

Welcome to the second day of the 50th IEEE Photovoltaic Specialists Conference!

Plenary Sessions:

Area 6 Plenary: David Ginger from the University of Washington gave a general overview of recent rapid advancements in performance, stability, scaling, and reliability of perovskites, also demonstrating that Pb content is an order of magnitude less than Si panels (from solder). Perovskite stability can be achieved with surface passivation, control of grain boundaries, and interfaces (a perovskite single crystal withstands acid). Interface control is key for performance, stability and module integration. Ginger emphasizes the need for outdoor testing to advance stability testing. Microscope and imaging tools can accelerate the development of materials and modules, and understand stability. Silane APTMS passivation suppresses PL quenching, and switching interlayers overcomes reverse bias breakdown.

Area 2 Plenary: Susanne Siebentritt from the University of Luxembourg provided an excellent run through of recent improvements in CIGS, a mature technology being manufactured at industrial scale, stable and with high efficiencies. This included an overview of recent efficiency enhancements with Ag alloying, understanding of surface modification with alkali treatments and their bulk effects, and the potential for future improvements by moving away from Ga grading and moving towards back surface passivation with novel hole transport layers. The potential for tandem devices with the wide range of bandgaps available from 0.9 eV CuIn(Se, Te)₂ to 2.4 eV CuGaS₂ as bottom, top, or in-between cells. Recent results show perovskite/CIGS tandem with 24.2%, or CIGS/Si tandem with 16% efficiency.

Area 11 Plenary: Izumi Kaizuka from RTS Corporation presented an overview of the IEA PVPS, with 31 members, 26 countries, and on 5 continents. Specifically, Task 1 Strategic PV Analysis and Outreach, a working group tracking trends in market, policy, and industry. She showed current annual installed capacity leaders by country, with China at the top with 106 GW. China has a large share of nearly 80% or more for the Si supply chain from production of polysilicon, ingots, cells, and module production. Total PV installed capacity is over 1 TW. For 2050 75 TW are needed, PV needs to maintain a growth rate of 25%. There are still challenges that need to be addressed: grid integration, sustainability, social acceptance and workforce needed. Waiting is not an option, we must embrace all stakeholders to move forward.

Minority Carriers Panel

Lyndsay McMillon-Brown (NASA GRC) moderated a panel discussion with Pilar Espinet Gonzalez (Aerospace Corporation), Mark Mikofski (DNV), and Silvana Ovaitt (NREL) on the topic of Organizational Culture. An in-depth review of the discussion will be posted separately.

Technical Sessions (Morning):

Area 1 - Thermoradiative Energy Conversion and Space

Eric Tervo (UW–Madison) began the session with a strong overview of the potential of InAs as a thermoradiative diode system. Experimental data shown to verify theoretical predictions for their realized device, which showed a record low reverse saturation current for an InAs diode. Michael Nielsen (UNSW) developed a thorough model and tested the behavior of HgCdTe commercial photodiodes as both thermoradiative and thermophotovoltaic diodes. Found that HgCdTe has a very promising theoretical thermoradiative power density limit, and illuminated paths towards moving closer to this limit. Stephen Polly (RIT) discussed thermoradiative cells as a primary power source for deep space missions to enhance performance of radioisotope power systems. Jianjian Wang (Advanced Cooling Technologies) proposed and analyzed a “TRAP”-cell concept: Thermo-Radiative Assisted Photovoltaic Cell that simultaneously harvests energy from incoming sunlight and outgoing thermal radiation in a single device, combining the TRD and PV concepts for space applications. TRAP cell can outperform a PV cell at high or low solar intensities, especially for high-temperature operation. Alex Fedoseyev (Solestial) showed enhanced efficiency using a down-converting nanoparticle layer in ultrathin Si solar cells, achieved a 22% current improvement compared to cells without the nanoparticles and an absolute efficiency increase of 4.3% under AMO.

