PROJECT NAME: Gaining Fundamental Understanding of Critical Failure Modes and Degradation Mechanisms in Fielded Photovoltaic Modules via Multiscale Characterization

Last 5 digits of project number: **09347**
Principal Investigator (PI): **Kristopher O. Davis**
Lead Organization: **University of Central Florida**
PI Email: kristopher.davis@ucf.edu

BACKGROUND and OVERVIEW

- Develop multiscale characterization methods and apply them to field exposed photovoltaic (PV) modules
- Link observed performance degradation to specific loss mechanisms (i.e., optical, recombination, resistive, selectivity) to root causes
- Relate these findings to accelerated aging test results and identify areas of high priority for PV reliability and durability research

METHODS

- Large-scale analysis of time-series power (P_{MP}) and current-voltage (*I-V*) data
- Field-based UV fluorescence (UVF) imaging, photoluminescence (PL), and non-contact electroluminescence (EL) imaging
- Comprehensive indoor module characterization
- Destructive testing and materials characterization
- Statistical, machine, and deep learning of these datasets to extract key features of the data and build multimodal models

KEY MILESTONES

- Analyze and publish time-series performance data from at least 15 PV systems (completed)
- Perform a quantitative comparison of field-based and lab-based UVF images in terms of the observed defects (images from > 100 modules compared with 150 as the goal)
- Retrieve and perform destructive characterization on at least 10 different module types (six completed, four in progress)
- Submit at least ten peer-reviewed journal articles (six published/submitted, four in preparation)

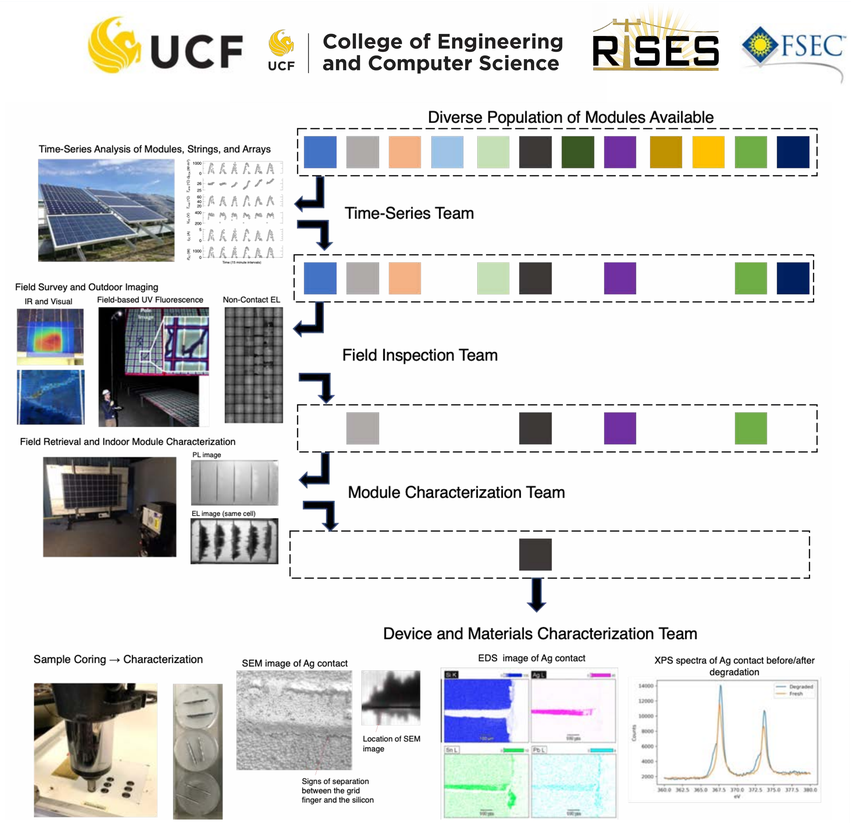
CONCLUSION

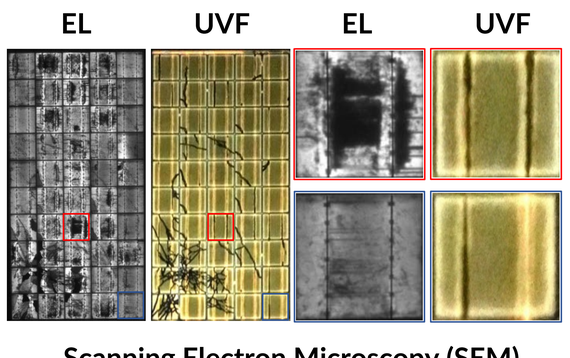
- Helped identify key defects responsible for significant power loss in field exposed silicon heterojunction PV modules
- Identified multiple examples of significant contact corrosion in fielded silicon aluminum back surface field (Al-BSF) PV modules
- Developed new analysis tools for a variety of measurement techniques
- Developed and implemented FAIRification methods for PV data

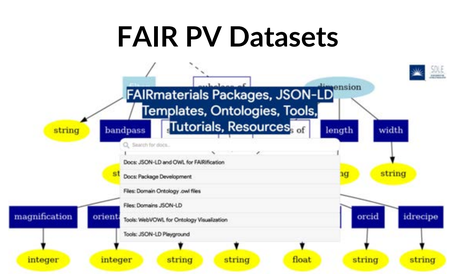
PHOTOVOLTAICS TRACK

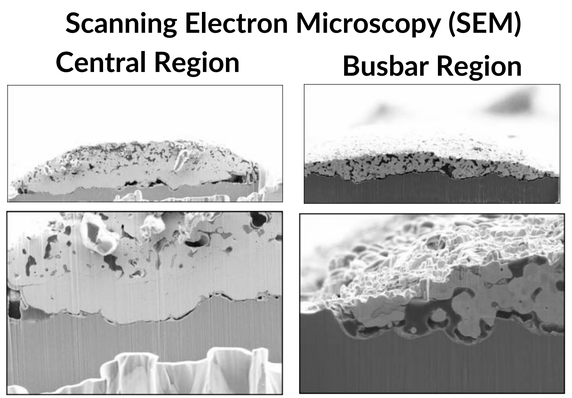
Multiscale characterization and advanced data analysis can help **determine the root cause of durability defects** in PV modules in a rigorous, but time-efficient manner.

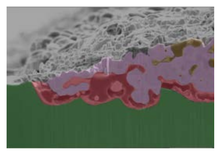
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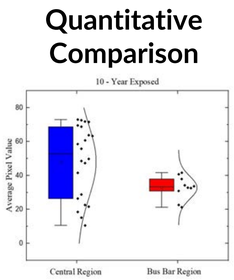












Additional project contributors: Liggett M, Babu B, Oltjen WC, Yu X, Yao AD, Matam M, Gabor AM, Knodle PJ, Neal CJ, Barcelos E, Seal S, Seigneur HP, Bruckman LS, French RH, Li M, Colvin DJ, Davis KO

PROJECT NAME: Photonic Curing of Printed Copper Contacts for High Efficiency and Low Cost Silicon Heterojunctions

Last 5 digits of project number: **10494**
Principal Investigator (PI): **Kristopher O. Davis**
Lead Organization: **University of Central Florida**
PI Email: kristopher.davis@ucf.edu

PHOTOVOLTAICS TRACK

Printable copper metallization for silicon heterojunctions enabled by photonic curing using a **scalable laser technology**

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BACKGROUND and OVERVIEW

Develop a copper (Cu) metallization process for silicon heterojunction (SHJ) photovoltaic (PV) cells that is:

- Scalable (i.e., no physical vapor deposition, plating, or masking steps)
- Minimizes optical shading losses
- Minimizes voltage drop caused by series resistance (R_S) losses
- Does not negatively impact the surface passivation quality or the durability of SHJ cells

METHODS

- In-line printing of high viscosity Cu pastes
- In-line laser sintering using carbon dioxide (CO_2) lasers, a highly scalable laser technology
- Comprehensive and detailed characterization of the resistive losses associated with the Cu metallization, as well as any damage to the underlying passivation layer leading to increased recombination losses
- Materials characterization will also be used to determine process-structure-property relationships
- Previously demonstrated this approach can be used with silver (Ag) metallization on SHJ PV cells

KEY MILESTONES

- Cu bulk line resistivity less than 5 µOhm-cm
- Cu/ITO contact resistivity less than 10 mOhm-cm^2
- Cu finger line width less than 40 µm
- Cell efficiency with the Cu metallization of at least 22.0%
- Submit at least three peer-reviewed journal articles
- Create a commercialization plan and receive feedback from at least five advisory board members
- Host a demonstration event at the EnergyWhiz Olympics in Cocoa, Florida

CONCLUSION

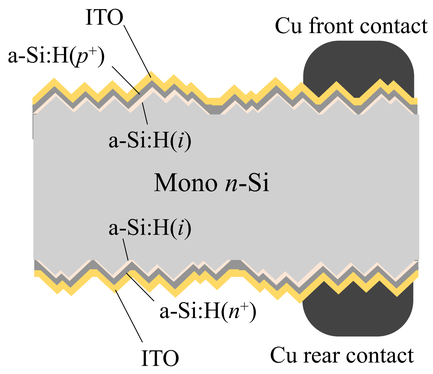
If successful, this project will introduce an enabling technology that can:

- Increase SHJ cell efficiencies and lower manufacturing costs with potential applicability to other absorbers
- Reduce price volatility and vulnerability in the PV supply chain
- Help train and education the future U.S. PV workforce

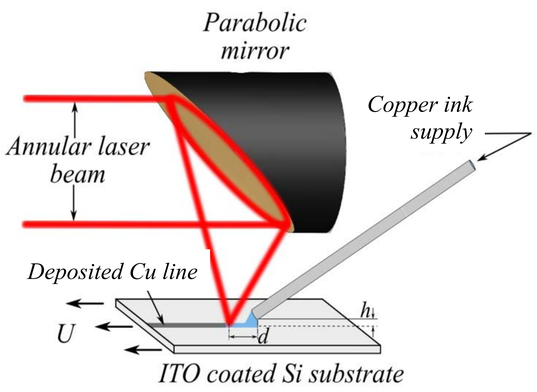
UCF

UNIVERSITY OF DELAWARE

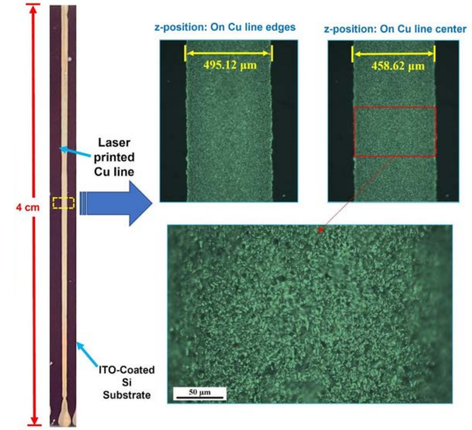
Silicon Heterojunction (SHJ) Photovoltaic (PV) Cell



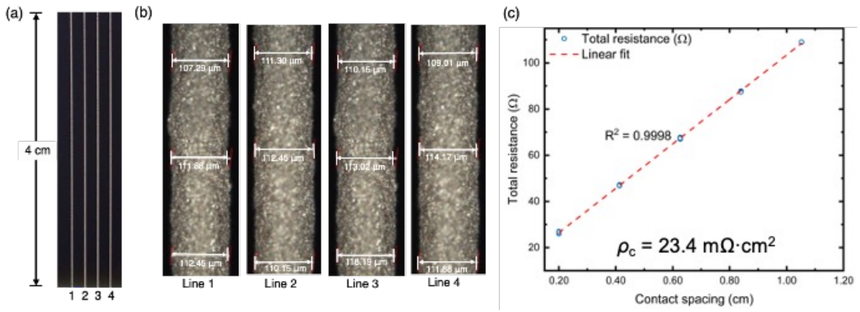
Printing and Laser Sintering Approach

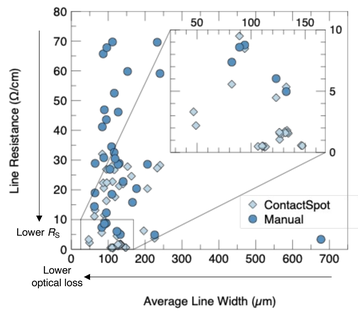


Preliminary Results: Cu Printing

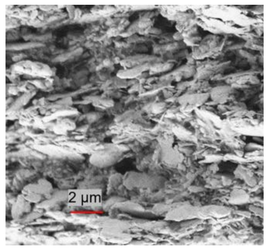


Prior Results: Ag Printing



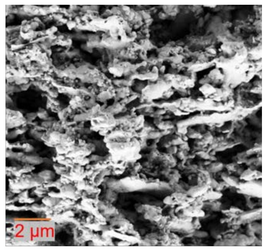


Poorly Sintered Ag Contact



$\rho_b \cong 24.5\ \mu\Omega \cdot cm$

Well Sintered Ag Contact



$\rho_b \cong 5.5\ \mu\Omega \cdot cm$

Cross-Sectional Scanning Electron Microscopy (SEM) Images

Additional project contributors: Aravinda Kar, Ranganathan Kumar, Ujjwal Das

PROJECT NAME: Parallel-Processed Multi-junction Perovskite Solar Cells

Last 5 digits of project number: **09521**
Principal Investigator (PI): **David P. Fenning**
Lead Organization: University of California, San Diego
PI Email: **dfenning@ucsd.edu**

PHOTOVOLTAICS TRACK

Lamination of perovskite solar cells **relaxes process constraints**, achieves 21% efficiency, and provides a **parallelized pathway to tandems**

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BACKGROUND and OVERVIEW

- Perovskites are sensitive to harsh processing conditions, and tradeoffs are made to deposit the transport layer and contact atop the perovskite
- By laminating two half-cells at the perovskite layer, all other device layers can be deposited without exposing perovskite to harsh processing conditions (*e.g.* high temperature, sputtering, etc.)

