

Welcome to the last day of the 50th IEEE Photovoltaic Specialists Conference! No Plenary or poster sessions today, just the final technical presentations.

Technical Sessions (First Morning):

Area 1 - Colored PV and Luminescent Solar Concentrators

Stephan Collin presented an updated efficiency limit for multiresonant light trapping in solar cells that surpasses the Lambertian limit. Rebecca Saive showed an efficient collimation of diffuse light for solar utilization. Phoebe M. Pearce (UNSW) explored detailed efficiency optimization of colored solar cells. Stéphane Collin (C2N, IPVF) presented an updated efficiency limit for multiresonant light trapping in solar cells that surpasses the Lambertian limit. Mathis Van de Voorde (University of Twente, Karlsruhe Institute of Technology) discussed looking for optimal nanocrystal luminophores in solar concentrators. Bryce S. Richards (Karlsruhe Institute of Technology) presented semi-transparent PV technology with luminescent solar concentrators. Rebecca Saive (University of Twente) showed an efficient collimation of diffuse light for solar utilization in cloudy environments.

Area 3 - Reducing III-V Cost: Engineered Substrates and CPV

Jinyuon Cho (Umicore) gave an invited talk on a sustainable and affordable Ge substrate technology such as GeON (Ge on nothing) and PGe (porous Ge) wafers. Discussed Umicore's goal of 100% Zn-sourced or recycled Ge production as opposed to coal. GeOn shows maintaining substrate orientation and offcut. Both methods used to grow 3J or 1J device with same performance as bulk. 3-time reuse of substrates shown, with some increase in surface roughness. Targeting a pilot run of material by 2025, with full production by 2028. Theresa E. Saenz (NREL) showed III-V growth on V-groove Si substrates with TDD down to $3E6$ cm⁻² and a ~ 5 ns lifetime with buffer and thermal cycling process and an asymmetric step-graded filter. However cracking was observed when making devices. Carlos Algora (Universidad Politecnica de Madrid) discussed a 3J IMM targeting 3 kW/kg and LM upright on Ge, thinned substrate and back reflector for 1 kW/kg, with 30-60 micron total thickness. Showed a device on a 60 micron thinned Ge substrate with 91% of control performance, and a new design targeting 100% of control is in fabrication now with lessons learned. Konan Kouame (Universite de Sherbrooke) presented on the assembly of a CPV module using surface mount technology on glass, demonstrating same Voc and FF compared to a bare cell, with some loss in Jsc due to reflection at 1x and 900x suns. A temperature model was used to predict temperature and operation at 160x with 38% efficiency. Gan Li (Univ. of Tokyo) investigated front and rear p-type and n-type absorbers in homo and heterostructures. For the same structure, n-type absorbers show higher Voc; FJ/FHJ have higher Voc and Jsc than RJ/RHJ. Concluded n-type absorber is better, front junction is better, heterojunction is preferred.

Area 5 - Photovoltaic Modules and Systems Characterization

Tao Song (NREL) presented the criticality of thermal drift of cut-on wavelengths in long-pass filters used on filtered reference cell in primary outdoor calibrations. Proposed two possible solutions, actively cooling filter and thinner filter. Gisele A. dos Reis Benatto (DTU) illustrated how adding conformal prediction to machine learning is able to improve significantly the performance of electroluminescence (EL) compared to the standard deep learning classifier. Jarod Kaltenbaugh (UCF) introduced the “Findable, Accessible, Interoperable, Reusable” (FAIR) Data Principles that have been developed to provide guidelines to improve the management of digital assets, so that metadata and data are both human-readable and machine-readable: an example of application was shown, with over 1,500 photovoltaic (PV) data from the last 6 years of varying module technologies. Gisele A. dos Reis Benatto presented again, addressing the missing knowledge of what can be expected from the PV modules EL signal in the field, especially for daylight conditions. Sebastian Dittmann (Hochschule Anhalt) browsed on the uncertainty contributions that are dominant in LED solar simulators, specifically for bifacial modules. Finally, Brendan Wright (UNSW) showed how quality assessment methodology can be used to determine the preferred end-of-life (EoL) paths of fielded photovoltaic modules using luminescence imaging techniques. Model was more successful than manual (human) binning in relating EL to electrical qualities.

