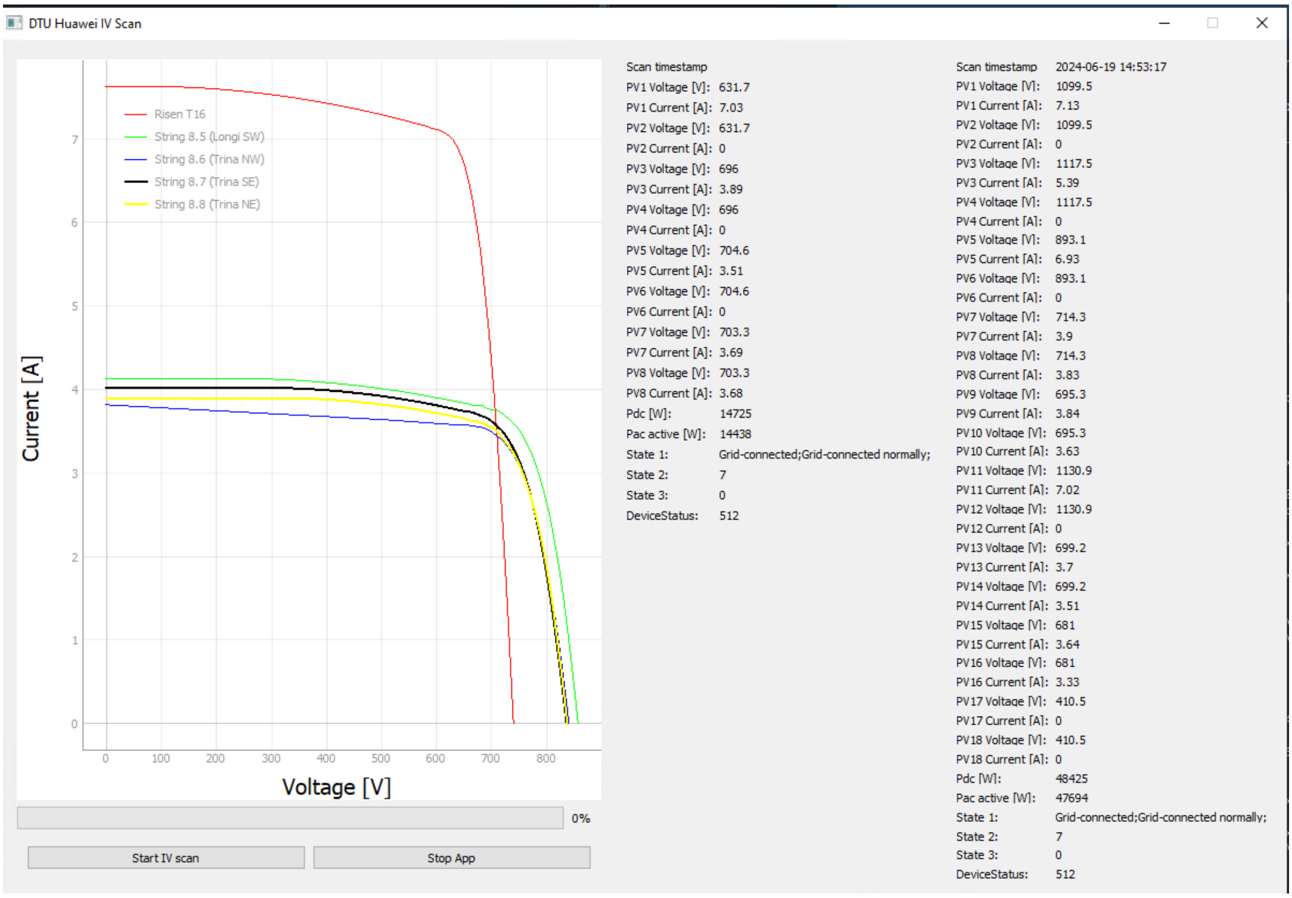


Figure 2. Digital communication interface with Huawei PV inverters for performance monitoring and IV data acquisition, for the Risø PV farm.

The digital interface is implemented as a Python application inside the Huawei IV Logger PC and is designed to communicate with Huawei SUN 2000 inverters and take control of their I-V scanning functionality, trigger and acquire string IV measurements on demand, and store them in a central SQL database.

The digital interface was tested in the field using the two Huawei SUN 2000 utility-scale inverters deployed at DTU, a 40 kW inverter connected to five PV strings and a 185 kW inverter connected to 12 strings. Figure 3 shows the application's graphical user interface, where inverter IV scans can be triggered, acquired, and displayed, together with the current electrical measurements of each string and the status of the two test inverters.

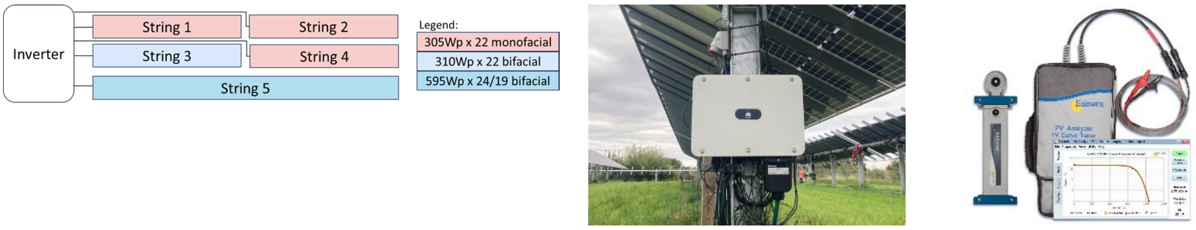


```
Scan timestamp
PV1 Voltage [V]:   631.7
PV1 Current [A]:   7.03
PV2 Voltage [V]:   631.7
PV2 Current [A]:   0
PV3 Voltage [V]:   696
PV3 Current [A]:   3.89
PV4 Voltage [V]:   696
PV4 Current [A]:   0
PV5 Voltage [V]:   704.6
PV5 Current [A]:   3.51
PV6 Voltage [V]:   704.6
PV6 Current [A]:   0
PV7 Voltage [V]:   703.3
PV7 Current [A]:   3.69
PV8 Voltage [V]:   703.3
PV8 Current [A]:   3.68
Pdc [W]:           14725
Pac active [W]:    14438
State 1:           Grid-connected;Grid-connected normally;
State 2:           7
State 3:           0
DeviceStatus:      512
```

```
Scan timestamp      2024-06-19 14:53:17
PV1 Voltage [V]:    1099.5
PV1 Current [A]:    7.13
PV2 Voltage [V]:    1099.5
PV2 Current [A]:    0
PV3 Voltage [V]:    1117.5
PV3 Current [A]:    5.39
PV4 Voltage [V]:    1117.5
PV4 Current [A]:    0
PV5 Voltage [V]:    893.1
PV5 Current [A]:    6.93
PV6 Voltage [V]:    893.1
PV6 Current [A]:    0
PV7 Voltage [V]:    714.3
PV7 Current [A]:    3.9
PV8 Voltage [V]:    714.3
PV8 Current [A]:    3.83
PV9 Voltage [V]:    695.3
PV9 Current [A]:    3.84
PV10 Voltage [V]:   695.3
PV10 Current [A]:   3.63
PV11 Voltage [V]:   1130.9
PV11 Current [A]:   7.02
PV12 Voltage [V]:   1130.9
PV12 Current [A]:   0
PV13 Voltage [V]:   699.2
PV13 Current [A]:   3.7
PV14 Voltage [V]:   699.2
PV14 Current [A]:   3.51
PV15 Voltage [V]:   681
PV15 Current [A]:   3.64
PV16 Voltage [V]:   681
PV16 Current [A]:   3.33
PV17 Voltage [V]:   410.5
PV17 Current [A]:   0
PV18 Voltage [V]:   410.5
PV18 Current [A]:   0
Pdc [W]:            48425
Pac active [W]:     47694
State 1:            Grid-connected;Grid-connected normally;
State 2:            7
State 3:            0
DeviceStatus:       512
```

Figure 3. The graphical user interface of the developed digital interface application to Huawei PV inverters for acquisition and monitoring of string IVs.

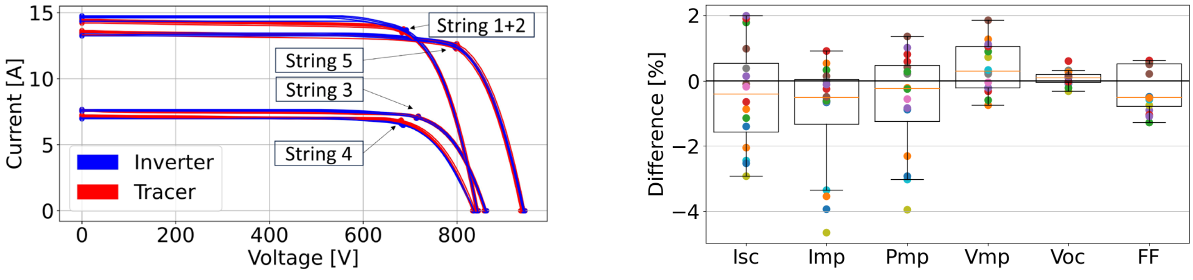
One of the research objectives connected to the development of the digital IV acquisition interface was to evaluate the accuracy of inverter-acquired IV curves compared to a commercial string IV tracer, typically used as a diagnostic tool for PV plants. To address this research objective, a study was conducted on the 40 kW PV inverter, connected to 5 PV strings of different types, depicted in Figure 4a and b. The digital IV acquisition interface is used to acquire string IV curves; these are then benchmarked against IV curves acquired for the same 5 strings with a Solmetric PVA-1500 IV Analyzer (Figure 4c) and are used as the reference in the comparison.



a) b) c)

Figure 4. Experimental setup for evaluating the accuracy of inverter acquired string IV curves: a) Array layout of tested strings at DTU Risø campus. b) Huawei SUN2000-40KTL-M3 inverter with IV sweep capabilities. The inverter can measure the IV curve of each string. c) Solmetric PVA-1500V4 portable IV tracer used to acquire baseline IV curves of the strings.

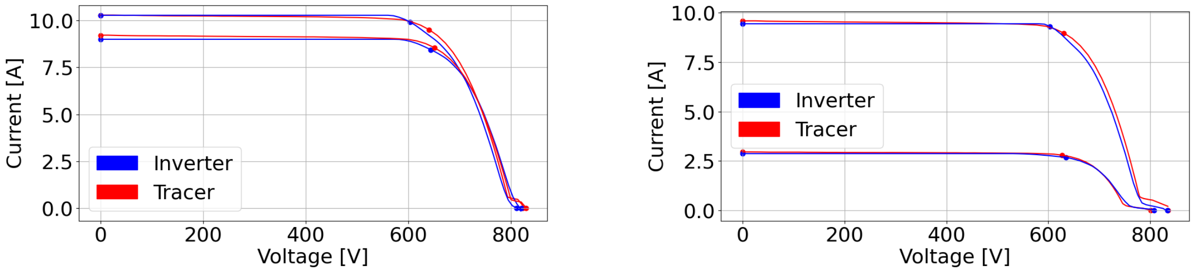
The results of this study have been published in, at the 2023 EUPVSEC, and are summarized here. The results from the first test, shown in Figure 5, reveal that under stable solar conditions (> 600 W/m^2 and no fast-changing irradiance), and without shading affecting the PV panels, the string IV curves acquired by the inverter are within 2-3% of the reference curves acquired wit[1]h the commercial IV diagnostic tool.



a) b)

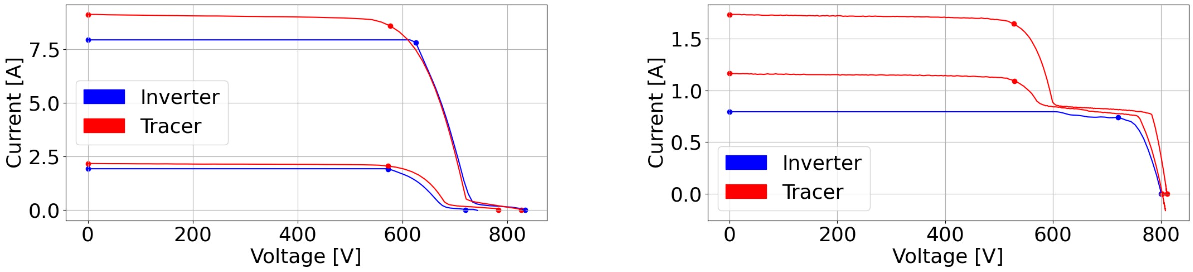
Figure 5. Results of **test #1** – **no shading in high irradiance conditions.** a) Comparison of inverter vs tracer acquired string IV curves: b) Differences between IV-tracer and inverter-measured IV curves across the IV parameters. Measurements on four different strings in high, stable irradiance without shading. Positive numbers mean the inverter is overestimated. Unique colors indicate the same measurement.