METHODS

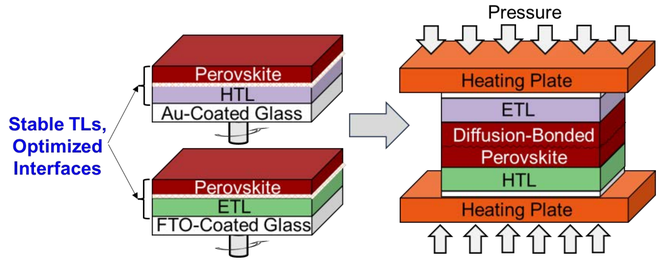
- Hot-pressing lamination enables device architectures otherwise out-of-reach due to constraints of perovskite process tolerance
- Lamination temperature, pressure, and time used to control laminated area and interface strength
- Explored B-site alloying in an effort to produce ultra-low bandgap perovskites for tandems

KEY MILESTONES

- Semi-transparent ~1.6 eV “wide gap” cell achieves 21.0% PCE
- Using inorganic CTLs in lamination achieves greater toughness after TC50 than *pristine* state-of-the-art architectures
- Demonstrated applicability to multiple compositions and thin films deposited by meniscus coating
- Goal to achieve laminated perovskite-perovskite tandem cell efficiency >20% PCE

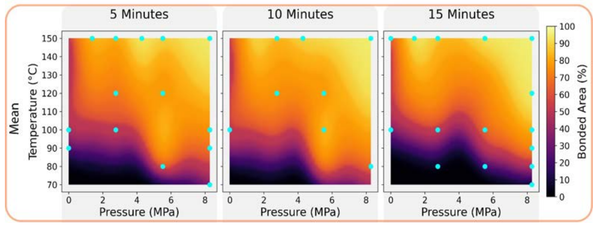
CONCLUSION

- 21% efficient laminated perovskite solar cells with ETL/HTL otherwise impossible without lamination
- 2 manuscripts published[1,2]
- Opportunities to relax process and environmental constraints in the manufacture of perovskite solar
- Continued focus will be on ISOS-L-2/3 stability tests of CTL combinations enabled by lamination and improving tandem efficiency



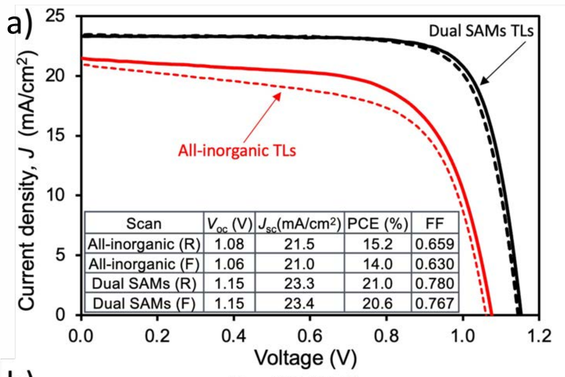
- Parallel processing of two half cell stacks to overcome chemical and processing limitations
- Lamination allows improved interface tuning and enables novel cell architectures

Gaussian Process Model of Percent Bonded Area

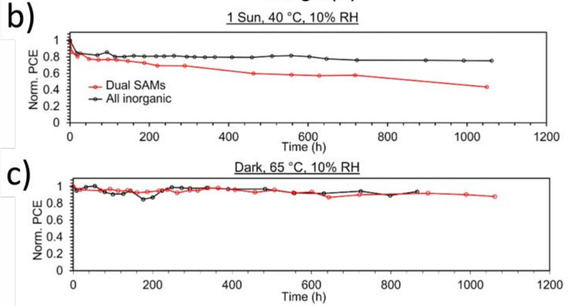


- Used machine learning to build a model of the lamination parameter space

Laminated Perovskite Solar Cell

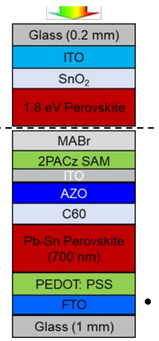


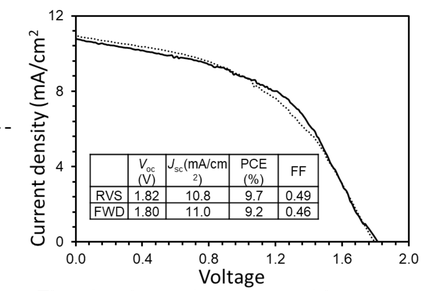
Scan	V_{oc} (V)	J_{sc}(mA/cm²)	PCE (%)	FF
All-inorganic (R)	1.08	21.5	15.2	0.659
All-inorganic (F)	1.06	21.0	14.0	0.630
Dual SAMs (R)	1.15	23.3	21.0	0.780
Dual SAMs (F)	1.15	23.4	20.6	0.767



- The highest reported PCE for any laminated PSC encapsulated between glass substrates.[1]

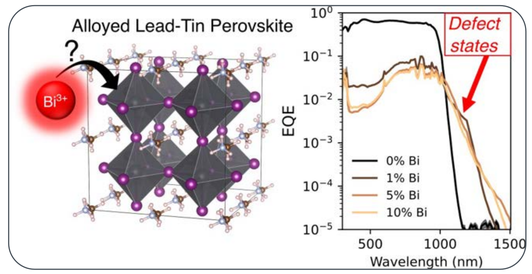
Laminated All-Perovskite Tandem





	V_{oc} (V)	J_{sc}(mA/cm²)	PCE (%)	FF
RVS	1.82	10.8	9.7	0.49
FWD	1.80	11.0	9.2	0.46

- First laminated all-perovskite tandems show promise, most losses coming from the recombination layer



- Bismuth in low-gap Pb:Sn introduced midgap defect states. Results published in ACS *Advanced Energy Materials*[2]

Additional project contributors: University of Michigan: Prof. Neil P. Dasgupta (co-PI), Clare L. Lanaghan, Dr. Md Aslam Uddin, Dr. Srinivas Yadavalli, UCSD: Jack R. Palmer

Photovoltaic Plant Predictive Maintenance Optimization under Uncertainties Using Probabilistic Information

Last 5 digits of project number: **09354**
Principal Investigator (PI): **Hao Yan**
Lead Organization: Arizona State University
PI Email: haoyan@asu.edu

PHOTOVOLTAICS TRACK

Propose: Multi-modal Generative Model and Reinforcement learning for time series prediction, event predict ion and maintenance policy optimization

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BACKGROUND and OVERVIEW

- ❑ Working data
  - ➢ Solar panel output & energy monitoring
  - ➢ Weather
- ❑ Objective
  - ➢ Failure detection & prediction
  - ➢ Maintenance schedule
- ❑ Challenge
  - ➢ High dimensional data & complex structure
  - ➢ Interdisciplinary collaboration

METHODS

- ❑ Anomaly & fault clustering:
  - ➢ Tensor decomposition & clustering
  - ➢ Manifold learning
- ❑ Failure detection and perdiction
  - ➢ Bayesian dynamic network (BDN)
  - ➢ CNN based multi-label fault detection
  - ➢ Tensor decomposition & prediction
- ❑ Predictive Maintenance Optimization
  - ➢ Multi-Modal learning for solar system simulation and event prediction
  - ➢ Reinforcement learning for maintenance policy

KEY MILESTONES

- ❑ In anomaly clustering, tensor decomposition achieved an accuracy of 0.64 and F1 score 0.484
- ❑ In fault prediction, SDE achieved an accuracy of 80.1%; CNN achieved F1 score of 0.753; Tensor method achieved F1 score>0.7 in 2 weeks scope, and mean RUL difference<3.
- ❑ In multi-modal learning, we achieve 7-day fault prediction up to 0.8(f1) and accurate sensor and event prediction

CONCLUSION

- ❑ Handle large-scale multi-modality datasets for real-time anomaly detection
- ❑ Integrate optimization and RL for maintenance optimization
- ❑ Public GitHub Repo for demo
- ❑ Demonstration with the large-scale real-time dataset from two operating power plants

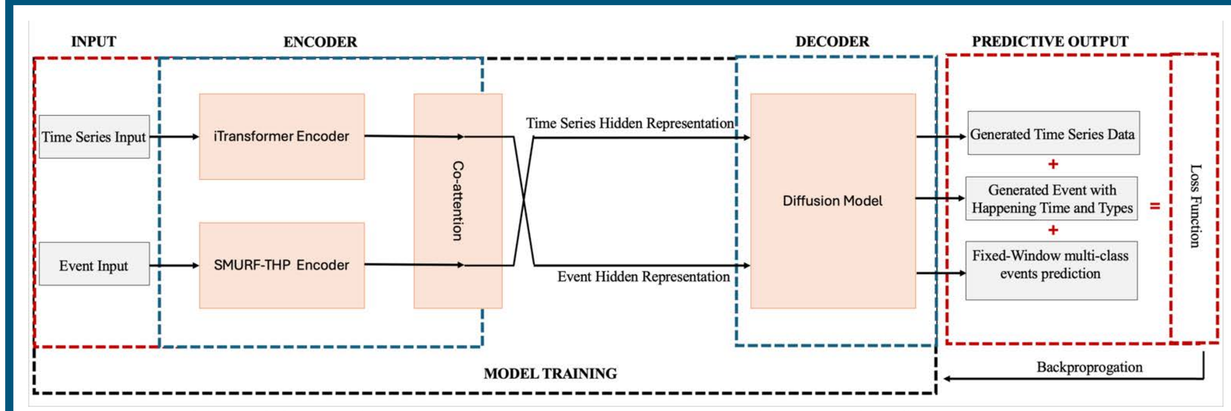


Figure 1: Multi-Modal Learning for Solar System Generation with Encoder (iTransformer, SMURF-THP), and diffusion model-based Decoder. Inputs: time series window with 3 months length; 10-event sequence including start time and event type mark.



Figure 3: Proposed Predictive Maintenance Policy Derived from the Reliability Curve

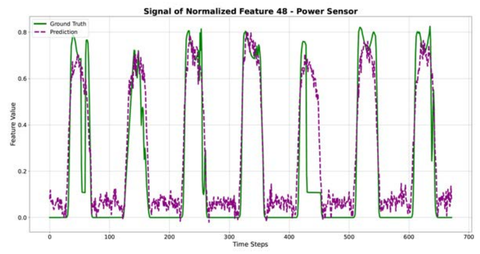


Figure 2: Time Series Generation Performance

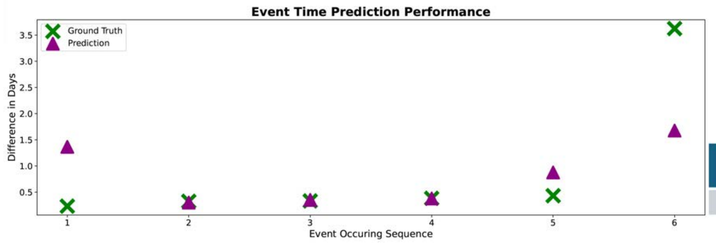


Figure 3: Event Occurrence Time Prediction

Fault Code	18	19	36	40	42	53	55	67	86	95	100
f1 score	0.62	0.67	0.61	0.58	0.58	0.81	0.65	0.58	0.61	0.61	0.62

Table 1: f1 score of Multi-Label Fault Prediction in 7-days

Additional project contributors: Jiayu Huang, Jiuyun Hu, Nan Xu, Qihang Xu, Co-PI Yongming Liu

PROJECT NAME: High-speed Solution Printing and Photonic Curing of Transparent Electrodes on Plastics

Last 5 digits of project number: **09518**
Principal Investigator (PI): **Julia Hsu**
Lead Organization: The University of Texas at Dallas
PI Email: **jwhsu@utdallas.edu**

PHOTOVOLTAICS TRACK

Demonstrated high-performance **transparent electrode** production on plastic substrates at 1.5 m/min using **photonic curing**, with projected processing speeds *exceeding 10 m/min*

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BACKGROUND and OVERVIEW

- Roll-to-roll manufacturing has the potential to enable low-cost, high-volume production of perovskite solar cells
- Commercialization of perovskite solar cells is currently limited by the high cost of vacuum-deposited and thermally annealed transparent conducting electrodes
- Solution printing and photonic curing can produce transparent conducting electrodes on plastics with higher speed and lower cost
- Target to increase web speed from 1 m/min for vacuum processing, to 10 m/min
- Hybrid transparent conducting electrodes benefit from each material's advantages.

METHODS

- Develop solution printing and photonic curing processes to fabricate hybrid transparent conducting electrodes of Ag metal bus lines, Ag nanowires, and IZO on PET – evaluate with R_{sh}, T_{avg} and σ_{rms}
- Fabricate perovskite solar cells on top of the hybrid transparent conducting electrodes and compare them to commercially available PET/ITO products
- Scale up blade-coating and photonic curing processing area and speed to enable lowest-cost manufacturing
- Scale up devices from lab scale to mini-module

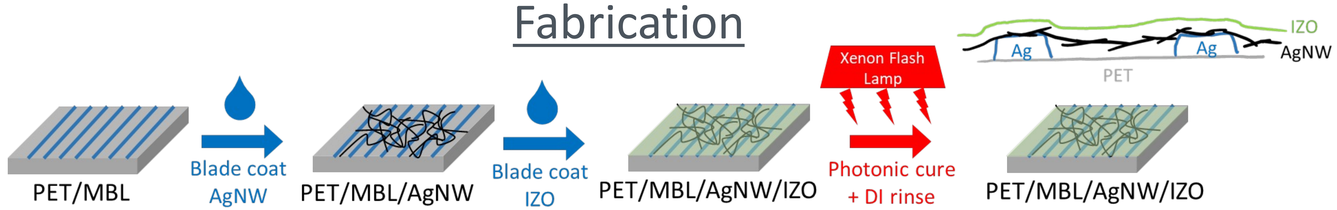
KEY MILESTONES

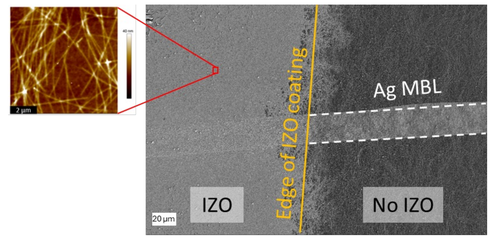
- Fabricated a hybrid transparent conducting electrode with R_{sh} = 11 Ω/□, T_{avg} = 81%, and σ_{rms} = 4.3 nm
- Achieved 10% average efficiency on perovskite solar cells made with the hybrid transparent conducting electrode
- Scaled up blade-coating and photonic curing process to 7 in x 8 in areas
- Gravure-printed hybrid transparent conducting electrodes can achieve 60 m/min – additional development is needed
- Developed a single-pulse photonic curing process with demonstrated webspeed of 1.6 m/min that is projected to speeds exceeding 10 m/min

CONCLUSION

- Demonstrated that solution printing and photonic curing can be applied in a roll-to-roll setup to achieve high-speed processing of high-performance transparent conducting electrodes on plastic
- Further development is required to demonstrate > 10 m/min processing speed
- Further development is required to make large-area perovskite solar cell devices

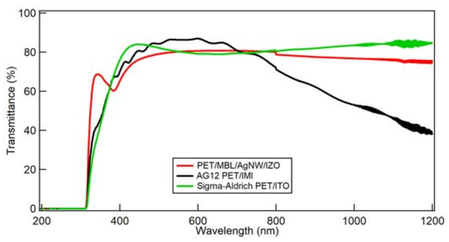
Fabrication



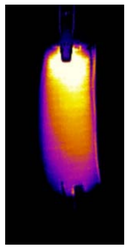


Properties

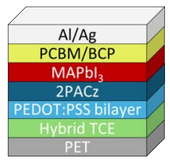
Sample	Vendor	T_{avg} (%)	R_{sh} (Ω/sq)	σ_{rms} (nm)
PET/MBL/AgNW/IZO	Hsu lab	81 ± 0.4	11 ± 0.5	4.3 ± 0.4
AG12 PET/IMI	Optical Filters	83 ± 0.2	10 ± 0.2	3.5 ± 1.2
PET/ITO	Sigma-Aldrich	81 ± 0.1	72 ± 8.2	1.8 ± 1.2

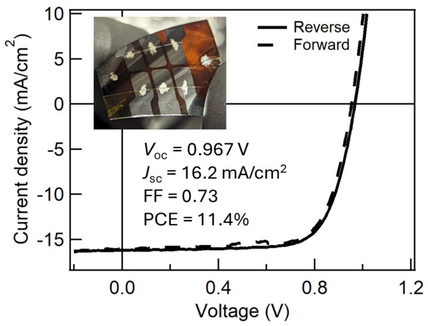




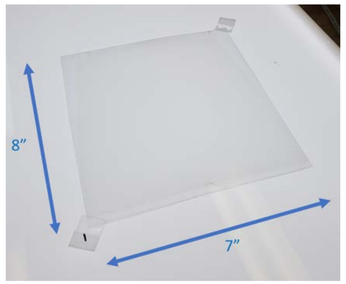


Perovskite Solar Cell Performance





Scalability





Additional project contributors: Robert Piper, Justin Bonner, Bishal Bhandari, Weijie Xu, Energy Materials Corporation, PulseForge

PROJECT NAME: Parallel-Processed Multi-junction Perovskite Solar Cells

Last 5 digits of project number: **09521**
Principal Investigator (PI): **David P. Fenning**
Lead Organization: University of California, San Diego
PI Email: **dfenning@ucsd.edu**

PHOTOVOLTAICS TRACK

Lamination of perovskite solar cells **relaxes process constraints**, achieves 21% efficiency, and provides a **parallelized pathway to tandems**

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BACKGROUND and OVERVIEW

- Perovskites are sensitive to harsh processing conditions, and tradeoffs are made to deposit the transport layer and contact atop the perovskite
- By laminating two half-cells at the perovskite layer, all other device layers can be deposited without exposing perovskite to harsh processing conditions (*e.g.* high temperature, sputtering, etc.)

