Final Report

New technology for localization and characterization of faults in solar cell systems
Det Energiteknologiske Udviklings- og Demonstrationsprogram

Project holder: EmaZys Technologies ApS

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Final report

1.1 Project details

Project title	New technology for localization and characterization of faults in solar cell systems
Project identification (program abbrev. and file)	Det Energiteknologiske Udviklings- og Demonstrationsprogram J. nr. 64014-0507
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	EmaZys Technologies ApS Green Tech Center Lysholt Allé 6, 7100 Vejle
Project partners	DTU Fotonik AAU Dept. of Energy Technology Kenergy ApS
CVR (central business register)	33645236
Date for submission	

Short description of project objective and results

UK

The purpose was to develop and demonstrate a new efficient and flexible technology for fault localization and diagnosis in PV systems. The technology is aimed the growing PV service market. Measurements can be carried out at the string level, and O&M costs are minimized. At the same time performance is optimized and the cost of energy is lowered. During the project an effort was made to secure both development and demonstration, but also successful commercialization of the technology in focus. The project contributed to a stronger understanding of the scientific concepts involved, but also the relevance of those concepts to customers who must daily deal with technical issues in the solar PV energy industry.

DK

Projektets formål er at udvikle og demonstrere en ny, effektiv og fleksibel teknologi til fejlsøgning/.diagnosticering i PV anlæg. Teknologien kan anvendes bredt på det stigende servicemarked (O&M) og kan måle på strenge af flere solcellepaneler, hvorved O&M omkostningerne minimeres. Samtidig optimeres performance og ”Cost of Energy” nedsættes. Undervejs i projektet er der arbejdet med at udvikle og demonstrere, men også kommercialisere teknologien, der har været i fokus. Projektet har bidraget til en større forståelse af de involverede videnskabelige koncepter, men også disse princippers relevans for kunder der til dagligt må løse tekniske problemstillinger i solenergiindustrien.

1.2 Executive summary

The project aims to develop, demonstrate the Z100 solar measuring instrument. The Z100 is based on a new technology invented by EmaZys Technologies, and the instrument is used to test and especially debugging in all types of PV systems.
In the photovoltaic industry, there have been tremendous developments and most components are now placed far down in price, but there remains a problem with respect to finding cheap and effective solutions to technical maintenance, service and troubleshooting of PV systems. Here Z100 pose a significant economic advantage, because the instrument contributes to time savings of several “hours per task” when solar energy engineers worldwide perform tasks in maintenance at an accelerating pace. Errors and system damage affect electricity production negatively, but with Z100 errors can quickly be located and repaired, and the overall energy price is hereby reduced.
At EmaZys the efforts has been concentrated at actually building prototype circuits and software to be used together with the project partners. At partners DTU and AAU the focus can best be described as “experimental physics” involving experiments aimed at accelerating degradation in solar panels and solar PV system components. Subsequently performance testing and analysis of components was done. Especially the focus has been at stressing and degrading solar panels at high electric potential, and track down damage patterns. The
The knowledge picked up experimentally has then been integrated into the Z100 by EmaZys and field-test demonstration has been carried out by partner Kenergy.
One of the best commercial results obtained is that the project has helped EmaZys to secure a sales partnership contract with EKO Instruments (Japan). EKO is a pioneer in testing equipment for agriculturally and solar energy, and so we have found the optimum partner with towering technical standards. Along with EKO, EmaZys

has now launched the instrument MP-21, which is a further development of the Z100 which is extended with a user interface in Japanese.

1.3 Project objectives

The overall project goals has been to develop and demonstrate the Z100 technology which is a new impedance spectroscopy based technology aimed at measuring the health condition of solar PV generators i.e. solar panels. Also, the technology has the capability to actually position a fault in solar PV installation, thereby making debugging and troubleshooting a routine task that may be carried out by ordinary technical staff.

	
The Z100 PV Analyzer from EmaZys Technologies. Front view	The Z100 PV Analyzer from EmaZys Technologies. Open box.

The project was worked out strictly according to a schedule plan involving milestones such as hardware and software for the prototype instruments (Z100) to be activated at the partners, development of updated and improved analytical models, and finally testing and demonstration at actual solar PV stations in Denmark and abroad. Those milestones along with the commercial milestones, has secured that the project outcome was actually a product ready to be manufactured at modern facilities and marketed across the world. Also the outcome was new valuable knowledge for further studies and project work.

CAD Illustration of the Z100 orange solar PV tester. Here connected to a string of solar panels ready to start testing.

The innovative content of the project lies in the commercialization of a concept that, so far, has only been applied in the laboratory. The impedance method, which was the core scientific concept in this project, does not involve the measurement of electric power. It is thus possible to design a product containing only few power electronic components. This reduces the cost price and increases the robustness of the product. The method involves measuring an Alternating Current (AC) current response, based on an AC voltage input. This is done while the terminals of the impedance instrument are galvanically isolated, from the PV system terminals. The principle is thus to characterize the PV material, and *not a DC current* from the PV system. For this reason it is possible to characterize systems in the dark, and at very low light intensities, and thereby reduce close down time.

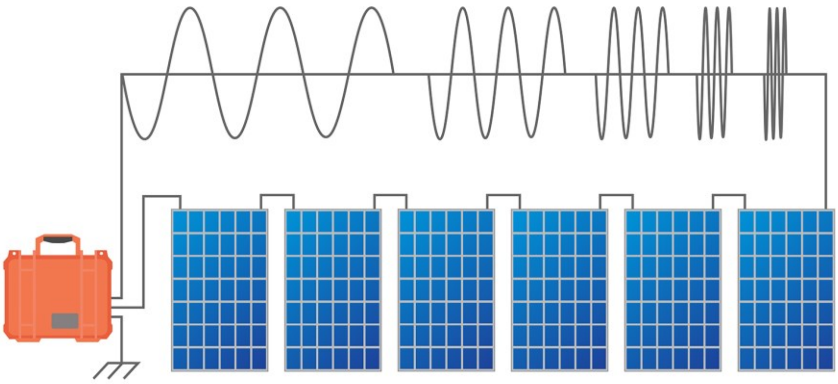


Illustration of the main testing principle of the Z100 PV Analyzer regarding impedance spectroscopy. The unique feature is that Z100 is actively emitting test frequencies, while measuring the resulting signals. The analysis of the resulting signals leads to bot position and type of electrical fault.

Often occurring forms of PV degradation such as "potential induced degradation" (PID), "broken bypass diodes", "cable disconnect", grounding fault", "micro cracks" and "snail tracks" all have a characteristic impedance spectrum. Therefore the impedance method can accurately state what kind of degradation there is observed/measured, while conventional methods can only conclude that some unspecified degradation is affecting the electricity production i.e. affecting current and voltage characteristics of the system.

The development work in the project was focused at a laboratory setting, where DTU and AAU has created simulated sunlight for illumination of entire panels. The measurement electronics from EmaZys (Z100 boxes) were then tweaked, so that they could measure provoked and simulated system faults, in any type of light environment. The electrical impedance of solar cells is a sensitive function of AC voltage frequency, light intensity and colour distribution. A key result was thus the team behind the project demonstrated that PID can be measured using impedance spectroscopy both in theory, in the laboratory and not the least in the field by using the Z100. This result is an essential outcome of the project and it has a clear commercial application. To some extend the same type of results were achieved with micro-cracks i.e. we have shown that impedance testing can be used to detect such faults. The progress of the work is however not as advanced as the work with PID.

Project results and dissemination of results

1.3.1 Test Methods at DTU and AAU

A total of 20 Solvis SV36 crystalline Silicon modules were characterized indoors via current-voltage (I-V), impedance spectroscopy (IS) and Electroluminescence (EL) methods. All 20 test modules received additional I-V and IS measurements outdoors with the Emazys Z100 for a minimum of one month at the DTU Fotonik outdoor test facility. The 20 test samples consisted of 7 modules that were mechanically, thermally, and/or electrically stress tested in a laboratory environment at Aalborg University (AAU).

A list of all module ID's and their corresponding stress tests is provided in Table 1.3.1. The 20 modules are separated into two groups. None of the modules in Test Group 1 were stress tested in the laboratory environment. However, these modules did receive 4 months of outdoor exposure in the field. Test Group 2 does contain modules that were stress tested in the laboratory environment. A brief description of the laboratory stresses is as follows: modules labelled as "uC" were mechanically load tested (MLT) to induce micro cracks (uC). Five of the six uC modules also received a thermal stress known as Humidity Freeze (HF), wherein the samples were exposed 10 cycles in a hot-humid environment (85°C/85% relative humidity) for 20 hours and then thermally shocked by rapidly bringing the temperature down to -40°C. Lastly, the module labelled as "PID" was exposed to a high electrical bias so as to induce a failure mode known as Potential Induced Degradation (PID).

The original test plan called for stress testing more than 7 modules, but due to limited access to a climate chamber, this amount of stress testing was all time would allow. The remaining 13 test modules were not stress tested other than the 1 to 4 months of outdoor exposure they received during the field test. These modules are considered control modules and their measured I-V and IS parameters will be compared to the stress tested modules.

Table 1.3.1: Module IDs and corresponding stress tests for the 20 test samples.

