4^{th} EUROREGIONAL WORKSHOP ON PHOTOVOLTAICS, PV MONITORING and BIG DATA

EUROREG-PV 2022

16^{th} – 17^{th} June 2022

Tržaška cesta 25, Ljubljana, Slovenia

http://euroreg-pv.fe.uni-lj.si

BOOK OF ABSTRACTS

University *of Ljubljana*
Faculty of *Electrical Engineering*
Laboratory of Photovoltaics and Optoelectronics

About this publication

Published:	July 2022
Editors:	Boštjan Glažar, Marko Topič
Print:	On-line only
Copies:	-
Published by:	Laboratory of Photovoltaics and Optoelectronics Faculty of Electrical Engineering University of Ljubljana Tržaška cesta 25 SI-1000 Ljubljana Slovenia

Organisation of the workshop

Chairman:

Prof. Dr. Marko Topič, UL FE

Co-chairman:

Prof. Dr. Rutger Schlatmann, HZB, Germany

Program committee:

Prof. Dr. Marko Topič, UL FE
Prof. Dr. Rutger Schlatmann, HZB
Prof. Dr. Steve Albrecht, HZB
Dr. Caroline Ulbrecht, HZB
Dr. David Moser, EURAC
Prof. Dr. Marko Jankovec, UL FE
Prof. Dr. Janez Krč, UL FE

Organising committee:

Dr. Boštjan Glažar, UL FE (chairman)
Matej Guštin, UL FE
Dr. Matevž Bokalič, UL FE

Laboratory of Photovoltaics and Optoelectronics – LPVO
http://lpvo.fe.uni-lj.si
Faculty of Electrical Engineering – FE
http://www.fe.uni-lj.si
University of Ljubljana – UL
http://www.uni-lj.si

About the workshop

Yesterday photovoltaics represented one of the fastest growing technologies. Today, even in this area we are faced with stagnation, but we don’t want to see as a problem but as a challenge and an opportunity. We believe that even in times of economic and financial crisis photovoltaics represents a promising, sustainable economic sphere.

3rd workshop, 2016

The Euroregional workshop is intended to gather experts together with PhD students. It is organised as a forum of global R&D trends. You will get the chance to meet researchers from across the Europe, get to know their research projects and share the common issues and challenges.

The workshop consists of the following sessions:

1. **Performance, reliability, and sustainability of photovoltaic systems**
2. **Indoor and outdoor monitoring of PV modules and systems**
3. **Big-data approach in the field of photovoltaics**
4. **Power electronics and other BoS components**
5. **Advanced material and device characterization techniques**
6. **Advanced concepts of solar cells and PV modules**

Program

Thursday, 16th June 2022

morning

9:00 – 9:50	***Registration & Coffee***	
9:50 – 10:00	**Opening of the workshop** *Marko Topič & Rutger Schlattman*	
	Session I, *Chairman: Marko Topič*	
10:00 – 10:45 INVITED	Ralph Gottschalg Fraunhofer CSP, Halle (Saale), Germany	What value can artificial intelligence add to PV system diagnostic?
10:45 – 11:30 INVITED	Atse Louwen EURAC, Bolzano, Italy	The role of digitalization in advanced O&M of PV
11:30 – 11:45	Darjo Uršič Univ. of Ljubljana, Fac. of. Elec. Eng., Ljubljana, Slovenia	Indoor monitoring for PV powered IoT
11:45 – 12:00	Žan Ajdič Univ. of Ljubljana, Fac. of. Elec. Eng., Ljubljana, Slovenia	Progress of perovskite solar cells at LPVO
12:00 – 13:30	***Lunch break***	

Thursday, 16th June 2022

afternoon

	Session II, *Chairman: Ralph Gottschalg*	
13:30 – 14:00	Marko Jankovec Univ. of Ljubljana, Fac. of. Elec. Eng., Ljubljana, Slovenia	LPVO solutions for advanced PV monitoring
14:00 – 14:15	Milan Kovačič Univ. of Ljubljana, Fac. of. Elec. Eng., Ljubljana, Slovenia	Reduced graphene oxide in solar cells
14:15 – 14:30	Marko Remec Univ. of Ljubljana, Fac. of. Elec. Eng., Ljubljana, Slovenia	WLED monitoring setup for research perovskite solar cells
14:30 – 14:45	Saša Sladić and Vera Gradišnik Faculty of Engineering Rijeka, Croatia	Silicon Carbide Benefits for PV and Automotive Applications
14:45 – 15:30	***Coffee break***	
	Session III	
15:30 – 15:45	Marko Jošt Univ. of Ljubljana, Fac. of. Elec. Eng., Ljubljana, Slovenia	Bichromatic LED setup for advanced characterization of tandem solar cells
15:45 – 16:00	Martin Ledinsky Institute of Physics, Prague, Czech Republic	Mapping the Transport Paths in Silicon Passivating Contacts with Conductive AFM Tomography
16:00 – 16:15	Jure Pušnjak Univ. of Ljubljana, Fac. of. Elec. Eng., Ljubljana, Slovenia	TCAD modelling of solar cells
16:30 – 18:00	**LPVO monitoring PV tour**	
19:00 – 21:00	***LPVO floating PV tour,*** *Location: Ljubanica river*	