Test #2 was designed to assess the lower threshold of the inverter-acquired IV curves to detect partial shading by inducing cell-level shading on the PV string. The results show that the inverter-acquired IV curves have sufficient resolution to capture these events, and the resulting IVs are comparable to that of the commercial IV tracer.



a) b)

Figure 6. Results of **test #2** – small partial shading detection. a) one cell was fully shaded on two out of 22 modules; b) two cells were shaded on two out of 22 modules. The two shaded cells are on different cell strings within the modules.



a) b)

Figure 7. Results of **test #3** – medium and high shading detection. a) two cells were shaded on four out of 22 modules. The two shaded cells are on different cell strings within the modules. b) a full cell row on five out of 22 modules was shaded using a mesh with 50% light transmittance.

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[1] Bartholomäus, Martin, Luca Morino, Peter B Poulsen, and Sergiu V. Spataru. "Evaluating the Accuracy of Inverter Based String IV Measurements." In Proceedings of 40th European Photovoltaic Solar Energy Conference and Exhibition. Lisbon, Portugal: WIP, 2023. https://doi.org/10.4229/EUPVSEC2023/4CV.1.4

In test #3, shown in Figure 6, we induced higher levels of partial shading, which has revealed some limitations of the inverter in measuring the full I-V characteristic when the module is heavily shaded or when the solar irradiance is low. This result was surprising, as higher levels of shading should be easier to detect. Therefore, shading detection should only be performed under high illumination conditions, and several repeat measurements should be taken to confirm the shading presence and distinguish it from a measurement artifact.

Similar erroneous behavior of the inverter IV measurement has been observed for variable irradiance conditions, where distorted I-V characteristics have been measured for otherwise unshaded and healthy PV strings. Therefore, repeat measurements should be taken under the similar operating conditions or time of day to check IV measurement consistency

Study of field performance and degradation of next generation PV technologies

We assessed the degradation of a total of 189 current generation bifacial PV modules from four different module types. Figure 8 shows, where these PV modules were mounted on DTUs PV plant in Risø and degraded in the Danish outdoor climate. Table 1 specifies the module data sheet parameters of each of the types of modules. The modules vary in size, cell technology and power rating (295 to 595Wp) and deployment time.

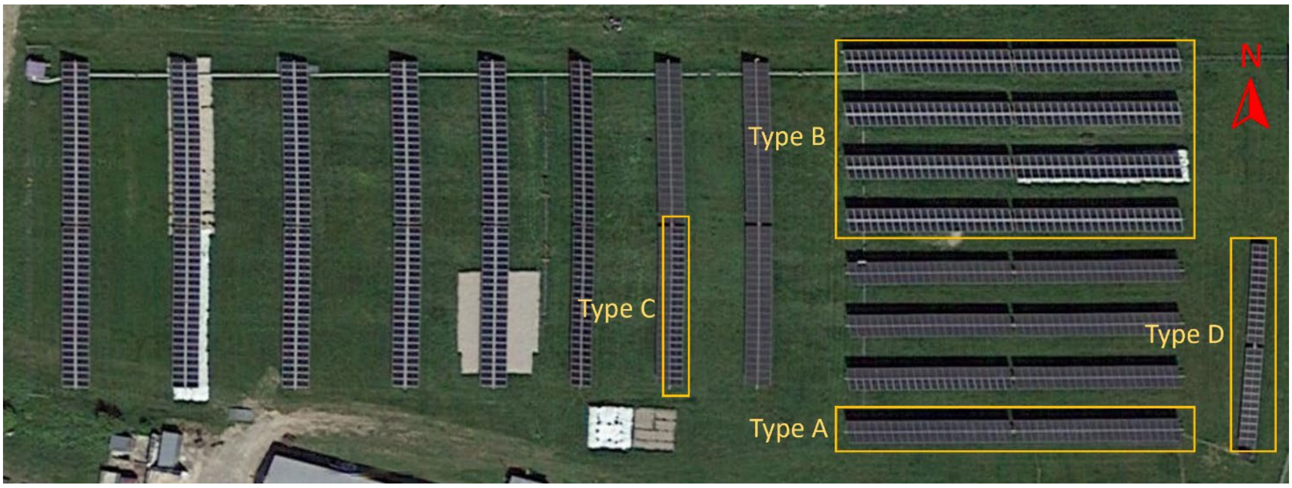

Figure 8: PV plant at DTU’s campus in Risø, Denmark, where the 189 bifacial modules from 4 different module types were deployed. The strings that accommodated the modules are marked. Modules have been deployed for 2.1 to 4.5 years. Type A and B are on fixed-tilt structures oriented 25 degrees south, Type C and D are on horizontal single-axis tracker tracking from east to west. Image: adapted from Google maps.

Table 1: Specifications of modules tested for this study (I-V from nameplate). The glass thickness is the same on the front and back side.

Type	A (Risen)	B (Trina 295)	C (Longi LR6)	D (Longi LR4)
Deployment [years]	2.1	4.5	3.5	2.5
No of modules tested	16	125	22	26
Isc [A]	18.21	9.58	9.66	11.36
Imp [A]	17.2	8.97	9.23	10.66
Pmp [W]	595	295	310	435
Vmp [V]	34.6	32.9	33.6	40.8
Voc [V]	41.5	39.9	40.7	49.1
Dimensions [mm]	2172x1303	1674x1002	1698x996	2094x1038
Frame	AL-frame	frameless	AL-frame	AL-frame
Cell count	120	60	120	144
Cell format	half-cut	full cell	half-cut	half-cut
Cell size	M12	M0	M0	M6
Glass depth [mm]	N.A.	2.5	2	2
Encapsulant	EVA (meas)	EVA (PE meas)	EBA/PE (meas)	PE (meas)
String Vmp [V]	761.2	723.8	739.2	1060.8
String Pmp [kW]	13.09	6.49	6.82	11.31
No of busbars	12	5	5	9
Bifaciality [%]	70±5	N.A.	>=70-75	70±5
Efficiency [%]	21	17.7	18.3	20
Mounting	Fixed south, 25°	Fixed south, 25°	HSAT East-West	HSAT East-West
Vintage	N.A.	N.A.	N.A.	N.A.

To test module degradation, both indoor electroluminescence (EL) imaging and indoor flash testing (with an Endeas 540XLi large area flasher, accuracy class AAA per IEC 60904-9 Ed.1) were performed. We calculated the degradation rate (yearly degradation) of relevant IV parameters versus data sheet specifications. Results are shown in Figure 9. It reveals that degradation rates across all parameters lie within 1% per year for the three shown module types. Manufacturers often guarantee no more than 0.5% per year, which is not reached in all module types. However, excessive degradation was not observed.

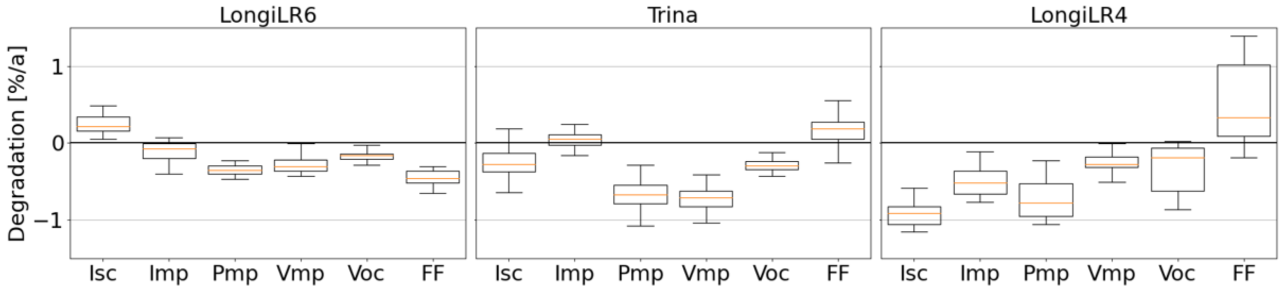

Figure 9: Annual degradation rate of I-V parameters from flash tests at standard testing conditions on the front side compared to data sheet specifications of each module type. The orange line shows the median value, the box covers the 25th to 75th percentile and whiskers show the rest of the spread excluding outliers.

EL images reveal different well known and rather unknown failure modes, an overview of which is shown in Figure 10.

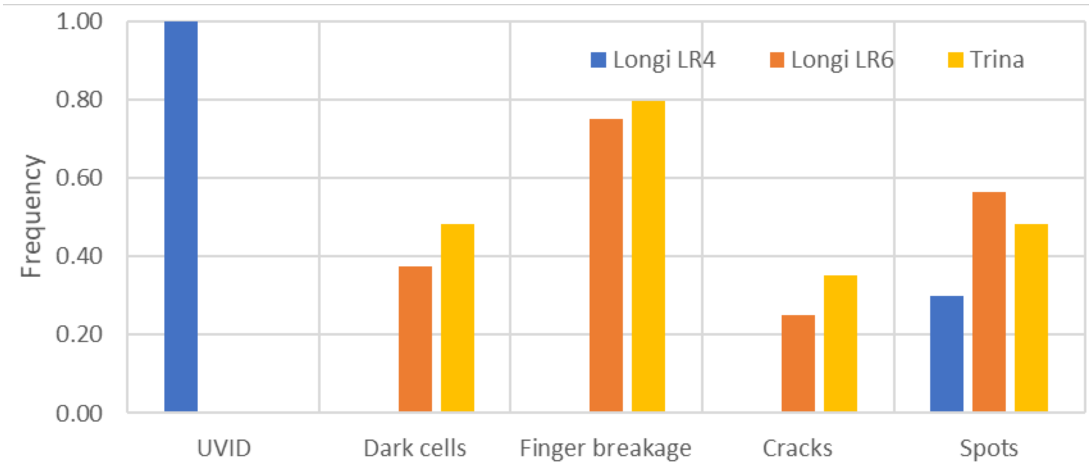

Figure 10: Frequency (number of affected modules relative to total number of inspected modules per batch) of common faults observed in EL images per module type.

While dark cells (cell mismatch), finger breakage, cracks and spots are well known failure modes, however the type of UVID (UV induced degradation) we observed in Longi LR4 modules is not well described in the literature. Figure 11 shows visual impressions of EL images capturing different failure types.

Figure 11: Top left: Spots on a Longi LR6 module; Top right: broken grid fingers on a Longi LR6 module; Bottom left: line crack on a Longi LR6 module; Bottom right, UVID type imprint in a Longi LR4 module.

We conclude that the degradation of bifacial modules from this test is not significantly higher than what was previously reported for monofacial modules. Degradation is mostly dominated by known faults, but a new type of fault was documented, which however does not seem to cause excessive degradation. This study is also limited to a maximum of 4.5 years of outdoor exposure, and less for some modules. In the meantime, new developments in the market for bifacial PV with regards to cell types, encapsulants and growing module sizes are happening, renewing the need for outdoor degradation tests.

Before assessing the reliability of the latest large-format bifacial modules, we first benchmarked the degradation rates of first-generation bifacial modules (1.0x1.6m^2 form factor) that were installed ca. 2018. We used 4-years of monitoring data, and the ‘year-on-year' analytical method implemented in the RdTools python library[2] to extract linear degradation rates (Rd) of the bifacial and monofacial modules installed at DTU Risø (~300 kWp total).

The Rd for 42 individual strings is shown below in Figure 12. The system types are grouped into tracked/fixed-tilt and bifacial/monofacial. The bifacial tracker system is the main system type analyzed and shows the widest spread of Rd (-1.1%/yr to –0.2%/yr). The median Rd shown in 3 out of 4 system types overlap with the other box plot distributions suggesting (not proving) that there is no significant difference in Rd among the system types. For example, there is no significant difference between the Rd of fixed-tilt mounted bifacial modules and monofacial modules. Tracked monofacial modules are the outlier system type showing significantly lower Rd (median Rd = -0.2%/yr).