METHODS

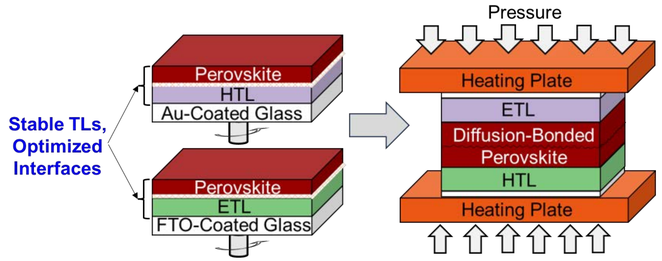
- Hot-pressing lamination enables device architectures otherwise out-of-reach due to constraints of perovskite process tolerance
- Lamination temperature, pressure, and time used to control laminated area and interface strength
- Explored B-site alloying in an effort to produce ultra-low bandgap perovskites for tandems

KEY MILESTONES

- Semi-transparent ~1.6 eV “wide gap” cell achieves 21.0% PCE
- Using inorganic CTLs in lamination achieves greater toughness after TC50 than *pristine* state-of-the-art architectures
- Demonstrated applicability to multiple compositions and thin films deposited by meniscus coating
- Goal to achieve laminated perovskite-perovskite tandem cell efficiency >20% PCE

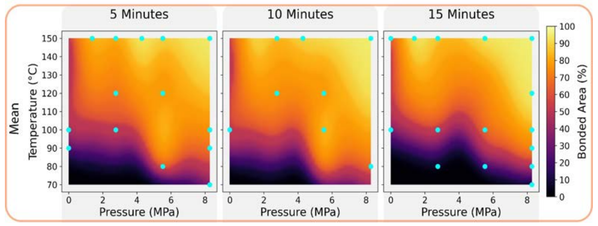
CONCLUSION

- 21% efficient laminated perovskite solar cells with ETL/HTL otherwise impossible without lamination
- 2 manuscripts published[1,2]
- Opportunities to relax process and environmental constraints in the manufacture of perovskite solar
- Continued focus will be on ISOS-L-2/3 stability tests of CTL combinations enabled by lamination and improving tandem efficiency



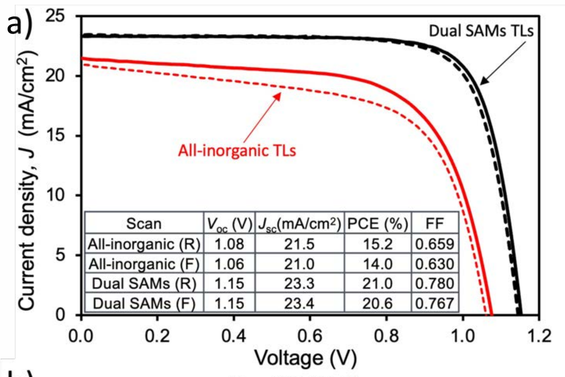
- Parallel processing of two half cell stacks to overcome chemical and processing limitations
- Lamination allows improved interface tuning and enables novel cell architectures

Gaussian Process Model of Percent Bonded Area

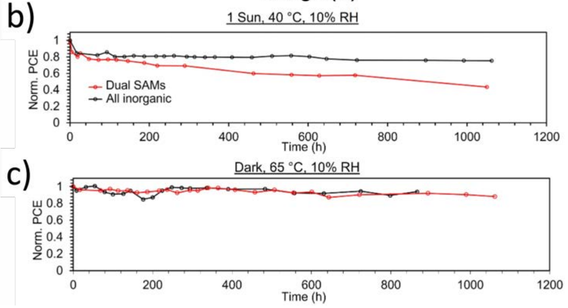


- Used machine learning to build a model of the lamination parameter space

Laminated Perovskite Solar Cell

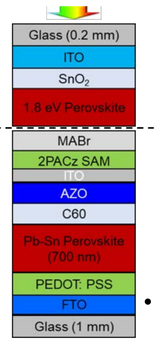


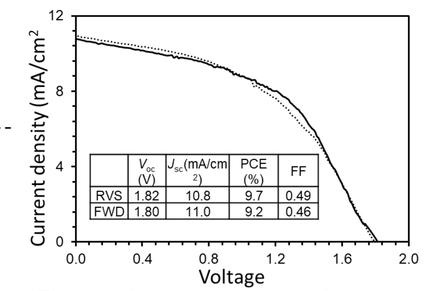
Scan	V_{oc} (V)	J_{sc}(mA/cm²)	PCE (%)	FF
All-inorganic (R)	1.08	21.5	15.2	0.659
All-inorganic (F)	1.06	21.0	14.0	0.630
Dual SAMs (R)	1.15	23.3	21.0	0.780
Dual SAMs (F)	1.15	23.4	20.6	0.767



- The highest reported PCE for any laminated PSC encapsulated between glass substrates.[1]

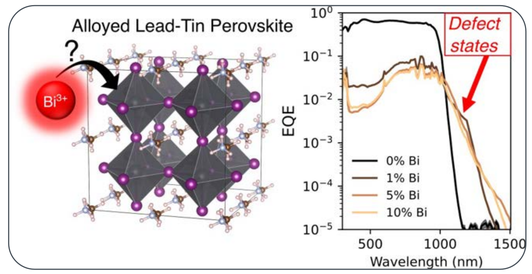
Laminated All-Perovskite Tandem





	V_{oc} (V)	J_{sc}(mA/cm²)	PCE (%)	FF
RVS	1.82	10.8	9.7	0.49
FWD	1.80	11.0	9.2	0.46

- First laminated all-perovskite tandems show promise, most losses coming from the recombination layer



- Bismuth in low-gap Pb:Sn introduced midgap defect states. Results published in ACS *Advanced Energy Materials*[2]

Additional project contributors: University of Michigan: Prof. Neil P. Dasgupta (co-PI), Clare L. Lanaghan, Dr. Md Aslam Uddin, Dr. Srinivas Yadavalli, UCSD: Jack R. Palmer

PROJECT NAME: Scalable charge transport layers based on electrically conductive conjugated polymers to achieve high efficiency and long-term durability in perovskite solar cells

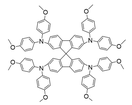
Last 5 digits of project number: 09524
Principal Investigator (PI): **Juan-Pablo Correa-Baena**
Lead Organization: Georgia Institute of Technology
PI Email: **jpcorrea@gatech.edu**

BACKGROUND and OVERVIEW

- ❑ Hole transport layer (HTL) play a crucial role in organic-inorganic hybrid perovskite solar cell (PSC) functionality as well as a limiting factor toward high-efficiency and long-term stability

Limiting factors:

- Interfacial degradation between perovskites and HTLs
- Moisture & oxygen induced degradation
- Ionic migration



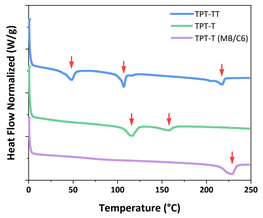
Spiro-OMeTAD
2,2',7,7'-Tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene

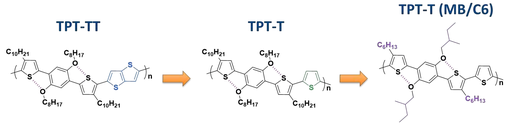


PTAA
Poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine

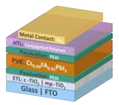
METHODS

- Synthesis of novel HTLs and ETLs





PSC Device Fabrication (n-i-p)



- Solution processed in glovebox (N_2)
- CP Concentration: 20mg/mL in chlorobenzene

KEY MILESTONES

- 20% efficiency with new HTLs and ETLs
- Long term stability at 85°C for 1000 hr
- Feasibility analysis based on industry input
- 3 publications

CONCLUSION

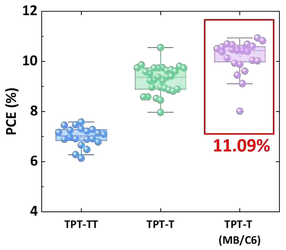
- Thermally stably HTLs and ETLs are crucial for long-term device stability
- The project has produced both HTLs that are more stable than PTAA and Spiro under thermal stress.
- New work in ETL synthesis promises to improve thermal stability.

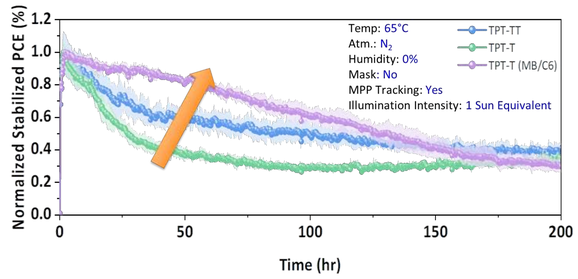
PHOTOVOLTAICS TRACK

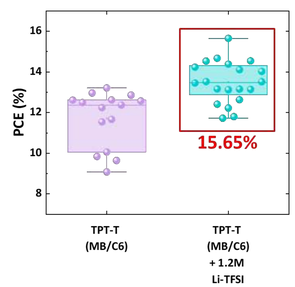
New Conjugated Polymers and Small Molecules **Improve Thermal Stability** of Perovskite Solar Cells

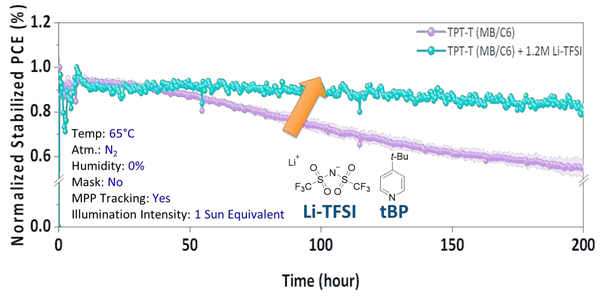
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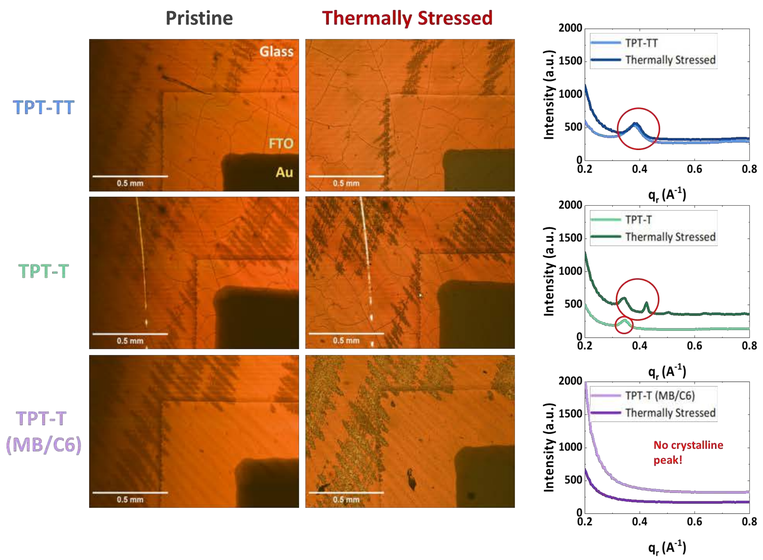
Hole transport layers

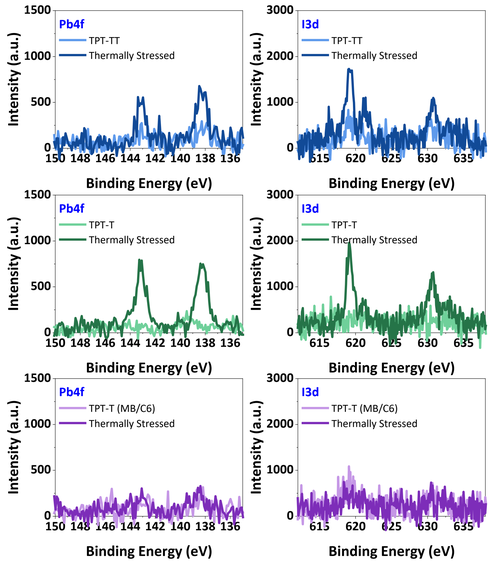




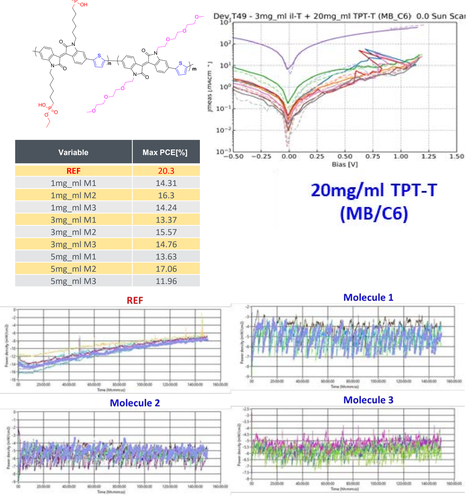








Electron transport layers



Additional project contributors: Prof. John Reynolds, Dr. Carlo Perini, Dr. Sina Saburi, Dr. Justine Wagner, Sanggyun Kim

PROJECT NAME: Mitigating Performance Degrading Defects in Ga-Doped Czochralski Si Solar Cells with Data-Informed Modeling

Last 5 digits of project number: **11156**
Principal Investigator (PI): **Sumit Agarwal**
Lead Organization: **Colorado School of Mines**
PI Email: **sagarwal@mines.edu**

BACKGROUND and OVERVIEW

- Field degradation in Ga-doped Czochralski Si solar cells due to light and elevated temperature induced degradation (LeTID) leads to efficiency loss, and field regeneration can take ~25 years.
- This project aims to minimize LeTID by developing predictive physics-informed neural networks (PINNs) that are trained by high-throughput experiments and atomistic simulations.

METHODS

- Experimentally, we will use carrier lifetime measurements and electron paramagnetic resonance spectroscopy to establish the connection between the extent of LeTID and wafer pre-annealing conditions with different levels of hydrogen injection from SiN_x
- Generate and train a neural network that translates the vacancy cluster distribution predicted by the PINN model into an experimentally measurable lifetime. We will test this model by predicting lifetime for different annealing conditions.

KEY MILESTONES

- Experimentally establish the global relation between wafer processing and the extent of LeTID.
- Establish a predictive modelling framework that connects the thermal annealing and hydrogen injection to carrier lifetime.
- Use the PINN model to predict the most promising industrially-viable technology for LeTID suppression in Ga-doped Cz Si, and verify that in 90% of the experiments, LeTID is reduced by at least 50%.
- Anticipated start date of the project is May 1, 2024

CONCLUSION

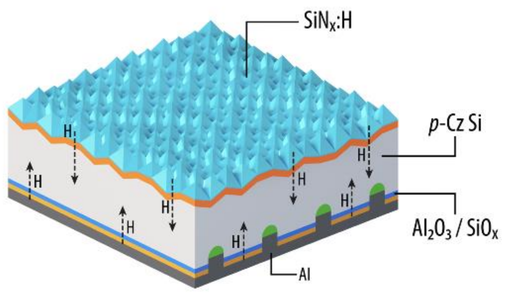
- Establish a PINN framework that connects thermal annealing and hydrogen injection during cell processing to carrier lifetime. Experimentally, predict the most promising industrially-viable technology for LeTID suppression in Ga-doped Cz Si.
- Mitigation of LeTID during manufacturing prior to deployment will improve field reliability of Ga-doped passivated emitter rear contact (PERC) modules during their 25-year lifetime.