Friday, 17th June 2022

morning

8:45 – 9:15	***Coffee break***	
	Session IV, *Chairman: Marko Jankovec*	
9:15 – 10:00 PLENARY	Steve Albrecht TU Berlin/HZB, Berlin, Germany	Perovskite tandems in competition for record efficiencies
10:00 – 10:45 PLENARY	Antonin Fejfar Czech Academy of Sciences, Prague, Czech Republic	Great expectations for photovoltaic energy resources
10:45 – 11:15 INVITED	Carolin Ulbrich HZB, Berlin, Germany	PV monitoring and big data at HZB
11:15 – 11:30 INVITED	Pierre-Jean Alet CSEM, Neuchâtel, Switzerland	High-resolution intraday forecasts of PV production with advanced machine-learning architectures
11:30 – 11:45	***Coffee break***	
11:45 – 12:00	Kristijan Brecl Univ. of Ljubljana, Fac. of. Elec. Eng., Ljubljana, Slovenia	PV system performance assessment by TDP model
12:00 – 12:15	Julián Ascencio-Vásquez ASVA Consulting, Santa Cruz de Tenerife, Spain	Hybrid data-driven techniques to optimize PV fleet energy yield
12:15 – 12:30	Guillermo Oviedo Hernandez BayWa r.e., Rome, Italy	NB-IoT/5G wireless retrofit approach for PV monitoring
12:30 – 13:30	***Lunch break***	

Friday, 17th June 2022

afternoon

	Session V, *Chairman: Antonin Fejfar*	
13:30 – 13:45	Paolo Graniero HZB, Berlin, Germany	Machine Learning on Perovskite Stability Data: Critical Issues in Current Shared Databases
13:45 – 14:00	Florian Scheler HZB, Berlin, Germany	Design principles for constructing the ideal interface: a perovskite/C60 case study
14:00 – 14:15	Aleš Vlk Institute of Physics, Prague, Czech Republic	Urbach energy and defect formation during the halide perovskite growth
14:15 – 14:30	Mark Khenkin HZB, Berlin, Germany	Correlating Indoor and Outdoor Degradation in Perovskite Solar Cells
14:30 – 14:45	Bor Li HZB, Berlin, Germany	Up to 1.94 V open-circuit voltage in highly efficient perovskite/silicon tandem solar cells using polymeric interlayers in the top contact
14:45 – 15:00	**Closing remarks,** *Marko Topič & Rutger Schlattman*	

	Online Special Session – BALKAN-PV HUB panel *Chairman: Marko Topič*	
	Marko Topič ETIP-PV Chair	Introduction to Euroreg-PV Workshop and Balkan-PV HUB
	Rutger Schlatmann PV-COMB Director	TAPAS project and networking possibilities
	Natalia Maticiuc HZB	VIPERlab project and mobility across Europe
		Discussion on networking in Europe and Balkan PV Hub
		Concluding remarks and Action Plan

This page was intentionally left blank.

ABSTRACTS

Thursday, 16th June 2022

What value can artificial intelligence add to PV system diagnostics?

David Dassler, Ralph Gottschalg
Fraunhofer Center for Silicon Photovoltaics (CSP)
Otto-Eissfeldt-Str. 12, 06120 Halle (Saale), Germany
Ralph.Gottschalg@csp.fraunhofer.de

Abstract

Artificial Intelligence (AI) is seen by many as a panacea for PV system diagnostics. The amount of research being conducted may be the strongest growing sector in the PV systems area but the uptake of AI in the industry so far is limited. The reason is that in some occasions, the value is not being seen. It is shown in this contribution that one needs to look at specific steps in the life cycle of a PV plant to understand and maximise the value of detailed system diagnostics. Through a number of examples it is demonstrated that the value that can be delivered by AI is being determined by the overall system design and specifically by the metrology being employed. A metric for the usefulness of AIs is proposed, specifically the impact on the LCOE of a PV System. It is shown that AIs may lead to cost reductions but may also cause an increase of LCOE and thus would actually have a negative value. The root-causes of this are given as well as methods to maximise the value of AI driven system diagnostics.

The role of digitalization in advanced O&M of PV

Atse Louwen*, David Moser

Eurac Research, Institute for Renewable Energy
Viale Druso 1, 39100 Bolzano, Italy; *atse.louwen@eurac.edu

Abstract

With the fast and large deployment of photovoltaics, operation and maintenance of PV is becoming an ever more data driven activity. For O&M operators in this field, it is necessary to apply digitalization in their activities to improve cost-effectiveness, and to ensure quality and bankability of PV. Data that is available from component manufacturing and testing, system design and construction, and field monitoring and inspection should be collected in a standardized manner, combined in digital systems, and processed and analysed automatically to maximize the benefits of digitalization approaches. Proper KPIs, and more importantly a well validated cost-based metric, are subsequently necessary to distil clear actionable information from large PV O&M related dataflows. In this talk we present examples from our experience from various research projects related to digitalization of PV. Based on these examples we highlight issues, current activities in O&M digitalization and future prospects for the PV sector. We discuss in detail the first cost-based failure mode and effects analysis method for PV, the Cost Priority Number, the issues that need to be resolved to allow for proper implementation in the sector, and several examples of the use cases of this method in the context of digitalized PV O&M.

ENERGY HARVESTING FROM A SINGLE PEROVSKITE SOLAR CELL IN INDOOR OFFICE ENVIRONMENT

Darjo Uršič, Matija Pirc, Marko Jošt, Marko Topič, Marko Jankovec

University of Ljubljana, Faculty of Electrical Engineering,
Tržaška cesta 25, SI-1000 Ljubljana, Slovenia
darjo.ursic@fe.uni-lj.si, matija.pirc@fe.uni-lj.si, marko.jost@fe.uni-lj.si, marko.topic@fe.uni-lj.si, marko.jankovec@fe.uni-lj.si

Abstract

Rapid progress of perovskite solar cell (PSC) technology is not only showing high potential for outdoor applications, but indoor ones, as well. High yield in low-light conditions makes PSC technology ideal candidate for indoor energy harvesting applications in a domain of ever growing Internet of Things (IoT).

