PEARL TF PV

Final report - Public

March 2021

Performance and Electroluminescence Analysis on Reliability and Lifetime of Thin-Film Photovoltaics

Projectnummer:	TEUE116203
Projecttitel:	PEARL TF PV
Penvoerder:	TNO
Partners:	Delft University of Technology, Solar Tester, Kies Zon (Yellow Solar BV), Straightforward, EigenEnergie
Partners in Era.net project:	Forschungszentrum Julich (coordinator), Helmholtz-Zentrum Berlin für Materialien und Energie, PI Photovoltaik-Institut Berlin, Austrian Institute of Technology, Crystalsol GmbH
Projectperiode (NL):	1-2-2017 t/m 31-1-2021

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1. Public summary

In the Solar Eranet project PEARL TF PV, 11 partners from the Netherlands, Austria and Germany, from industry, research institutes and universities have contributed towards improved reliability and predictability of thin film PV performance. This knowledge is required to increase the profitability of thin-film photovoltaic projects by increasing energy yield, reducing operating and maintenance costs, improving accuracy of investment models, and increasing bankability. The main results are:

- Large scale field inspection of thin film PV modules before and after installation by electroluminescence (EL, 6000+ measurements) and current voltage measurements. This allowed assessment of the impact of initial performance and appearance in EL on long term performance.
- Software for automatic degradation feature recognition, among others based on artificial intelligence (PV AIDED), used on the EL images.
- Identification of the physical and chemical nature of the degradation features visible by imaging techniques in thin film modules
- Determination of common degradation mechanisms in thin film modules and definition of mitigation approaches.
- Definition of preconditioning techniques, optimized for accuracy and execution costs

With these results, possibilities for field inspection and energy yield prediction of thin film modules have been enhanced and simplified. This will lead to a reduced Levelized Cost of Energy (LCOE), due to higher yield and better predictability. Due to the diversity of the consortium, the results could directly be applied in commercial projects. Moreover, the scientific results have been presented by the consortium in 11 peer-reviewed publications, 2 conference proceedings, 16 oral presentations and 20 poster presentations at major international conferences. More information on the project can be found on https://pearltf.eu.

PEARL TF PV

1. Introduction

The increasing role of PV in the energy infrastructure as well as its integration will require longer and more predictable lifetimes. Lifetime demands will increase from 25+ years now to superior lifetimes of 35 years or even the lifetime of a building in 2025 (SET Plan 2017).
An ETIP report [ETI19] recently highlighted the importance of long-term reliability: it is not only desirable to minimize the degradation as much as possible, but even more important to be able to predict degradation and enable fast detection. This will enable a more accurate estimation of the expected service lifetime of a device and its electricity yield (Figure 1). This is an important prerequisite for large scale investments (e.g. PV facades and large power plants).

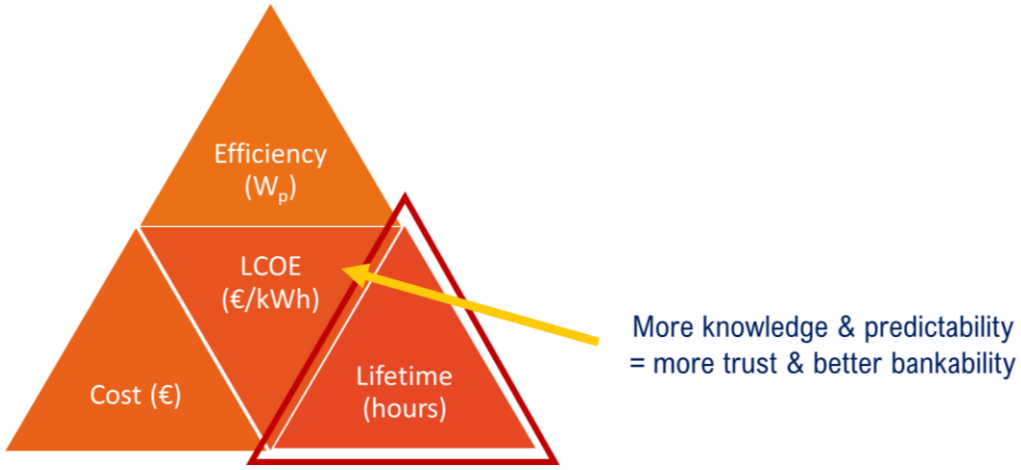

Figure 1: Factors influencing the Levelized Cost of Energy (LCOE) of PV electricity.