Area 2 - Ternary Alloys and Doping

Niranjana Mohan Kumar (ASU, Best Student Presentation Award Finalist) presented XANES, PL, and SEM measurements tracking the migration of Se through a CdSeTe absorber due to heat treatments and CdCl₂ treatments. This powerful and insightful spatially resolved x-ray fluorescence measurements of the impact of chlorine on Se-Te inter-diffusion, including quantitative assessment of the diffusion coefficients. Evidence of a liquid phase low temperature eutectic mechanism was presented. Deborah McGott (NREL) Presented on undoped CdSeTe, highlighting the effect that Se plays in CST films. She presented a number of measurements (DLTS, hall, PL) correlating the n-type grain boundaries to increased performance of the films. Camden Kasik (Colorado State University) presented on CdZnTe back contact layers. PL measurements taken before and after CZT deposition showed an increase in the PL intensity, corresponding to reduced recombination. Robert Klie (University of Illinois Chicago) showed high resolution microscopy images of CST, along with DFT to calculate dislocation core density of states. Machine vision, including AI and ML is being utilized to identify different types of defects within the high resolution microscopy images. Mayank Mate (Colorado State University) presented a novel study of the As-related point defects and complexes in CdSeTe:As using the XANES method. The results included a powerful insight into the mechanism of incorporation of As on specifically identified sites, including complexes with Cl and O. This gives some valuable insight into the mechanisms of compensation of p-type doping. Cl on Te was particularly highlighted. The possibility of metastability under particular bias conditions was raised. A 275 C Cd overpressure and elemental As was found to affect the device performance quite significantly, with efficiencies up to 15%. Srisuda Rojsatien (ASU, Best Student Presentation Award Finalist) presented on As-local structures, and how they change upon exposure to x-rays or bias. As-Cl complexes were shown to be significant and present, however, these complexes were electrically inactive.

Area 4 - Metallization, Interconnection, Module Integration, and Recycling/Sustainability and Novel PV Integrations – 1

Samuel Harrison (CEA-INES) showed the impressive potential of Shingle SHJ using Cu plating metallization with no loss, or even improved, efficiency. Steven Di Gregorio (Colorado School of Mines, Best Student Presentation Award Finalist) presented that reactive Ag ink can give efficiency ~ 21.6% with 90% less Ag usage than traditional usage. Radovan Kopecek (International Solar Energy Research Center) approximated that year 2025-2030 will experience a key migration period to huge commercialization of n-type solar cells. Mathis Van de Voorde (Twente) presented a novel method - string-printing - for transparent contacts (Ag, possibly Cu) with a promising future if can be upscale with high throughput. Michael W Martinez-Szewczyk (ASU, Best Student Presentation Award Finalist) presented “Damp Heat Performance of Silicon Heterojunction Solar Cells with Reactive Silver Ink Metallization”

Area 6 - Advances in Halide Perovskite Materials

Melissa Davis (High-Performance Materials Institute, NREL) discussed the development of a robust tool to study the mechanism behaviors of the perovskite films while flexed, using simulation matched measured SEM images of mechanical stress, providing a technique to standardize stress testing. Jackson W. Schall (NREL, Best Student Presentation Award Finalist) presented on the observation of metastabilities and irreversible degradation. Radiative recombination accounts to metastability. Transient characterization of spatial non-uniformity of PL intensity possible pathway for high throughput screening of device quality for manufacturing. Dan Wargulski (Helmholtz-Zentrum Berlin für Materialien und Energie, Best Student Presentation Award Finalist) presented on the calculation of lattice constants, band gap energies, and luminescence peak energies of perovskite nanoparticles using high resolution electron microscopy. Uwe Rau (EK5-Photovoltaik, JARA-Energy) showed that two component models are needed to correctly interpret device transient photovoltage data: take into account carriers in the absorber and contact layers. Marie Solange Tumusange (Toledo)- Combining spectroscopic ellipsometry and external quantum efficiency (simulated and measured) measurements yield depth sensitive current loss data, which allow comparisons of effects of different hole transport layers during aging in PTAA, PEDOT:PSS, P3CT HTLs. Saivineeth Penukula (ASU)- studied the ion migration in halide perovskite which is dominated by the halide vacancies. Suppressing mobile ion concentration mitigates degradation of halide perovskites. This can be done by using triple halide perovskites, using small cation additives, and using antioxidants.

Area 8 - Performance Loss and Diagnostics

Rodrigo del Prado Santamaría (Technical University of Denmark, Best Student Presentation Award Finalist) talked about detecting PID with outdoor daytime EL using novel bias modulation technique. Chiara Barretta (PCCL) investigated performance loss rates of 6 PV systems (19 silicon modules) that have been operating in Italy for 12 years. Used near infrared (NIR) spectroscopy to identify encapsulant and backsheet types. Analyzed spectral data with multivariate data analysis (MVDA) to detect polymer degradation signs that are not visible with the naked eye. Daniel Fregosi (Electric Power Research

Institute) compared performance loss rate analysis using weather inputs from satellite based and a ground based irradiance source. Concluded that free data (e.g., ERA5) can get results comparable to other sources. Andreas Livera (University of Cyprus) proposed a software solution to enable early failure detection and performance loss diagnosis of PV systems. Approach is based on real-time analysis of measurement data, machine learning, and statistical analysis. Showed a test case for a 1.8 MWp PV plant in Greece. Samantha Wilson (Power Factors) showed that snow can improve bifacial gain by several percent, but this increase decays within a few days after snowfall. Results are derived from a 2022-2023 study on about 100 sites with rear sensors. Highlighted the need for improved pre-construction models.