We are demonstrating ultra-low power IoT node capable of monitoring and harvesting energy directly from a single small-area lab-scale PSC. Device is further used to characterize prolonged indoor performance and degradation of cells inside simulated office environment.

Progress of perovskite solar cells at LPVO

Žan Ajdič, Marko Jošt, Marko Topič
University of Ljubljana, Faculty of Electrical Engineering
Tržaška 25, 1000 Ljubljana, marko.jost@fe.uni-lj.si

Abstract

Perovskite solar cells are a novel photovoltaic technology that have emerged as an efficient and low-cost solution for electricity generation. Their power conversion efficiency has eclipsed 25%, with stability and scalability research coming into spotlight. In this contribution, we will show the progress of perovskite research at LPVO. We will describe fabrication of perovskite solar cells and present recent results using SnO_2 as an electron transport layer. The stability of devices with SnO_2 will be analysed, along with the addition of PEIE surface modifier. Finally, we will present highly efficient a 1 cm^2 devices.

LPVO solutions for advanced PV monitoring

M. Jankovec, B. Glažar, K. Brecl, U. Barbič, M. Topič
University of Ljubljana
Faculty of Electrical Engineering
Tržaška cesta 25, SI-1000 Ljubljana, Slovenia
marko.jankovec@fe.uni-lj.si

Abstract

Reliable and accurate long-term monitoring of photovoltaic (PV) modules in indoor controlled or realistic outdoor environments is a necessary part of any PV technology research and development laboratory. Any new technology, material or even a slight variation of material composition should be thoroughly tested before applying for different degradation or failure modes that it may induce solely or in unfortunate combination with already proven compound. Only by long-term monitoring various failure modes of PV cells and modules can be reliably detected and evaluated.

LPVO offers different monitoring solutions. Outdoor PV monitoring system offers continuous maximum power point (MPP) tracking of small and large area PV modules with sequential IV curve scanning. Additionally, weather, irradiance and spectral data can be acquired, and high voltage bias can be applied to PV modules to check for potential-induced degradation (PID) effects. For irradiance monitoring a new outdoor reference solar cell is available which consists of a back-contacted solar cells and temperature compensation circuitry. Additionally, an IoT connected bifacial irradiance sensor is under development, which will allow standalone monitoring of direct irradiance and albedo and other environmental parameters such as temperature and humidity and send the data via GSM network to the cloud service. Humidity sensors can be further embedded in the PV module for measuring the moisture ingress in the PV modules and thus offer another insight into the PV module degradation mechanism and failure modes. The results can be used either for material parameters determination or to validate the simulations of moisture ingress in the field. Wired and wireless solutions have been developed.

For indoor monitoring of large batches of lab-scale solar cells a micro-MPP tracking (uMPPT) system is available, which can track hundreds of small size low-power perovskite solar cells and acquire all electrical data simultaneously. Furthermore, sequential IV scanning with external source-measurement unit (SMU) is possible for most accurate IV curve scanning. The uMPPT system can be scaled up to any number of channels. Currently only passive MPP tracking is available for single cell perovskites, while for tandems and minimodules a 4-quadrant active MPP tracker is under development allowing higher voltage range and reverse bias.

Reduced graphene oxide in solar cells

Milan Kovačič, Janez Krč and Marko Topič
Univ. of Ljubljana, Fac. of. Elec. Eng., Ljubljana, Slovenia
milan.kovacic@fe.uni-lj.si

Abstract

An all-thin film tandem solar cells, combined of a bottom CIGS and a top perovskite (PK) cell, is considered here. This combination already exhibits high conversion efficiencies, while to reach its full potential, introduction of novel materials and optimization of current materials and interfaces of the device needs to be accomplished. Here we analyse optical properties of highly promising graphene oxide (GO) material and its optical effect on the entire tandem structure. By using a suitable laser treatment method, energy levels of GO can be tuned to match energy levels of neighbouring photovoltaic layers, enabling efficient charge transport throughout the device. GO layers at two positions in the tandem device are investigated, namely as an interlayer between the top and bottom cell, to improve recombination junction properties and at the top of PK sub-cell at the position beneath the top transparent conductive layer to improve the conductivity of the top electrode and to protect the PK layers during deposition of the top transparent conductive oxide. Using experimentally verified optical simulations, we show that parasitic absorption in laser treated GO layers highly affects the photocurrent of the tandem, indicating the need for usage of very thin (few nm) GO to minimize optical losses. We further show that improvements in optical properties are possible, if parasitic absorption of laser treated GO layer(s) would be reduced, which could be achieved by additional tunning of the laser treatment parameters. Given results present an important guideline for required electrical improvements according to optical effects of introduced graphene oxide layers, to achieve highly efficient CIGS/PK solar cells.

WLED monitoring setup for research perovskite solar cells

Marko Remec[1,2], Marko Jošt[1], Marko Topič[1]
[1]Faculty of Electrical Engineering, University of Ljubljana, 1000 Ljubljana, Slovenia
[2]Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, 12489 Berlin, Germany
marko.remec@helmholtz-berlin.de, marko.jost@fe.uni-lj.si, marko.topic@fe.uni-lj.si

Abstract

Due to the fast development of perovskite photovoltaics (PV) and consequently many different novel device structures, an increasing number of characterization and stability studies is required in order to test and assure the reliability of perovskite PV device operation. For long-term stability, day-night cycles with light-dark periods represent significantly different stress than applying constant illumination. Effects of elevated temperatures or temperature cycling may only add additional stress.