Each unexpected yield reduction or increase in maintenance expenses will seriously threaten the economic viability of the plant. This is also true for thin film PV: Due to their thin stack solar cell stacks, potentially low production cost, attractive aesthetic properties, possibilities for flexibilities and freedom in shape and size as well as very promising efficiencies (Figure 2), thin film PV is an attractive investment option. However, this is only the case for reliable and predictable PV.

Figure 2: Various applications of CIGS thin film photovoltaics (TNO/Solliance and EigenEnergie)

2. Aim of PEARL TF PV

For all PV technologies, including thin film one, it is attractive to be able to optimally learn from (preinstallation) testing of the PV, for example by electroluminescence and current voltage measurements. This requires optimal interpretation of the test results, which will reduce uncertainties into investment models and maintenance reserve estimates. In turn, this allows increased bankability of thin film PV projects.
The aim of PEARL TF PV was to enable cost reduction of electricity from TF-PV plants, by reliably identifying the failure mechanisms in thin film modules, thus increasing the long term plant energy yield, reducing O&M costs, improving accuracy of investment models, and increasing bankability of TF-PV projects.
An electroluminescence (EL) imaging-based methodology will be developed by an intensive study of the origin of failures and their impact on the module yield and lifetime.

3. Results and discussion

In PEARL TF PV, 11 partners all along the PV value chain contributed. Together, the commercial partners had direct access to 100.000s PV modules, thereby providing a very attractive starting point. This allowed the participants of the PEARL TF PV consortium to execute in-depth research based on actual effects, that occur on a limited number of occasions in the field.

PEARL TF PV executed nanometer research on square kilometres of device: The world as a laboratory

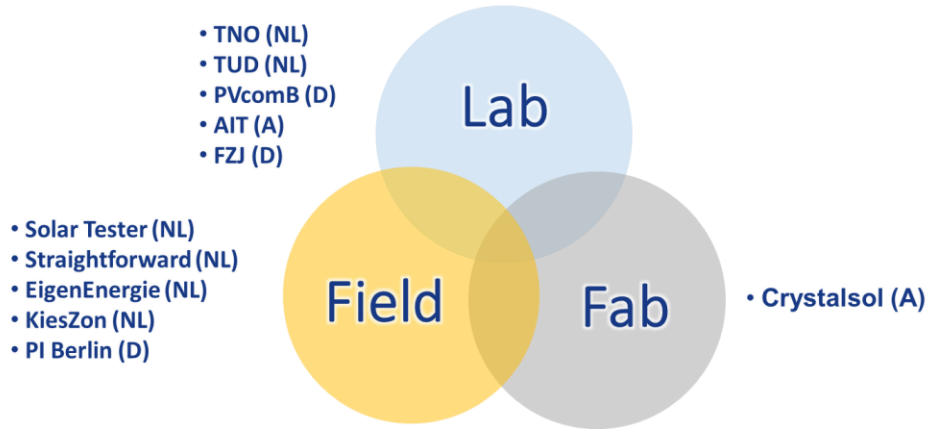

Figure 3: Partners in the PEARL TF PV consortium

The highlight results of PEARL TF PV are:

- Measurement and/or remeasurement of 5900 thin film modules, resulting of 6000 IV and 9500 EL measurements, majorly by the mobile test setup depicted in Figure 4. The modules are of different producers and measured at different times. On average, the performance of the PV modules installed in the field showed a positive trend, indicating that these thin film modules improved in efficiency due to field exposure.
- Development of software, among others “PV AIDED”, based on artificial intelligence, allowing the automatic identification of features on EL images. This allowed comparison

of the development of the module performance and the number or shape of the features in the modules (Figure 5).