A small sample of individual PV panels (N=20) was brought to the lab for I-V and EL testing, and to validate the Rd calculated from the monitoring data. The I-V data showed that some of the degradation is due increased series resistance, which was not possible to discern from the monitoring data. The Rd extracted from the flash I-V data were within 0.1%/yr to 0.6%/year of the median rates shown in Figure 12. Interestingly, the median Rd of the tracked monofacial panels was –0.6%/yr using the flash data highlighting the uncertainties involved in Rd analyses (e.g., data filtering, sensor data quality, data storage etc.).

Overall, the median degradation rate (Rd) of the 42 bifacial and monofacial PV strings shown in Figure 12 is –0.65%/yr. Considering the uncertainties of the year-on-year method, this result is in close agreement with the Rd published in peer-reviewed studies on legacy PV modules[3,4].

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[2] https://rdtools.readthedocs.io/en/stable/

[3] D Jordan, J Wohlgemuth, and Sarah Kurtz. “Technology and Climate Trends in PV Module Degradation”. In: Jan. 2012, pp. 3118–3124. DOI: 10.4229/27thEUPVSEC2012-4DO.5.1.

[4] Dirk Jordan et al. “Compendium of photovoltaic degradation rates”. In: Progress in Photovoltaics: Research and Applications 24 (Feb. 2016), n/a–n/a. DOI: 10.1002/pip.2744.

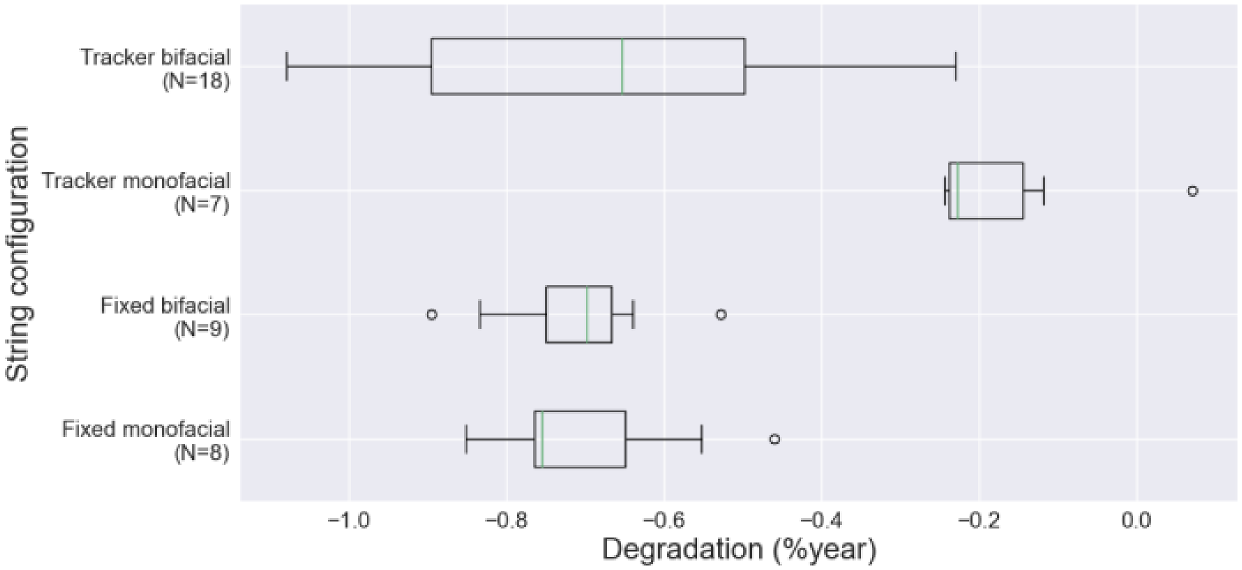
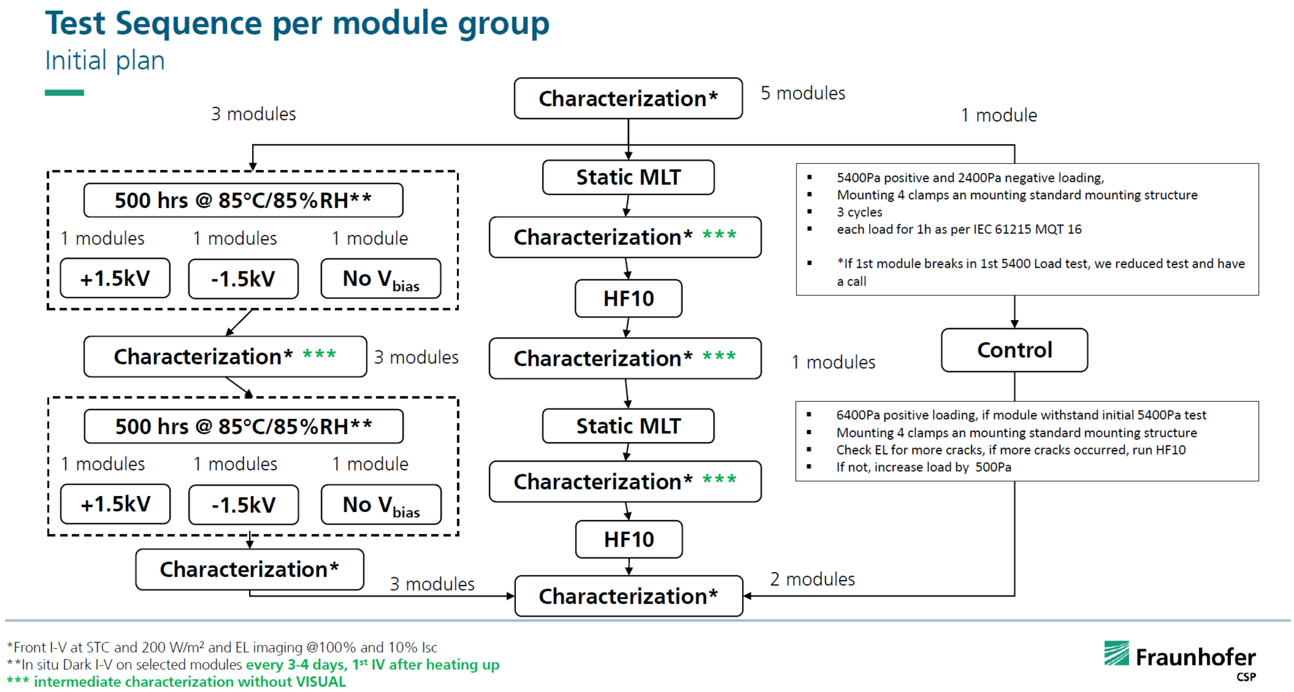


Figure 12. Box plots showing distributions of degradation rates calculated for 42 individual bifacial and monofacial strings installed at DTU Risø. Medians are represented with green lines. Figure credit: Raul Alcacer Galan’s MSc thesis.

Next generation PV module reliability

As part of the degradation investigation, we contracted the German research institute Fraunhofer CSP to conduct and report on “Accelerated Module testing for PID and Mechanical load” of 24 PV large format PV modules according to the following test plan, shown in Figure 13.


Test Sequence per module group

Initial plan

- 5400Pa positive and 2400Pa negative loading,
- Mounting 4 clamps an mounting standard mounting structure
- 3 cycles
- each load for 1h as per IEC 61215 MQT 16
- *If 1st module breaks in 1st 5400 Load test, we reduced test and have a call

- 6400Pa positive loading, if module withstand initial 5400Pa test
- Mounting 4 clamps an mounting standard mounting structure
- Check EL for more cracks, if more cracks occurred, run HF10
- If not, increase load by 500Pa

*Front I-V at STC and 200 W/m² and EL imaging @100% and 10% Isc
In situ Dark I-V on selected modules **every 3-4 days, 1st IV after heating up
***** intermediate characterization without VISUAL**

Figure 13 Test sequence for large format module accelerated stress testing

Providing the following conclusions:

Potential Induced Degradation and Damp Heat Test:

- PERC type modules show PID sensitivity during the test for negative potential (-1,500 V) after 425 h and 1000 h however power loss is limited, because only cells near the frame and near the Junction box are effected.
- DH and positive potential (+1,500 V) show only neglectable power loss
- N-Type modules are stable regarding STC power and low light in all conditions but there are features in EL occurring for both polarities

Mechanical load and Humidity Freeze:

- Modules version A does not fulfil the load capacity specification in the manual (test load: 5,400 Pa) which is most likely related to a glass strength problem
- Modules version B withstand the static mechanical load (test load: 5,400 Pa). Without glass breakage there is virtually no power loss measured after Mechanical Loading/Dynamic Mechanical Loading.
- HF10 and second DML show also no significant change
- After the final HF10, the power loss is still low, there are only minor abnormalities in the EL

These overall positive results, indicate that even after substantial accelerated ageing of the large format modules, it’s not easy to provoke and detect failure modes - neither known nor new not previously seen.

After completion of the tests in Germany, the stressed PV modules were returned to DTU-Risø for renewed testing and deployment in the park for additional degradation studies to be performed.

Risen Degradation results

We tested 16 current generation Risen RSM-595 modules for degradation after two years of field exposure with the methods described above, using indoor IV flash test and EL imaging. Figure 14 shows the annual degradation of the IV parameters of this module type. It displays much higher degradation than the other three module types tested, reaching an annual degradation rate of 3.5% per year at the maximum power point. Losses seems to stem equally from current losses (at Isc and Imp) and voltage losses (at Voc and Vmp). The fill factor is affected the least, which hints for stable series and shunt resistance of the modules.

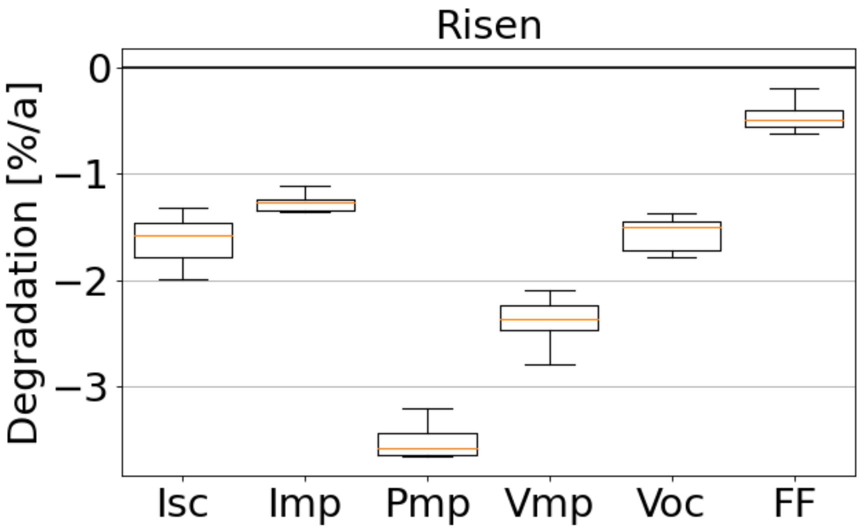


Figure 14: Annual degradation rate of I-V parameters from flash tests at standard testing conditions on the front side compared to data sheet specifications of the Risen modules. The orange line shows the median value, the box covers the 25th to 75th percentile and whiskers show the rest of the spread excluding outliers.

Figure 15 shows EL images of the two most degraded PV modules of this type, displaying dark cells around the perimeter of the module and a checker-board pattern, which are both typical for potential induced degradation (PID).