We present a multi-channel indoor white light emitting diode (WLED) testing setup for laboratory-scale perovskite solar cells, capable of monitoring up to 216 devices simultaneously. The monitoring setup can control both irradiance and temperature, enabling us to perform different test procedures that include cycling of light or temperature, such as simulating the day-night cycle.

Silicon Carbide Benefits for PV and Automotive Applications

Sasa Sladic, Vera Gradišnik
sladics@riteh.hr, Vera.Gradisnik@riteh.hr
Faculty of Engineering Rijeka
University of Rijeka

Abstract

Semiconductor devices in PV and automotive applications operate under high temperatures. That means semiconductor material is exposed to increased temperature due to sun radiation or ICE (internal combustion engine) operation or due to heavy load during the charging or discharging of EV (electric vehicle) batteries. That could cause malfunction of silicon devices because of temperature dependent random processes. Wide Band Gap (WBG) semiconductor materials like Silicon Carbide could obtain proper operation on higher temperatures. It seems also other SiC properties could accelerate positive trend of involvement of electric vehicles since SiC could ensure rapid charging and better performance during regenerative braking in electric vehicles.

Bichromatic LED setup for advanced characterization of tandem solar cells

Marko Jošt, Gašper Matič, Marko Topič
University of Ljubljana, Faculty of Electrical Engineering
Tržaška 25, 1000 Ljubljana, marko.jost@fe.uni-lj.si

Abstract

The perovskite-based tandem solar cells are a novel photovoltaic technology that has shown the potential as a new player on the PV market. They have already overcome the record single-junction power conversion efficiency and are now heading towards industrialization. However, to be successful their stability and operation under different conditions have to be understood completely. Here, we present a tool designed specifically for the characterization of tandem solar cells. The tool is based on a bichromatic light source that enables independent biasing of each subcell. This facilitates light source calibration and allows prolonged testing of different temperature and light intensity conditions. We will also show how to obtain individual subcell *J-V* curves using the tool. The above mentioned long-term stability testing and subcell selective characterization make the bichromatic LED a powerful tool for tandem solar cell analysis.

Mapping the Transport Paths in Silicon Passivating Contacts with Conductive AFM Tomography

Matěj Hývl[1], Gizem Nogay[3], Philipp Loper[2], Franz-Josef Haug[2], Quentin Jeangros[3], Antonín Fejfar[1], Christophe Ballif[2,3] and Martin Ledinský[1]

[1]Institute of Physics, Academy of Sciences of the Czech Republic, Cukrovarnická 10, 162 00 Prague 6, Czech Republic
[2] Ecole Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT), Photovoltaics and Thin-Film Electronics Laboratory (PV-Lab), Rue de la Maladière 71b, 2000 Neuchâtel, Switzerland
[3] PV-Center, Centre Suisse d'Électronique et de Microtechnique, Rue Jaquet-Droz 1, CH-2002 Neuchâtel, Switzerland

The correspondence author is Martin Ledinsky ledinsky@fzu.cz
hyvl@fzu.cz, gizem.nogaypoulin@csem.ch, franz-josef.haug@epfl.ch, quentin.jeangros@epfl.ch, fejfar@fzu.cz, christophe.ballif@csem.ch

Abstract

Hole-selective passivating contacts are used as an effective strategy to decrease recombination losses in c-Si solar cells. Our research deals with high thermal budget contacts: thin silicon oxide (SiO_x) and a boron-doped Si-rich SiC_x layers on Si wafer are annealed at temperatures above 750°C. During annealing, thin SiO_x layer may disrupt, while SiC_x layer partially crystallizes. Optimal performance of the contact is achieved with annealing temperature around 850°C. To explore the transport mechanism through the contact we performed a series of C-AFM tomography measurements. 3D current map of the layers is constructed from consecutive scans with large force applied to the AFM tip, removing the material. This enables us to directly visualize the 3D reconstruction of the charge carrier transport through the selective contact. C-AFM tomography reveals conductive channels spanning vertically through the sample starting from interfacial SiO_x going up to the sample surface. Visualisation of the charge carrier transport paths offers the direct explanation of the optimal performance of the contact annealed at 850°C – oxide layer remains sufficiently compact passivate the c-Si wafer, while the poly-SiC_x layer is already crystalline enough to efficiently compensate for the transport barrier of the oxide.

Electrical modelling of recombination junction in perovskite/CIGS tandem solar cells

Jure Pušnjak, Janez Krč, Marko Topič

Faculty of Electrical Engineering, University of Ljubljana
Tržaška 25, 1000 Ljubljana
jure.pusnjak@fe.uni-lj.si

Abstract

Perovskite and CIGS solar cells are both part of the thin-film technology. The technology allows smaller thicknesses of cells – several µm instead of several hundred µm. Thin-film solar cells have lower carbon footprint per kWh produced. This and tuneable optical and electrical properties of both materials are the reasons for perovskite/CIGS tandem to be considered one of the more promising candidates for next generation high efficiency solar cells. Tandem solar cell efficiency can be increased by adding novel materials with suitable opto-electric properties to improve the recombination junction. One of such proposed materials is graphene oxide.

We used electrical simulations using Sentaurus TCAD simulating tool by Synopsys to simulate the recombination junction of the said tandem solar cell. The simulated junction consisted of NiO, which is used as a hole transport layer in perovskite solar cell and ITO, which is a bottom layer in perovskite and top layer in CIGS proposed 4T tandem structure. We have shown that tunnelling is an important charge carrier transport mechanism in the recombination junction and tested the effect of different tunnelling mechanisms. Measurements have shown presence of serial and shunt resistance so we included both into our model. At the end we included a thin layer of reduced graphene oxide to further improve charge carrier transport.