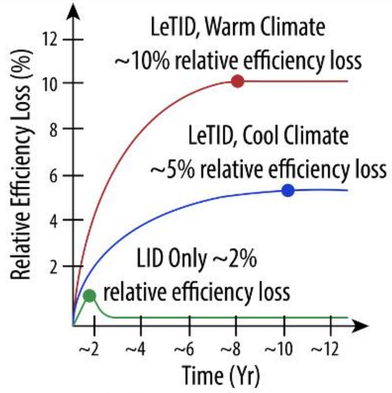
PHOTOVOLTAICS TRACK

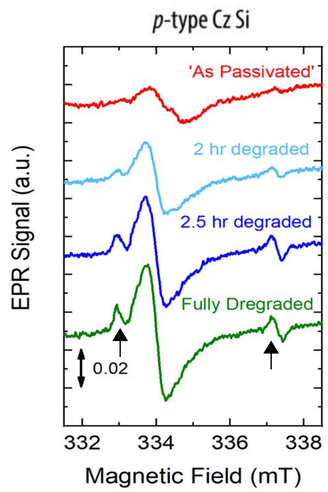
Predict and mitigate light and elevated temperature induced degradation in Ga-doped Czochralski Si solar cells by developing physics-informed neural networks trained by high-throughput experiments and atomistic simulations

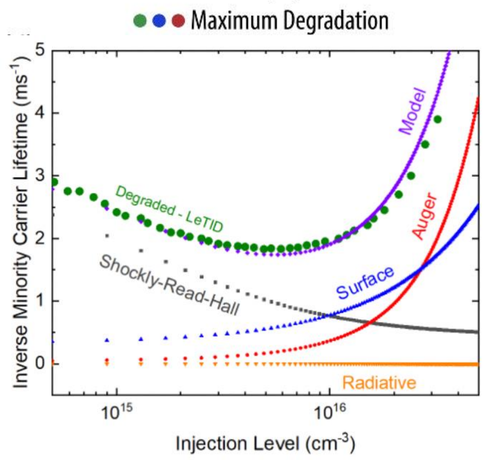
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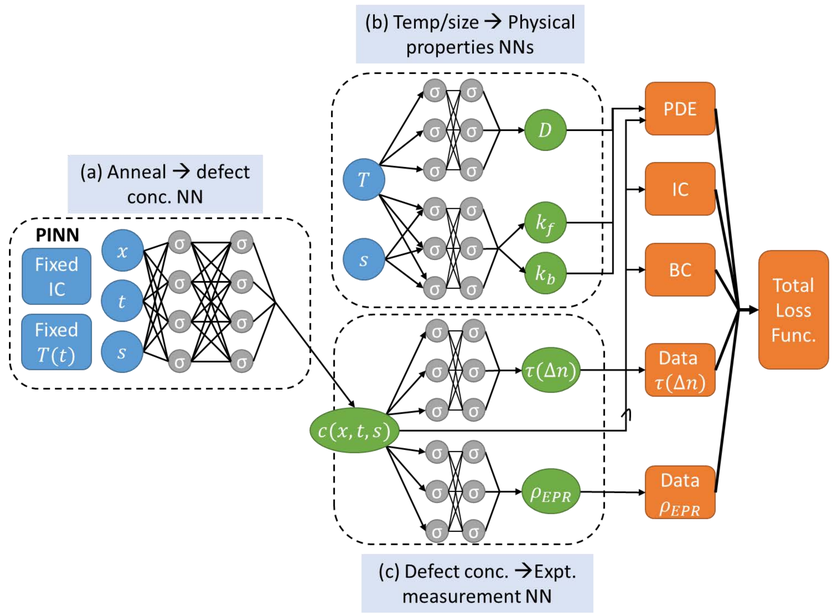
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Additional project contributors: Talid Sinno (University of Pennsylvania); Lu Lu (Yale University); Paul Stradins (National Renewable Energy Lab)

PROJECT NAME: CdTe Photovoltaics Accelerator and Consortium Management

Last 5 digits of project number: **37989**
Principal Investigator (PI): **Lorelle Mansfield**
Lead Organization: **NREL**
PI Email: lorelle.mansfield@nrel.gov

BACKGROUND and OVERVIEW

- Cadmium telluride (CdTe) is a leading, rapidly scaling PV technology built on U.S. innovations.
- CTAC is a CdTe consortium that brings together companies and research centers to work on the most important challenges in U.S. CdTe PV production.
- The goal is to accelerate activity and collaboration to increase CdTe module efficiencies and deployment while decreasing manufacturing costs and maintaining durability.

METHODS

- NREL selected consortium leadership through a competitive request for proposals.
- University of Toledo convenes CTAC to work on high-impact topics in CdTe including:
    - Next generation absorbers
    - Front interface
    - Back interface
    - New markets
    - Road mapping
    - Supply chain analysis

KEY MILESTONES

- Energy Secretary Granholm announced CTAC leadership entities on August 1, 2022: University of Toledo, Colorado State University, First Solar, Sivananthan Laboratories, and Toledo Solar.
- First Solar attained a new world record arsenic-doped CdSeTe solar cell with 22.3% efficiency.
- CTAC's CdTe PV Technology Roadmap predicts expanding U.S. production to 100 GW/year.

CONCLUSION

- CTAC leadership and NREL are closely collaborating to share knowledge, reduce duplicated effort, and accelerate tech to market.
- The CdTe PV Technology Roadmap outlines a research path to even higher CdTe efficiency and market penetration.
- The Supply Chain Report confirms that tellurium supply will not limit CdTe deployment.

PHOTOVOLTAICS TRACK

Cadmium Telluride Accelerator Consortium (CTAC) **connects research** and **industry** to expedite **CdTe** photovoltaic technology **development** to market **deployment**

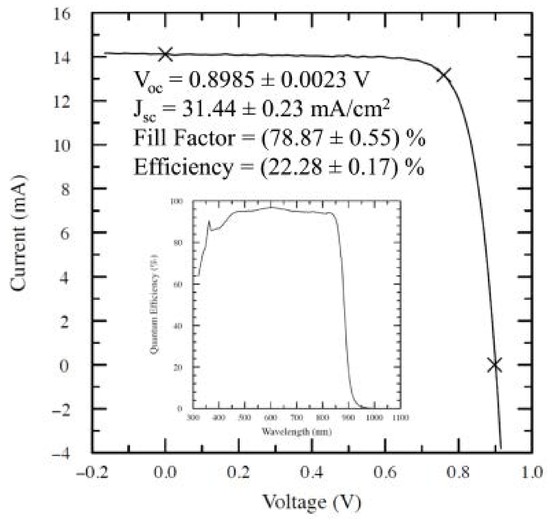
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CTAC Cadmium Telluride Accelerator Consortium
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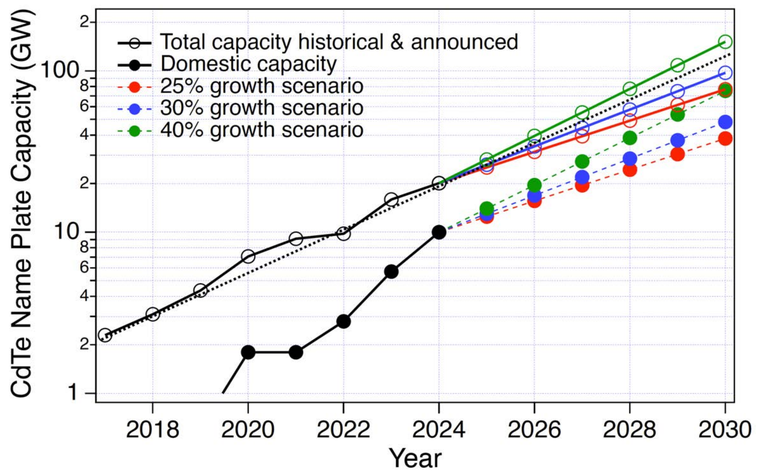
NREL

Take a picture to **download** the **full paper**

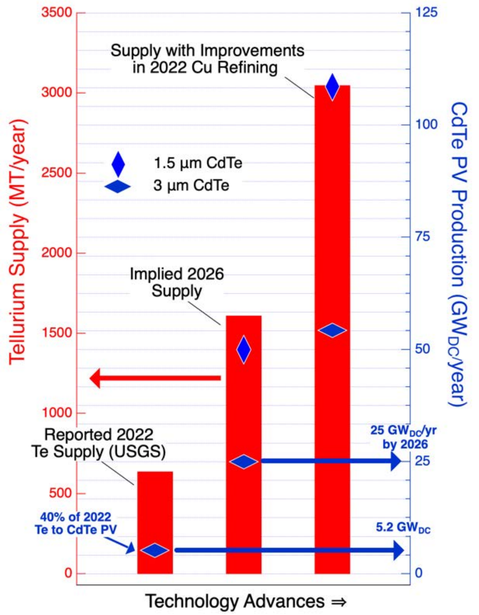
THE UNIVERSITY OF TOLEDO 1872 — WRIGHT CENTER for PHOTOVOLTAICS INNOVATION AND COMMERCIALIZATION — First Solar — Colorado State University — Sivananthan Laboratories — TOLEDO SOLAR



Current–voltage and quantum efficiency for world record 22.3% efficiency First Solar cell. DOI: 10.1109/JPHOTOV.2023.3282581



Historical and future growth of CdTe PV industry with different growth scenarios on the global and domestic scales. Black dashed line is a historical CAGR of 37%.



Reported, implied, and projected tellurium supply data (left axis) and corresponding annual production rare for CdTe PV (right axis).

Key project contributors: Michael Heben (CTAC Director), James Sites, Gang Xiong, Dingyuan Liu, Ramesh Dhere, Alex Dmitriev, Matthew Reese, Casey Schorzman, Bill Peters, Meghan Hughes, and others.

PROJECT NAME: CdTe Photovoltaics Accelerator and Consortium Management

Last 5 digits of project number: **37989**
Principal Investigator (PI): **Lorelle Mansfield**
Lead Organization: **NREL**
PI Email: lorelle.mansfield@nrel.gov

BACKGROUND and OVERVIEW

- Cadmium telluride (CdTe) is a leading, rapidly scaling PV technology built on U.S. innovations.
- CdTe requires continuous innovation to increase module efficiencies and decrease manufacturing costs while maintaining durability.
- The core CTAC institutions engage new partners in areas of strategic importance.

METHODS

- CTAC identifies areas of interest and works with NREL and SETO to craft requests for proposals.
- NREL periodically releases RFPs on SAM.gov.
- Proposals are selected based on merit criteria defined in the RFPs including technical merit.
- Winning proposals are awarded firm fixed price contracts with NREL.
- Awardees are integrated into CTAC operations.

KEY MILESTONES

- Two solicitations for external projects have been administered on behalf of CTAC.
- 13 projects have been awarded in four topic areas with an average value of $300 k and average duration of 26 months.
- The third RFP for CdTe-related projects is open now!

CONCLUSION

- CTAC leadership and NREL have developed closer collaborations to share knowledge, reduce duplicated effort, and accelerate tech to market.
- The CdTe community is expanding through external projects that encourage new ideas and partners.

Additional project contributors: Michael Heben, CTAC leadership, Casey Schorzman, Bill Peters, Meghan Hughes, Matthew Reese, and others.

PHOTOVOLTAICS TRACK

With **CTAC** guidance, **NREL** solicits proposals and **awards projects** to support **CdTe** photovoltaics research and industry

NREL

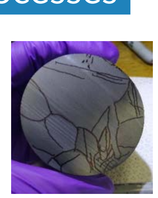
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New Device Configurations and Processes

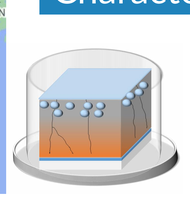
Funded Projects	Org.	RFP
Ultra-Thin High-Efficiency CdTe/MgCdTe Double-Heterostructure Solar Cells With Light-Trapping Features	ASU	2023
Innovative High-Voltage CdSe Solar Cells	ISU	2023



CdTe:I crystal by MVB
Dr. John McCloy, WSU



U.S. map of project locations



$AsCl_3$ vapor annealing
Dr. Feng Yan, ASU

High Efficiency Devices

Funded Projects	Org.	RFP
Advanced Back Contacts and Surface Photovoltage/Surface Photovoltage Spectroscopy Characterization	U of U	2022
Advanced Activation and Contact Approaches for Cadmium Zinc Telluride Solar Cells	UD	2022
Toward High-Efficiency n-Cadmium Selenide Telluride Solar Cells	USF	2022
Vapor-Assisted Group V Diffusion Doping Control in High-Efficiency CdSeTe Solar Cells	ASU	2023
Optimizing Iodine-Doped CdTe for Potential n-Type Solar Cells	WSU	2023
Solution-Processed Buffer Layers for CdTe Solar Modules	nexTC	2023

New RFP Announced March 18th!

RFX-2024-10015: 2024 Small Projects to Accelerate Cadmium Telluride Technology Development

Check it out on SAM.GOV
Topic Areas:

1. High-efficiency devices and new manufacturing processes.
2. Characterization, modelling, and simulation.
3. Enhancing the domestic CdTe supply chain.

Please submit questions to cdterfp@nrel.gov!

Important Dates		
Issue Date	3/18/24	
Submit Questions	4/5/24	
Response Due Date	4/29/24	4pm MDT
Award Selection Anticipated		October 2024

Characterization, Modelling, and Simulation

Funded Projects	Org.	RFP
3D In Situ Correlative X-Ray Studies of Defect Chemistry, Structure, and Electrical Performance During Dopant Activation	ASU	2022
Microcontact Arrays Measuring Local Carrier Transport in Cadmium Telluride Solar Cells	U of U	2022
Toward Automated Atomic-Resolution Scanning Transmission Electron Microscopy and Machine Learning for Achieving High-Efficiency Cd(Se)Te Solar-Cell Devices	UIC	2023

Tellurium Supply

Funded Projects	Org.	RFP
Selective and Efficient Recovery of Tellurium from Copper Processing Streams	S&T	2022
Identifying High-Potential Areas for Tellurium Extraction Within Existing Base and Precious Metal Supply Chains	UNR	2023

From Devices to Atoms: Assessing Perovskite Device Stability and Metastability by Spatially Resolved In-Situ and Targeted Ex-Situ Characterization

Last 5 digits of project number: **38044**
Principal Investigator (PI): **Dana Kern**
Lead Organization: National Renewable Energy Lab
PI Email: **dana.kern@nrel.gov**

BACKGROUND and OVERVIEW

- Metal halide perovskite (MHP) photovoltaics have reached high efficiencies, but **durability** is lacking.
- MHP solar cells exhibit both **reversible metastabilities** and **irreversible degradation** under operational stressors.
- In-situ characterization methods during perovskite stress testing are needed for **rapid** and **multi-scale** assessment of degradation pathways.

METHODS

- Task 1 develops methods for **rapid, spatially-resolved device screening** with in-situ electro-optical imaging under stress/rest cycling.
- Task 2 develops methods to **understand interface properties** using scanning probe microscopy.
- Task 3 **builds a library** to connect macroscopic device features with underlying microscopic causes of reversible/irreversible processes in perovskites. This is accomplished by correlated cross-platform data analysis including electron microscopy.

KEY MILESTONES

- Demonstrated in-situ electro-optical imaging to assess perovskite degradation modes; showed **applicability to multiple industry collaborators**.
- Developed **scanning thermo-ionic microscopy (STIM)** as a method for assessing ion mobility.
- Used electron-beam microscopy to categorize both **processing defects** and **degradation modes**.

CONCLUSION

- We have developed **in-situ characterization tools** to assess MHP device durability under light and heat.
- We ensure **broad applicability** of methods by collaboration with multiple industry and university partners.
- Our techniques utilize multi-scale analysis and cross-platform correlation of defect signatures to **link detailed chemical understanding to rapid electro-optical screening techniques**.