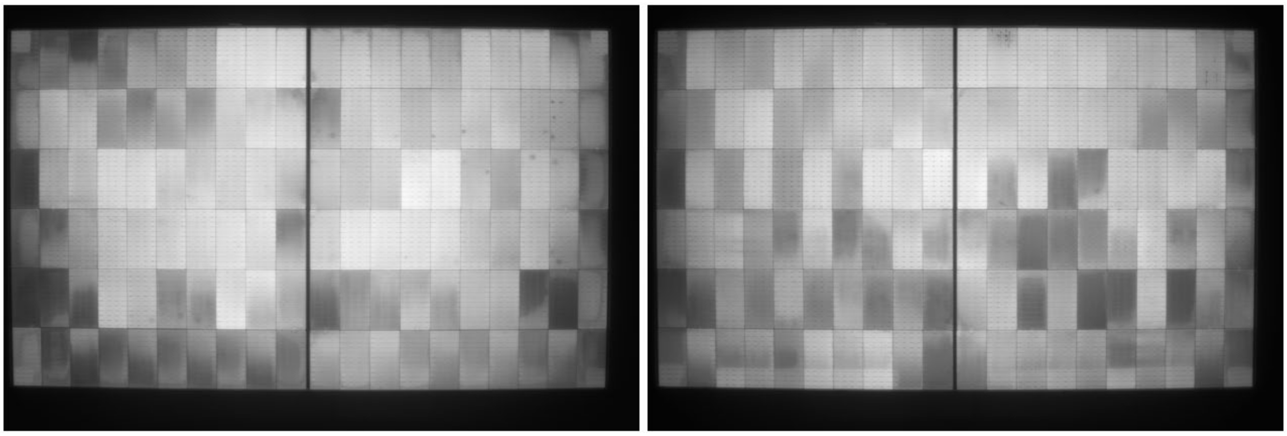
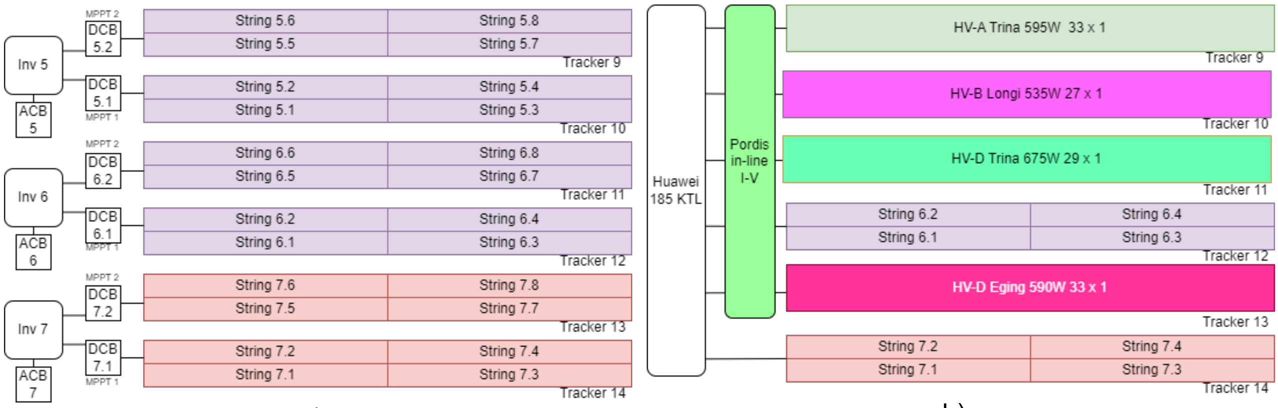


Figure 15: EL images of the two most degraded Risen modules after two years of outdoor exposure. Dark cells around the perimeter and in a checker-board pattern are typical for potential induced degradation. These two modules have a significant power loss of 53.1W (left) and 54.6W (right) compared to the 595Wp on the data sheet.

To assess the long-term reliability of the large format PV modules, and in complement to the accelerated stress testing performed at Fraunhofer, we deployed four types of next-generation PV modules at the DTU Risø PV farm. A total of 122 large format modules were deployed in four high voltage (1500 V) PV strings, depicted in Figure 16b as HV-A, HV-B, HV-C, and HV-D.



a) b)

Figure 16. Layout of the DTU Risø PV farm, south oriented field: a) before retrofit; b) after installation of the new Huawei inverter and new digital string monitoring box (Pordis), both capable of string IV curve monitoring, as well as the deployment of four next-generation large format/high voltage PV modules for long term performance testing.

This required retrofitting of the existing PV trackers (depicted in Figure 16a and Figure 17a), initially deployed in 2018, and the decommissioning of approx. 300 modules, half of which were characterized in the laboratory as part of a bifacial PV module degradation study, that is currently in preparation.

The deployment of high voltage PV strings was also required, as well as the replacement of the existing PV inverters, which were only rated 1000 Vdc, with a current generation utility-scale PV inverter rated for 1500 Vdc. However, such an inverter requires an 800 Vac grid connection, whereas' DTUs electrical grid is designed for 400 Vac. This required the installation of an additional high-power transformer shown in Figure 17b.

Finally, the system is fully operational and instrumented, and its performance monitored, and it will provide valuable insight into the long-term reliability and performance risks associated with large format high voltage PV modules.

a)

b) c)

Figure 17.Pictures from the DTU Risø PV farm showing: a) the large format PV module strings deployed in this project for long-term testing; b) the new transformer installed for connecting the new high power inverter to the grid; c) the Pordis string I-V monitoring deployed on tracker 11.

Diagnostic string combiner box (DSCB)

A diagnostic string combiner box (DSCB) was developed using two main components

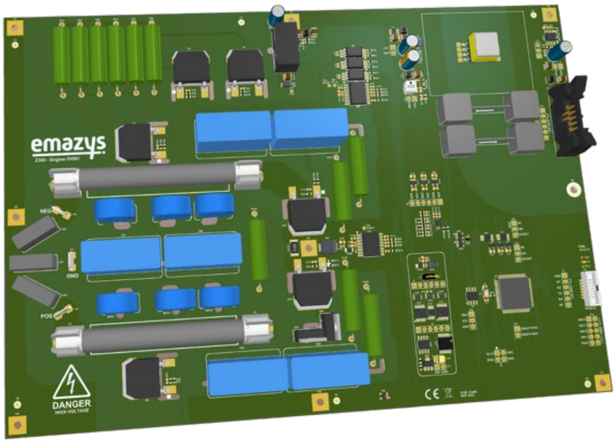
1. A Printed Circuit Board Assembly PCBA (Z300 msr_engine) entirely developed for the project by the team at emazys
2. A commercially available string combiner box from HIS renewables (OEM product by KACO)

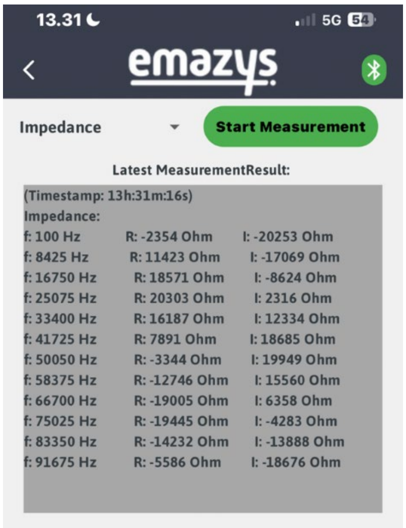
The combiner box is considered a consistent connection point, that allows the PCBA to be utilized in the field. During the project the msr_engine was installed in a hard case to allow transporting between the laboratory and the field. While testing and demonstrating the msr_engine, it was thus brought the DTU/RISØ photovoltaic plant where individual PV module strings could be tested. This approach was demonstrated and approved at our meeting at Micro Technic in Aarup DK, with representatives from EUDP on 02.05.2023.

Figure 18 a) Photo of the HIS commercial combiner box installed at RISØ/DTU. b) Photo from the development of msr_engine PCBA at the emazys laboratory. See otange box on the left. On the right we see an ITECH PV simulator 1500V/30A power supply which was sourced for the project.

In a market ready product version of the DSCB (at a higher TRL than planned for this project), individual module strings are switched on/off at msr_engine terminals by a commercial circuit interrupter and a multiplexer (high voltage relay / safety PLC). Such components are commercially available and hence their application was not considered important to further develop for this project.

The decision was to focus on the msr_engine with a specification adequate for “state of the art” PV module strings. This means the final PCBA msr_engine can handle DC power up to 45 kW per string. The total combiner box maximum power handling capability can range from 4 kW initially to 100 kW, as module strings are added to the design. We distinguish between the maximum power handling of the DSCB, and the maximum power handling of the msr_engine.





Latest MeasurementResult:

```
(Timestamp: 13h:31m:16s)
Impedance:
f: 100 Hz      R: -2354 Ohm    I: -20253 Ohm
f: 8425 Hz     R: 11423 Ohm    I: -17069 Ohm
f: 16750 Hz    R: 18571 Ohm    I: -8624 Ohm
f: 25075 Hz    R: 20303 Ohm    I: 2316 Ohm
f: 33400 Hz    R: 16187 Ohm    I: 12334 Ohm
f: 41725 Hz    R: 7891 Ohm     I: 18685 Ohm
f: 50050 Hz    R: -3344 Ohm    I: 19949 Ohm
f: 58375 Hz    R: -12746 Ohm   I: 15560 Ohm
f: 66700 Hz    R: -19005 Ohm   I: 6358 Ohm
f: 75025 Hz    R: -19445 Ohm   I: -4283 Ohm
f: 83350 Hz    R: -14232 Ohm   I: -13888 Ohm
f: 91675 Hz    R: -5586 Ohm    I: -18676 Ohm
```

Figure 19 a) 3D rendering of the emazys msr_engine PCBA capable of impedance testing PV modules strings up to 1500 V DC. b) In this table we see the raw and uncalibrated data measured by the msr_engine during connection to a string of bifacial Trina 590W modules at DTU/RISØ. During the test the voltage was at +1300V.

Design phase: msr_engine PCBA

The msr_engine was created as a technology suite capable of connecting to a PV module string with 3 terminals PV+, PV- and GND. The msr_engine has its own internal multiplexer, that allows measuring a range of parameters between 2 of the 3 connected terminals. The measurement functions are as follows:

- Voltage measurement from 0 to 1500V DC including determination of correct polarity. In a practical testing scenario, the open circuit maximum voltage is measured.
- Current measurement from 0 to 30 A DC. In a practital testing scenario the short circuit maximum current is measured.
- Measurement of isolation resistance “Riso”. Typically, the obtained values range from 0 to 40 MOhm.
- Impedance measurements based on the AD5933 IC from Analog Devices. In a practical scenario, the impedance measurements are carried out from 100 Hz to about 100 kHz with an excitation amplitude of about 1 V.

Based on this specification we then created to overall design for a PCBA, that could do these measurements in a safe and reliable way. It is important to note, that the PCBA developed is an entirely new electronic design for emazys. This means that the controller electronics, for remote control of the test circuit also had to be made from start. The key aspect of the msr_engine + controller PCBA pair was, that they can communicate as well as transmit/export data. We therefore decided that the msr_engine main Micro Controller Unit (MCU) should be the STM-32, and the controller main Micro Controller Unit (MCU) should be the ESP-32. In this way the controller can readily communicate via Bluetooth and WIFI.

This combination of MCUs make it possible to interface with the Skylark cloud platform (as introduced by Micro Technic) and a range of other cloud platforms such as e.g. google firebase. The interfacing software was built in flutter, which is an app based Integrated Development Environment, that makes it extremely fast to build and adapt new features. The underlying Firmware for the 2 MCUs was also developed as an integral part of the project.