ABSTRACTS

Friday, 17th June 2022

Perovskite tandems in competition for record efficiencies

Steve Albrecht

Technische Universität Berlin - Division Perovskite Solar Cells, Helmholtz-Zentrum Berlin
Kekuléstr. 5, D-12489 Berlin, Germany
steve.albrecht@helmholtz-berlin.de

Abstract

Integrating metal halide perovskite top cells with crystalline silicon, CIGS, or low band gap perovskite bottom cells into monolithic tandem devices has recently attracted increased attention due to the high efficiency potential of these cell architectures. To further increase the performance of these fascinating tandem solar cells to a level of predicted efficiency limits well above 30%, optical and electrical optimizations as well as a detailed device understanding of this advanced tandem architecture need to be developed. Here we present our recent results on monolithic tandem combinations of perovskite top-cells with crystalline silicon, CIGS, Sn-Pb perovskites as well as tandem relevant aspects of perovskite single junction solar cells.

Recently we have shown that self-assembled monolayers (SAM) could be implemented as appropriate hole selective contacts. The implementation of new generation SAM molecules enabled further reduction of non-radiative recombination losses with high open circuit voltages and fill factor. By fine-tuning the SAM molecular structure even further, the photostability of perovskite composition with tandem-ideal band gaps of 1.68 eV could be enhanced by reduction of defect density and fast hole extraction. That enabled a certified efficiency for perovskite/silicon at 29.15%. By optical optimizations, we could improve this value to 29.80% recently.

In addition to the experimental material and device development, also main scientific and technological challenges and empirical efficiency limits as well as advanced analysis methods will be discussed for perovskite based tandem solar cells. In addition, first results for upscaling of these industrial relevant tandem solar cells by thermal evaporation and slot-die coating will be shown.

Great expectations for photovoltaic energy resources

Antonín Fejfar, Mykhailo Khytko, Martin Ledinský
Institute of Physics, Czech Academy of Sciences
Cukrovarnická 10, 162 00 Prague, Czech Republic
fejfar@fzu.cz

Abstract

As the global installed photovoltaic (PV) capacity reached 1 TW earlier this year [1], the European Commission has stated an ambition to bring online 320 GW_p by 2025 as part of the REPowerEU [2], in an effort to wean the bloc off Russian gas. In Czechia the EGÚ study from 2019 installing PV on the suitable roofs could cover ~27% of electricity [3] and most of people are interested in obtaining PV at home.

Great expectations of energy independence are, like in the Charles Dickens's novel, confounded by humble origins and high hopes for better future, yet with moments of disappointments and exasperation. Czechia went through a PV boom in 2010 and ensuing stagnation [4] and European Union as a whole struggles to produce the PV modules it needs for the Green Deal [5] .

Our team has extensive experience with research of thin films and nanostructures for the PV. We now face demand for expertise concerning PV, including production and application, not only from individuals, but also from institutions. The Czech Academy of Sciences with 54 institutes wants to assess the PV potential at its more than 100 buildings, at particular areas of their roofs.

Coincidentally, 3D models of large cities are available, e.g. [6]. PV assessments, aimed at linking the roofs with the weather forecasts [7] and data from existing PV installations, which we would like to connect as linked data and as experience base for further PV adoption.

[1] Humans have installed 1 terawatt of solar capacity, generated over 1 petawatt of solar electricity in 2021, PV magazine. (2022).
[2] Communication from the Commission to the European Parliament, Solar Energy Strategy, 2022. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A221%3AFIN&qid=1653034500503.
[3] Potenciál solární energie v ČR. https://faktaoklimatu.cz/infografiky/potencial-solarni-energie-cr-strechy.
[4] The age of Czech solar power: after years of stagnation, is a rebirth imminent?, Energy Transition. (2019). https://energytransition.org/2019/03/czech-solar-power-after-years-of-stagnation/.
[5] I. Kougias et al, Ren. Sust. Energy Reviews. 144 (2021) 111017.
[6] 3D model Prahy, https://app.iprpraha.cz/apl/app/model3d/.
[7] Medard Online, http://www.medard-online.cz/.

PV monitoring and big data at HZB

Carolin Ulbrich[1], Mark Khenkin[1], Maximilian Riedel[1], Niklas Albinius[1], Ulas Erdil[1], Marko Remec[1,2], Xingzhi Guo[1], Florian Scheler[1,2], Paolo Graniero[1,3], Christian Utama[1,4], Björn Rau[1], Rutger Schlatmann[1]

[1]Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany
[2]University of Ljubljana, Faculty of Electrical Engineering, Ljubljana, Slovenia
[3]Freie Universität Berlin, Department of Information Systems, Berlin, Germany
[4]Freie Universität Berlin, Department of Economics, Berlin, Germany

Abstract

PV monitoring at HZB spans from the Perovskite samples a few mm² in size, produced in our in-house laboratories, tracked with µmpp tracker systems from the University of Ljubljana to conventionally monitored industrial modules of various technologies to a BIPV installation. This contribution gives an overview on the challenges we tackle and the solutions we found while acquiring more than a full year of mpp-tracked outdoor data of a Perovskite cell along with respective indoor tests. We also show how we track our BIPV installation data and what challenges we faced here during the installation and data analysis. The BAIP (Consulting office for building-integrated Photovoltaics) office shares some of their experience with architects and planners.