PHOTOVOLTAICS TRACK

Spatially-resolved characterization of perovskite solar cells shows origins of point-like processing defects and **spatial nature of degradation modes.**

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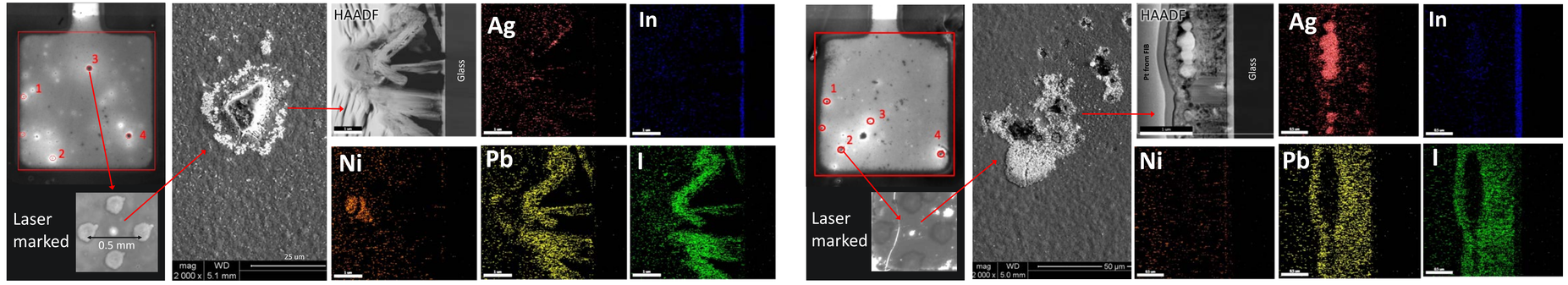
Electro-optical imaging | Scanning probe microscopy | Accelerated stress testing

luminescence → SEM → STEM

- Disruption in transport layers allows metal (Ag) intrusion
- Ag intrusion leads to shunts & defects observed in electro-optical imaging.

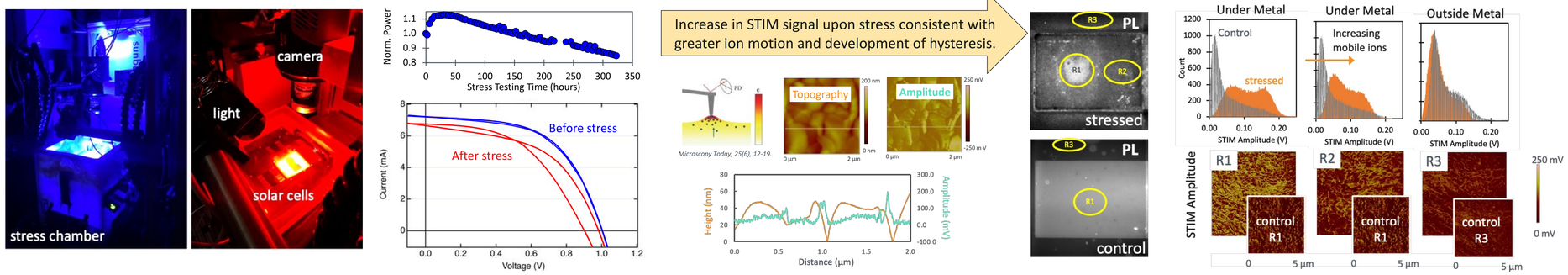
Result: Multi-scale analysis and cross-platform correlation of defect signatures links detailed chemical understanding to rapid electro-optical screening techniques.

Example of Processing Defects



Example of Degradation Analysis

0 → 300 hours



Contributors: Mowafak Al-Jassim, Steve Johnston, Harvey Guthrey, Andrew Norman, Chun-Sheng Jiang, Nikita Dutta, Jackson Schall, Goutam Paul, Andrew Glaws, Andrew Ballen (UCF)

Advanced Perovskite Cells and Modules

Last 5 digits of project number: **38256**
Principal Investigator (PI): **Joseph J. Berry**
Lead Organization: NREL
PI Email: joe.berry@nrel.gov

BACKGROUND and OVERVIEW

- Capitalizing on opportunities for transformational PV technologies enabled by metal halide perovskites (MHPs) such as tandems requires a range of critical material specific research needs
- This project addresses critical considerations for MHP based or enabled PV devices. These are centered around enabling science to ascertain requirements for stable high efficiency operation that can be manufactured at scale.

METHODS

- Hypothesis driven research and development in application focused context.
- Material and device characterization to link the role of material purity and associated supply chain considerations on performance (both efficiency and stability) that impact manufacturability
- Develop data and process infrastructure to more rapidly evaluate key challenges and transition enabling science from lab to industrial partners
- Integrated approach to understand and solve issues of variability in device performance critical for commercialization.

KEY MILESTONES

- Established state of the art all-perovskite tandems
- Identification of characterization with potential for predicting stability
- Linked indoor and outdoor cell stability test and cell insights to modules
- Development of transferable baseline process
- Work on universal workflow language and UI to capture and document process details

CONCLUSION

- Project has advanced knowledge critical to advancing MHP-based PVs from the research lab to manufacture and deployment.
- Project develops basic scientific insight on MHP materials and validates this understanding with MHP-PV technology demonstrations
- The project has advanced state-of-the-art in MHP-PV and provided critical insight to US-based MHP industrial efforts both in materials and metrology

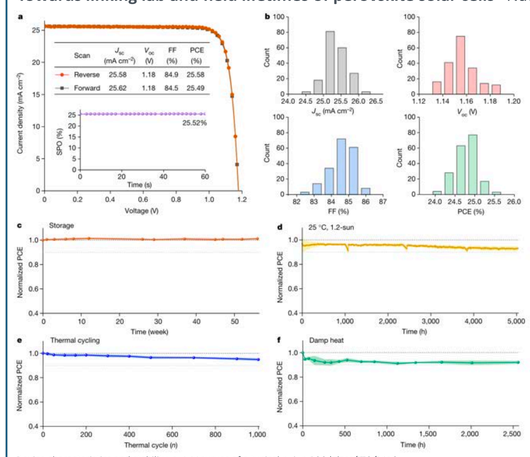
PHOTOVOLTAICS TRACK

Fundamental material ***science*** is critical for development & deployment of metal halide perovskite-based ***photovoltaic technologies*** including multijunctions.

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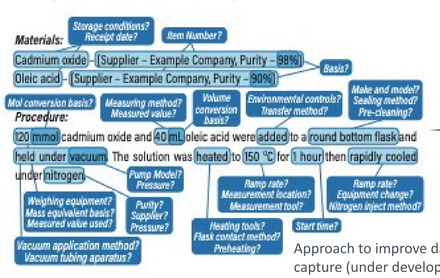
"Towards linking lab and field lifetimes of perovskite solar cells" Nature (https://doi.org/10.1038/s41586-023-06610-7)



Device characteristics and stability. a, J–V curves of a typical p–i–n PSC (glass/ITO/MeO-2PACz/$Rb_{0.05}Cs_{0.95}MA_{0.05}FA_{0.95}Pb(I_{0.95}Br_{0.05})_3$/$C_{60}$/$SnO_2$/Ag) b, Statistical comparison of photovoltaic parameters from 192 devices. FF, fill factor. c,d, Device efficiency evolution for unpackaged PSCs under storage in dark in N_2 (ISOS-D-1I) (c) and operation under continuous 1.2-sun at 25°C in N_2 (ISOS-L-1I) (d). e,f, Device efficiency evolution for packaged PSCs under repeated thermal cycling (−40°C to 85°C) in the dark in air (ISOS-T-3) (e) and under damp heat testing at 85 °C and 85% relative humidity in the dark in air (ISOS-D-3) (f).

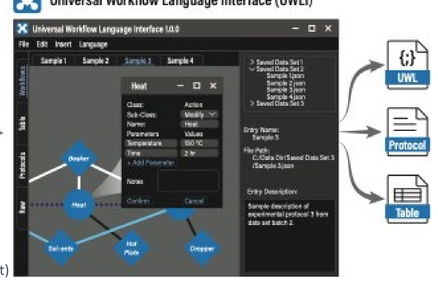
Temperature-dependent stability study. a, Averaged operational stability of unencapsulated p–i–n PSCs under continuous 1.2-sun in N2 at five different temperatures (25°–85°C, as indicated). b,c, Comparison of the temperature-dependent T80 values (b) and the corresponding hourly degradation rates (k = $1/T_{80}$) (c). The error bars represent the standard deviations from 8–17 individual devices for each temperature.

Example of missing data from process reporting from literature

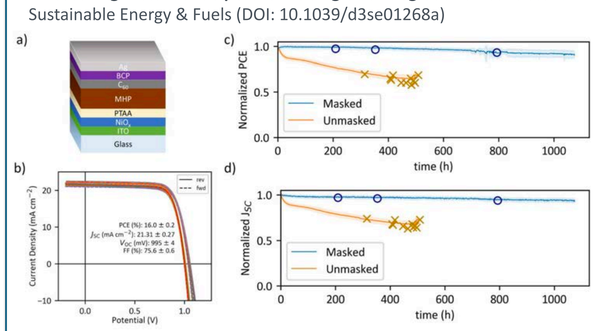


Approach to improve data capture (under development)

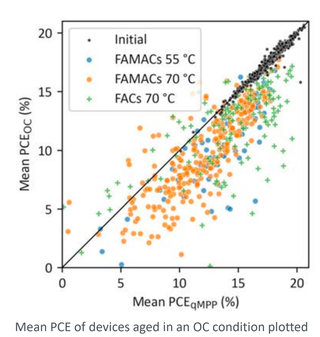
Universal Workflow Language Interface (UWLi)



"Measuring metal halide perovskite single cell degradation consistent with module-based conditions"
Sustainable Energy & Fuels (DOI: 10.1039/d3se01268a)

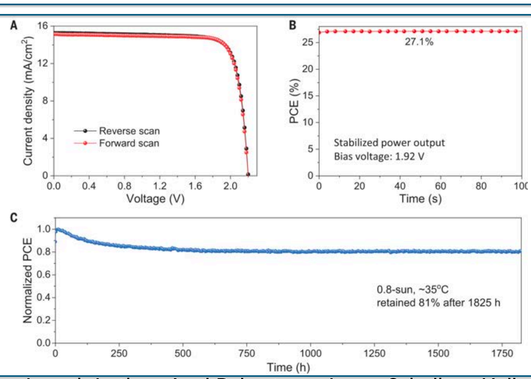


(a) Device architecture used in masking study. (b) Initial performance of masking study devices as measured on a solar simulator before aging. Normalized PCE (c) and JSC (d) of devices during aging. X and O markers in the plots indicate the time and final figure of merit value of devices before device dropout or step-edge failure, respectively.



Mean PCE of devices aged in an OC condition plotted against mean PCE of devices aged in a qMPP condition on the same substrate. Initial data are shown in black while post-aging data are shown in blue, orange, and green. A one-to-one parity line is shown for reference. Data is shown for triple-cation (FAMACs) and double-cation (FACs) PSCs with various device layers, additives, and treatments. Samples were aged for 168 h under illumination at 55 °C or 70 °C.

"Compositional texture engineering for highly stable wide-bandgap perovskite solar cells"
Science
(https://www.science.org/doi/10.1126/science.adf0194)



(A) J-V curves of an all-perovskite tandem solar cell incorporating the gas quench–based 1.75-eV WBG PSC. The device area was 0.059 cm^2 as defined by a metal aperture. (B) The corresponding SPO efficiency near the MPP. The narrow-bandgap bottom cell is based on 1.25-eV Sn–Pb perovskite ($FA_{0.6}MA_{0.4}Sn_{0.6}Pb_{0.4}I_3$). (C) Long-term stability of the tandem device under continuous ~0.8-sun illumination at ~35°C in N_2. The tandem device retained ~81% of its maximum efficiency after 1825 hours

Additional project contributors: Rosemary Bramante, Robert Epps, Ross Kerner, Su Geun Ji, Seul-Gi Kim, Joseph Luther, Axel Palmstrom, Laura Schelhas, Kelly Schutt, Robert Tirawat, Fengjiu Yang, Shuai You, Kai Zhu

PROJECT NAME: NREL CdTe Core

Last 5 digits of project number: **38257**
Principal Investigator (PI): **Matthew Reese**
Lead Organization: **NREL**
PI Email: **matthew.reese@nrel.gov**

PHOTOVOLTAICS TRACK

Fundamental material science is critical to improved understanding of the **Cd(Se,Te)** PV system for increased performance.

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BACKGROUND and OVERVIEW

- Cd(Se,Te) PV is domestically manufactured and is a large piece of the US PV market (~30% in 2021[1])
- Cd(Se,Te) PV has suffered from low photovoltage far below its entitlement (ideal Voc ~1.1 V)
- We use advanced synthesis, characterization, and modeling to provide understanding as to the limitations from materials, interfaces, and devices to improve performance with a focus on Voc.

1. *https://www.eia.gov/electricity/generatorcosts/*

METHODS

- In addition to complete devices, we synthesize model systems (MBE sX films) and test structures (e.g., single heterostructures, double heterostructures, non-graded absorbers, bevels) and leverage material generated by First Solar to work on problems in parallel to understand and improve the front interface, absorber/dopant activation, and back contact
- Use advanced characterization (including XPS, UPS, AES, spectrally corrected PL, LTPL, TRPL, DLTS, KPFM, SSRM) and modeling (SCAPS, COMSOL) for deeper insight

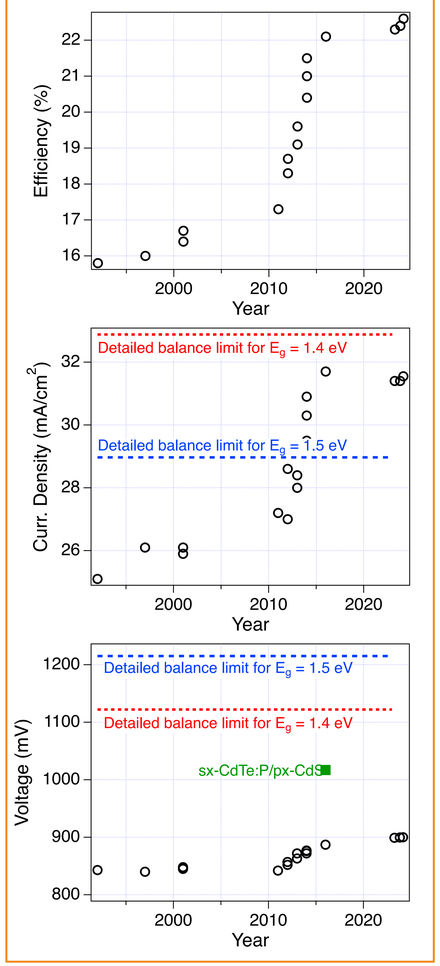
KEY MILESTONES

- Reduce the impact of band tails from As activation to less than 25 mV impact on open circuit voltage in Group V doped samples with carrier concentrations of at least 10^{16} cm^{-3} for at least 5 samples (1.2.1, complete)
- Measure lifetimes ≥10% of the radiative limit at the relevant dopant concentration of a CdSeTe absorber in a double heterostructure configuration (2.2.1, N/C)
- 23.5 % cell efficiency achieved by a collaborating institution OR 21% by NREL with < 100 mV V_{oc} deficit relative to simulations assuming no losses from band tails or front or rear interface recombination (3.4.1, N/C)

CONCLUSION

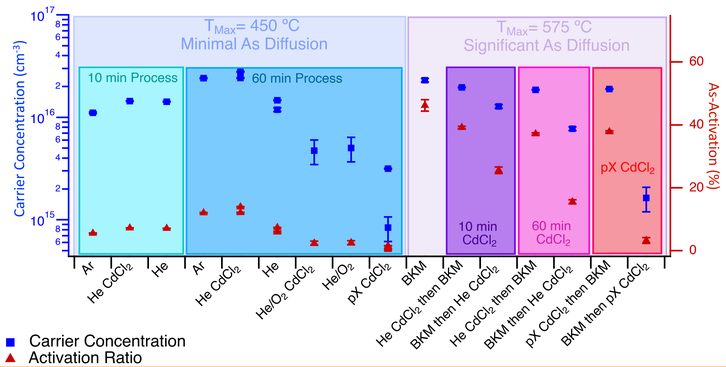
- Absorber quality in terms of activation and lifetime are two major loss mechanisms adversely affecting photovoltage and larger performance
- Performance enhancement will be driven by fundamental understanding that leads to increased voltage
- Record CdTe efficiencies are going up again
- NREL is working closely with the larger community to collectively identify and understand losses to guide efficiency improvement