Test Group 1		Test Group 2	
Module ID	**Lab Stress Test**	**Module ID**	**Lab Stress Test**
ENV_01	None (control)	DH_02	None (control)
ENV_02	None (control)	PID_01	None (control)
ENV_03	None (control)	PID_05	PID
ENV_04	None (control)	TC_05	None (control)
ENV_05	None (control)	uC_04	MLT then HF
HF_01	None (control)	uC_05	MLT then HF
HF_02	None (control)	uC_06	MLT then HF
HF_03	None (control)	uC_07	MLT then HF
HF_04	None (control)	uC_08	MLT then HF
HF_05	None (control)	uC_09	HF (no MLT)

1.3.2 Stress tests

To correlate panel faults and degradation modes with the AC impedance spectrum, the panels as in Table 1.3.1 have undergone various stress and degradation tests in controlled laboratory environment at AAU. Two main degradation types have been investigated in the lab, PID and microcracks.

1.3.2.1 Potential induced degradation tests

An MSc project at AAU has been carried out within this project by Matei I. Oprea, focusing on PID degradation detection using impedance spectroscopy (see [1]). The following description of the PID setup and the measurement results are reproduced from this MSc thesis.

The setup for the accelerated degradation test is shown in Figure 1 The module is wrapped in an aluminium foil of 10μm thickness. To assure connection between panel surface and the conductive material a soft, flexible polymer mat was placed over and under the module. The frame and the foil are joined together with a metallic annulus with bolt and nut, and grounded. Prior preparation of the frame is required as usually an insulating coating is applied on commercial modules. The panel terminals are shorted together and a negative 1000V potential is applied using a high voltage DC source.

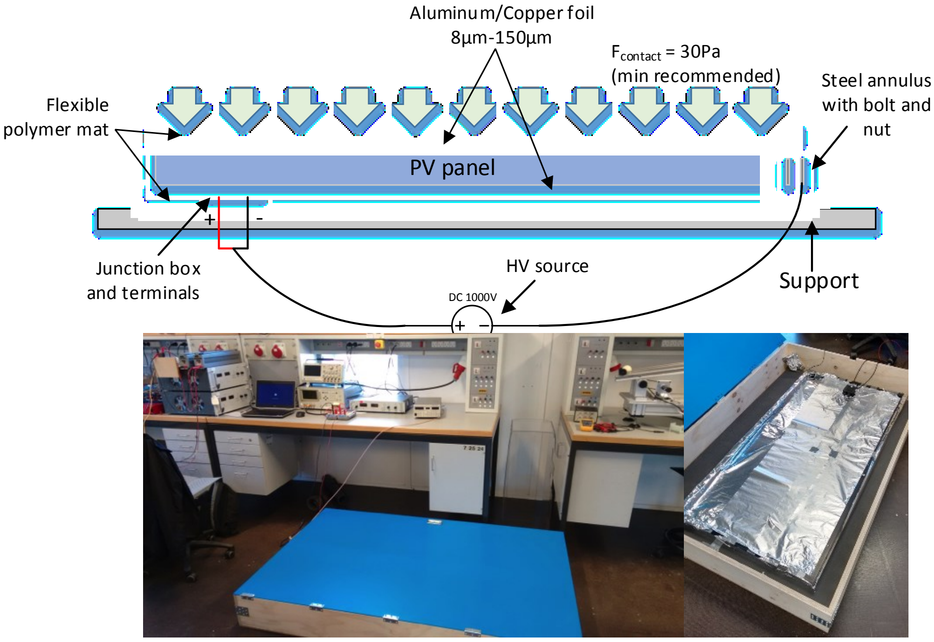


Figure 1: PID test setup at AAU, scheme & principle (top) and setup photo (bottom)

The voltage is provided by a Stanford Research PS350 High Voltage DC source. The source is capable of both polarities, positive and negative, with adjustable voltage in the range of 40V to 5kV. The current is limited to a maximum of 5.25mA. To control and monitor the experiment remotely – due to the long-term running of the tests - a LabVIEW script has been developed.

Typical laboratory measurement results are shown below (from [1])

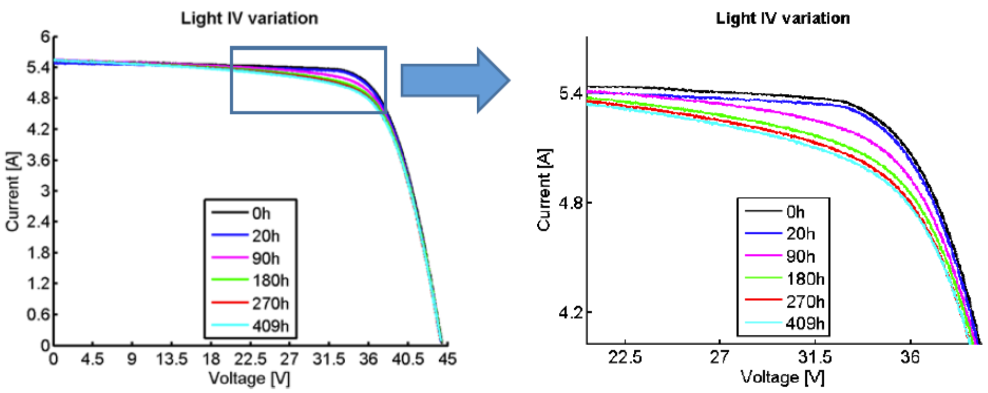


Figure 2: Evolution of the light -IV curve of a test panel exposed to PID tests.

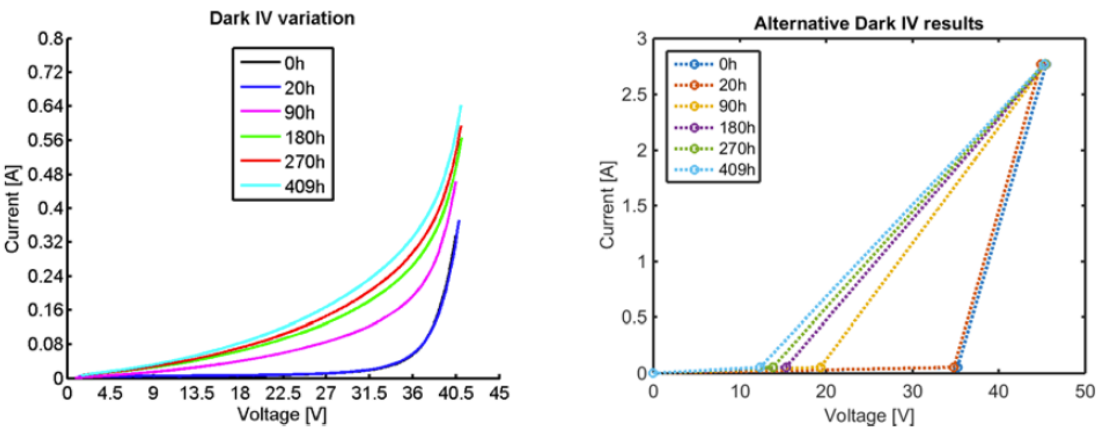


Figure 3: Evolution of the dark -IV curve of a test panel exposed to PID tests.

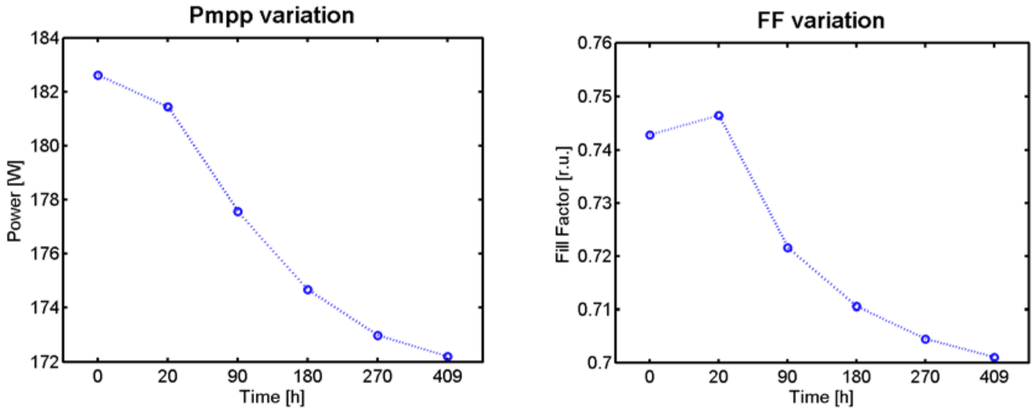


Figure 4: Evolution of the peak power (left) and fill factor (right) of a test panel during the PID tests