Area 11 - Economics, Policy, and Energy Justice

Galen Barbose (LBNL) gave an excellent analysis of what the key components of net billing rates and demand response provide value to the electricity system. Arnulf Jaeger-Waldau (DG JRC) provided a summary of policy changes in the European solar market, with Australia and Netherlands already surpassed 1 kW installed capacity per capita. Prashant Kumar Upadhyay (Solar Energy Corporation of India) highlighted the data-driven approach for RE penetration. He highlighted the approach of inviting bids for supply against monthly profiles. Unique PPA and bid structures allow for procurement of renewables to align with variable load. Mesude Bayrakci Boz (Penn State Hazleton) showed LMPs decrease in most regions and times of year with solar, a few increases due to transmission constraints. Nisitaa Karen Clement Pradeep (Tufts, Best Student Presentation Award Finalist) presented that the installation of PV on houses of worship are correlated with increased growth in their neighborhoods. For Black and Asian demographics specifically, correlation only applies to neighborhoods with high school graduation > 85%, and only for median income < \$40,000 in case of Black demographics. Future work will attempt to establish causation. AC Lemay (Princeton) Political affiliation has an impact on solar adoption, with Republicans in the US, more than Democrat dominant areas, having a strong motivation for electricity cost savings.

Technical Sessions (Afternoon):

Area 3 - Thermophotovoltaics and Photonic Power Converters

The session covered recent research in both thermophotovoltaics and photonic power converters. The invited speaker Iván García (Universidad Politecnica de Madrid) discussed thermal battery storage using molten silicon combined with Ge based TPV cells with a simulated efficiency of 15% with paths to further improvement. The session continued another talk by Iván García with discussions of InGaAs TPV cells with alternating polarity. Bora Kim (UI Urbana-Champaign, Best Student Presentation Award Finalist) discussed the current flow through different heterointerfaces for laser power converters that would operate at 80 K. Though reducing majority carrier barriers the redesigned cell shows a better performance at low temperatures. Gavin P Forcade (University of Ottawa, Best Student Presentation Award Finalist) simulated and analyzed experimental 10-junction photonic power converters at 1520 nm that experimentally demonstrated an efficiency of 45.6 % and over 5 V generated. Upon further modeling, a path towards an achievable 54 % c-band PPC was discussed, taking into account effects such as luminescent coupling. The session ended with an interesting talk from John Geisz (NREL) who demonstrated a method of measuring

junction temperature with transient voltage measurements to isolate voltage losses from temperature from voltage losses from series resistance.

Area 5 - New Characterization Methods and Data Analysis

The combination of talks provided a fascinating overview of how characterization from the micro to the plant-level macro can advance both understanding and manufacturing efficiency of PV technology. Yan Zhu (UNSW) utilized dynamic calibration method on steady state and non-steady state photoluminescence measurements to obtain injection dependent lifetime. The lifetime obtained is then used to predict device performance and fit different recombination mechanisms. Demonstrated the efficacy of the method using a perovskite thin film. Thøger Kari (Danish Technical University) highlighted the issues encountered measuring for utility scale PV module EL using a drone mounted camera that suffers from significant motion blur. Identified several pathways to recover good quality images when using a well calibrated camera. Ganga R. Neupane (NIST) showed beautiful hyperspectral luminescence images showing how the spatial emission from polycrystalline CdSeTe varies over a wide range of wavelengths that correlates to defect emission from the bulk and grain-boundaries. Dirk W Steyn (Colorado School of Mines) demonstrated how a surprising wealth of information can be obtained from resistivity measurements, parameters that can be obtained using this method include contact resistance, carrier lifetime and spreading resistance of p-polysilicon on n-silicon. Gaia Maria N. Javier (UNSW) presented an evaluation of cell efficiency fluctuations using a moving window RF analysis. Johnson Wong (Aurora Solar Technologies) gave fascinating insights on how statistical analysis can identify process tool faults from batch level performance data and provide paths for manufacturing optimization.