Can data science help us in the development of this field? We investigate big data methods in the analysis of publications written on Perovskite solar cell manufacturing and acquired data. We also test how to build trust applying explainable artificial intelligence (XAI) methods and tested some of these algorithms in respect to PV system fault detection.

Keywords: Perovskite solar cell, stability, encapsulation, outdoor, accelerated ageing

High-resolution intraday forecasts of PV production with advanced machine-learning architectures

Rafael Carrillo, Jelena Simeunovic, Baptiste Schubnel, Renaud Langou and Pierre-Jean Alet

CSEM, Sustainable Energy Center
Jacquet-Droz 1, Case postale, CH-2002 Neuchâtel, Switzerland
Pierre-Jean.Alet@csem.ch

Abstract

State-of-the-art methods for forecasting photovoltaic power production derive from weather forecasts obtained through numerical simulation, satellite-based cloud motion tracking or full-sky imaging, depending on the temporal horizon. They come with limited resolution or high computational costs.

The paper presents an alternative approach which exploits the intuition that PV systems are effectively low-grade weather stations. In this approach, the number of data points compensates for the quality of the instrumentation. To turn this intuition into an operational solution, we introduced advanced graph machine learning architectures which combine state-of-the-art algorithms from different fields (social networks, natural language processing, etc.)

The solution was trained and evaluated on real and synthetic datasets which are representative of the spatial and technical distribution of PV systems in Switzerland. On the most demanding dataset, the median normalised root-mean-square error for six-hour ahead forecasts reaches 15.5%, and the technique significantly outperforms commercial solutions.

PV system performance assessment by TDP model

Kristijan Brecl[1], Julián Ascencio-Vásquez[2]
[1]University of Ljubljana, Faculty of Electrical Engineering, Ljubljana, Slovenia
[2]ASVA Consulting, Santa Cruz de Tenerife, Spain
kristijan.brecl@fe.uni-lj.si

Abstract

The evaluation of a large fleet of PV systems or performance calculation of PV systems with spare metadata information is usually very challenging and time consuming. Recently, we developed Typical Daily Profiles (TDP) methodology for a fast and accurate evaluation of PV systems. TDPs are representative hourly profiles of the observed parameter (e.g., power, irradiance and temperature) on a monthly basis. Beside the calculation of the common PV system performance parameters, TDPs help also to detect the orientation and inclination angles of PV systems.

The TDP model will be presented on two cases: calculation of PV performance parameters on a fleet of large PV systems in Chile and evaluation of PV systems with very diverse orientations across Slovenia.

Hybrid data-driven techniques to optimize PV fleet energy yield

Julián Ascencio-Vásquez
ASVA Consulting
38650 Santa Cruz de Tenerife, Spain, Julian@asvaconsulting.com

Abstract

Optimizing a single photovoltaic (PV) power plant can be achieved by collecting the as-built documentation, operational monitoring data and O&M tickets and processing all that data with comprehensive data-driven techniques. However, when a PV fleet is analyzed using publicly available data (e.g., TSOs data), the access to detailed information (layout, BoM, inverter-level data, etc.) is minimal. For this reason, simple but powerful algorithms need to be developed to extract as much as useful information out of the datasets in order to increase the total energy yield. To achieve this purpose, the combination of physical, statistical and machine learning approaches play an important role in analyzing and optimizing the multiple PV power plants.

This work presents hybrid data-driven techniques applied to a large and growing PV fleet in Chile operating since 2012 up to date. The analyzed portfolio includes over 300 PV systems equivalent to 5GW installed capacity spread over the entire country. Outcomes of such algorithms can help to visualize and highlight underperforming PV systems and trigger on-site investigations on them. The main results highlight the amount and reasons of energy and monetary losses that can be recovered by applying timely- and costly-effective actions.

NB-IoT/5G wireless retrofit approach for PV monitoring

G. Oviedo Hernandez[1]*, M. Berliocchi[2]*, P. S. Enriquez Paez[1], C. Isnardi[2]

[1] BayWa r.e. Operation Services S.r.l., R&D department
Via di Settebagni 390, 00139 Rome, Italy
[2] Raptech S.r.l.
Via di Settebagni 390, 00139 Rome, Italy
*Corresponding authors (guillermo.hernandez@baywa-re.it and berliocchi@raptech.it)

Abstract

Current PV monitoring systems typically rely heavily on wired networks to establish connections between the SCADA sensors and the Internet. As showed by our preliminary results in the framework of the TRUST-PV project[1], new wireless technologies such as Narrow Band-IoT/5G prove promising for both, new and existing PV plants. Such Internet of Things (IoT) approach offers substantial advantages over the state-of-the-art communication solutions such as LAN (Local Area Network, based on Ethernet cables), RS-485 serial interfaces (with Modbus protocol), PLC (Power Lines Communications), ADSL, Optical fiber, 3G or 4G cellular technologies or Satellite Communication.

Moreover, good signal penetration, long battery life, very low latency times and high data rates reducing the energy consumed by the IoT nodes per transmitted bit, make this approach a valid candidate even for monitoring applications at PV module level. While current monitoring systems often stop at string level, the IoT approach explored in this work will unleash the potential of big data analytics for failure detection and diagnosis, allowing, just to name an example, the automated categorization and clustering of PV modules based on measured power classes, in order to find the optimal string reconfiguration to minimize mismatch losses (due to their uneven degradation).

Key words: PV monitoring, big data, wireless technology, failure analysis, IoT

Acknowledgment

The work of the authors was supported by funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 952957, project TRUST-PV.