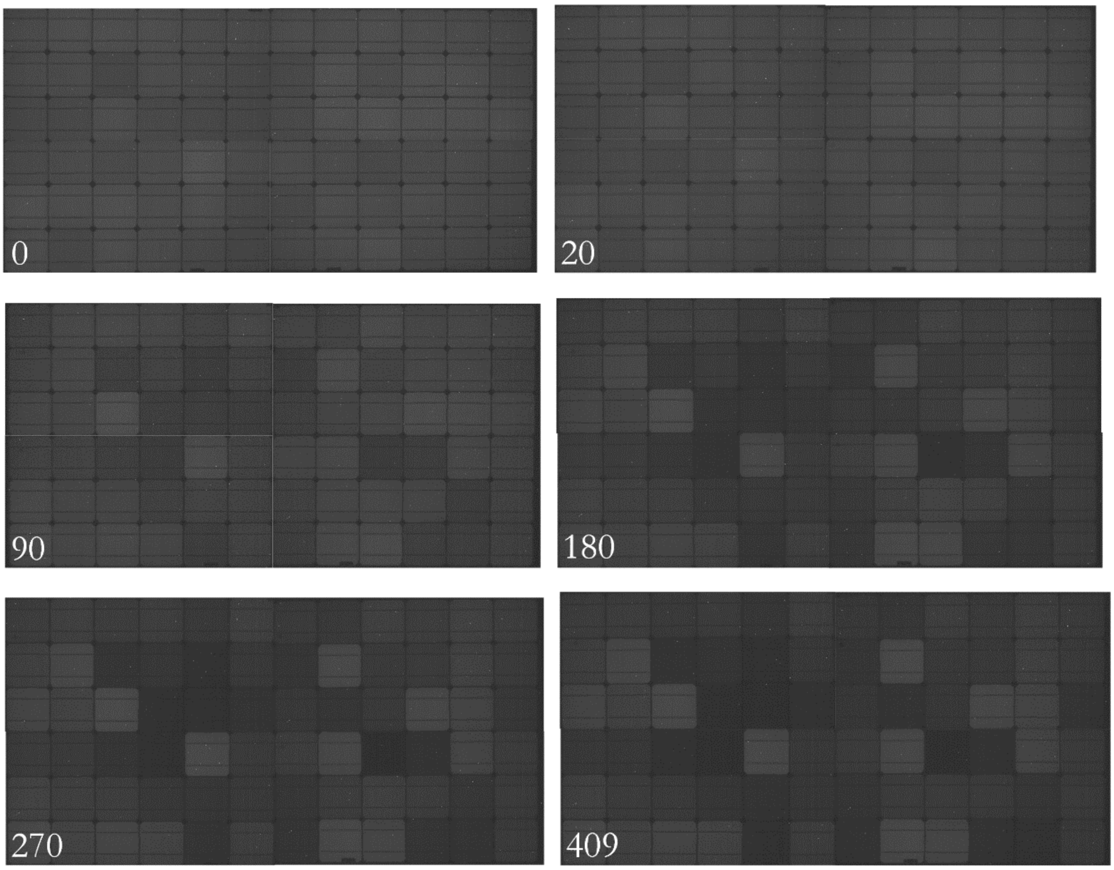


Figure 5: Electroluminescence images taken of the test panel during the PID degradation tests. The numbers in the bottom left corner of the images indicate the exposure time to PID in hours. The progress of degradation can be clearly seen as increasing number cells become darker.

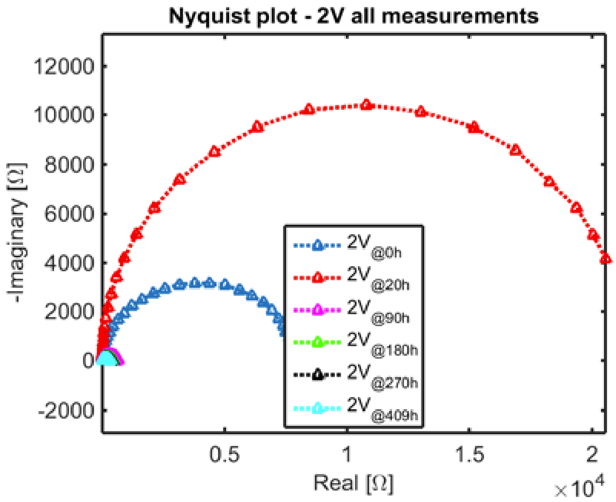


Figure 6: Variation of the impedance spectra during the PID tests

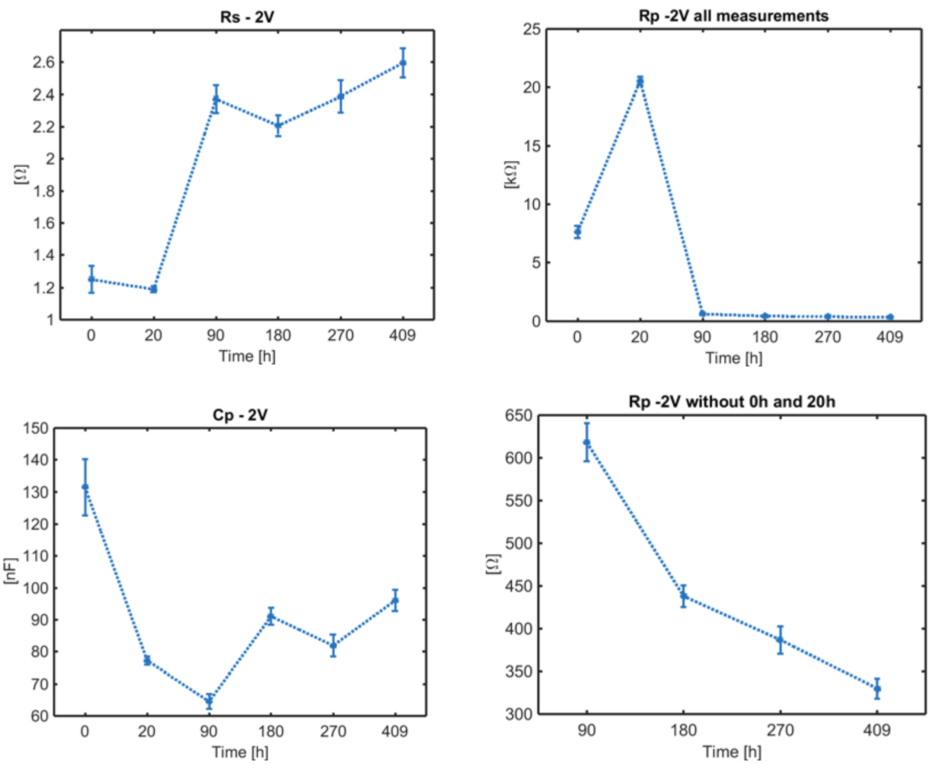


Figure 7: Evolution of the key panel parameters during the PID tests, determined with AC impedance spectroscopy. Top left – series resistance, top right – parallel resistance, bottom left – panel capacitance, and bottom right – parallel resistance focusing on the values after 90 h of PID exposure.

The lab measurements shown in Figures 2-5 clearly show the presence of potential induced degradation, and Figure 6-7 confirm that this type of degradation also affects the AC impedance and parameters of the panel, which can be measured using e.g. the Z100.

1.3.2.2 Microcracks and fractures

To investigate the effect of microcracks and fractures on the PV panels parameters, we have conducted a series of stress tests creating increasing number and severity microcracks on the panels.
This was done in two main phases: in the first phase, the panels have been mechanically stressed using loads, as shown below. In the second phase, the panels

were placed in an environmental chamber for humidity-freeze cycles per the IEC 61215 standard.

Figure 8: Mechanical loading of the panels to inflict microcracks and cell fractures.

Phase 1: mechanical loading: The mechanical stress test has been done in three stages, placing increasing weight on the panels.
To assess the degradation evolution, the panels have been thoroughly characterised at every stage by:

- Dark and light I-V curve measurement (flash test) using the state-of-the art Spire Spi-SUN 5600 SLP Sun simulator. During these measurements, the panel efficiency, peak power and main parameters as Rs, Rp, FF have been measured and recorded.
- Electroluminescence (EL) measurements using a high sensitivity short-wave infrared (SWIR) InGaAs camera by Photonic Science. The EL tests provide a very high-detail image of the panel showing the micro-cracks and is an essential tool to confirm and visualise the existence and extent of microcrack damage on the panels.
- AC impedance spectroscopy, using both the Emazys Z100 as well as an HP 4284A Precision LCR Meter as reference. Rs, Rp, and Cp have been axtracted from the AC impedance tests at each stage of the degradation.

Phase 2: Environmental chamber tests: In the second phase, after completion of the mechanical tests, the panels have been placed in an environmental chamber (Angelantoni DY 1200C) gave undergone multiple humidity-freeze cycles. A HF cycle is shown below:

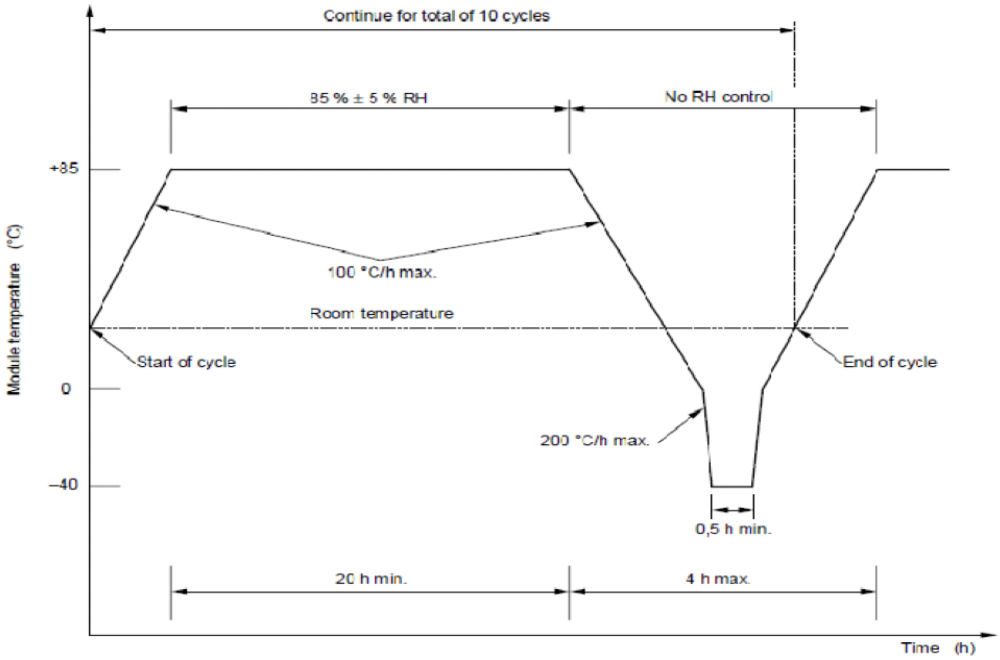


Figure 9: Temperature profile of a HF cycle for type-testing PV panels according to the IEC 61215 standard.