"CdTe" Records over Time

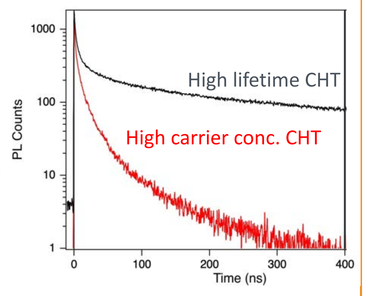


Towards improved absorber quality

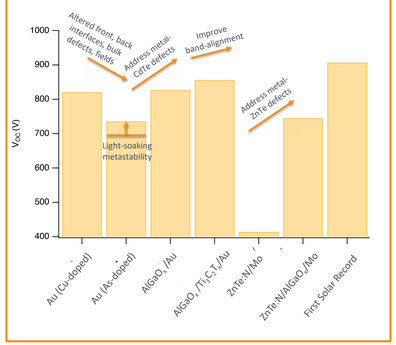
Establish necessary & sufficient conditions for high activation with model system



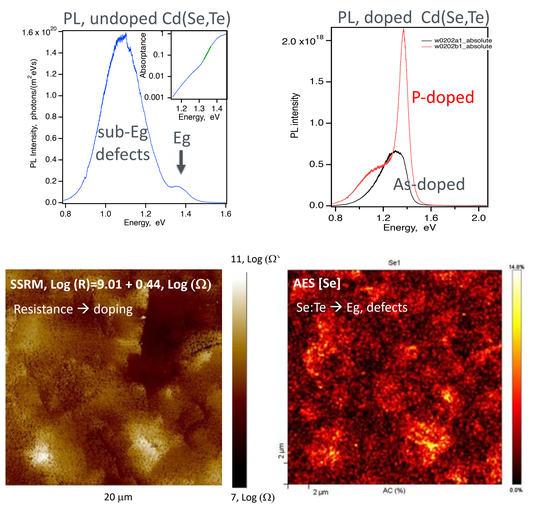
$CdCl_2$ conditions are critical to τ and N_A



With sufficient absorber quality, back contact quality matters

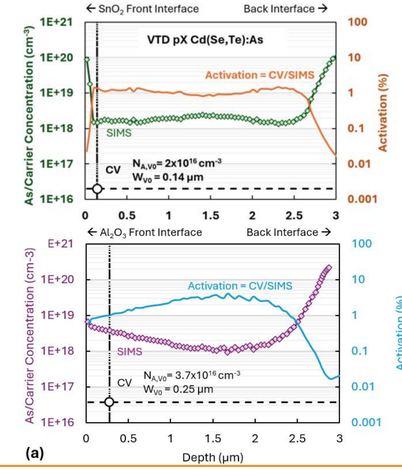


Electronic disorder contributes to V_{oc} loss

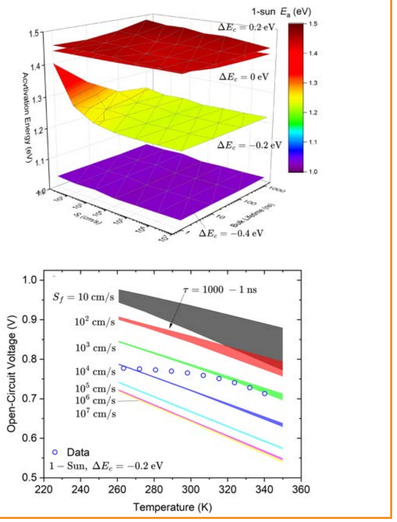


Front interface is a major limiter

XPS and D-SIMS show As distribution and activation can be controlled with front interface choice: SnO2 vs. Al2O3



Modeling of JV(T) data show poor CBO



Additional contributors: D. Albin, E. Colegrove, J. Duenow, S. Glynn, B. Good, A. Hattori, C-S. Jiang, D. Kuciauskas, L. Mansfield, A. Mathew, D. McGott, H. Moutinho, M. Nardone, C. Perkins, B.E. Sartor, C. Wolden

PROJECT NAME: PV Fleet Performance Data Initiative

Last 5 digits of project number: **38258**
Principal Investigator (PI): **Chris Deline**
Lead Organization: National Renewable Energy Laboratory
PI Email: **chris.deline@nrel.gov**

BACKGROUND and OVERVIEW

- High-frequency commercial and utility-scale PV system data have been collected to examine performance trends at a fleet scale.
- Open-source software tools are developed for deployment at scale: satellite image detection, time-series data quality, performance analysis
- Findings are aggregated, anonymized and published in private and public reports

METHODS

- More than 8.5 gigawatt (GW) capacity, 2200 sites and 24,000 inverters—approximately equivalent to 6-7 % of the entire US PV market
- Large-scale analysis deployed on NREL HPC
- Industry-leading data reporting focused on actionable outcomes
- Open-source github projects: RdTools, PVAnalytics, panel-segmentation

KEY MILESTONES

- Industry recruitment and partner data reporting
- Conference and journal publications focused on degradation, performance index, pollen soiling, availability, extreme weather and data QA.
- Improved accuracy in RdTools degradation analysis
- Metadata and data quality correction methods
- Generation of synthetic PV data for validation
- End-to-end Monte Carlo analysis using distributions of performance loss factors **(in progress)**

CONCLUSION

- **Major findings to date:** Systems degrade at -0.75%/yr on average; 90% of systems are performing within 10% of PVWatts expected on a monthly basis; Pollen Soiling can lead to 7%-10% loss, even with rain events; Extreme weather can result in long-term performance loss for hail > 1" and wind > 56mph. Inverters have a median 98%-99% availability depending on system & inverter size

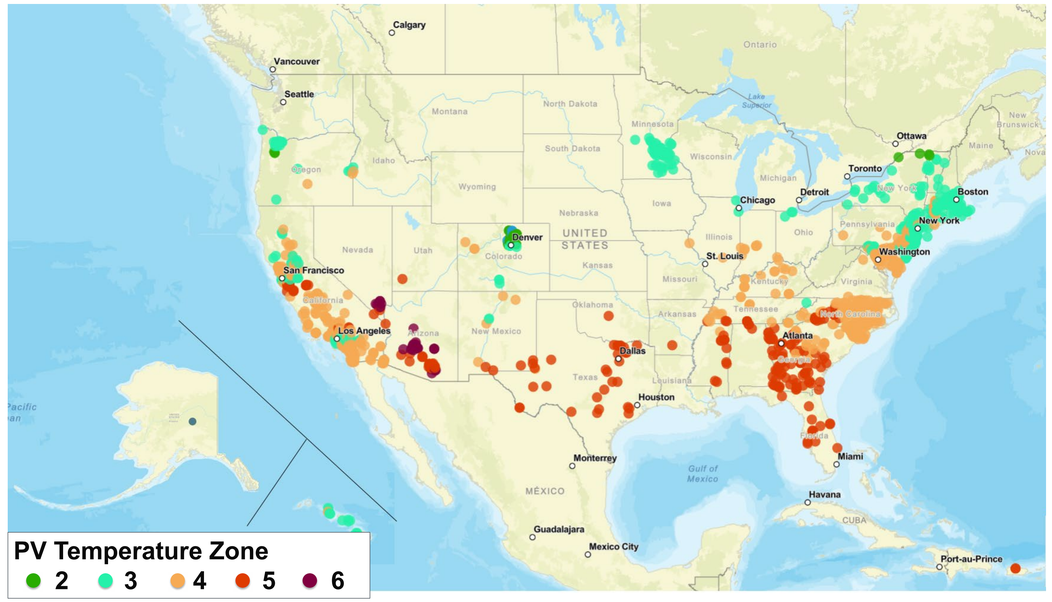
PHOTOVOLTAICS TRACK

High impact analysis of the US PV Fleet: **Soiling, degradation, inverter availability, snow, extreme weather impact,** and **performance loss** using HPC and open-source software

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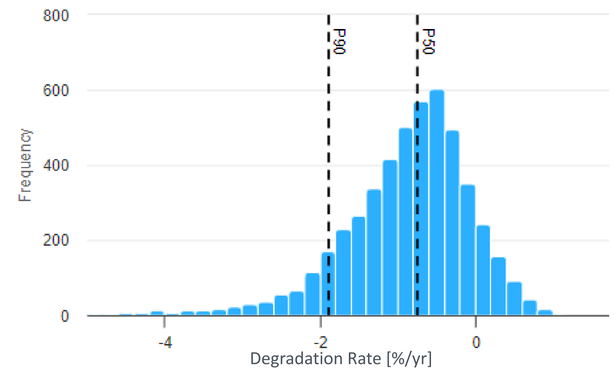
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>2200 systems, > 24k Inverters, ~8.56 GW capacity

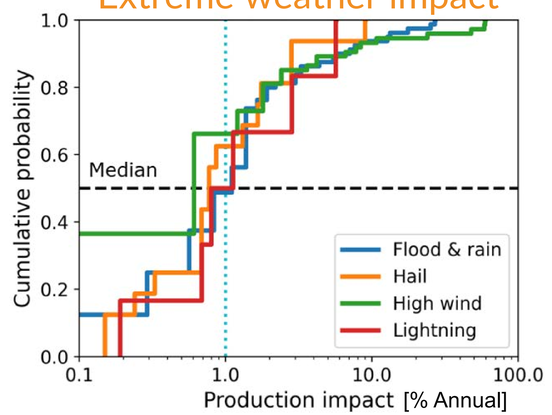


US PV Temperature Zone for each system, based on Karin et al. 2019

System Degradation Rate Distribution



Extreme weather impact



Additional NREL contributors: D. Jordan, M. Muller, K Perry, M. Deceglie, R. White, M. Springer and thanks to all our PV Fleet data partners.

PROJECT NAME: DuraMAT: Durable Module Materials Consortium

Last 5 digits of project number: **38259**

Principal Investigator (PI): **Teresa M. Barnes**
Lead Organization: NREL
PI Email: **Teresa.Barnes@nrel.gov**

BACKGROUND and OVERVIEW

- DuraMAT seeks to forecast the 30+ year reliability of modern modules. Historical data and tests may be misleading for new modules and cells.
- We start from fundamental research questions about how a material, or module will change over time rather than starting from field failure observations.
- Forecasting requires the ability to quickly determine if observations are real problems, the development of scaling relationships, and rapid validation without waiting years for field performance.

METHODS

- There have been 50 projects funded through DuraMAT since FY22, with 23 currently active.
- Current portfolio is targeted on predictive modeling and reliability forecasting with multiple projects focused on reliability risks in high-energy yield glass-glass modules.
- Projects are designed to link modeling with lab based accelerated testing and outdoor field performance.
- All projects share data to a common datahub.

KEY MILESTONES

- Demonstrate Datahub contains data from >85% of DuraMAT projects
- Development of predictive degradation modeling tools for high energy yield modules using fundamental kinetically-driven material models and a probabilistic failure models based on large scale field data.
- Identify module materials and designs that enable a 50-year module and mechanisms that trigger premature wear-out.

CONCLUSION

- Newer modules with many busbars, half-cut cells, and glass-glass encapsulation are more tolerant of cracked cells and less likely to exhibit power loss.
- A reliability forecasting strategy is being developed to quantitatively predict changes in modules over long lifetimes.
- Currently quantifying emerging issues related to UV, hybrid encapsulants and thin glass in high-energy yield modules and cells.

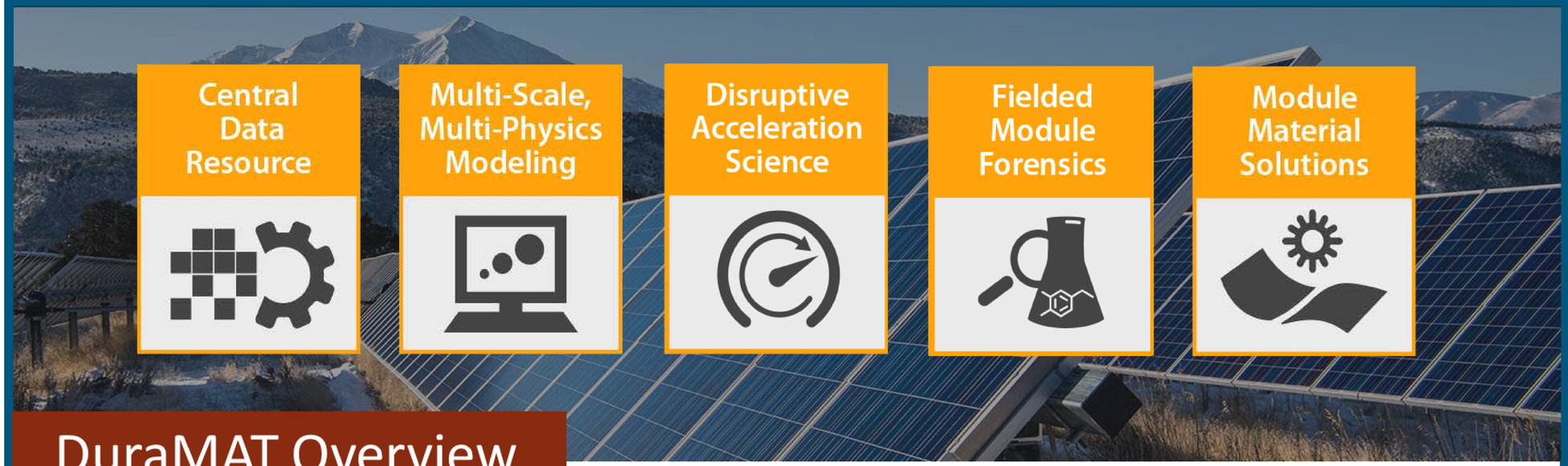
PHOTOVOLTAICS TRACK

DuraMAT: Identifying **wear-out** mechanisms, characteristics and rates to inform design decisions for **50-year** photovoltaic modules

Teresa M. Barnes, Michael Owen-Bellini, Clifford Hansen, Anubhav Jain, Lindsay Steinman, Dennice Roberts

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DuraMAT Overview

The Durable Module Materials Consortium (DuraMAT) brings together **DOE national lab** and **university** research capabilities with the photovoltaic (PV) and **supply-chain industries** through **five core objectives** (above), with the goal to accelerate a sustainable, just, and equitable transition to zero carbon electricity generation by 2035.

Additional project contributors: Sandia National Laboratories, BERKELEY LAB

DuraMAT Goals for FY22-27

- Which materials and module designs will enable sustainable, high-energy yield 50-year modules, and how do we ensure that these new modules are not going to fail prematurely?
- What triggers wear out, defined as a rapid increase in degradation at end of life, and what are the characteristics, rates, and mechanisms of long-term degradation in PV modules?