- Execution of accelerated lifetime tests, like damp heat and partial shading, on cells and minimodules with and without features similar to features observed in full scale modules. This allows to assess the effect of the features as well as the degradation conditions on the long term performance (Figure 6). Moreover, the physical and chemical nature of these features were also identified.
- Definition of common degradation mechanisms occurring in thin film (CIGS) PV modules.
- Study of advanced thin film PV installations, focussing on esthetical integration. An example (roof tiles) is displayed in Figure 7.
- Preconditioning settings have been compared, studied and optimized. This will greatly reduce the time and costs of performance measurements, making it more attractive for large scale application.
- Partners in PEARL TF PV have greatly worked on dissemination of the results, in order to share them with the whole community and speed up their application outside of the consortium. The complete list can be found in chapter 5.

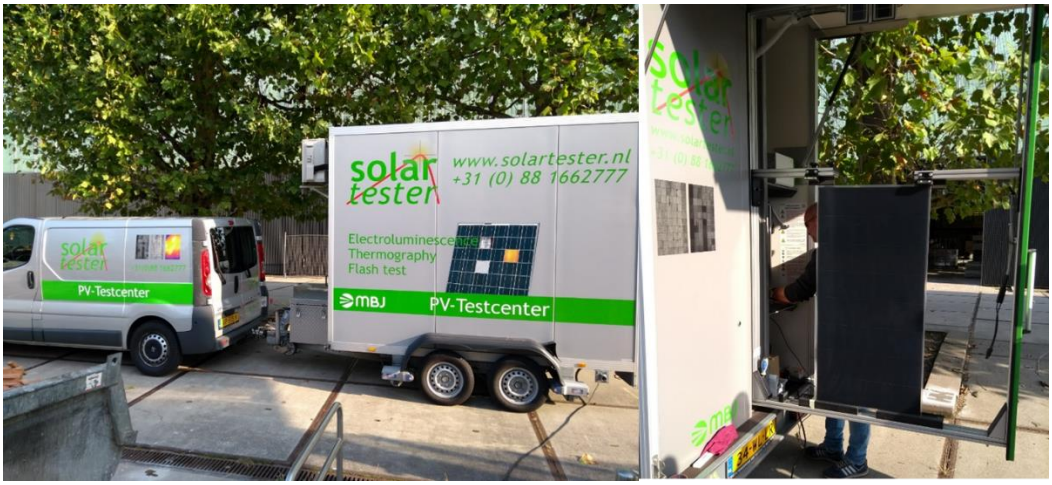

Figure 4: (Left) Mobile PV tester (Right) Placement of a thin film PV module in the tester

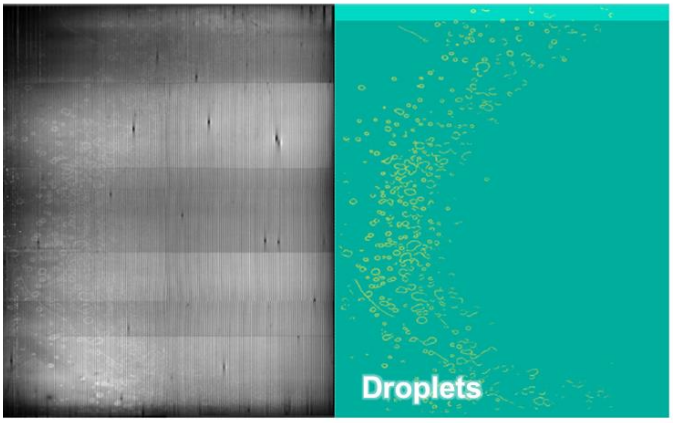

Figure 5: (Left) EL image of a thin film module (Right) Identification of 'droplets' by software PV AIDED.