Figure 10: Panels placed in the Angelantoni DY 1200C environmental chamber at AAU, to be undergone humidity-freeze tests.

Key measurement results are shown below.

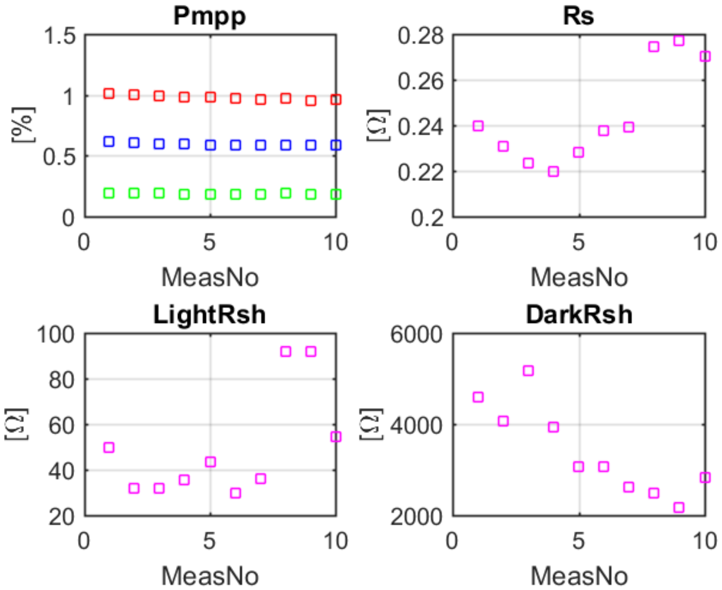
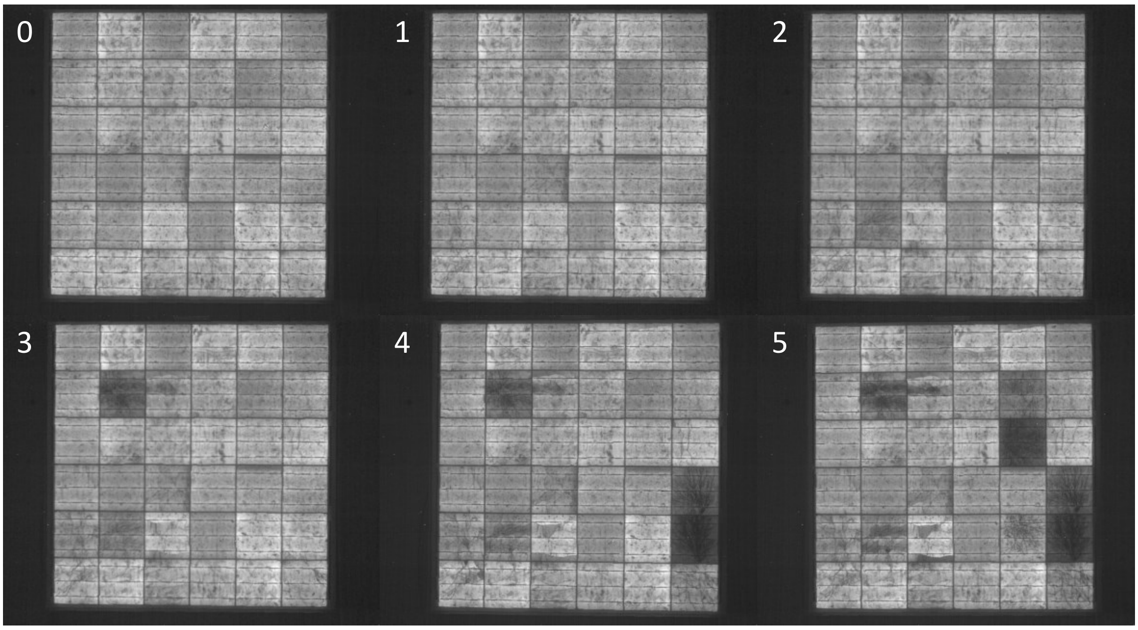


Figure 11: Key parameters based on I-V measurements during the progression of microcracks. The x axis (MeasNo) indicates the phases of the degradation: 0:- no degradation, 1-5 – increasing mechanical degradation, 6-10 – increasing number of humidity-freeze cycles. The peak power (top left graph) is given in % of datasheet values. The bottom right graph shows the parallel resistance determined from dark I-V measurement



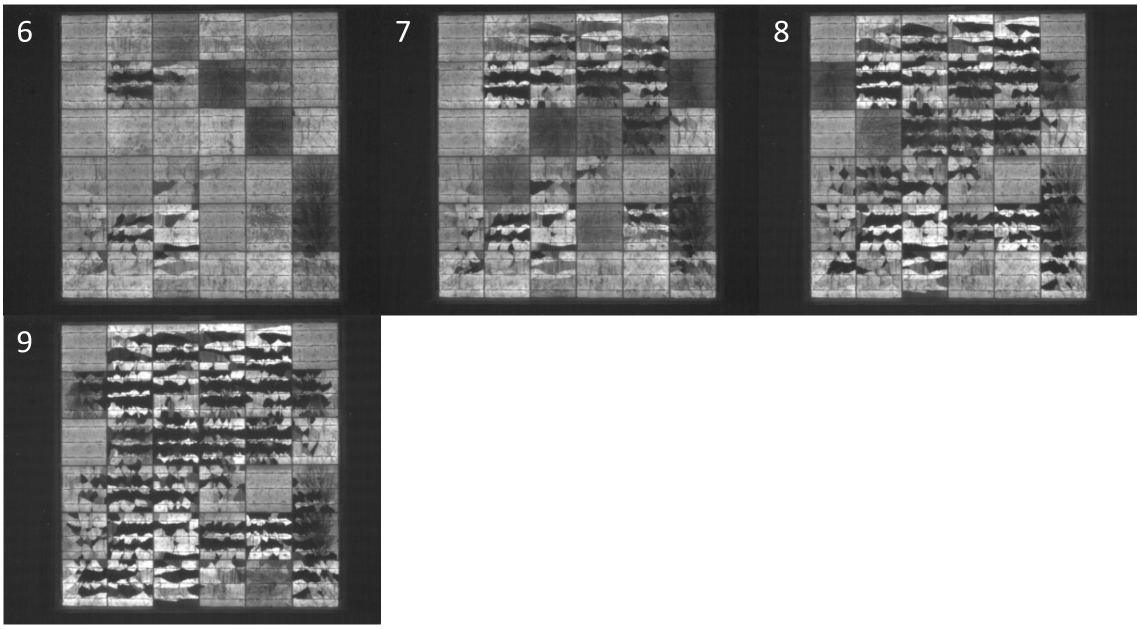


Figure 12: EL images of a test panel at various stages of microcracks and fractures stress test

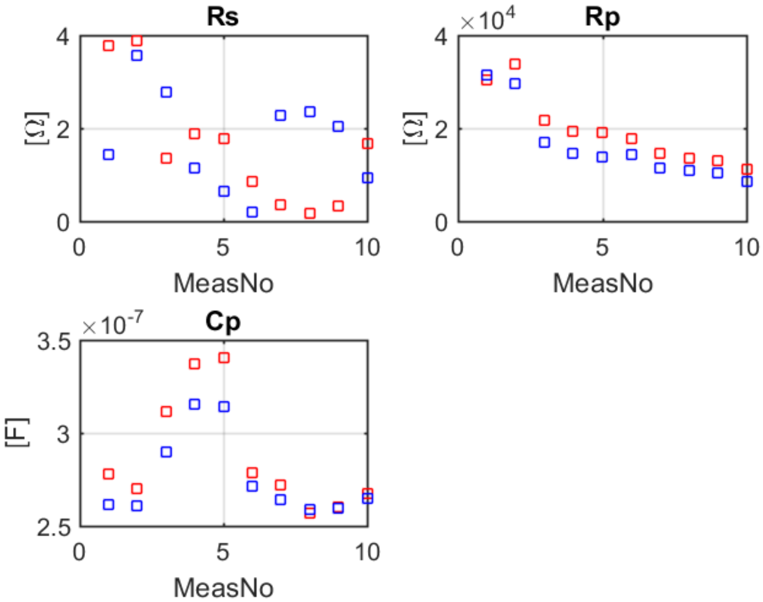


Figure 13: Key parameters based on AC impedance measurements during the progression of microcracks. The x axis (MeasNo) indicates the phases of the degradation: 0:- no degradation, 1-5 – increasing mechanical degradation, 6-10 – increasing number of humidity-freeze cycles.