[1] https://trust-pv.eu/

Machine Learning on Perovskite Stability Data: Critical Issues in Current Shared Databases

Paolo Graniero*[1,2], Mark Khenkin[2], Hans Köbler[2], Noor Titan Putri Hartono[2], Rutger Schlatmann[2], Antonio Abate[2], Carolin Ulbrich[2]

[1] Freie Universitaät Berlin, Garystr. 21, 14195 Berlin

[2] Helmholtz Center Berlin for Materials and Energy, Hahn-Meitner-Platz 1, 14109 Berlin

*paolo.graniero@fu-berlin.de

Machine Learning on Perovskite Stability Data: Critical Issues in Current Shared Databases

In the last decade, the success of perovskite solar cells in terms of efficiency has attracted thousands of researchers. The amount of data generated and published is ever increasing: the possibility arises to collect all these data and analyze them with statistical and machine learning (ML) methods to gain insights beyond what can be obtained by single studies. A notable example of such an effort is the Perovskite Database Project (Jacobsson (2021)).

Even though this dataset is much larger than any ever collected on perovskite devices, there are still issues, especially regarding stability data, the focus of our work. The issues we consider critical regard data quality and numerical reporting of stability.

Data quality is the main limiting factor in the performance that any ML algorithm can reach. On the one hand, we need to improve the data quality, especially in terms of missing values; on the other, even with a higher quality dataset, the lack of a universally accepted figure of merit for stability introduces high uncertainty in any analysis.

We discuss both limiting performance of ML algorithms on the Perovskite Database and non-agreements among figures of merit for stability using in-house data of more than 700 aging curves.

Design principles for constructing the ideal interface: a perovskite/C60 case study.

Florian Scheler[1*], Silvia Mariotti[1], Daniele Mantione[2], Artem Musiienko[1], Sebastian Keßler[1], Dorothee Menzel[1], Fengjiu Yang[1], Amran Al-Ashouri[1], Lars Korte[1], Steve Albrecht[1]

[1] Solar Energy department, Helmholtz-Zentrum Berlin, 12489, Berlin, Germany
[2] POLYKEY S.A., 20002, Donostia, Spain
*Kekulestraße 5, 12489 Berlin / florian.scheler@helmholtz-berlin.de

Abstract

Molecular Interface modification has been established as a major strategy to reduce the number of defects or change energetic misalignment causing losses in perovskite solar cells, especially at the interfaces with the charge selective materials. [1] Self-assembled monolayers used as the hole-selective material have been shown to result in a near loss-less interface between perovskite and hole selective material.[2] However, similar schemes for the interface with the electron selective material (ESM) (i.e. mostly C60) are rather scarce.

Ionic liquid post treatments may result in high efficiencies as extensively demonstrated in the literature before.[3] Starting form an optimised piperazinium iodide treatment, we explore the influence of changing the molecular structure and moieties on the use as molecular modifier at the ESM/triple halide perovskite interface (1.68eV). [4]

By doing so, we try to build a data foundation and eventually find rules, that allow for the ab-initio design of the ideal interface.

[1] YE, Junzhi, et al. Defect passivation in lead-halide perovskite nanocrystals and thin films: toward efficient LEDs and solar cells. Angewandte Chemie, 2021, 133. Jg., Nr. 40, S. 21804-21828.
[2] AL-ASHOURI, Amran, et al. Conformal monolayer contacts with lossless interfaces for perovskite single junction and monolithic tandem solar cells. Energy & Environmental Science, 2019, 12. Jg., Nr. 11, S. 3356-3369.
[3] LI, Fengzhu, et al. Regulating surface termination for efficient inverted perovskite solar cells with greater than 23% efficiency. Journal of the American Chemical Society, 2020, 142. Jg., Nr. 47, S. 20134-20142
[4] XU, Jixian, et al. Triple-halide wide–band gap perovskites with suppressed phase segregation for efficient tandems. Science, 2020, 367. Jg., Nr. 6482, S. 1097-1104.

Urbach energy and defect formation during the halide perovskite growth

Aleš Vlk,[1] Nada Mrkyvkova,[2,3] Vladimír Held,[2] Peter Nádaždy,[2] Riyas Subair,[2] Eva Majkova,[2,3] Matej Jergel,[2,3] Martin Ledinsky,[1] Antonín Fejfar,[1] Jianjun Tian,[4] and Peter Siffalovic,[2,3]

1 Laboratory of Thin Films, Institute of Physics, ASCR,
Cukrovarnická 10, 162 00 Prague, Czech Republic
2 Institute of Physics, Slovak Academy of Sciences,
Dúbravská cesta 9, 845 11, Bratislava, Slovakia
3 Center for Advanced Materials Application, Slovak Academy of Sciences,
Dúbravská cesta 9, Bratislava 845 11, Slovakia
4 Institute for Advanced Materials and Technology, University of Science and Technology Beijing, 100083 Beijing, China

vlkal@fzu.cz, nada.mrkyvkova@gmail.com, held.vladimir@gmail.com, nadazdy.peter@gmail.com, riyas3190@gmail.com, fyzievad@gmail.com, matej.jergel@savba.sk, ledinsky@fzu.cz, fejfar@fzu.cz, tianjianjun@mater.ustb.edu.cn, siffalov@gmail.com

Abstract

Over the past decade, we are witnessing a rapid growth of power conversion efficiencies of the perovskite solar cells approaching the conventional silicon single-crystal performances. Nowadays, the short circuit currents J_{SC} almost reached the fundamental limit. Therefore, the biggest space for improvement lies in the open-circuit voltage V_{OC} and fill factor FF of a solar cell. Both properties are directly affected by active defects in the absorber material. V_{OC} is reduced by non-radiative recombination on local defects, and FF is proportional to the charge carrier's lifetime, which is also affected by defect density. A detailed understanding of the defect formation process is therefore crucial for its reduction and improvement of the final photovoltaic properties.