PROJECT NAME: Hands-On PV Workshop (HOPE)

Last 5 digits of project number: **38260**
Principal Investigator (PI): **Silvana Ovaitt**
Lead Organization:NREL
PI Email: silvana.ovaitt@nrel.gov

PHOTOVOLTAICS TRACK

HOPE for a brighter future: 12 years+ providing the ultimate learning experience at the Hands-On PV Workshop

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HOPE Webpage ····◄

HOPE news story····►

BACKGROUND and OVERVIEW

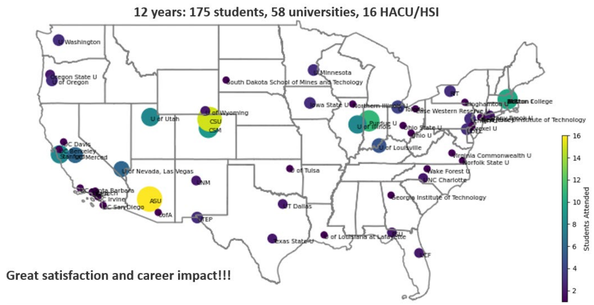
HOPE is a one-week school held at NREL each summer to educate graduate student photovoltaic researchers in the fundamentals of PV, specific cell technologies, and measurement & characterization techniques. The program brings students and their faculty advisors from universities across the U.S. to spend a week in an in-depth, intensive program, including hands-on lab experiences in solar cell fabrication and testing.

METHODS

- We include fundamental PV content including overviews of the leading PV materials, current-voltage, and quantum efficiency measurements of solar cells as well as certification techniques used at NREL, module materials, construction, and outdoor testing.
- The laboratory hands-on device fabrication sessions make up a full day or more
- We also do in-lab characterization sessions in small groups with techniques selected based on student interest (e.g., XPS, module PL/EL, DLTS)

KEY MILESTONES

- Hold HOPE each year (2022, 2023, 2024)
- Add systems-level content to Hope (2022)
- Expand applicant pool for HOPE (2023)
- Increase the size and reach of the workshop (2024)



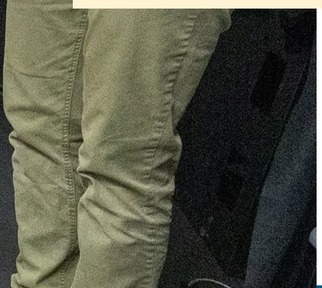
CONCLUSION

HOPE trains graduate students in PV R&D methods, preparing them for jobs in the PV sector. These students also disseminate their training within their research groups and universities, increasing the quality of U.S. PV research. Some of HOPE's content is shared publicly on our website.



Agenda Overview

- Fundamental/Introductory PV Sessions
  - 4 hrs previous flipped-classroom content prior to program start
  - 3.5 hrs on-week presentations
- Certification & Measurements – 7 hrs
- Technology Fabrication Sessions – 8 hrs (students grouped by technology area)
- Measurement & Characterization Sessions – 4.5 hrs (per student across 9 areas)
- Special Sessions:
  - PV sustainability solutions, guest lectures by professors – 1 hr
  - PV Start-up & Entrepreneurship talk – 1 hr
  - Perovskite Panel by HOPE professors – 1.25 hr
  - Solar in Space, NREL-NASA talk – 1 hr
- Systems Level Content:
  - Modules, Reliability, and Field Experience: 4 hrs
  - Industry Panel: 1.5 hr
  - Systems-level presentations: 3 hrs
- Professional Development & Networking:
  - Career panel: 1.5 hrs
  - NREL Staff interactions: 8 hrs total across activities (poster session, tea, lunches, and individual meetings)



Additional project contributors: 40+ NREL Staff per year; current leadership team Rachael Arnold, Pat Kline, Tabitha Goetz. Previous PIs: Sarah Kurtz, Adele Tamboli, Annie Greenway

PROJECT NAME: III-V Photovoltaics

Last 5 digits of project number: **38261**
Principal Investigator (PI): **Myles Steiner**
Lead Organization: **NREL**
PI Email: **myles.steiner@nrel.gov**

PHOTOVOLTAICS TRACK

Mechanical spalling and reuse of GaAs and Ge substrates is a scalable pathway to lower cost, high-efficiency III-V photovoltaic cells

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BACKGROUND and OVERVIEW

- III-V solar cells have demonstrated the highest PV efficiencies and are the ideal materials choice for some photovoltaic applications.
- Lowering the fabrication costs of III-V PV will facilitate the opening of new terrestrial markets.
- Costs are divided approximately evenly between the substrate, epitaxy and processing.

METHODS

- Controlled and acoustic spalling of GaAs wafers.
- Regrowth of planarization layers by MOVPE and HVPE, to smooth out faceted surfaces.
- Cleanroom processing of exfoliated thin films to demonstrate high efficiency III-V solar cells.
- Electroplating of copper front and back metal, followed by annealing and characterization.
- Technoeconomic modeling.

KEY MILESTONES

- ✓ Demonstration of a front-junction GaAs cell grown on a spalled substrate, with Woc ≤ 0.45 V.
- ✓ Demonstration of a GaInP/GaAs cell on a spalled substrate, with an operational tunnel junction.
- Demonstration of multiple reuses of a GaAs substrate to grow ≥30% GaInP/GaAs tandems.
- TEA of growth on spalled GaAs, updating existing cost models to incorporate planarization and regrowth.

CONCLUSION

- We have shown good epitaxially regrown III-V material on spalled surfaces, demonstrating the ability to re-planarize a faceted surface.
- We have fabricated high efficiency GaAs cells from 2” spalled GaAs, with reasonable yield.
- The project will demonstrate a pathway to multiple reuse of a GaAs wafer for growth of high efficiency III-V tandem cells for terrestrial and space applications.

Key aspects of cost reduction

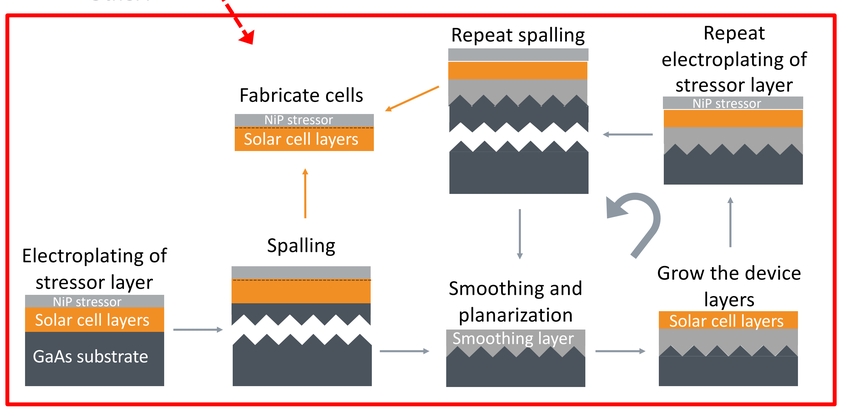
Metallization and processing
- Copper electroplating
- Screen/inkjet printing
- Non-photolithographic methods

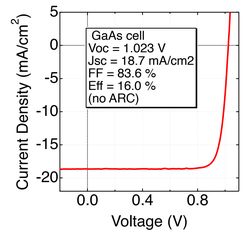
Re-growth of III-V device
- MOVPE
- HVPE
- Smoothing and planarization

Choice of substrate
- GaAs, Ge,…

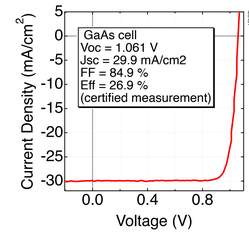
Substrate removal and reuse
- Spalling
- Epitaxial liftoff
- Laser ablation
- Other?

Fracture mechanics, studied by external partners
Colorado School of Mines, ASU, Crystal Sonic, Stanford…

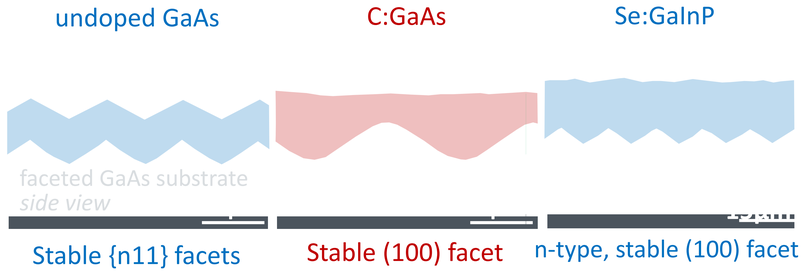




GaAs solar cells after controlled spalling from a 2” wafer and mounting to a temporary handle.



GaAs solar cell grown on a spalled and re-planarized GaAs wafer. From Schulte *et al.*, Joule (2023)



In-situ planarization of GaAs(100) facets during the growth of three different alloy/dopant layers. The thin lines in each SEM image are AlGaAs marker layers to help show the progress. The C:GaAs evolves toward a smoothed surface.

← Process flow for multiple reuses of a GaAs(100) substrate. Grey and orange arrows indicate the process flow for the substrate and spalled film, respectively. The cycle on the right side can be repeated as many times as possible.

Additional project contributors: Colorado School of Mines, Arizona State University, Crystal Sonic, Inc.

PROJECT NAME: PV Cell and Module Performance Testing

Last 5 digits of project number: **38262**
Principal Investigator (PI): **Nikos Kopidakis**
Lead Organization: **NREL**
PI Email: nikos.kopidakis@nrel.gov

PHOTOVOLTAICS TRACK

ISO accredited PV performance testing at the *highest level of accuracy*, available to *all stakeholders* in PV R&D and industry

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Link to our group's website

SCAN ME

BACKGROUND and OVERVIEW

- Objective and accurate characterization of cell and module performance is fundamental to gauging R&D progress, establishing bankability, reducing risk, and lowering the cost of PV-produced electricity
- Our group maintains the "gold standard" for PV performance calibrations in the US.
- We provide performance measurements for all PV technologies at the highest level of accuracy.

METHODS

- Performance testing of cells and modules with world-leading high accuracy under ISO 17025 quality control standards
- Continuous evaluation and improvements of hardware and procedures for accurate testing of emerging technologies including perovskites and tandems
- Advanced module-level characterizations include QE and temperature-controlled stabilized measurements
- Stewardship of the world-renowned Cell and Module Efficiency charts

KEY MILESTONES

- Uncertainty Analysis of perovskite module calibrations (completed)
- Publish report on the results of a module round robin between CMP and three private PV testing laboratories in the US (in progress)
- Demonstrate IV results on 3 tandem PV cells with 2 junctions and spectral response in the 350-1200 nm range under the LED simulator and show agreement with measurements in the OSMSS (completed)

CONCLUSION

- Trusted resource for PV performance expertise and advising for all technologies
- Unique to the US (and rare worldwide) PV performance testing capabilities enable new insights
- Our services are available to anyone via a measurement request web portal
- >2,000 measurements quarterly in support of DOE-funded R&D programs and the PV industry

The PV calibration chain in the US Maintained by this project

NREL PV Cell and Module Performance

- Absolute radiometry traceable to the **World Radiometric Reference**
  With NREL SRRL

Primary calibration

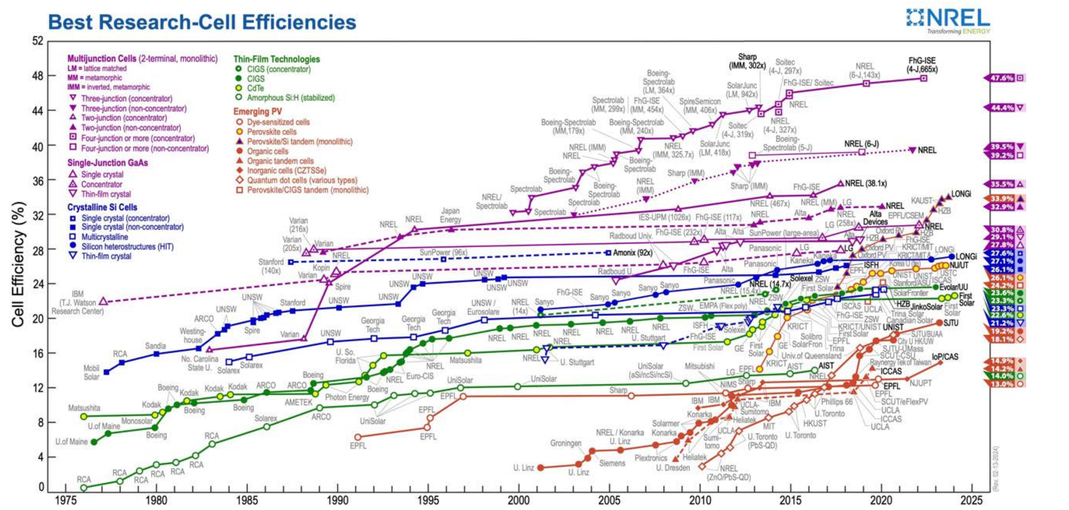
- **Highly accurate** primary reference cell calibrations (0.40% uncertainty)
- The **only primary calibration laboratory** in the US

Secondary calibration

- Calibration of **reference cells and modules**
- **World's lowest uncertainty** of 1.1% in Pmax for module calibrations

PV cell and module efficiency

- Efficiency measurements of cells and modules or **any size and any technology**
- Curator of **historic PV efficiency records**



- Creating accurate and standardized testing protocols for commercial and emerging PV
- Hardware and methods to test all PV technologies with world-leading accuracy
- Trusted source of independent and accurate PV performance results worldwide



Multisource LED solar simulator for M6-size multijunctions

Additional project contributors: Tao Song, John Geisz, Jeremy Brewer, Josh Gallon, Daniel Friedman

R&D to Ensure a Scientific Basis for Qualification Tests and Standards

Last 5 digits of project number: **38263**

Principal Investigators: **Ingrid Repins, Steve Johnston**

Lead Organization: **National Renewable Energy Laboratory**

PI Emails: **Ingrid.Repins@nrel.gov**, **Steve.Johnston@nrel.gov**

BACKGROUND and OVERVIEW

- The reliability of PV systems is key to their success in producing low-cost, clean, secure, and resilient energy.
- In response to tremendous cost pressure, the industry continues to introduce new, lower-cost products and methods. Risk of reliability issues increases when products, methods, or use conditions change.
- We develop tests and standards that allow customers to assess susceptibility of a product to an observed degradation mechanism and allow manufacturers to design it out of their products.

METHODS



KEY MILESTONES

- 28 peer-reviewed journal articles,
- 14 international standards have been published, with NREL leading the project on 3, and on the project team for 11.
- Annual PV Reliability Workshop (PVRW) with > 200 attendees, for stakeholder input.
- Research highlights - Module imaging and microscopy for root cause analysis; validated cell fracture model; coupon-level tests for encapsulants, abrasion, and UV weathering; science-based tests for higher-temperature systems; stricter re-test guidelines; PID tests, modeling, and standards.

CONCLUSION

- The new tests we have developed and standardized help manufacturers and customers evaluate new designs and quantify risk of failure or degradation.
- We continue to seek collaborations to increase the amount of publicly-available information and science regarding system failures, to obtain significant sample sizes, and to speed standards development.

PHOTOVOLTAICS TRACK

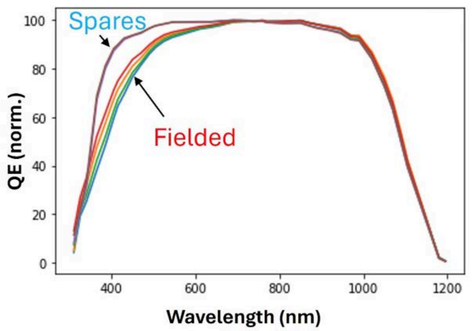
We Developed **Tests and Standards** to **Prevent** Observed PV **Degradation** from Happening in Future Products

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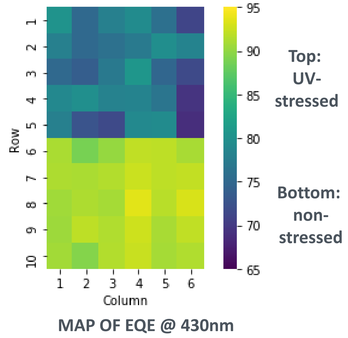
Check out what stakeholders are saying at our workshop!

Examples:

n-type silicon modules from a utility scale demonstrated 2.4%/yr degradation in power loss.