The lab measurement results shown in Figure 11 and Figure 12 clearly show the onset of microcracks (and their evolution into fractures), while the AC impedance measurement shown in Figure 13 confirm that this type of degradation measurably affects the AC parameters of the panels.

1.3.3 Indoor Measurements

1.3.3.1 Current-Voltage (I-V)

I-V tests have been performed both at DTU and AAU. At AAU, I-V characterisation has been carried out using the state-of-the art Class A+A+ A+ Spire Spi-SUN 5600 SLP Sun simulator, where the following parameter have been measured and recorded:

- Peak power (Pmp) – to assess overall performance degradation due to e.g. PID or microcracks
- Current and voltage at peak power (Imp, Vmp), and Fill Factor (FF) – to assess distortion of I-V characteristic due to the degradation
- Series and parallel resistance (Rs and Rp)

The measurement repeatability of the Spi-Sun is better than 0.25%, the same as the EcoSun10L used at DTU Fotonik.
At AAU Dark I-V measurements were also performed. During dark I-V measurement, current is injected into the PV panel (in dark conditions) using a DC power source, and the corresponding voltage drop on the panel together with its absorbed current is monitored. Typically, dark IV gives a better accuracy for the shunt (parallel) resistance (Rsh) measurement.

Further indoor I-V characterization was performed with the EcoSun10L solar simulator at DTU Fotonik (Figure 14). This measurement system consists of a programmable LED-based light source and a single quadrant load, which can acquire light I-V curves from individual PV modules. The EcoSun10L has several advantages over Xenon (Xe) and metal-halide light sources that are traditionally used for indoor PV module characterization. Namely, the EcoSun10L can tune the light source's spectrum to conditions more representative of the sun, the LEDs can be used as a steady-state or pulsed-light source, and the LEDs do not require the lengthy charge time that Xe or metal-halide lamps typical need. The EcoSun10L solar simulator provides DTU-Risø with the state-of-the-art in indoor PV characterization methods.

Figure 14: EcoSun10L LED-based solar simulator

The EcoSun10L solar simulator provides measurement repeatability better than ±0,25% for maximum power (Pmp) measurements. This means that the measurement system is capable of detecting relative performance changes (e.g. before and after stress testing) of greater than ±0,25%. DTU operators measure a control module at the beginning and end of every lab session to ensure the measurement system remains stable within the ±0,25% limit.

Figure 15 shows how the indoor measurements of Test Group 2 deviate from the Solvis SV36 nameplate values for every I-V characteristic of interest - short circuit current (Isc), open circuit voltage (Voc), and max power (Pmp) separated into current (Imp) and voltage (Vmp). A comparison to the nameplate values simply allows all characteristics to be placed on a common axis. The figure is color coated by lab stress test to highlight the approximate extent of degradation between control (red) and stress tested modules (green and blue). Notice how the micro crack (uC) group shown in blue are on average 4,4% (6,6 W) lower in Pmp than the control modules. The losses in Pmp are due to a combination of Imp and Vmp losses, which indicates a reduction of shunt resistance (Rp) and an increase in series resistance (Rs). The module tested for PID showed no significant deviation to the control modules. Not shown in this graph is test module uC_04, which had a severe Pmp loss of 33%.

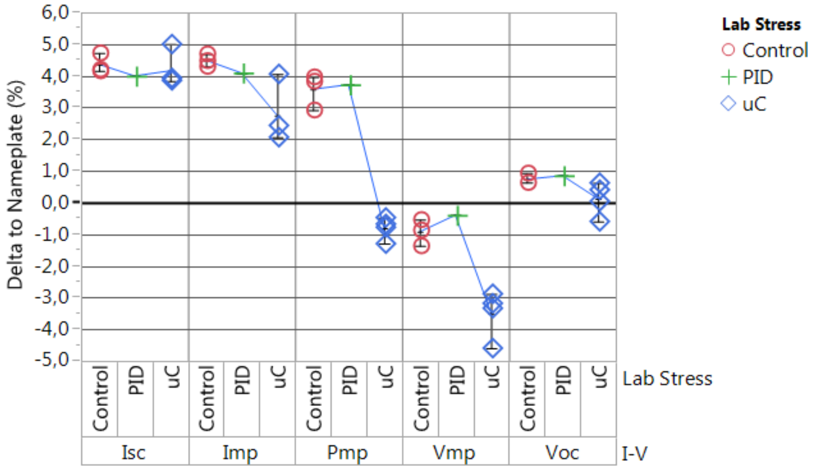


Figure 15: Delta to Solvis SV36 nameplate ratings relative to the indoor I-V measurements of Test Group 2.

Figure 16 shows efficiency measurements at multi-irradiance on a select group of modules in Test Group 2. These measurements were taken at a constant temperature of 25°C and will be used to validate the outdoor I-V data across multiple environmental conditions. The Rs and Rp parameters are extracted from this multi-irradiance I-V data and will be compared to the Rs and Rp parameter extracted from the outdoor data set (Section 1.3.4.1).

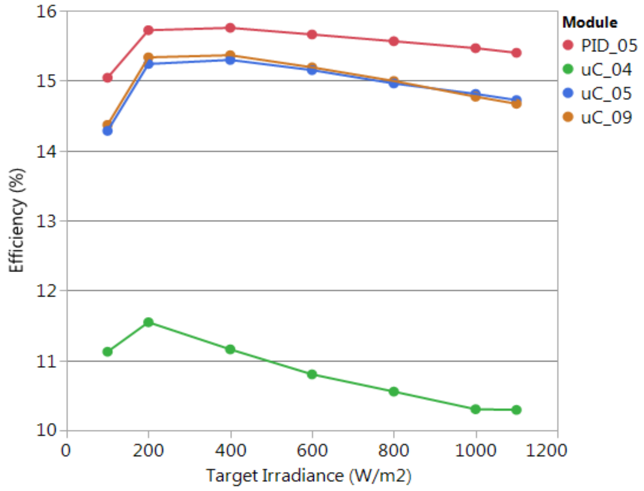


Figure 16: Multi-irradiance efficiency of group 2 modules.

1.3.3.2 Impedance Spectroscopy (IS) – at DTU and AAU

At DTU, a Gamry Reference 3000 Potentiostat was used to make indoor IS measurements (Figure 17). The IS data are then used to extract the AC characteristics of the test samples. IS measurements were taken on Test Group 1 after 4 months of outdoor exposure on the field system, while IS measurements of Test Group 2 were taken before they received any outdoor exposure. The Gamry

Reference 3000 Potentiostat is similar to the Emazys Z100 in that it is a research grade instrument used for measuring electrochemical impedance. The Gamry is capable of injecting small signals at frequencies from 20 Hz to 100 kHz. As the frequency is varied, a number of impedance spectra are measured from which the parameters of interest - series resistance (Rs), shunt resistance (Rp) and parallel capacitance (Cp) - can be extracted. The Rs, Rp and Cp parameters are then used to detect the extent of module degradation.

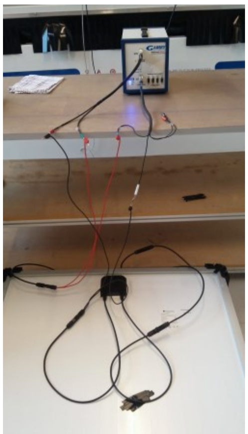


Figure 17: Indoor Gamry Potentiostat (left) and test set up with Solvis SV36 module (right).

Figure 18 shows the Nyquist plot of the indoor IS measurements taken with the Gamry 3000. All measurements were taken in the dark at open circuit. The plot is color coated by stress test. It is clear from the figure that the shape of the curves in the uCrack group (blue) is fundamentally different from the control and PID groups. If the Nyquist plots in Figure 18 are projected to form complete semi-circles, we can see that the second x-axis crossing will be less for the uCrack group than for the PID and Control groups. According to the AC circuit model found in the literature, the first x-axis crossing is equal to Rs and the second x-axis crossing is equal to Rs+Rp. Since all three groups are roughly equal at the first x-axis crossing (Rs), the uCrack group will have a lower Rp value than the PID and control groups. Both the I-V and IS datasets confirm the low Rp values of the uCrack group. The complete set of extracted parameters – Rs, Rp and Cp - are shown in Figure 19.