In our study, we used a simultaneous measurement of in-situ photoluminescence (PL) and grazing-incidence wide-angle X-ray scattering (GIWAXS) to observe the perovskite layer crystallization process in a real-time.

Our study provides direct control of perovskite growth and, more importantly defect formation and eventual passivation. The most significant advantage of such approach is that the addition of passivating agents can be precisely timed, and the effect immediately measured. This will lead to a significant improvement of V_{OC} and FF in the finalized photovoltaic device.

Correlating Indoor and Outdoor Degradation in Perovskite Solar Cells

Mark Khenkin, Ulas Erdil, Marko Remec, Quiterie Emery, Hans Köbler, Jinzhao Li, Antonio Abate, Eva Unger, Rutger Schlatmann, Carolin Ulbrich

Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany
Hahn-Meitner-Platz 1, 14109 Berlin, Germany; mark.khenkin@helmholtz-berlin.de

Abstract

Stability is the key aspect to improve in order to advance promising perovskite photovoltaic technology to the market. Plenty of accelerated stress tests have been suggested to identify possible degradation mechanisms in perovskite solar cells (PSCs), however, their relevance to the real-world operation is yet to be tested. Since establishing a rooftop setup for research-size PSCs in Berlin, we achieved many months-long outdoor data series (up to 1,5 years) by utilizing vacuum lamination procedure with butyl edge sealant and polyolefin encapsulant. In this talk, we will share our experience with the outdoor stability of PSCs and compare it to the results of the indoor ageing tests (including light, temperature, electric bias and humidity in different combinations or cycles thereof). We emphasize the importance of the cycled stresses for PSCs due to reversible processes. Particularly when cycling the light as in the natural day-night cycle, the recovery in the dark may (depending on the device architecture) extend, shorten or leave unchanged the observed device lifetime.

Keywords: Perovskite solar cell, stability, encapsulation, outdoor, accelerated ageing

Up to 1.94 V Open Circuit Voltage in Highly Efficient Perovskite/Silicon Tandem Solar Cells Using Polymeric Interlayers in the Top Contact

B. Li[1], M. Härtel[1,2], A. Al-Ashouri[1], E. Köhnen[1], K. Sveinbjörnsson[1], A. Musiienko[1], P.Wagner[1], B. Stannowski[1], L. Korte[1] and S. Albrecht[1,2]

[1]Helmholtz-Zentrum Berlin für Materialien und Energie, Division Solar Energy, 12489 Berlin, Germany

[2]Technische Universität Berlin - Fakultät Elektrotechnik und Informatik, 10587 Berlin, Germany

Abstract

Metal halide perovskite solar cells have been improving significantly over the past decade. Their versatile material properties allow the combination with silicon solar cells in monolithic tandem configurations achieving power conversion efficiencies (PCE) above 29 %.[1] Semitransparent top contact layers are a key element for high efficiency perovskite based tandem solar cells.[2] In addition, these top contact layers, namely tin oxide (SnO_2) deposited by atomic-layer deposited (ALD) and indium zinc oxide (IZO) deposited by RF-magnetron sputtering, protect the perovskite solar cells against decomposition reactions in humid air and at high temperature, thus improving long term stability. However, the deposition process of top contact layers often induces fill factor (FF) and open circuit voltage (V_{OC}) losses due to perovskite degradation and/or process related defect generation.[3]

In this work, V_{OC} differences between tandem-relevant cells processed with different electron-selective contacts are quantified. We show how V_{OC} losses can be mitigated by using an ultrathin polymer interlayer between the perovskite absorber and the n-type top contact. The perovskite can be protected by introducing polyethylenimine ethoxylated (PEIE), a polymeric interlayer, which reduces degradation and non-radiative recombination losses. This is shown by an increased steady-state photoluminescence quantum yield and improvements in V_{OC}. Additionally, an enhanced nucleation growth of SnO_2 on PEIE[4] allows for a thinner and denser SnO_2 film. Combined with a thinner C60 layer due to the protective property of PEIE, an overall optical improvement of the top cell transmission could be achieved. Interestingly, PEIE as interlayer between perovskite and C60 can also reduce recombination losses and improve electron extraction as analysed by transient surface photovoltage. These modifications overcome the top contact limitation, increase the overall performance, and push perovskite/silicon tandem solar cells one step closer towards surpassing 30% PCE.

[1] A. Al-Ashouri, et al., Monolithic perovskite/silicon tandem solar cell with >29% efficiency by enhanced hole extraction, Science **2020** 370 (6522) 1300, (DOI:10.1126/science.abd4016).
[2] M. Jošt, et al., Monolithic Perovskite Tandem Solar Cells: A Review of the Present Status and Advanced Characterization Methods Toward 30% Efficiency, Adv. Energy Mater. 2020 10 1904102, (DOI:10.1002/aenm.201904102).
[3] A. F. Palmstrom et al., Interfacial Effects of Tin Oxide Atomic Layer Deposition in Metal Halide Perovskite Photovoltaics, Adv. Energy Mater. **2018** 8 1800591, (DOI:10.1002/aenm.201800591).
[4] Raiford, J. A. et al., Enhanced Nucleation of Atomic Layer Deposited Contacts Improves Operational Stability of Perovskite Solar Cells in Air. Adv. Energy Mater. **2019**, 1902353, (Doi.org/10.1002/aenm.201902353).