Area 6 - Scale-Up, Scalable Processing, and Stability of Halide Perovskite Solar Cells and Modules

Muneeza Ahmad (ASU) had a great presentation talking about the tensile stress in perovskites and how this leads to degradation. Explained the origin of stress is associated with thermal, intrinsic and applied stresses. Also showed how additives could help improve stress degradation, and how stress influenced optical properties. Kshitiz Dolia (University of Toledo) investigated various Cs-based compositions on the light temp degradation in cells. The samples were encapsulated during his study. Results showed that performance dropped during increasing UV Dosage. UV radiation lead to most severe degradation in the initial phase of the UV investigation. This presentation showed degradation but the microstructure SEM photos did not show any physical defects. Muzhi Li (ASU) presented strategies to improve the mechanical robustness of perovskite solar cells. Carrier transport layers in PSCs tend to be weakest, which is the source of fragility in PSCs. Fracture energy decreases with the inclusion of bulky cations. Tamanna Mariam (University of Toledo) used EL/PL analysis to determine module degradation. Showed how EL images differ with different acquisition time and temperatures, and that the EL bias with heat stress doesn't affect the device performance. PL intensity increases due to the structural phase transition with the change in temperature and the thermal stressing time. Sofia Masi (Universidad Jaume I) talked about PbS QDs which was good to see because most presentations did not include QDs. The speaker discussed how QDs showed better performance and how these cells/minimodules have performed well during stress and strain. Guanidinium in FAPI increases stability, which decreases at the higher concentration. Carla Costa (CEA INES) Speaker talked about perovskites in space!! Presented the In-situ & ex-situ study of protons and electrons irradiations of perovskite solar cells. No degradation of the PSCs have been reported if PTAA gets removed after bombardment with the proton radiation. On the other hand, ex situ measurement has shown irreversible degradation by the glass.

Area 7 - Strategies for Performance Monitoring and Rating

A combination of industrial and research level solutions for PV performance monitoring, fault detection. Several talks promoting standardization of data management, data processing, as well as PV performance analysis methods and output. Jesus Montes-Romero (University of Cyprus) discussed real time edge computation and AI services lead to effective fault detection and diagnosis on small and large scale PV systems. Developed digital twin for PV performance modeling and fault diagnosis at high power output predictive accuracies of <1.6%. Timon Sebastian Vaas (Forschungszentrum Julich, RWTH Aachen University) showed plausibility filtering can improve data quality while also be used to identify potential issues with PV modules and systems. Karel De Brabandere (3E) presented that a combination of drone inspection and time-series analysis can assist in estimating losses in PV systems and detecting problems. Raymond Wieser (Case Western Reserve University) showed the use of spatiotemporal GNNs outperforms physics-based and deep learning-based imputation methods for missing time-series data. Clifford W. Hansen (Sandia National Laboratories) showed Orange Button provides a taxonomy to standardize data transactions and lower labor costs associated with data "friction". Li C. Rendler (Fraunhofer ISE) discussed alternative PV module layouts have the potential to improve shading tolerance in certain situations, thereby potential lower energy costs for PV systems.