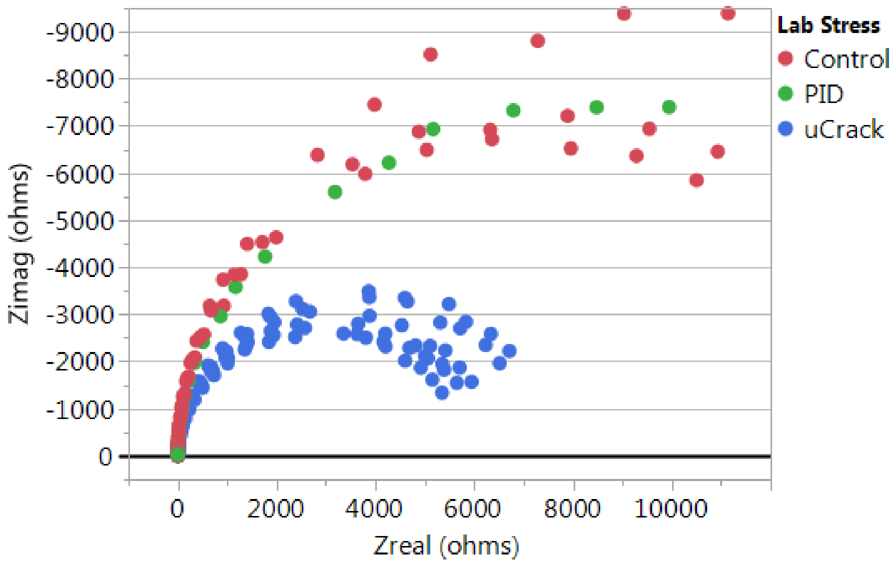


Figure 18: Nyquist plot of indoor IS measurements of modules in Test Group 2.

Figure 19 shows that Rp is 2 to 3 times higher in the control groups than the uCrack group. This result indicates that the Rp parameter could be a good indicator to detect power loss due to micro cracks. In regard to the Rs and Cp parameters, there is considerable overlap between the control and uCrack groups, which indicates that these parameters may not be as useful for detecting power loss due to micro cracks. Note that the parameter solution set (Rs, Rp, Cp) is non-unique, meaning that values for a given parameter will change as other parameters are adjusted. It is therefore important to select realistic values as starting points in the fitting routine.

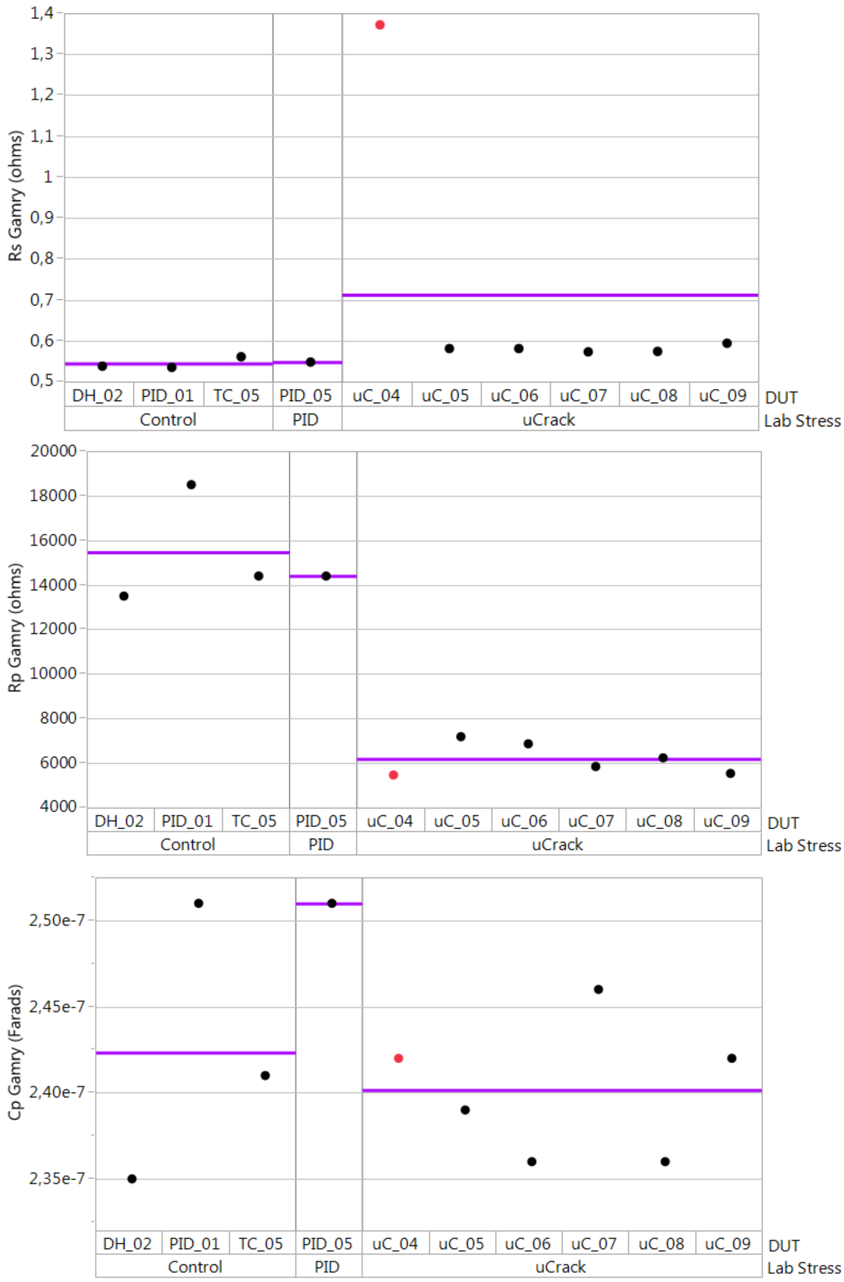


Figure 19: Extracted Parameters from the indoor IS measurements of Test Group 2. Highlighted in red is uC_04, which had significant (33%) power loss after MLT.

AAU used an HP 4284A Precision LCR Meter as reference for impedance spectroscopy measurements. This is a general purpose LCR meter with a frequency range of

20Hz - 1 MHz and a current (50μA – 20mA RMS) or voltage excitation signal (5mV to 2V RMS). The HP 4284A has a basic accuracy of ±0.05% and a six-digit resolution. Impedance measurement range is 1Ω - 100kΩ. DC voltage bias is maximum ±40V and DC current bias is up to ±100mA. To automate the process, a LabView script has been developed.

A simple RC equivalent circuit model has been used for fitting and determining the PV panel's AC parameters, as shown in Figure 20 below:

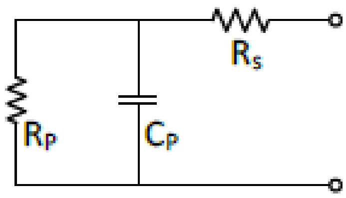


Figure 20: RC equivalent circuit model considered for determining the AC impedance parameters of the PV panels.

Various fitting methods have been used to obtain the AC parameters based on the above circuit [1].
More details on the fitting and AC parameter determination can be found in [1].

1.3.3.3 Electroluminescence measurements

Electroluminescence is the photon emissions from the PV cell material due to radiative recombination, which occurs while electric current is applied to the panel. EL provides a very sharp picture of the current density distribution over the panel, revealing even minor faults such as micro-cracks, which are invisible to infrared imaging and I-V measurements. In this project EL imaging was used at AAU to confirm degradation or faults in the PV modules

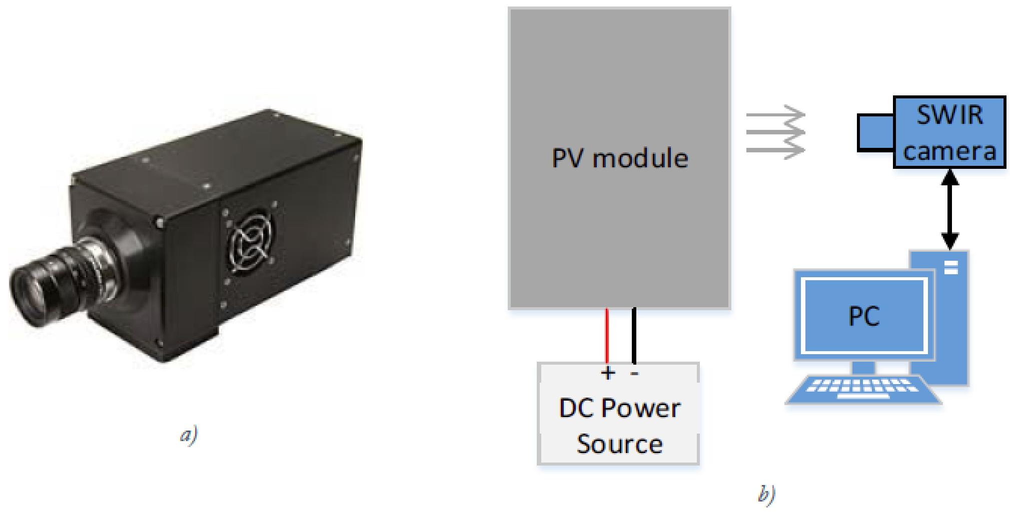


Figure 21: Photo of the EL (SWIR) camera used (a) and the experimental setup for performing the measurements (b)

1.3.4 Field Measurements

The outdoor I-V and IS measurements were carried out in an advanced test bed that uses relays to switch individual modules from a grid-tied power producing circuit to a measurement circuit. The wiring diagram is shown in Figure 22 and the actual platform is shown in Figure 23. In reality the test bed consists of 10 measurement channels for 10 individual modules, but only three modules are shown in Figure 22 to demonstrate the concept. The test samples are in their normal operation when in the grid-tied power producing circuit (left panel). Then the modules are individually switched out of the power circuit into a measurement circuit consisting of I-V (center panel) and IS (right panel) measurements. The relays and measurement system are controlled via LabVIEW using the FPGA based Compact Rio technology where fast data acquisition is possible. Quality checks in the measurement routines allow only one panel at a time to be switched to the measurement bus. This advanced measurement system was designed as part of this project, but it will continue to provide DTU with a first-class PV testing capability well into the future.