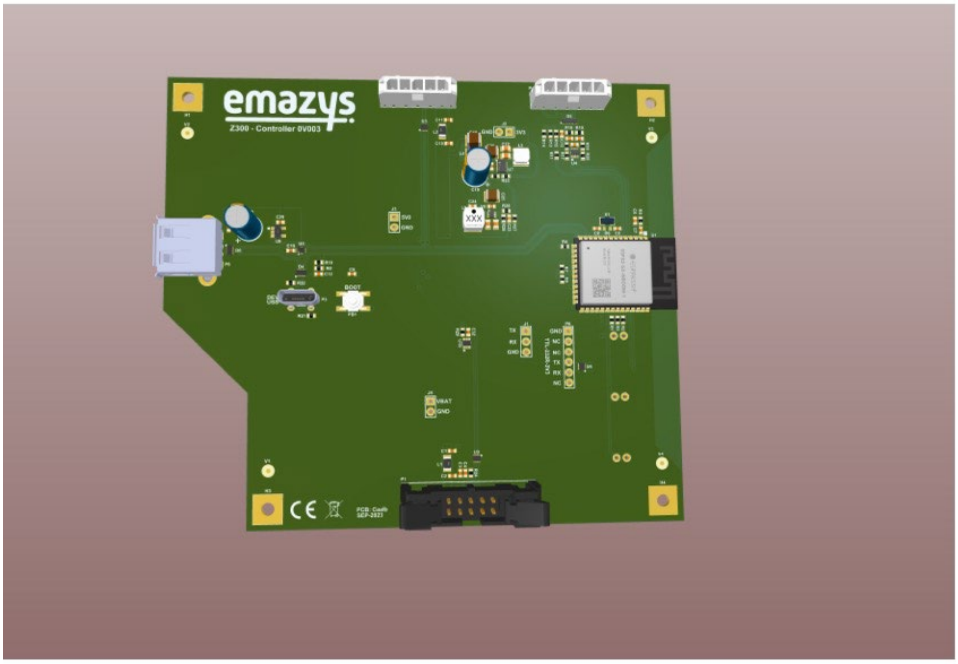
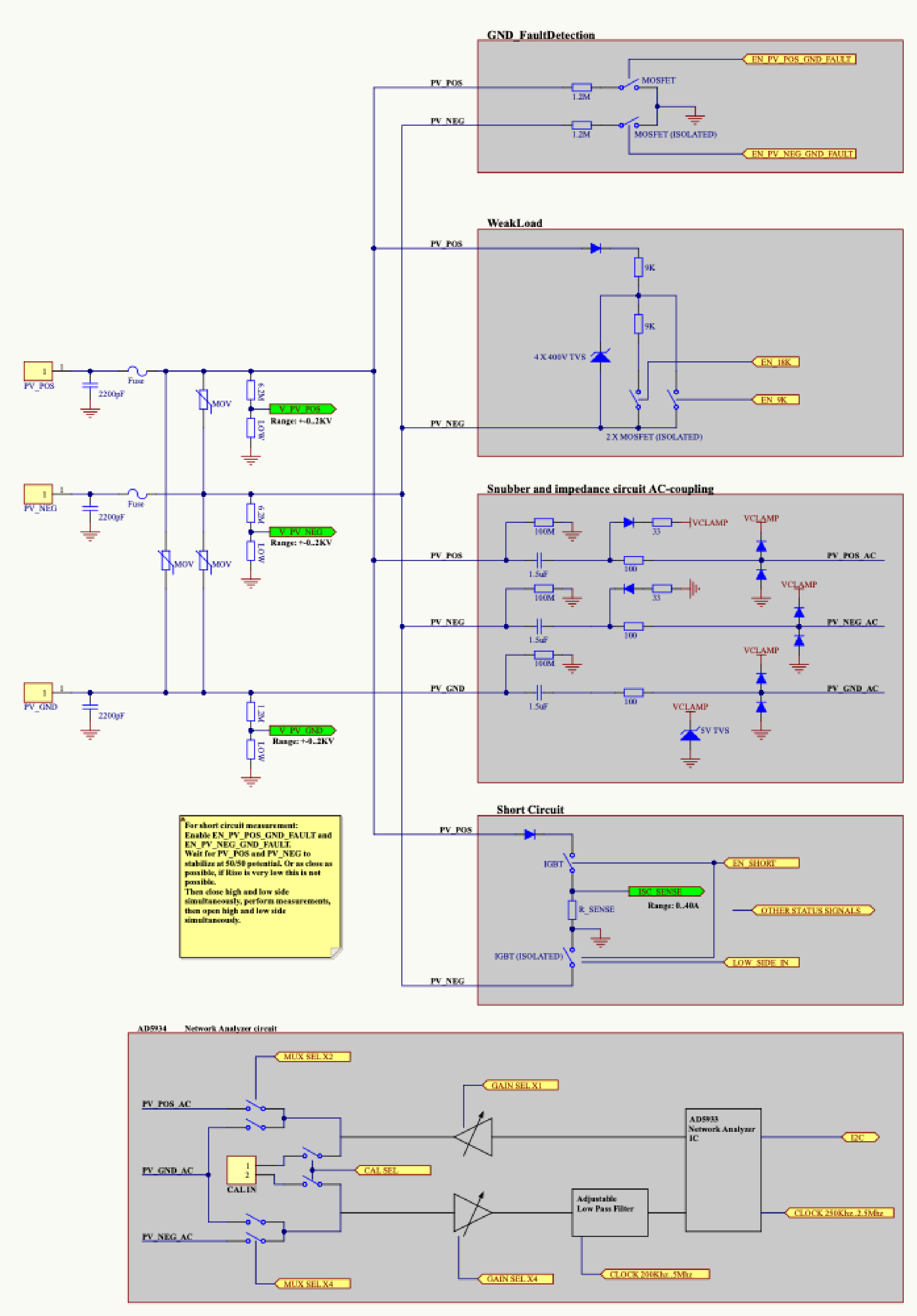


Figure 20 In this 3D rendering we see the PCBA that was developed as a controller unit for the msr_engine. Essentially this PCBA make it possible to remotely control and harvest data from the msr_engine in a variety of different setups and applications



For short circuit measurement:
Enable EN_PV_POS_GND_FAULT and EN_PV_NEG_GND_FAULT.
Wait for PV_POS and PV_NEG to stabilize at 50/50 potential. Or as close as possible, if Riso is very low this is not possible.
Then close high and low side simultaneously, perform measurements, then open high and low side simultaneously.

Figure 21 In this illustration we see the main building blocks of the emazys msr_engine PCBA that was developed for integration solar power plant components.

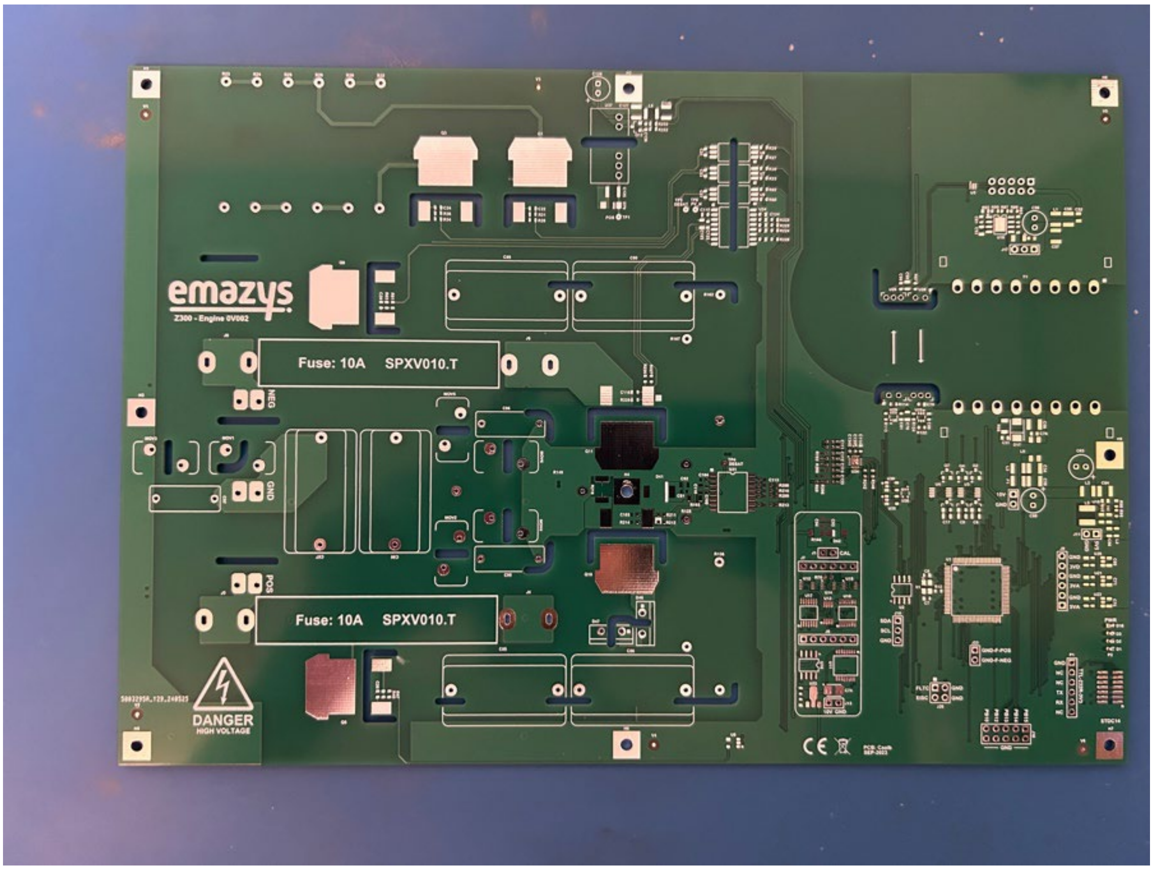


Figure 22 In this photo we see the final msr_engine PCB V2. The PCB is not populated with components. The V2 version of the PCB has the controller circuit integrated and comes at a lower cost than the original pair (msr_engine + controller). It is this version 2 PCB, that has the more potential when it comes to the long-term commercialisation of the project results.

To assure the precision and accuracy of measurements carried out with the msr_engine, we developed a new device for calibration. In the photo below we see the calibration electronics which was designed and built entirely for the project. The calibration box (P-box) is fully functional and based on. The same main MCU architecture, firmware and user interface as the msr_engine. This will allow a potential industrialisation of the combined technology package.

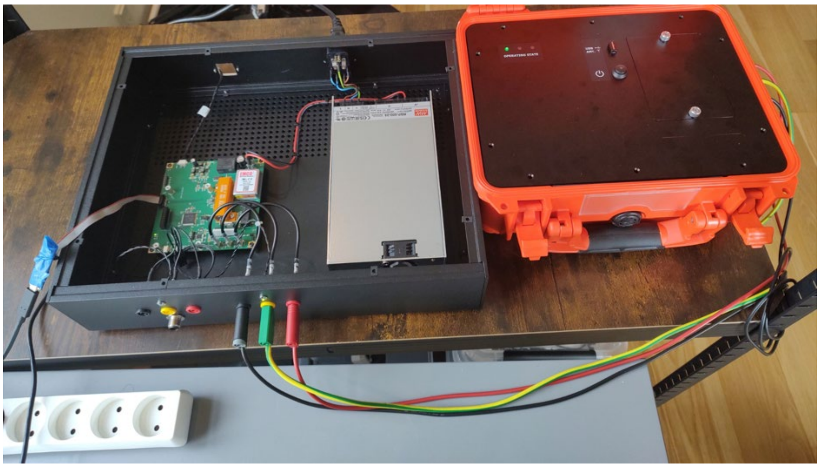
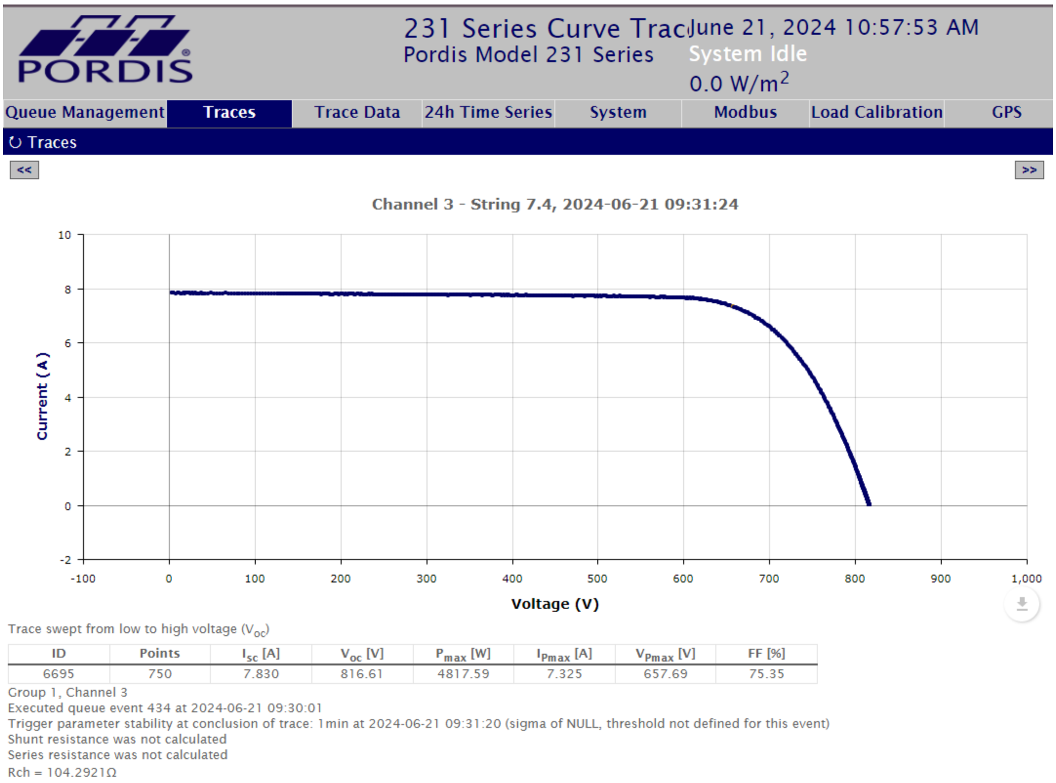


Figure 23 Calibration box designed and built for calibration of the msr_engine.