Area 7 - System Design, Optimization and Performance

Philippe Holzhey (Adolphe Merkle Institute, Oxford, Best Student Presentation Award Finalist) showed leveraging the flexibility of perovskite PV enables reduction of installation (50%) and transportation costs, making the lifetime (16 years) and efficiencies (17%) requirements lower than commercial rigid silicon PV technologies. Erin M. Tonita (University of Ottawa, Best Student Presentation Award Finalist) presented that while fixed tilt mounting is preferable at lower latitude (<45 degrees N), HSAT becomes competitive at higher latitudes for both monofacial and bifacial silicon panels with similar row to row spacings. Must also consider land-use, module cost and energy density. Rahul Rajeevkumar Urs (Khalifa University) demonstrated the levelized cost of hydrogen depends on albedo of photovoltaic systems, where higher albedo can reduce LCOH for different system configurations. Mandy R. Lewis (University of Ottawa, Best Student Presentation Award Finalist) presented that optimal ground reflector positioning depends on time of day and breakeven point for cost depends on location, but generally right beneath the torque tube is ideal for most cases to enhance energy yield. Nils-Peter Harder (Palaiseau) showed that the placement of albedo enhancement material matters, and tracking/fixed-tilt have different positions for best placement enhancers, where generally the trends are not highly dependent on location (latitude).

Area 8 - Reliability of Perovskite Modules

In this session we learned that there is progress in understanding perovskite degradation, and still a lot of work to do (which the progress will inform). Ingrid L. Repins (NREL) presented that acceleration factors of common test protocols are rather low, these tests are not looking far into the future. Acceleration factor can build confidence for a robust perovskite market, despite the short history. Laxmi Nakka (National University of Singapore, Best Student Presentation Award Finalist) showed that PID can be partially recovered - potential for successful mitigation at cell level; underlying charge transport materials affect the behavior. A mitigation strategy was proposed for helping the pathway for further PSC deployment. Sona Ulicna (NREL) showed revised test plans with lower stresses helps to better understand degradation mechanisms and failure mechanisms Karim MEDJOURI (IPVF) discussed that aging PSCs in outdoor conditions shows metastable behavior - significant loss of performance over 1-2 k h, then recovery through 1 y. This behavior isn't seen in indoor aging, and the mechanism is under study. Lyndsey McMillon-Brown (NASA GRC) presented that encapsulated perovskites (MAPI) are optically and chemically stable for ten months in lower earth orbit (5400 thermal cycles); there is measurable tensile strain. Light soaking had a healing effect reducing strains. Exitonic lifetime was almost tripled.

Area 10 - Solar Resource Uncertainty and Soiling

Vicente Lara Fanego (Solargis) They investigated the robustness of existing soiling estimation and proposed a new parametrization approach to improve the estimation. Ayush Chutani (Michigan Technological University, Best Student Presentation Award Finalist) aimed to quantify the amount of snow on the panels through a newly designed snow sensor validated on a single axis tracking system in order to create a more advanced control system for power generation. Javier Lopez-Lorente (DNV) investigated the spatial variability of albedo and evaluated the accuracy of data provided at different time intervals and from different sources. Conducted rear side irradiation study (3 years hourly average data used), and calculated the accumulated DC energy yield for a period of 3 years. Joshua T Peterson (GroundWork Renewables) showed the errors of co-located pyranometers due to the directional response, up to 7.8 W/m² or an error of approximately 1.8%, and proposed a method to minimize it. Kristen Wagner (Clean Power Research) reported updates on their solar resource dataset and on the site-specific uncertainty, DNI and DHI, and environmental factors. Stephen Wilcox (NREL) presented a method to improve the estimation of uncertainty associated with the radiation measurements

Area 11 - Environmental Sustainability

Zhenni Wu (Forschungszentrum Julich) showed that circular recycling is needed to handle the resource challenges of the TW level PV. We can recycle most components of perovskite cells without loss in efficiency. Challenges remain in loss of thin cell layers such as SnO₂ that must be reapplied. Christopher C Bondoc (Villanova, Best Student Presentation Award Finalist) showed that modules with recycled materials need to have a lifetime of at least 25 years. Novel Recycling methods achieve 95% recycling of Si cells. Annick Antil (Michigan State University) presented that carbon footprint is dominated by electricity use and % renewables in grid, with transportation being the smallest impact. Suggestion for outsourcing production to areas with greener grids, but that's not sustainable, so we need to decarbonize

where the production is. Vasilis Fthenakis (Columbia) discussed reduction of degradation of CdTe modules from 0.3 to 0.1% would increase the module lifetime from 30 to 50 years and reduce the carbon footprint by over 40%. Elaine J. Kupets (NREL) presented that current scientific analysis shows that disposing CdTe modules in landfills does not pose a significant environmental risk based on the toxicity of the metals in the module. Parikhit Sinha Net (First Solar) presented net zero strategies facilitate localization of PV supply chains by enabling manufacturing in resource constrained locations.