Area 11 - Economics, Policy, and Energy Justice and User Behavior, Education in Institutes of Learning, and Workforce Development

Wonderful presentations about educating students with projects, developing solar boat and robot for PV module inspection. Ways to help low-income communities with PV were presented. Alanis M. Colón (University of Puerto Rico at Mayaguez) gave a wonderful presentation about project-based learning by developing PV inspection robot. Students can learn various skills. Will Gorman (Lawrence Berkeley National Lab) showed relatively small PV+battery systems can serve backup critical load without heating and cooling considered. Heating and cooling remain challenging for small PV+battery. Christoph Kondzialka (Ulm University of applied Sciences) discussed the obligation to have smart meter required and regulatory barriers need to be removed to realize the concept Guillermo Serrano (University of Puerto Rico at Mayaguez) showed nice experience for students. Speed improved year by year. Wonderful presentation with movies. Rodrigo F. Calili (Pontifical Catholic University of Rio de Janeiro) presented a success case introducing PV in low-income communities in Brazil via solar cooperative. Workforce development also provided. Anna Carolina P. Sermarini (Pontifical Catholic University of Rio de Janeiro) showed current subsidies of electricity are not effective for low-income communities. If social tariff are applied to distributed PV, more benefit created.

Technical Sessions (Second Morning):

Area 2 - Interfaces and Modeling

Giovanni Fevola (DESY) showed X-ray microscopy provides detailed, 3D insight on voids in CIGS devices. Aubin JC. M. Prot (University of Luxembourg) explained how depth-dependent PL measurements expose inter-grain band gap fluctuations in CIGS solar cells. Michael F. Miller (The Ohio State University) explored the effects of RbF treatment on defects in CIGS devices using DLTS and DLOS measurements. Marit Kauk-Kuusik (Tallinn University of Technology) presented performance improvements in monograin kesterite solar cells. Adam B. Phillips (University of Toledo) performed numerical simulation of bifacial CdTe solar cells and explored the potential of these devices, including that band bending at the back contact is important in bifacial CdTe. Uwe Rau (IEK-5 Photovoltaik, JARA-Energy) showed a different perspective on the fundamental physics of photovoltaic devices.

Area 3 - Reducing III-V Cost: Spalling

Dubbed “spallapalooza” by one attendee these presentations focused on a variety of work surrounding material spalling and related devices using MOVPE, HVPE, or dopant diffusion. Kevin L Schulte (NREL) saw unusual shunting behavior in cells grown on leading to large values in local ideality factor. A light surface etch allowed improved growth without these effects. Jacob Boyer (NREL) showed perfect planarization is not required to achieve high performance cells on previously spalled surfaces. William E. McMahon (NREL) demonstrated surface kinetics control using dopants to strongly enhance smoothing or roughening. Spalling direction (Ga or As terminated) also matters. Andrew Nyholm (Caltec) discussed the first GaAs devices using combined epi-free and substrate reuse by spalling demonstrate high potential for drastic cost reduction. Ryan France (NREL) showed identification and mitigation through etching of deleterious spalled Ge surface defects enable improving performance of III-V cells.

Area 4 - Passivated, Carrier-Selective, and Heterojunction Contacts – 2

Xixiang Xu (Longi Green Energy Technology) WR of 26.81% Silicon heterojunction technology (SHJ) demonstrated thanks to the successful integration of nanocrystalline doped hydrogenated silicon (nc-Si:H), surface passivation quality is further enhanced by field effect and the contact resistance is highly restrained. On the other hand, oxygen doping at front nc-Si:H broadens the band gap and the transparency to short-wavelength sunlight is increased for higher short-circuit current density. Combined with new transparent conductive oxide and advanced metallization, intrinsic properties of silicon emerge from intricate power loss mechanism, causing unprecedented fill factor and record conversion efficiency in silicon solar cells. Ujjwal K Das (University of Delaware) Solid study presented on the passivation quality of a-Si:H/c-Si:H interfaces for DC-PEVCD processing. Post-annealing demonstrated better device performance, leading to high $iVoc$. Weiyuan Duan (IEK5-Photovoltaik) The presenter reviewed the eminent work which has been done in Forschungszentrum Jülich for chasing up Jsc in high efficiency SHJ solar cells. Three different parts of this work have been presented and discussed, including implementation of nanocrystalline silicon carbide based transparent passivating contact (TPC), front-side TCO-free design and Catalytic doping (Cat-doping) in SHJ solar cells. They achieved certified efficiency of 23.99% with a Jsc of 40.87 mA/cm² for TPC solar cells. Stefan Lange (Fraunhofer Center for Silicon Photovoltaics CSP) Contact degradation in SHJ solar cell for temperatures higher than 170 °C is observed. This correlates with a densification of a parasitic silicon oxide layer at the ITO/a-Si junction and an increase

of Si oxidation state within this layer. Xiaoning Ru (LONGi Green Energy Technology) demonstrated that the p-type SHJ solar cell efficiency can reach 26.6%, which is just 0.2% behind of its n-type counterpart.