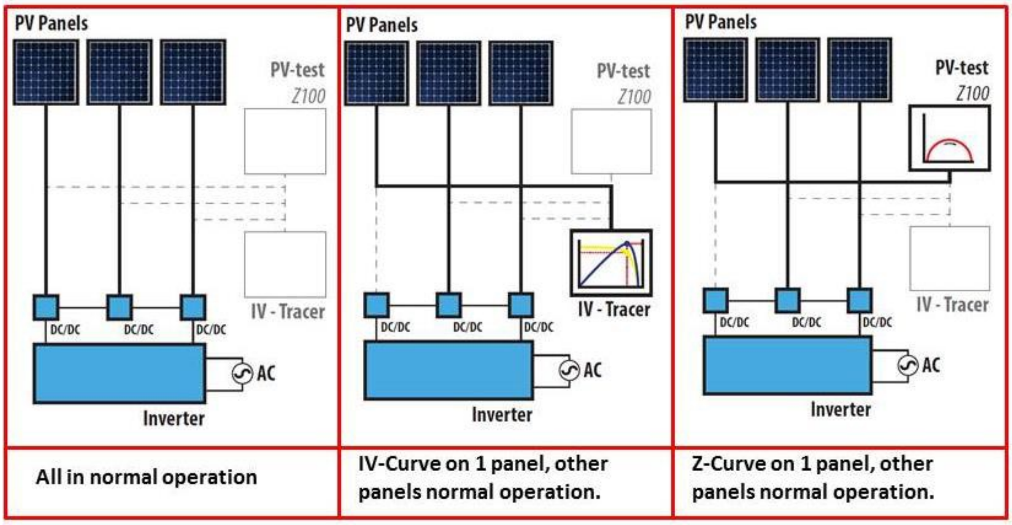


Figure 22: Concept of operation behind the outdoor test system.

Figure 23: Outdoor testbed for I-V and IS measurements with 10 measurement channels.

1.3.4.1 Current-Voltage (I-V)

The outdoor I-V curves are taken using a single quadrant electronic load and a 4-wire measurement approach. Simultaneous measurements of plane of array (POA) irradiance and back of module temperature (Tmod) are recorded during each I-V curve. Figure 24 shows how the I-V curves of one of the control modules change over the course of a clear-sky day in September. With the LabVIEW interface, the distribution of points on the I-V curves can be easily adjusted to accommodate analysis of the max power point, Rp, or Rs. For example, the distribution of I-V points in Figure 24 is weighted heavily in the max power point (Pmp) region.

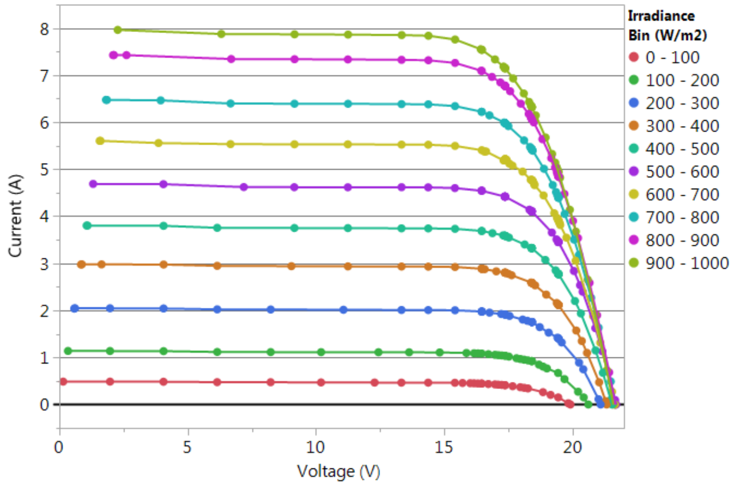


Figure 24: Outdoor mulita-irradiance I-V curves of a single Solvis SV36 module.

In Figure 25 we present a comparison of the Pmp data measured indoors and outdoors. This variability plot serves as a quality check for the indoor and outdoor test beds. The outdoor data in Figure 25 are binned by irradiance during a clear sky day when Tmod is near 25 °C. The data are then corrected to a common irradiance and temperature of 25°C. The analysis shows that there is a 1-5W delta between the indoor and outdoor data, wherein the outdoor data is typically lower. The indoor to outdoor Pmp delta at STC is 1,5W ±0,5W. This 1% absolute delta between test beds is considered sufficient, but could potentially be reduced if implementation of better outdoor temperature sampling, and corrections for spectrum and angle of incidence effects.

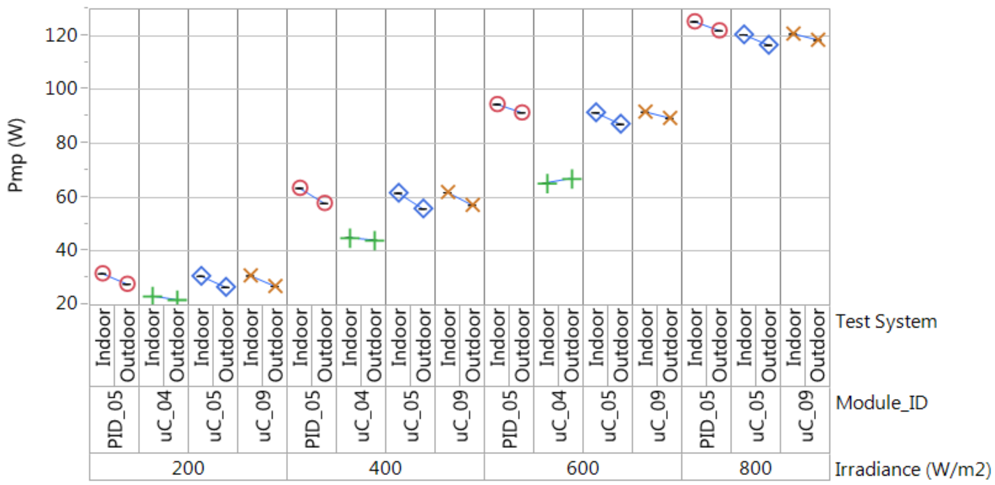


Figure 25: Variability between Pmp measured indoors and outdoors at multi-irradiance.

No power loss was observed in the Group 1 modules as a result of their 4 month outdoor exposure. This result is not surprising as the Solvis SV36 warranty is 0,8% power degradation per year and the precision of the outdoor test system is ±0,5% for Pmp measurements.

Figure 26 shows how the Rshunt (Rp) and Rseries (Rs) vary with light intensity as measured by the indoor EcoSun10L and outdoor test bed. The Rp and Rs values are calculated with the inverse slopes of the I-V curve near the short circuit and open circuit operating points, respectively. All the figures show the expected trend of decreased Rp and Rs with light intensity as described in the literature. Note that the Rp measured indoors (A) is 2 to 3 times higher than the Rp measured outdoors (B), while the general shapes of the curves and the relative rankings of the 4 modules are the same for both measurement systems. The Rp values of uC_04 are considerably lower than test samples uC_05 and uC_09. Recall that test sample uC_04 had a 33% Pmp loss while uC_05 and uC_09 had roughly 6% Pmp losses. This indicates that using Rp from the I-V data may be sufficient for detecting large Pmp losses due to micro cracks, but not sufficient for detecting losses from micro cracks on the order of 6% or less. Finally, the Rs measured indoors (C) shows good agreement with Rs measured outdoors (D). The Rs values of test sample uC_04 are separated from the by an offset of approximately +0,1 Ω.