One of the secondary objectives of this project was to investigate the feasibility of smart PV string monitoring boxes, with IV tracing capability, as a solution for PV plants with older generation inverters that do not have an I-V measurement capability themselves. In this regard a first of kind 1500 V in-string IV monitoring box was designed by Pordis for this project and deployed for continuous PV string monitoring at the DTU Risø PV plant (shown in Figure 16b and Figure 17c).



Trace swept from low to high voltage (V_{oc})

ID	Points	I_{sc} [A]	V_{oc} [V]	P_{max} [W]	I_{Pmax} [A]	V_{Pmax} [V]	FF [%]
6695	750	7.830	816.61	4817.59	7.325	657.69	75.35

Group 1, Channel 3
Executed queue event 434 at 2024-06-21 09:30:01
Trigger parameter stability at conclusion of trace: 1min at 2024-06-21 09:31:20 (sigma of NULL, threshold not defined for this event)
Shunt resistance was not calculated
Series resistance was not calculated
Rch = 104.2921Ω

Figure 24. Example of string IV measurements acquired with the Pordis string monitoring box.

The system is currently operational and collecting IV data from four PV strings, initial results (exemplified in Figure 24) show excellent IV curve measurement accuracy. A study is being conducted to evaluate its IV measurement accuracy under a range of operating conditions, and the results are planned to be published at the 2024 EUPVSEC conference.

Performance modelling, monitoring and fault detection

IV monitoring and fault detection

One of the main research objectives of this project was to evaluate the potential of string IV curves for enhancing the capabilities of PV plant condition monitoring systems and the accuracy in the detection and identification of faults and degradation of the PV modules.

In this project, we applied a bottom-up approach, studying the fault detection potential of IV measurements on the panel level for different types of PV faults and then scaling up the detection models to string IV level. We investigated four types of common PV failures and PV loss mechanisms: potential-induced degradation (PID), solar cell cracks, increased series resistance, and shading. In the next few pages, we will present the study results for the first two failure types.

PID is a solar cell degradation mechanism caused by the high voltage potential at the end of PV strings in respect to the grounded frame of the PV modules, that has been an issue for PV modules in the last 15 years, and is expected to be an issue as the voltage PV string increases from 1000 Vdc to 1500 Vdc.

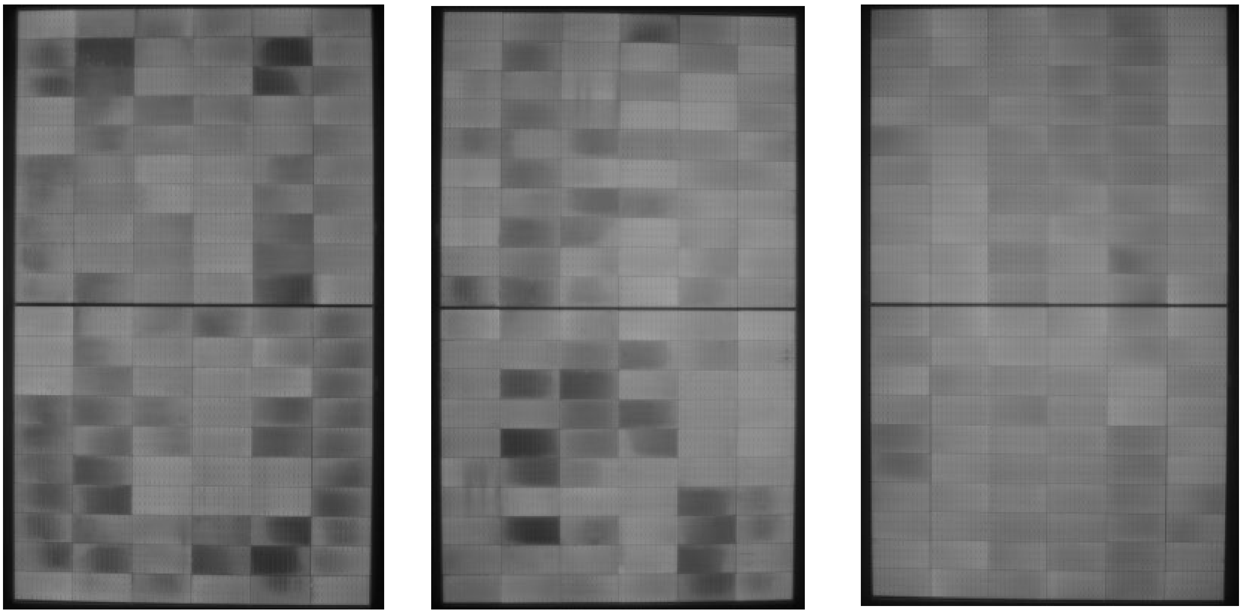


Figure 25. Electroluminescence images of the bifacial PV modules used in the potential induced degradation (PID) field IV detection test: a) module 6 – PID; b) module 7- PID; c) module 10 – control/no PID.

To develop IV-based detection methods for PID, we deployed three large format bifacial PV modules, two of which were affected by PID (Figure 25a and b) and one was used as a control (Figure 25c). These modules were deployed at the DTU Risø PV farm (as depicted in Figure 26), and connected to a module level IV curve monitoring system, where the IV characteristics of the modules, as well as in-plane irradiance and module temperature, were monitored over several weeks. Figure 27a shows the measured maximum power of the three modules measured over a clear sky day, showing the relative degradation of the PID module in respect to the control.

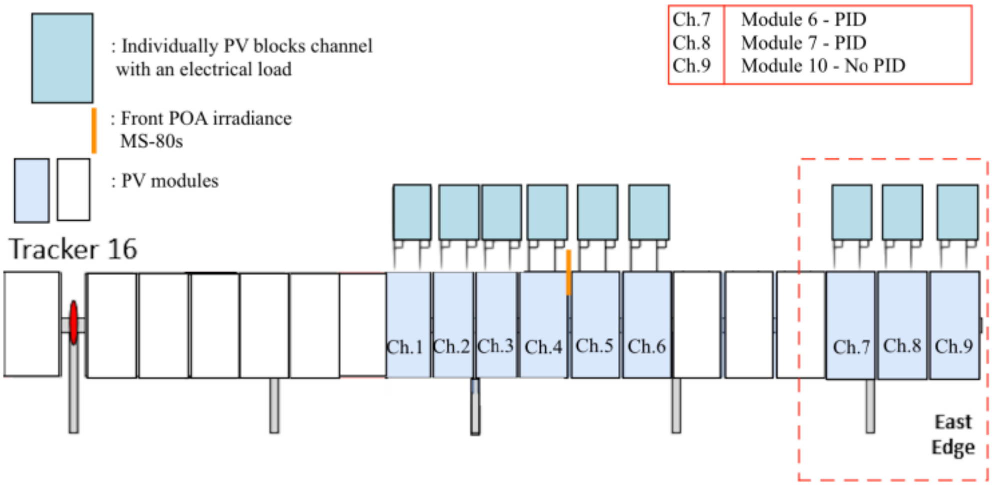
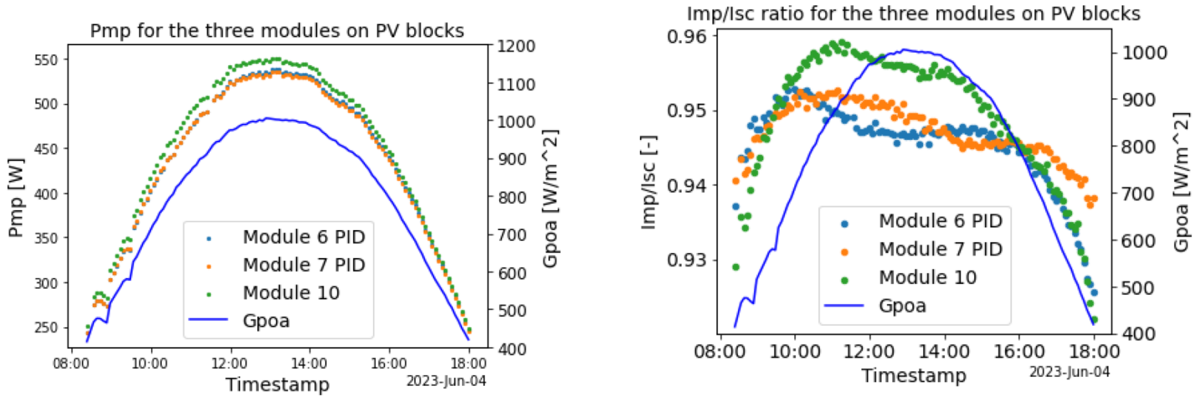


Figure 26. Field setup at DTU Risø for PV module outdoor IV characterization showing the deployment of the PID test modules on Tracker 16.

The collected IV data allowed us to extract parameters from the IV characteristic, such as the short circuit current (Isc) and open circuit voltage (Voc), that are otherwise not available through conventional inverter monitoring. These parameters allow the calculation of diagnostic indicators such as the Imp/Isc ratio, that are sensitive to changes in the shunt resistance of the module, which is typically affected when PV modules are degraded by PID. Such a situation can be observed in Figure 27b, where the Imp/Isc ratio of the PID modules (orange and blue) has decreased in relation to the control (green), indicating the shunt of these modules has decreased as well, which is a sign of PID.

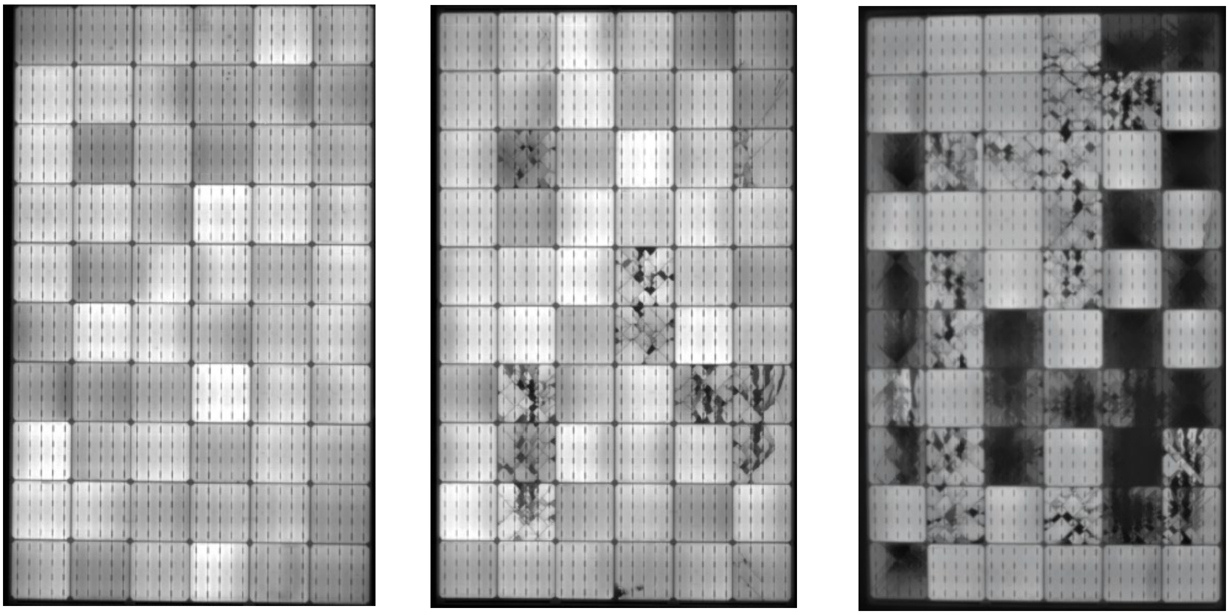


a) b)

Figure 27. Detection of PID in PV modules by Imp/Isc (derived from IV curves) monitoring: a) Pmp throughout a clear sky day for three modules, two with PID and one without; b) The change in Imp/Isc ratio throughout the day for three modules, showing increased shunt resistance losses in the PID modules (6 & 7) relative to the control module (10)

A similar study was conducted to develop an IV-based detection method for modules with solar cell cracks. Such cracks are typically caused by improper handling of the modules during transportation or installation, repeated wind and snow loads, and thermal diurnal cycling. Such cracks usually start small but progress over the years, causing power loss and localized heating, compromising the packaging of the PV module.