Area 8 - Degradation of Module Components and Material Interactions

Understanding of physical and chemical processes of materials during PV operation is essential in order to understand and mitigate failure modes. Ingrid L. Repins (NREL) defined a Research Opportunity Number (RON) for reliability researchers to assess different degradation scenarios based on the change in the LCOE, market susceptibility, and the status of accelerated tests that can detect and quantify the degradation mode. The RON was demonstrated for three example cases: light and elevated temperature degradation (LETID), backsheet cracking, and anti-reflective (AR) coating abrasion. Stephanie L. Moffitt (NIST) discussed complex orientation dependent crystallization effects at crack tip of aged PVDF; more isotropic materials would probably mitigate cracking. Xiaohong Gu (NIST) observed depth-dependent optical, chemical and mechanical degradation across the thickness of aged G/POE/CB coupons. For glass-side exposed samples, the closer to the glass side, the higher level of fluorescence, indicating the chromophores formation in the POE encapsulant likely depends on the UV intensity. Nanoindentation results showed a depth-dependent modulus loss in POE encapsulant after exposure. There is an interaction between backsheets and encapsulants since they impact each other's degradation and their is a depth profile of yellowing. Gernot Wallner (CDL-AgePol) developed and applied a fracture mechanics test methodology to examine the cyclic fatigue debonding of the EVA encapsulant from inorganic plies of PV modules under service-near superimposed loading conditions. Cyclic fatigue testing is very useful in investigating EVA - glass delamination in PV modules. Rik Van Dyck (KU Leuven, University of Hasselt, IMEC, EnergyVille) Showed how fiber Bragg grating sensors (FBGS) can be used to monitor in module strain and temperature during reliability tests. Showed how glass fiber reinforcement in the encapsulant reduces TE mismatch and thermally induced strains up to 10 % peak to-peak. Junki Joe (NREL) Studied the wear of gridlines bridging cell cracks. Gridline fracture overhang manifests electrical bridging behavior. Initial bridging distance is quickly reduced by blunting of fracture surfaces. With continued cycling, the minimum resistance continues to degrade.

Area 9 - Power Electronics and Grid Integration – 2

Aminul Huque (EPRI) presented the development of library models for smart inverter components with IEEE 1547-2018 as an open DER library based on Python. The models of the different components can be integrated with high modularity. Patrizio Manganiello (Delft University of Technology) proposed a strategy for minimizing the mismatch losses due to partial shading when operating PV string. The proposal relies on converter based Differential Power Processing Configuration. Javier Hernandez-Alvidrez (Sandia National Laboratories) discussed a PHIL test bed for testing grid forming devices. The strategy is based on controlling the power amplifier as a following unit. Hyeonjung(Tari) Jung (University of Minnesota) presented per-unit dynamic models for PV Inverters as an effort for normalizing dynamical-system models for energy-conversion interfaces. Joseph A. Azzolini (Sandia National Laboratories) presented the development of a model-free service transformer capacity for assessing HCA constraints by using residential data from smart meters. Hyeonjung(Tari) Jung (Midcontinent Independent System Operator,

Best Student Presentation Award Finalist), presented the characterization capacity of solar, wind, and storage units considering existing methods and the novel direct loss of load (DLOL) method validated in a simulation using Monte Carlo study considering weather, thermal and technical variation.