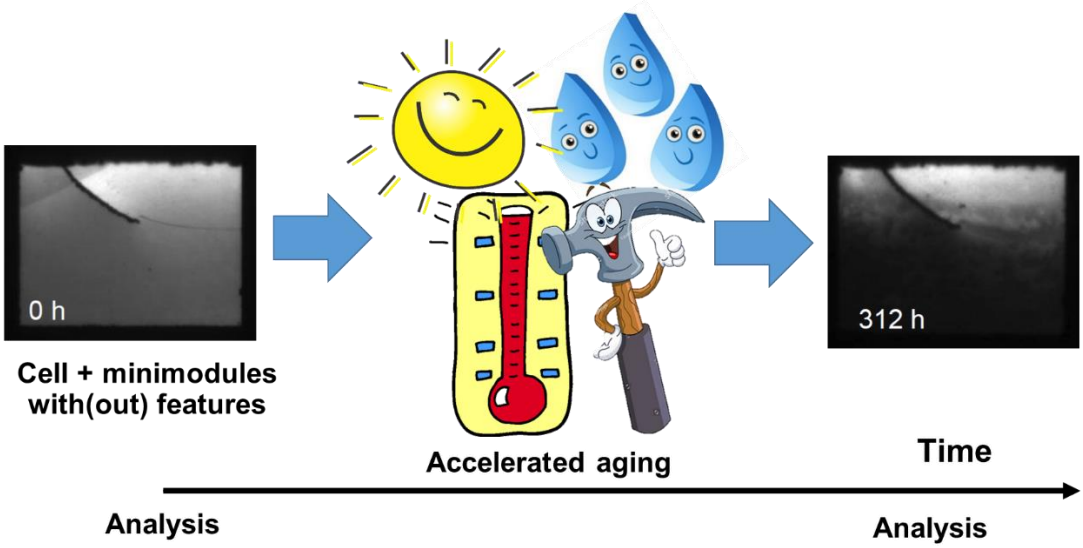

Figure 6: Procedure to assess the impact of initial features on long term performance.

Figure 7: Test roof based on thin film roof tiles.

4. Follow up

The partners from PEARL TF PV are very enthousiastic to continue the collaboration, in order to make new steps in tool and knowledge development, and make these available to the full community. The partners are currently searching for possible calls to resubmit a successive project to PEARL TF PV, due to the large joint successes obtained. The partners are convinced that this unique consortium comprising the full value chain can really make a large differences.

On top of international calls, various Dutch partners are currently studying the possibility of collaboration in several other initiatives.

5. Dissemination results of the project

PEARL TF PV resulted in a large number of peer reviewed publications (11) and oral (16) and poster presentations (20) at important international conferences and workshops. Moreover, 17

BSc and MSc students were able to execute their internship or graduation project in the framework of PEARL TF PV. Dutch partners were involved in a large number of contributions (10 peer reviewed publications, 2 conference proceedings, 14 oral presentations, 11 poster presentations and 8 MSc theses). PEARL TF PV was also featured in the December 2018 issue of Solar Magazine.