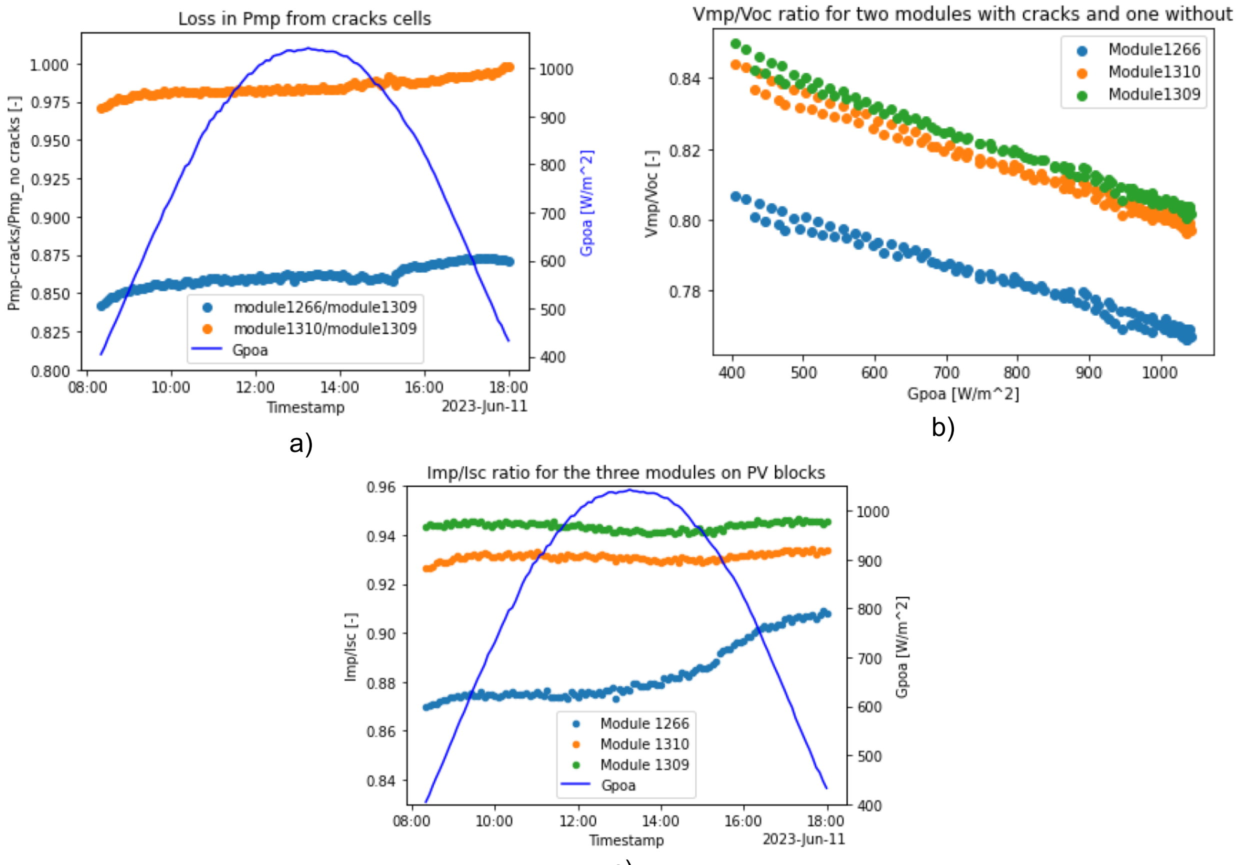
In this study, we used three mono facial PV modules, where two had different numbers of cracked solar cells (Figure 28b and c) and one (Figure 28a) was a healthy control module of the same type. The modules were deployed in the same setup, presented in Figure 26, and IV measurements were acquired over several weeks.



a) b) c)

Figure 28. Electroluminescence images of the bifacial PV modules used in the solar cell crack field detection test: a) module 1309 – control/no cracks; b) module 1310- moderate cracks; c) module 1266 – severe cracks.

The relative power loss caused by the solar cracks in the two degraded modules, relative to the control is depicted in blue and orange in Figure 29a, ranging from 2.5% to 15%.



a)

b)

c)

Figure 29. Results of the solar cell crack detection test from IV curves: a) power loss over a clear sky day in the two degraded modules (1310 and 1266) relative to the control module (1309); b) changes in the Vmp/Voc ratio in the degraded modules relative to the control module, over a clear sky operation day, showing increased series resistance losses; c) changes in the Imp/Isc ratio in the degraded modules relative to the control module, showing increased shunt resistance losses;

Solar cell cracks are a complex degradation mode, affecting several electrical properties of the cell, primarily causing an increase in the series resistance due to poor electrical contact of the cracked cell bits, as well as a decrease in shunt resistance due to small, short circuits between the layers of the cell, caused by the crack. Therefore, to identify this degradation mode, we can use two diagnostic indicators calculated from the IV characteristic of the module: the Imp/Isc ratio, which is sensitive to shunt resistance changes, and the Vmp/Voc ratio, which is sensitive to series resistance changes.

From Figure 29 b and c, we can observe that both (orange and blue) these IV-based diagnostic indicators decrease compared to the healthy control module (green), indicating the presence of solar cell cracks.

These studies have shown and validated through field measurements that IV-based diagnostic parameters can be used to identify the type of degradation in PV modules. The results of these studies have been published as part of a master thesis entitled “PV array condition monitoring based on inverter enabled I-V curve measurements“ and finalized in 2023[5].

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[5] https://findit.dtu.dk/en/catalog/64e69faef716212052e2c6a5

For scaling up the IV-based fault detection method from module IV curves to string IV curves, we start with the fact that modules are constituted from a series of connected cells, and the PV module IV curve is the aggregation of the IV curves of the solar cells. In a similar manner, PV strings are constituted from a series of connected PV modules, and the string IV curve is the result of aggregating the module level IV curves. Therefore, a sensible assumption is that IV-based diagnostic indicators will have similar sensitivities and correlations with the failure modes between PV panels and PV strings. To validate these assumptions, we performed similar string-level tests, where a third of the modules in the PV strings were degraded by different failure modes and string IVs were collected using the digital inverter IV collection interface as well as the Pordis. Preliminary results are presented in a master thesis entitled “Comprehensive Evaluation of Inspection Techniques for Fault Detection in Ground-Mounted Photovoltaic Systems,” which is concluding at the beginning of July 2024. Moreover, we are currently analyzing the data and a publication is planned.

Modelling the IV of bifacial modules

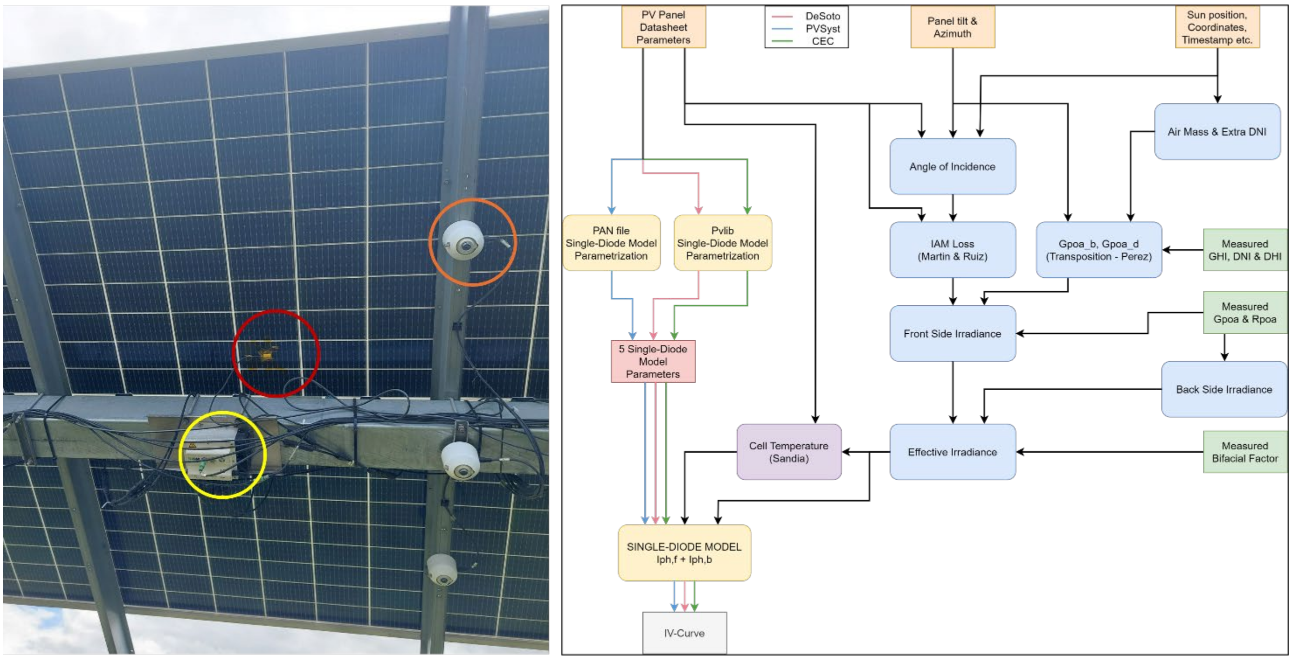


Figure 30: Left side: Rear irradiance sensor (orange), module temperature sensor (red) and IV load to measure IV curves (yellow) from the Eko system. Right side: Modelling flowchart for modelling the IV characteristics of bifacial PV modules.

We benchmarked models for IV curves of bifacial PV modules using an outdoor IV-curve tracing system by EKO. The electrical IV characteristics, rear and front irradiance and module temperature were recorded for eight bifacial modules from three different module types. Sensors are shown in Figure 30 on the left. The IV curves were also modelled based on data sheet specifications using three different electrical equivalent circuit models: PVSyst, CEC and DeSoto, for which the modelling flowchart is shown in Figure 30 on the right. The modelling error for three significant points on the IV curve, Isc, Pmp and Voc, compared to the measurements is shown in Figure 31 below. We use the normalized mean bias error (NMBE, a measure for the bias of a model – does it tend to over- or underestimate the parameter overall?) and the normalized root mean squared error (NRMSE, a measure for the variance of a model – how far is the modelled parameter off from the measured parameter at each instance?).

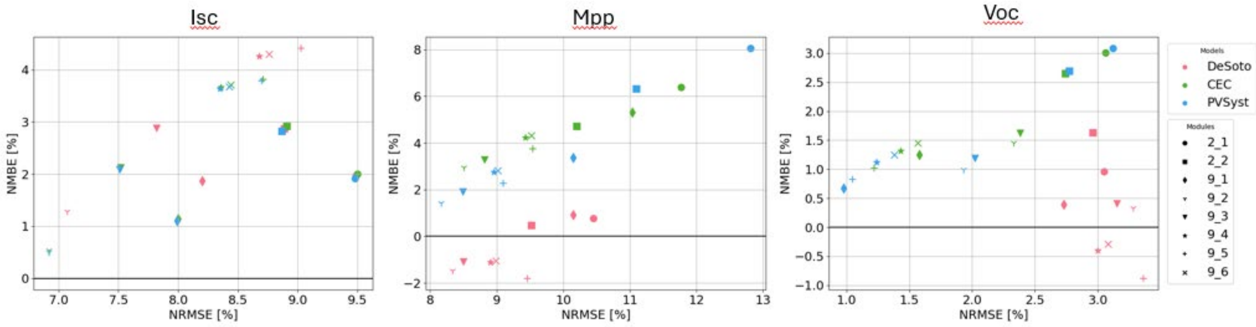


Figure 31: NMBE versus NRMSE at Isc (left), Pmp (middle) and Voc (right). Each PV module is marked with a unique shape and each model used is marked with a color.