Area 10 - Site-Specific Factors on Solar Resource and Tracking

Using and providing open datasets or tools was a common theme in the session. Aron Habte (NREL) presented that new TPY datasets show a better match with long term averages compared to conventional TMY. Jennifer L. Braid (Sandia National Laboratories) highlighted the importance of horizon profiling, while showing that there are variations in results based on methods, so care is needed. Marc Perez (Clean Power Research) discussed a regional analysis that rolled shade impacts into a larger energy impact by land type summary. Guillermo A. Farias-Basulto (Helmholtz-Zentrum Berlin für Materialien und Energie) showed spectral response of PV devices are relevant to installation angle (35 deg vs 90 deg tilt) - includes publicly available solar spectra measurement data. Vasilis Fthenakis (Columbia University) presented a student project that explored the cost and performance impacts of tilted single axis tracking systems. Kurt Rhee (Nevados Engineering) described a modeled tracking optimization approach was to have about 2x the gain of conventional terrain-optimized GCR settings (over naive GCR-based control).

Closing Ceremony

In closing this year's conference, we again congratulate the Cherry Award winner Jenny Nelson and Wenham Award winner Yifeng Chen. We would like to thank all of the Area Chairs, Sub-Area Chairs, Session Chairs, and Reviewers for all of their hard work and contributions!

The Napkin Award is presented to the committee member who offered the greatest enhancement to the technical program of the conference. This year's winner was Jacob Krich, the Area 1 Chair.

Student Award Winners

Congratulations to the Student Winners from each area for their excellent presentations listed below:

Area	Recipient, affiliation	Title
1	Gemma Giliberti, Politecnico di Torino	Impact of current collection grids on the scalability of 3-terminal perovskite/silicon tandems with bipolar transistor architecture
2	Gregory Manoukian, Drexel University	Quantifying bulk and surface recombination in CdSeTe absorbers by modeling terahertz and photoluminescence decays
3	Emily Kessler-Lewis, Rochester Institute of Technology	Simultaneous solar power generation and bidirectional data transmission
4	Alexander Eberst, RWTH Aachen University, Julich GmbH	Development of gradient layers to improve the efficiency of transparent passivating contact solar cells
5	Dirk Steyn, Colorado School of Mines/NREL	A new method for the evaluation of majority and minority carrier contact resistivity of polysilicon on oxide contacts
6	Julia Huddy, Dartmouth College	Large-area uniformity mapping of high-speed flexography-printed perovskite solar cells via scanning photoluminescence
7	Mandy Lewis, University of Ottawa	Energy yield and economics of single-axis tracked bifacial photovoltaics with artificial ground reflectors
8	Rodrigo del Prado Santamaria, Technical University of Denmark	Evaluating multi-bias modulation for diagnostics of PV modules in daylight electroluminescence inspections
9	Hyeonjung (Tari) Jung, MISO Energy	Characterizing capacity contribution of renewable resources over time in renewable-heavy transmission system: miso case study
10	Priya Gupta, Indian Institute of Technology Roorkee	Application of noise-assisted multivariate data analysis for hour-ahead GHI forecasting
11	Jacob Stid, Michigan State University	The United States renewable energy landscape: management and potential impacts

Upcoming conferences:

A new conference is starting this year: Middle East and North Africa Solar Conference (MENA-SC) which will be held from 15-18 November 2023 in Dubai, with 6 technical areas. Abstracts due August 1.

<https://www.mbrsic.ae/en/mena-sc/about-mena-solar-conference/>

The EUPVSEC will be held from 18-22 September 2023 in Lisbon, Portugal. This will be the 40th anniversary of EU PVSEC.

<https://www.eupvsec.org/>

PVSEC-34 and CPVC20 will be held from 6-10 November 2023 in Shenzhen china. The abstract deadline is July 20.

<https://www.pvsec-34.com/>

Finally, the location of the 52nd IEEE PVSC was revealed by the future Conference Chair Arno Smets offering current Conference Chair Mariana Bertoni to pick a name from a hat revealing a video of Seattle, WA from. The conference will be from June 9-14, 2024. For international contributors, visa information will be available from September 2023 when the website goes online!