5.1 Peer-reviewed publications

- M. Theelen, K. Bakker, H. Steijvers, S. Roest, P. Hielkema, N. Barreau, and E. Haverkamp, “In Situ Monitoring of the Accelerated Performance Degradation of Solar Cells and Modules: A Case Study for Cu(In,Ga)Se_2 Solar Cells”. In: Journal of Visualized Experiments 140 (2018), e55897
- K. Bakker, H. N. °Ahman, K. Aantjes, N. Barreau, A. Weeber, and M. Theelen. “Material Property Changes in Defects Caused by Reverse Bias Exposure of CIGS Solar Cells”. In: IEEE Journal of Photovoltaics 9.6 (2019), pp. 1868–1872
- K. Bakker, A. Weeber, and M. Theelen. “Reliability implications of partial shading on CIGS photovoltaic devices: A literature review”. In: Journal of Materials Research 34.24 (2019), pp. 3977–3987
- K. Bakker, H. N. °Ahman, T. Burgers, N. Barreau, A. Weeber, and M. Theelen, “Propagation mechanism of reverse bias induced defects in Cu (In, Ga)Se_2 solar cells”. In: Solar Energy Materials and Solar Cells 205 (2020), p. 110249
- K. Bakker, A. Rasia, S. Assen, B. B. S. Aflouat, A. Weeber, and M. Theelen. “How the absorber thickness influences the formation of reverse bias induced defects in CIGS solar cells.” In: EPJ Photovoltaics 11 (2020)
- E. Sovetkin, T. Weber, E. J. Achterberg, and B. E. Pieters. “Encoder-decoder semantic segmentation models for electroluminescence images of thin-film modules”. In: IEEE Journal of Photovoltaics 11 (2) (2020) 444-452
- M. Theelen, V. Ntinas, H. Steijvers, H. ’t Mannetje, Z. Vroon, The influence of glass substrates on the damp heat degradation of ZnO: Al films, Thin Solid Films 715 (2020) 138429
- E. Sovetkin and B. E. Pieters. “Artificial Intelligence, Big Data, Data Science and Machine Learning in Statistics”. In: ed. by A. Steland and K. L. Tsui. under preparation. Springer, 2021. Chap. Singular Spectrum Analysis method for electroluminescence images of thin-film photovoltaic modules
- K. Bakker. “On the tunneling mechanism behind reverse bias breakdown in CIGS solar cells”, in preparation
- A. Mittal, M. Rennhofer, T. Weber, G. Ujvari, E. J. Achtenberg, and E. Sovetkin, “Harmonizing Power Stabilization Methods on Thin-film Photovoltaics: A Round-Robin Test”. In: Thin solid films, in preparation
- A. Kingma, F. Naziris, K. Bakker, Karolina Mack, Björn Rau, Vito Huhn, Mirjam Theelen, Study of the physical and chemical origin of features observed in luminescence and thermography images of Cu(In,Ga)Se_2, submitted to Solar Energy Materials and Solar Cells (2020)

5.2 Oral presentations and proceedings at conferences

During the project the following presentation have been made:

- M. Theelen, T. Weber, A. Kingma, R. Aninat, E.-J. Achterberg, R. Verhagen, R. van Gestel, B. Pieters, K. Bakker, A. Weeber, K. Mack, M. Riedel, B. Rau, M. Rennhofer, L. Plessing, V. Huhn, and E. Sovetkin. “PEARL TF PV: An in-depth investigation on the prediction of long term performance of thin-film photovoltaic modules”. In: 37th EU PVSEC, oral, 2020