Generally, the models tend to overestimate the Isc and Voc by 3% and 1% respectively. The Pmp is overestimated by the CEC and PVSyst model, but the DeSoto is unbiased on average. The RMSE error for Voc is much smaller than for Isc or Pmp. Also, there is no clear best candidate to model the IV characteristics of bifacial PV modules – for example, the DeSoto model is the best for Pmp in our case, but it has the highest NRMSE for modelling Voc

Implementation of the central PV plant condition monitoring system (PVP-CMS)

Field testing and demonstration

Since ca. 2020, the majority of European Energy's utility-scale PV parks feature Huawei inverters that are capable of performing on-demand I-V scans. However, European Energy does *not* use the Modbus RTU protocol to communicate with these inverters, rather European Energy uses the M-BUS protocol, which is commonly used in electricity metering. This detail means that the interface developed at Risø for the 185 kW and 40 kW inverters (using modbus RTU) could not be used, and instead, a manual procedure was used to perform I-V scans on select strings at two select parks in Denmark. These two PV sites contain 105 MWp of recent bifacial modules and they were selected for analysis because of their proximity to DTU Risø, and because the PV panels installed in these parks are the same as the panels installed DTU Risø (i.e., Risen RSM120 series, and Longi LR5 series). The rationale was that if the I-V scan data revealed possible PV degradation modes, then DTU could easily travel to these sites to perform detailed string diagnostics such as EL imaging, while also having the possibility relevant investigations using the advanced equipment on campus. But as it will be elaborated below, an onsite inspection was found not necessary, after analyzing the IV data from 105 MWp of PV strings.

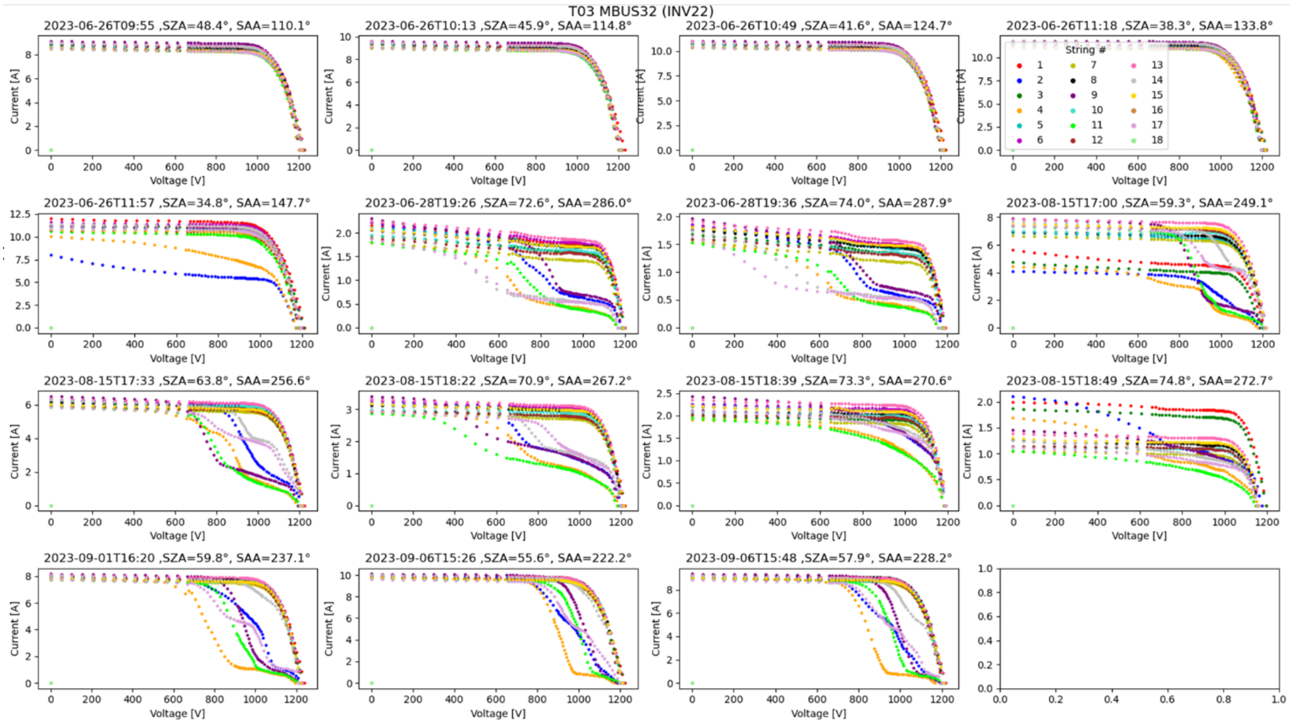
Users can implement Huawei's I-V scan feature with one of two different methods: 1) a 'park-level' scan, which performs I-V sweeps of every inverter in the park at once, or 2) an 'inverter-level' scan, which performs I-V scans of all strings connected to a particular inverter. The park-level scans must be performed in high irradiance conditions (G > 600W/m2). and we found that this method is prone to several errors including, but not limited to: excessive time delays between inverter scans (up to 90 seconds), incorrect timestamps of I-V measurements made on different inverters, and datalogger freezing. On the other hand, the inverter-level scan can be performed in all weather conditions and is not prone to the errors observed in the park-level I-V measurement method. The down side of both methods is that they require an operator to manually initiate I-V measurements and to store the data. In this sense, the I-V interface developed at Risø will be highly advantageous for PV sites using the modbus RTU protocol.

The two parks studied contain hundreds of different PV strings and a detailed analysis of continuous I-V data on all strings was not possible with current state-of-the-art. The approach to analyzing the PV string condition was to first take a series of park-level I-V measurements (1-3 measurements/day) over two clear sky days.

The VMP/VOC and ISC/IMP ratios of these few thousand I-V curves were then analyzed and roughly a half dozen candidate strings were identified based on low VMP/VOC ratios relative to the rest of the park.

An I-V measurement campaign based on inverter-level scans was thereafter performed during the summer of 2023. These I-V measurements spanned a range of irradiance (100–1000 W/m2) and sun heights (5°–55°). This was important because, for certain PV failure modes, the power loss and I-V curve signatures can change dramatically based on prevailing weather conditions. The intermittently measured I-V data were joined with the continuous PMAX, VMAX and IMAX data for comparison. A typical set of raw I-V curves measured on a single inverter (18 strings) from June to September is shown in Figure xyz_b. Each frame of Figure xyz_b shows an inverter-level I-V measurement performed at one point in time: the solar zenith angle (SZA) and solar azimuth angle (SAA) at the time of measurement are written above each frame. Apparent in Figure xyz_b is that at high sun elevation, there is little difference among PV strings, whereas at low sun heights the differences are significant. The shape of the inflection points in the I-V curves at low sun angles suggest that the underperformance is due to partial shading, and the continuous PMAX, VMAX, IMAX data support this hypothesis. The curves shown in Figure xyz_b are representative of the other five inverters analyzed in detail.

From the I-V data collected on 105 MWp of recent bifacial PV modules i.e., Risen RSM120 series, and Longi LR5 series) we concluded that the periodic underperformance was due to partial shading, not due to irreversible failure modes. Variations in slope between tables in PV parks can be significant, which can cause different partial shade behaviour even for strings at the same table height. This can confound performance analyses, which is why topography information ought to be included when analyzing I-V curve data from real PV parks.



I-V curves measured on 18 strings connected to a single inverter. These measurements were performed between June and September 2023.

6. Utilisation of project results

The technological advancements developed during the DigitalPV project, including the digital I-V curve analysis and Electrical Impedance Spectroscopy (EIS), will be utilized by project partners such as DTU Electro, emazys ApS, and Micro Technic A/S. These tools will enhance the performance and reliability of photovoltaic systems by enabling more precise monitoring and predictive maintenance. Future utilisation includes integrating these technologies into new PV installations and retrofitting existing systems to improve their efficiency and lifespan.

The commercialisation of the project results will be primarily undertaken by European Energy which will incorporate the new O&M tools into their PV projects, thereby increasing their market competitiveness. In that respect the company will be a vehicle for scaling emazys develop smart combinerbox. Emazys is among the first to have a tool working under 1500V conditions.

The project has already begun to generate economic benefits, including increased turnover and exports for the commercial project partners. Employment opportunities have also risen due to the need for skilled professionals to implement and manage the new technologies. The project partners anticipate continued growth in these areas as the technologies are further commercialized and adopted in the market. According to emazys' market analysis, there is significant potential for cost savings and efficiency improvements in PV O&M, which can lead to higher ROI for PV system owners and operators and the DigitalPV have given the company a competitive advantage.

The PV market is highly competitive, with several key players such as SMA Solar Technology AG, ABB, and SolarEdge Technologies offering advanced O&M solutions. The unique digitalisation features of the DigitalPV project, such as the integration of EIS and advanced I-V curve analysis, provide a competitive edge by enabling more accurate fault detection and preventive maintenance. Emazys new PV testers are designed to solve the "needle in the haystack" challenge more efficiently than standard test equipment, which is often not optimized for troubleshooting but for energy conversion efficiency testing.

Entry barriers include the high initial cost of integrating advanced monitoring tools into existing PV systems and the need for specialized knowledge to operate these tools effectively. These barriers can be overcome by providing comprehensive training programs and demonstrating the long-term cost savings and performance benefits of the new technologies. The emazys Z300 PVT kit, with its robust design and comprehensive fault-finding capabilities, is aimed at reducing the time and cost associated with PV system troubleshooting – a tool been developed based on findings in the DigitalPV project.

The DigitalPV project contributes to energy policy objectives by enhancing the efficiency and reliability of renewable energy sources. The advanced O&M tools developed help in reducing downtime and increasing the energy output of PV systems, thereby supporting the transition to a more sustainable energy grid and contributing to national and international renewable energy targets.

Some of the project work was done on the DTU side by a PhD student making it possible to utilize the large amount of experimental work towards research and dissemination to the PV community.

- Riedel-Lyngskar, N., Bartholomaus, M., Vedde, J., Poulsen, P. B., & Spataru, S. (2022). Measuring Irradiance With Bifacial Reference Panels. IEEE Journal of Photovoltaics, 12(6), 1324 - 1333. https://doi.org/10.1109/JPHOTOV.2022.3201468
- Bartholomäus, M., Morino, L., Spataru, S. V., & Poulsen, P. B. (2023). Evaluating the Accuracy of Inverter-Based String IV Measurements. In Proceedings of the 40th European Photovoltaic Solar Energy Conference and Exhibition (EUPVSEC). Lisbon, Portugal: WIP. Retrieved from EUPVSEC Conference Programme 2023.

- Bartholomäus, M., Morino, L., Spataru, S. V., & Poulsen, P. B. (2024). Benchmarking equivalent circuit models for the IV characteristic of bifacial photovoltaic modules. Submitted to Journal of Photovoltaic Energy – to be published.
- Bartholomäus, M., Morino, L., Spataru, S. V., & Poulsen, P. B. (2023). Field Degradation Study of Bifacial Photovoltaic Modules in Northern Europe. In Proceedings of the 40th European Photovoltaic Solar Energy Conference and Exhibition (EUPVSEC). Lisbon, Portugal: WIP. Retrieved from EUPVSEC Conference Programme 2023.
- 1 master thesis'es were realized, PV array condition monitoring based on inverter enabled IV curve measurements, Asger Kappel Skau and Marco Stefano Luzzani.

A highly market-oriented article was also made by emazys.

- Rand, A. (2024). Electrical Issues in PV Systems: The Landscape of Solar Energy Operations. PES Solar Magazine, 1(24), 1-5. Retrieved from PES Solar.

7. Project conclusion and perspective

The DigitalPV project has successfully developed and demonstrated advanced digital tools for the operation and maintenance (O&M) of modern photovoltaic systems. Key accomplishments include the development of a digital interface for I-V curve scanning, implementation of Electrical Impedance Spectroscopy (EIS) for detailed module diagnostics, introduction of predictive maintenance tools utilizing machine learning and big data approaches, and the creation of a diagnostic string combiner box capable of impedance testing PV module strings up to 1500V DC. These technologies have significantly improved the reliability and efficiency of PV systems, facilitating early fault detection and optimizing performance.

The next steps for the developed technology include further refinement of calibration routines for impedance measurements, expanded deployment of the digital interface and EIS tools across more PV installations, integration of these technologies into commercial PV projects by European Energy A/S and other partners, continued development of the diagnostic string combiner box for broader market application, and ongoing research and field testing to enhance the precision and applicability of the developed tools.

The project results are expected to have a significant impact on the future development of PV technology by enhancing the performance and reliability of PV systems through advanced digital monitoring and diagnostics, reducing maintenance costs and increasing the return on investment for PV system owners, supporting the transition to a more sustainable energy grid by improving the efficiency and uptime of renewable energy sources, and contributing to national and international renewable energy targets through improved O&M practices. The successful outcomes of the DigitalPV project will likely pave the way for wider adoption of these advanced technologies, setting new standards for PV system maintenance and performance optimization.