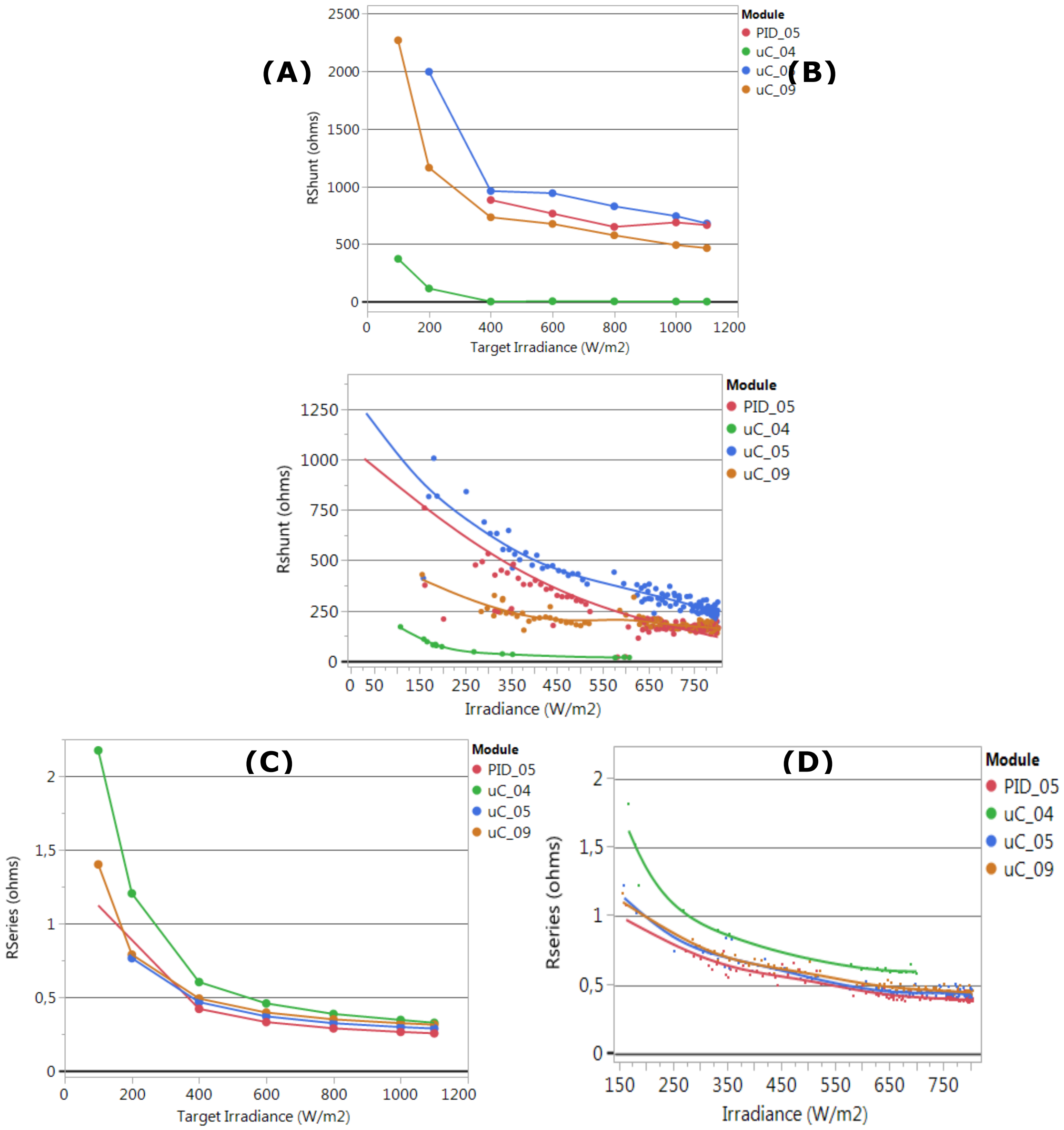


Figure 26: Shunt resistance (top - a, b) and series resistance (bottom - c, d) as functions of irradiance, as measured by the indoor EcoSun10L (left - a, c) and outdoor test bed (right - b, d).

1.3.4.2 Impedance Spectroscopy (IS)

Figure 27 shows the indoor and outdoor Nyquist plots as measured by the Gamry 3000 and the Emazys Z100, respectively. All measurements were taken in the dark since IS data measured in light conditions will no longer fit the basic AC circuit model found in the literature. The Emazys IS real and imaginary data have been corrected for the Z100s internal electronic interface. Note that the indoor IS data has already been discussed in Section 1.3.3.2.

A key feature of the IS data measured with the Emazys Z100 is that the Nyquist plots barely form quarter circles. The lack of curvature is currently a significant limitation to accurately extracting the Rp and Cp parameters. Figure 28 illustrates an ideal Nyquist plot for extraction of the Rs, Rp and Cp parameters. In comparing the ideal Nyquist plot to the measured Emazys Z100 data, we can see that the Rp and Cp parameters are compromised in the Emazys data set. This is because Cp is extracted from the zenith point, or where imaginary impedance is at its minimum, and Rp is extracted from the second x-axis crossing where applied frequency equals zero. Unfortunately, the Emazys Z100 is only capable of generating frequencies from 100 Hz to 100 kHz, while the Gamry is capable of 20 Hz to 100 kHz. It is recommended that the Emazys Z100 include the capability to perform impedance measurements at frequencies as low as 20 Hz in order to accurately extract the Rp and Cp parameters.

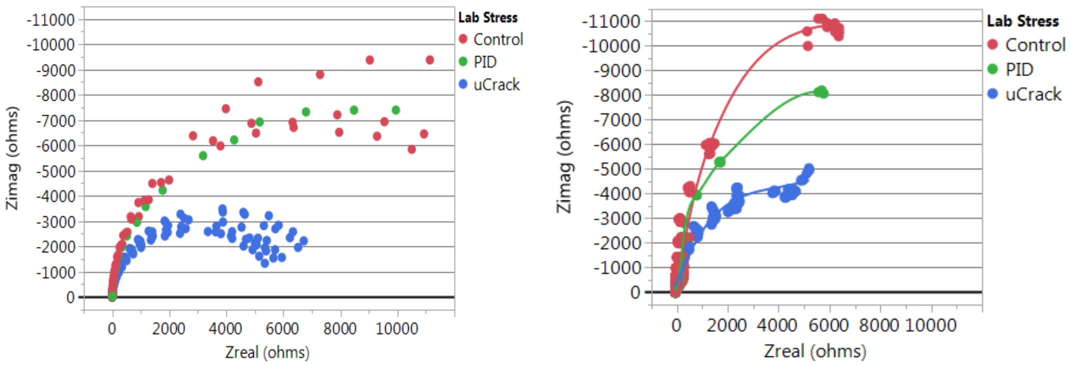


Figure 27: Nyquist plots of Test Group 2 modules generated with IS data measured by the indoor Gamry (left) and outdoor Emazys Z100 (right).

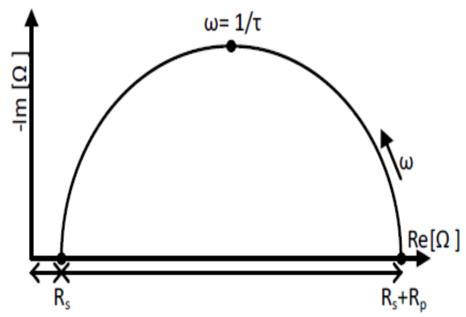


Figure 28: Ideal Nyquist plot for Rs, Rp and Cp parameter extraction. Note that τ=Rp◦Cp

1.4 Utilization of project results

At EmaZys Technologies the project results are fully utilized and transferred into commercial actions. EmaZys is currently working with EKO Instruments in Japan, and the aim is to scale up exports from Denmark to Japan. The current forecast for the Japanese market appears ideal, and the demand for more cost effective solutions for operations and maintenance is growing month by month. At EmaZys we are optimistic and we see a substantial business opportunity in the partnership. It should be taken into account that EmaZys is focusing on more sales partnerships during 2017 Q1+Q2, and the interest is growing. EmaZys has engaged in a sales partnership with ELMA Instruments (DK) about distribution in Scandinavia. Just recently EmaZys initiated collaboration with Beijing HUA TONG Terui Photon-Technology Co., Ltd. and also here the aim is to scale up exports. China is the biggest and most dominating solar PV energy market in the world today.

The project consortium is currently investing how to integrate the technology in system components, and hence open up for access to the market for new installations, as well as the market for operating existing power plants.

It is worth mentioning that the Z100 product is owned by nearly 20 customers in Demark alone, and the domestic dissemination efforts about the need for solar PV service and the project results, has been fruitful and caught up by the "first movers" in the Danish market. In this respect the technology has shown its value, and is currently helping to avoid PV power plant downtime and lost energy. All sold instruments are active testing and troubleshooting installations, with the very simple aim of producing as much green energy as possible, while keeping the total cost of energy as low as possible.

	
CAD file showing the front part of the MP-21 product developed for EKO Instruments.	CAD file showing the back part of the MP-21 product developed for EKO Instruments.

Project conclusion and perspective

In conclusion the project has been successful and all milestones, including commercial milestones, has been reached. Besides each project participant has gained in learning and level of activities that were inspired by the content of the project.
The R&D effort has been focused at using impedance test methods for tracking degradation patterns in solar PV modules. Initially the test and experimentation has been carried out on a laboratory scale and advanced solar light simulation has been established for this purpose. In this phase of the project laboratory equipment was used in combination with the Z100 PV Analyzer from EmaZys Technologies. Successful results were achieved within showing the impedance testing, and hence the Z100, may be used to track and find potential induced degradation in solar panels, and to some extend it is also shown that the method and instrument may be used for the detection of micro cracks in solar cells. The findings from the laboratory was converted into testing algorithms and software for the Z100, which meant that the improved version of the Z100 instrument could be demonstrated on a real scale in the field. Since the first technology and product demonstrations a commercial path was made plausible, and Z100 sales began in August 2015. As of January 2017 the total revenue related to Z100 sales has passed 1 mio. DKK, and a partnership with EKI Instruments (Japan) was established in 2016. The aim is now to fulfil a growth strategy and fully deploy the project results and other developments on an international scale, by working with key players in the main markets such as Japan, China and US.

Annex

Add links to relevant documents, publications, home pages etc.

[1] M. I. Oprea, "Fault Detection in PV Arrays Using Advanced Characterization Methods," Master Of Science in Energy Engineering, Department of Energy Technology, Aalborg University, Aalborg, 2015.

Website links
www.emazys.com/eudp