- R. Aninat, K. Bakker, L. Jouard, M. Campillay, G. Gomez, and M. Theelen. “Shunting defects induced by shading on a Cd-free commercial CIGS module”. In: eMRS, oral, 2020
- K. Bakker, H. Nilsson Åhman, N. Barreau, K. Aantjes, T. Burgers, A. Weeber, and M. Theelen. “Propagation mechanism of wormlike defects in CIGS solar cells”. In: EuroCORR, oral, 2020
- K. Bakker, A. Rasia, S. Assen, B. Ben Said Aflouat, A. Weeber, and M. Theelen. “How the absorber influences the formation of reverse bias induced defects in CIGS solar cells”. In: EUPVSEC, oral, 2020
- A. Mittal, M. Rennhofer, T. Weber, G. Ujvari, E. J. Achtenberg, and E. Sovetkin. “Harmonizing Power Stabilization Methods on Thin-film Photovoltaics: A Round-Robin Test”. In: Virtual Chalcogenide PV Conference. 2020
- M. Rennhofer, A. Mittal, A. Martin, L. Plessing, T. Weber, E. J. Achterberg, E. Sovetkin, and B. Pieters. “Optionen zur Harmonisierung der Leistungsmessung an Dünnschicht-Photovoltaik: Ein Ringversuch in PEARL TF-PV”. In: CONEXIO WEBINAR “Leistungsmessung an Dünnschicht-Modulen und Charakterisierung von Perowskit-Zellen”. 2020
- M. Theelen. “PEARL TF PV: An in-depth investigation on the prediction of long term performance of thin-film photovoltaic modules”. In: PEARL Cost Action workshop. invited. 2020
- P. Yilmaz, R. Aninat, G. Ott Cruz, T. Weber, J. Schmitz, and M. Theelen. “Post-Mortem Analysis of CIGS Solar Modules failed due to Potential Induced Degradation (PID)”. In: eMRS, oral, 2020.
- K. Bakker, H. Nilsson Åhman, K. Aantjes, N. Barreau, A. Weeber, and M. Theelen, “Propagation of reverse bias induced wormlike defects in CIGS solar cells”. In: IEEE 46th Photovoltaic Specialist Conference, oral, 2019.
- A. Mittal, T. Weber, E. J. Achterberg, and M. Rennhofer. “Harmonized power determination of thin film photovoltaics”. In: 17. Photovoltaik-Fachtagung & 10. Speichertagung. 2019.
- M. Theelen, J. Kroon, T. Weber, K. Bakker, D. Lincot, and J. Guillemoles. “Degradation mechanisms in PV”. In: EuroCORR. keynote. Oct. 2019.
- M. Theelen, T. Weber, and K. Bakker. “Degradation mechanisms in CIGS solar cells and modules”. In: MRS Spring Meeting. invited. Apr. 2019.
- M. Theelen. “Prediction the lifetime of thin film CIGS photovoltaics”. In: Sunday. invited. Nov. 2019.
- V. Huhn, A. Weeber, B. Rau, E. J. Achterberg, M. Rennhofer, M. Theelen, and T. Weber. “Performance and Electroluminescence Analysis on Reliability and Lifetime of Thin-Film Photovoltaics (PEARL TF-PV)”. In: 35th EU PVSEC, oral, 2018.
- M. Rennhofer, A. Mittal, A. Martin, and A. Plessing. “Performance analysis and preconditioning for CZTSSe mini-modules”. In: Integrated Photovoltaic Technical Conference, oral, 2018.