Special Session: Renewable Initiatives in Puerto Rico

This special session discussed efforts to increase the utilization and sustainability of solar and renewable energy systems in Puerto Rico. The talks spanned from small farm and community systems to goals for taking Puerto Rico to 100% renewable energy reliance by 2050. Manajit Sengupta (NREL) showed that Puerto Rico currently uses 3% renewable energy resources with all other energy sources (coal, natural gas, petroleum) shipped to the island. There is a need to improve resilience of the power system in Puerto Rico and to transition to more renewable energy sources. Goal of 100% renewable by 2050 and eliminate coal-fired generation by 2028. The PR100 study is at its halfway mark to determine how best to approach reaching these goals. Charles Fortmann (St. John's University) gave a snapshot of what a small scale PV system might be for a sustainable ecosystem in Puerto Rico. An emphasis on ensuring that the systems are integrated into the community and can last over time. In addition to building panel systems for phone charging and computer power, the university led team has also been assisting the community on to use and maintain rooftop solar systems to assist with pumping water for agriculture applications. Finally, Christopher Gregory (ASU) discussed engaging with multiple communities in Puerto Rico to understand how users interact with their energy systems to develop a quantitative model of solar resource and load data from community-wide surveys.

POSTER SESSION AWARD NOMINEES AND WINNERS:

AREA 1: FUNDAMENTALS AND NEW CONCEPTS - 1

Tal Kasher – Winner (Advances in GaAsP Top cells for use in GaAsP/Si Tandems)

V.S.A Chaluvadi (Modal Analysis of GaAs Nanowire Solar Cells for Optimal Device Design)

Tanja Jawinski (Highly crystalline In₂S₃:V thin films epitaxially grown on sapphire substrates: A potential candidate for intermediate band solar cells)

AREA 2: ABSORBER PREPARATION

Damilola Adeleye – Winner (Mitigation of phase separation in high Ga Cu(In, Ga)S₂ absorbers to achieve ~ 1 volt 15.6% power conversion efficiency)

Sinju Thomas (Microscopic origins of performance losses in (Ag, Cu)(In, Ga)Se₂ thin-film solar cells)

Bin Du (Pyrolyzer Assisted Vapor Transport Deposition of Antimony-doped Cadmium Telluride)

AREA 3: III-V COST REDUCTION STRATEGIES

Valentin Daniel – Winner (Characteristics of detachable III-V solar cells grown on porous germanium)

Theresa E. Saenz (Copper Metallization for III-V Solar Cells)

Corentin Jovanneav (Compact and high efficiency micro-CPV module with high wafer utilization rate)

AREA 6: SINGLE JUNCTION AND TANDEM HALIDE PEROVSKITE SOLAR CELLS

Dhurba B. Khadka – Winner (Modulating Efficiency and stability of Methylammonium/Br-Free Perovskite Solar Cells Using Fluoroarene Hydrazine)

Neetesh Kumar (Development of 3D/2D Perovskite Solar Cells using a Spray-Based Sequential Deposition)

Hadi Afshari (Stable High Temperature Operation in Metal Halide Perovskite Solar Cells)

AREA 9: POWER ELECTRONICS AND GRID INTEGRATION - 1

Rochid Darbali Zamora – Winner (Parametric Analysis of Photovoltaic Inverters Under Balanced and Unbalanced Voltage Phase Angle Jump Conditions)

Thunchanok Kaewnukultrn (Abnormal Responses of Residential Smart Photovoltaic Inverters to Cyberattacks)

Rasel Mahmud (Experimental analysis of distribution network voltage regulation using smart inverters)

AREA 11: ECONOMICS, POLICY, AND ENERGY JUSTICE AND TOWARDS 100% RENEWABLE ELECTRICITY

Pablo Mendez-Curbelo – Winner (Energy Injustice Metrics for Puerto Rico)

Mariela Colombo (Oxy-fuel combustion: A threat or an opportunity for solar)

Tadatoshi Takahashi (Supply Side Management with Agrivoltaics: Feasibility Study of Modeling Methodologies of Solar PV and Crop Response)