- T. Weber et al. “Repowering large scale assets: a successful repowering case study”. In: Intersolar Europe, oral, 2018.

During the project the seminar papers have been written, based on a conference contribution shown above:

- A. Kingma, S. Kulkarni, D. Roosen-Melsen, M. van den Nieuwenhof, F. Lanfranchi, K. Bakker, M. Theelen, H. Linden, M. Koetse, and P. Toonssen. “Failure mechanisms limiting the lifetime of thin-film photovoltaic semi fabricates with alternative moisture barrier foils”. In: 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC). IEEE. 2019, pp. 1972–1978.
- S. Mortazavi, K. Bakker, J. Carolus, M. Daenen, G. de Amorim Soares, H. Steijvers, A. Weeber, and M. Theelen. “Effect of reverse bias voltages on small scale gridded CIGS solar cells”. In: 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC). IEEE. 2017, pp. 2875–2880.

5.3 Poster presentations at conferences

- K. Bakker, A. Rasia, S. Assen, B. Ben Said Aflouat, A. Weeber, and M. Theelen. “How the absorber influences the formation of reverse bias induced defects in CIGS solar cells”. In: eMRS, 2020
- A. Kingma, D. Roosen, S. Kulkarni, M. van den Nieuwenhof, K. Bakker, P. Toonssen, and M. Theelen. “Reliability studies of rigid and flexible Cu(In,Ga)Se_2 devices with thermography and luminescence techniques”. In: NREL PVRW, 2020
- A. Mittal, M. Rennhofer, T. Weber, G. Ujvari, E. J. Achterberg, L. Plessing, and E. Sovetkin. “Power stabilization methods on thin-film photovoltaics: a round-robin test”. In: 37th EU PVSEC, 2020
- E. Sovetkin et al. “PV-AIDED: Photovoltaic Artificial Intelligence Defect Identification. Multichannel encoder-decoder ensemble models for electroluminescence images of thin film photovoltaic modules, PEARL TF-PV.” In: 37th EU PVSEC, 2020.
- M. Theelen, R. Hendrikx, N. Barreau, H. Steijvers, and A. Böttger. “The effect of damp heat-illumination exposure on CIGS solar cells: a combined XRD and electrical characterization study”. In: eMRS, 2020.
- P. Yilmaz, R. Aninat, G. Ott Cruz, T. Weber, J. Schmitz, and M. Theelen. “Defect Investigation by “Coring” for CIGS Solar Modules”. In: 37th EUPVSEC, 2020.
- A. Kingma, S. Kulkarni, D. Roosen-Melsen, M. van den Nieuwenhof, F. Lanfranchi, K. Bakker, M. Theelen, H. Linden, M. Koetse, and P. Toonssen. “Failure mechanisms limiting the lifetime of thin-film photovoltaic semi fabricates with alternative moisture barrier foils”. In: IEEE PVSC 2019
- M. Rennhofer, A. Mittal, A. Martin, and L. Plessing. “Stabilisierungsverfahren f ̈ur Harmonisierte Leistungsmessung an CZTS Modulen”. In: 34th PV-Symposium, 2019.
- T. Weber. “Stabilization methods for thin-film modules”. In: 10th IW-CIGSTech Workshop, 2019.
- E. Sovetkin, V. Huhn, A. Weeber, B. Rau, E. J. Achterberg, M. Rennhofer, M. Theelen, and T. Weber. “Performance and Electroluminescence Analysis on Reliability and Lifetime of Thin-Film Photovoltaics (PEARL TF-PV)”. In: 36th EU PVSEC, 2019.
- T. Weber et al. “Investigation of Stabilization Procedures for Power Determination of Thin-Film Modules”. In: 36th EU PVSEC, 2019

- K. Bakker, E. Gaona Peña, A. Weeber, and M. Theelen. “Evaluation of Different Models to Describe Reverse Breakdown Characteristics of CIGS solar cells”. In: NREL PVRW, 2018.
- M. Rennhofer, A. Mittal, A. Martin, and L. Plessing. “Performance Analysis and Preconditioning for CZTSSE Mini-Modules”. In: 16. ÖdOsterreichischen PV-Tagung, 2018.
- T. Weber et al. “A Review of potential induced degradation in three Thin-Film plants”. In: Module Reliability Workshop, 2018.
- S. Wendlandt et al. “Influence of Near Field Shadowing on the Performance Ratio of Thin Film Modules”. In: 35th EU PVSEC, 2018.
- K. Bakker, P. César Pérez Galicia, F. Lanfranchi, C. Tzikas, A. Weeber, and M. Theelen. “Small scale CIGS Solar Cells exposed to Reverse Bias Voltages”. In: 33rd EU PVSEC. poster. 2017.
- A. Mittal, D. Menz, and M. Rennhofer. “Stabilization Procedures For Power Determination Of Thin-Film PV-Modules”. In: Photovoltaic Technical Conference, 2017
- A. Mittal, D. Menz, and M. Rennhofer. “Stabilization procedures for power determination of Thin-Film PV-Modules”. In: 32. Symposium Photovoltaische Solarenergie, 2017
- S. Mortazavi, K. Bakker, J. Carolus, M. Daenen, G. de Amorim Soares, H. Steijvers, A. Weeber, and M. Theelen. “Effect of reverse bias voltages on small scale gridded CIGS solar cells”. In: IEEE PVSC 2017
- T. Weber, C. Hinz, M. Leers, P. Grunow, and L. Podlowski. “A Review of potential induced degradation in Thin-Film plants”. In: 33th EU PVSEC, 2017, pp. 1671–1676.

5.4 Bachelor, Master and PhD theses

- K. Bakker, PhD thesis “*Effect of reverse bias on the stability of CIGS devices”*, to be published
- W. Ananda, “Stabilization issues and micro-structure of CZTS”, PhD thesis, University of Vienna
- N. Zechner, “Influence of electrical dark bias treatment on the stabilization behavior of PV modules”, Master’s thesis, University of Vienna, 2021
- M. Gordon, “Features development for defect detection in thin-film modules, PEARLproject”, Seminar paper, FZJ, 2020
- M. Gordon, “Multichannel Features Encoder Decoder Networks”, Bachelor thesis, FZJ, 2020
- S. Lefevre, “EL and PL for reliability on CIGS”, Master’s thesis, TNO, 2020
- J. A. C. Rehm, “Correlation between opto-electronically detectable defects and locally resolved crystalline properties in layered Cu(In,Ga)Se_2 solar cells”, Master’s thesis, TU Berlin, 2020
- C. P. Aantjes, “Reverse Bias Induced Worm-like Defects in Cu(In,Ga)Se_2 Thin-Film Solar Cells”, Master’s thesis, TNO, 2019
- L. Gersant-Poulain, “Processing and interpretation of luminescence imaging of CIGS solar cells in reliability research”, Bachelor thesis, TNO, 2019
- M. Grieb, “Bewertung von Vorbehandlungsmethoden nach IEC Norm und Vorgabe der Hersteller zur Leistungsbestimmung an Dünnschicht Photovoltaikmodulen”, Bachelor thesis, PI Berlin, 2019
- M. Matousek, “Untersuchung der elektrischen Parameter von CZTS-Dünnschichtmodulen bei Umwelteinflüssen wie Licht und Temperatur”, Bachelor thesis, University of Vienna, 2019

- L. Schmidt, “Leistungsmessung von Dünnschicht PV-Modulen im Feld und im Labor zwecks Messmethodenanalyse und deren Optimierungspotenzial”, Bachelor thesis, PI Berlin, 2019,
- H. N. Ahman, “Morphology and composition of wormlike defects, occurring in CIGSe solar cells under reverse bias conditions”, Master’s thesis, TNO, 2018,
- T. Daschinger, “Elektrolumineszenz für die Groserien-Charakterisierung von Photovoltaik-Kraftwerken: Entwicklung, Erprobung und Bewertung Effizienter Aufnahmeverfahren”, Master thesis, PI Berlin, 2018
- A. Esposito, “Bias Induced Degradation Mechanisms of Solar Cells under Illuminated Dry-Heat Environment”, Master’s thesis, TNO, 2018,
- F. Hakka, “Bias Induced Degradation Mechanisms of CIGS Solar Cells under Illuminated Damp Heat Environment”, Master’s thesis, TNO, 2018
- F. Naziris, “Electroluminescence and Photoluminescence for Reliability research in CIGS solar cells”, Master’s thesis, TNO, 2018
- A. Rasia, “Analysis of CIGS solar cells under reverse bias conditions”, Master’s thesis, TNO, 2018

The project aims and results are described on the following website:

- PEARL-TF project website. Accessed: 2020-09-01. url: https://pearltf.eu/

5.5 Reports

Next to the Dutch report, two official international reports were submitted about the Solar Eranet project PEARL TF TV. It should be noted that strong overlap exists between the reports:

- All partners, Abschlussbericht (German report), *Performance and Electroluminescence Analysis on Reliability and Lifetime of Thin-Film Photovoltaics*, FKZ 0324193A, 2020
- PI Berlin (Report PI Berlin) Verwendungsnachweis, *PEARL TF-PV*, 2020, Förderkennzeichen: 0324193B

6. Conclusions and recommendations

In PEARL TF PV, we jointly and successfully gained knowledge on the reliability and lifetime on PV cell and module level. This was implemented in procedures and services for degradation prediction and detection, as well as methods to identify defects in CIGS and CdTe modules. These tools have proven valuable in the consortium and could also have great value for the whole PV community.

In the future, it is crucial to extend the impact of these tools, by cost-reduction, simplification and rapid application, thereby increasing their TRL. The information that this generates can also be used by the PV industry to develop more stable PV modules, less sensitive to degradation. It is also important to make the tools applicable to other types of PV technologies (e.g. perovskites coming to the market, but definitely also the market dominant c-Si). An increasing maturity of these tools would also allow to make them available for the complete PV community.

Furthermore, the applicability of tools and results should also be tuned to specific applications. It is important to estimate lifetime and reliability for different situations, like integrated PV, and PV in different climates. Therefore, degradation mechanisms and their sensitivity for conditions should become more and more known.