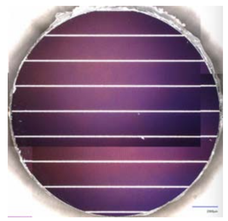


4,000 hours UV exposure at NREL reproduced the blue current loss



Working on:

- Microscopy to determine degradation mechanism
- Implications for standardized testing, where UV exposures are typically much shorter



Incorporation into international standards



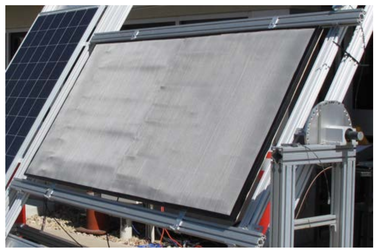
These tests written into current draft of IEC TS 62804-1 ed. 2

Field degradation due to potential-induced degradation polarization (PID-p) observed in the field

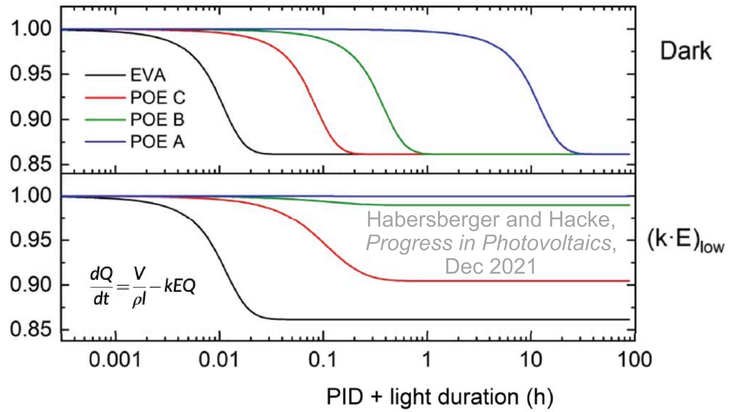


Swanson PVSEC 2005

Two test methods to recreate PID-p in the lab developed at NREL: metal mesh (below) and gel methods



Model for degradation behavior developed



Additional project contributors: Powermark, Sunset Technology, Arizona State University

PROJECT NAME: Core Silicon PV

Last 5 digits of project number: **38264**

Principal Investigator (PI): **Paul Stradins, David Young**

Lead Organization: **National Renewable Energy Lab**

PI Email: pauls.stradins@nrel.gov; david.young@nrel.gov

PHOTOVOLTAICS TRACK

Core Si PV project at NREL: **passivated contacts** based on **engineered pinholes**, **mechanisms of degradation**, all-passivated contact **device fabrication**, new **characterization** techniques

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BACKGROUND and OVERVIEW

- Project goals: increasing efficiency, lowering cost, and understanding degradation processes in Si cells
- Developed three types of novel passivated contacts based on engineered pinholes by MACE, SAM, pulse laser; One type implemented into 729 mV cell
- Achieved p-type poly contact with J_0< 1 fA/cm^2; applicable to textured surfaces and dielectric stacks; IP, by industrially relevant processes.
- LeTID mechanism studied by EPR

METHODS

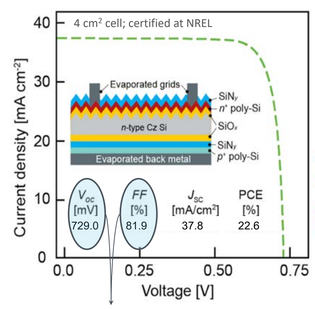
- Metal-assisted catalytic etch (MACE) to produce contact pinholes by nanogalvanic corrosion
- Self-assembled monolayers for dopant patterning
- Pulse laser for hyperdoping poly-Si with Ga
- EPR as defect identification tool (LID, LeTID in p-Cz Si; , defects and impurities in n-Cz Si)
- Develop state-of-the-art Si PV cleanroom at NREL (wafer-scale automated wetbench, furnaces, testing)
- PhD students get skills and join US PV industry

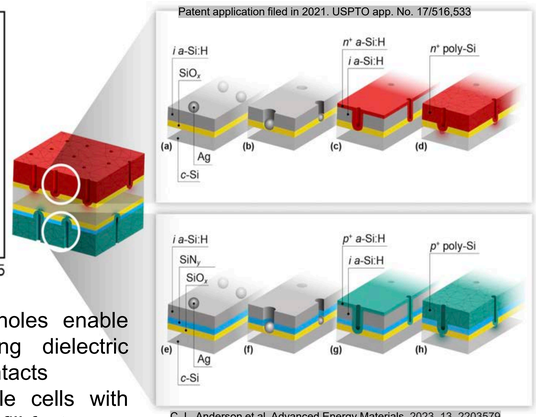
KEY MILESTONES

- Article on LeTID mechanism by EPR (completed)
- Novel p-type pinhole contact & cell (completed)
- New characterization techniques (in progress)
- Dopant patterning with SAMS (completed)
- LeTID mitigation in Cz-Si:Ga (in progress)
- Full-size wafer Si solar cell (tool installation delay)
- TA analysis on NREL cell designs (completed)

CONCLUSION

- Novel p-type contact and cell address remaining Si PV efficiency bottleneck
- EPR enables sensitive defect identification
- Anticipate industry interest in NREL technology
- New Si PV cleanroom attracts industry R&D
- Program graduated four PhD level workforce (Maxeon, First Solar, Heliene, Aerospace Corp.)

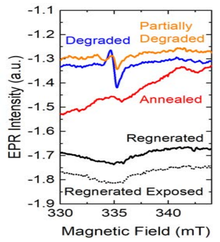


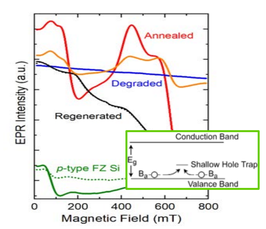


- Chemically etched nanopinholes enable current transport passivating dielectric stacks, ~ 1fA/cm^2 p+ poly contacts
- Our pinhole contacts enable cells with high open-circuit voltage and fill-factor

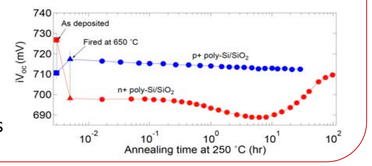
C. L. Anderson et al. Advanced Energy Materials, 2023, 13, 2203579

Light-Induced Degradation (LID) in Cz-Si:B – numerous ~ 10^{16} cm^{-3}, shallow hole traps created by light alongside with ~ 10^{12} cm^{-3} deep, recombination active defects: our EPR study.

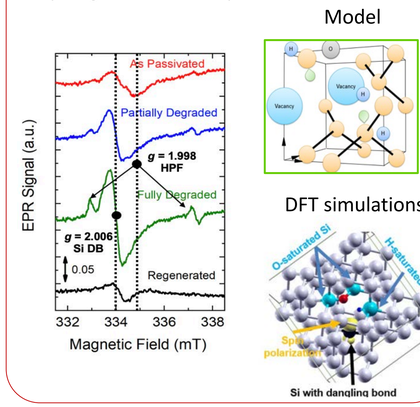




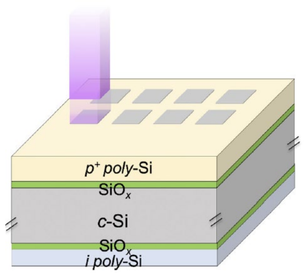
Different degradation behavior shown in n+ and p+ TOPCon contacts

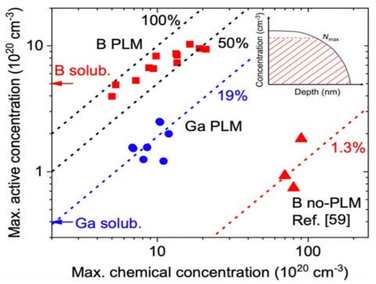


Light- and elevated Temperature Induced Degradation (LeTID) in Cz-Si:Ga our EPR study suggests Si dangling bond in partially hydrogenated vacancy

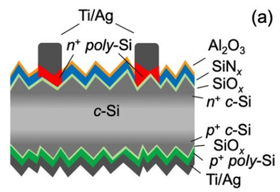


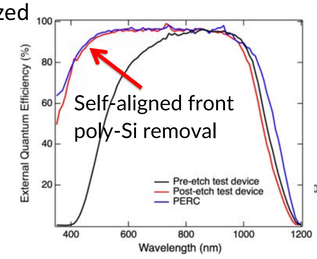
Nanosecond laser induced hyperdoping demonstrated in B- and Ga- p+ poly-Si contacts, several times over dopant solubility limit, with high % dopant activation

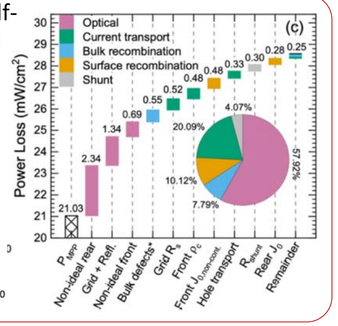




Solar cell with both p+ and n+ poly-Si passivated contact with self-aligned poly-Si removal between the gridlines, 21.03% produced Quokka-simulated, and TEA analyzed







Additional project contributors: Colorado School of Mines (all tasks), UT Austin (atomistic LeTID theory), P. Craig Taylor (EPR consultant)

PROJECT NAME: Solar Radiation Research Laboratory (SRRL)

Last 5 digits of project number: **38265**
Principal Investigator (PI): **Manajit Sengupta**
Lead Organization: **NREL**
PI Email: Manajit.Sengupta@nrel.gov

PHOTOVOLTAICS TRACK

World-leading Solar Radiation Research Laboratory enables **highest quality solar measurements for all solar energy plants in the US.**

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BACKGROUND and OVERVIEW

- SRRL activities ensure traceable solar irradiance measurements throughout the US for all solar energy projects by:

(a) providing easy access to a regularly updated world radiometric reference.
(b) Improved calibration methods for solar radiometers to enhance measurement accuracy
(c) Developing and updating international standards and best practices to enable high quality measurements.

METHODS

- Conduct NREL Pyrheliometer Comparison (NPC) to provide access to updated world reference.
- Broadband Outdoor Calibration (BORCAL) to improve calibration methods for solar radiometers.
- Lead ASTM, ISO and IEC committees to develop new standards.
- Produce Best Practices Handbook to disseminate latest knowledge to stakeholders.
- Disseminate high-quality data through the Measurement and Instrumentation Data Center (MIDC)

KEY MILESTONES

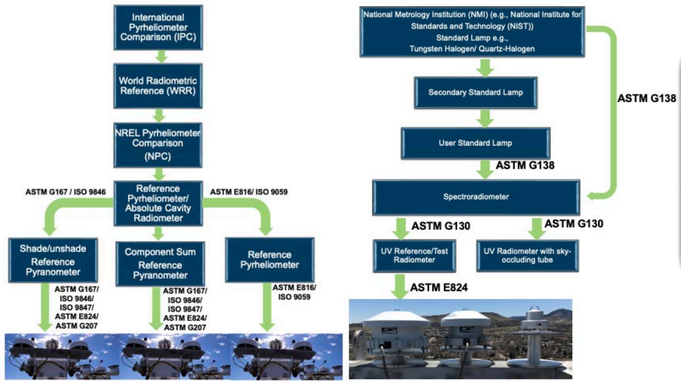
- Publish the fourth Edition of the *Best Practices Handbook for the Collection and Use of Solar Resource Data for use in Solar Energy Applications*.
- Publish ASTM G173 standard for reference spectrum.
- Publish annual reports on the NPC.
- Design multispectral albedo measurement system.
- Conduct BORCAL annually for all instruments in NREL's Baseline Measurement System (BMS).
- Provide high-quality data through MIDC.
- Publish baseline PV reference cell characteristics.

CONCLUSION

- NREL broadband and spectral instruments are calibrated annually using ISO-17025 accredited facilities.
- Measurements are disseminated through MIDC.
- NPC is conducted annually to disseminate World Radiation Reference.
- New standards are developed to ensure high-quality measurements for all US solar energy applications.
- Solar resource best practices are disseminated through active collaboration with national and international stakeholders.

Traceability of all solar measurements to world standard through inter-comparison and calibration.

Traceability of Broadband and Spectral Radiation



Transferring Calibrations to US stakeholders



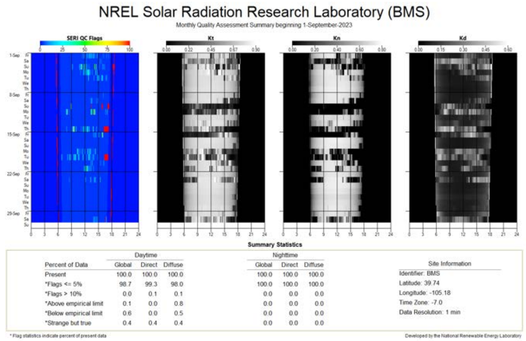
Solar Radiation Measurement at SRRL



NREL's Solar Measurement Network



High quality data is collected at SRRL



Best Practices Handbook



https://www.nrel.gov/docs/fy21osti/77635.pdf

High-quality solar data, standards and best practices are developed and disseminated through the MIDC website, NREL publications, and ASTM and ISO standards.

Additional project contributors: University of Oregon, Solar Consulting Services, Solar Resource Solutions, and PV Performance Labs

Tandem Photovoltaics Core

Last 5 digits of project number: **38266**
Principal Investigator (PI): **Emily Warren**
Lead Organization: NREL
PI Email: **emily.warren@nrel.gov**

PHOTOVOLTAICS TRACK

Advancing **tandem photovoltaic technologies** by simultaneously considering the efficiency, manufacturability, stability, and cost of tandem module designs.

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Link to Tandems Core publications

BACKGROUND and OVERVIEW

- Tandem solar cell research is a fast-paced field, with the potential to increase the efficiency of PV beyond 30%. However, there are multiple module configurations possible, and little consensus on the best approach for terrestrial deployment.
- NREL's Tandem Core focuses on unbiased, data-driven research to achieve commercially relevant tandem devices that can have market impact.

METHODS

- Experimental: our work focuses on demonstrating 2T and 4T metal halide perovskite (MHP)/Si tandem devices, while simultaneously addressing manufacturability, efficiency, and stability.
- Computational: efforts focus on accurate and efficient energy harvesting efficiency (EHE) predictions, outdoor data analysis, technoeconomic analysis (TEA) of manufacturing costs, and road-mapping.

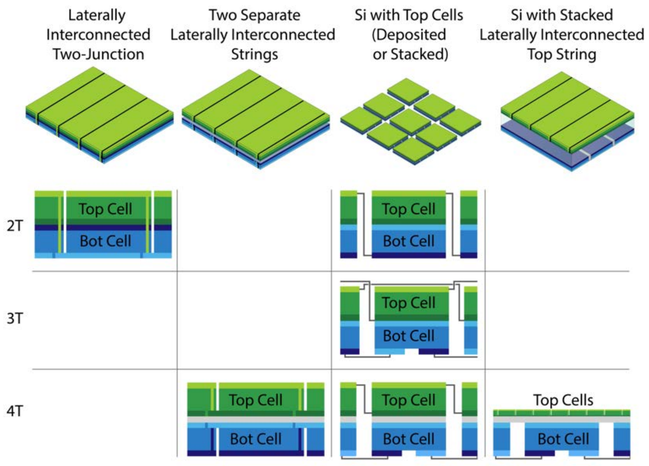
KEY MILESTONES

- Developed manufacturing flow for MHP modules with transparent back contacts, and integrated MHP with multiple types of Si for 2T tandems.
- Demonstrate fully packaged perovskite/Si tandem modules (4T) for outdoor deployment.
- Created open-source EHE model (PVCircuit) that allows comparison between different cell designs and configurations.
- Analyzed outdoor performance of tandem devices.
- Developed roadmap for tandem PV and TEA for perovskite/Si tandem manufacturing.

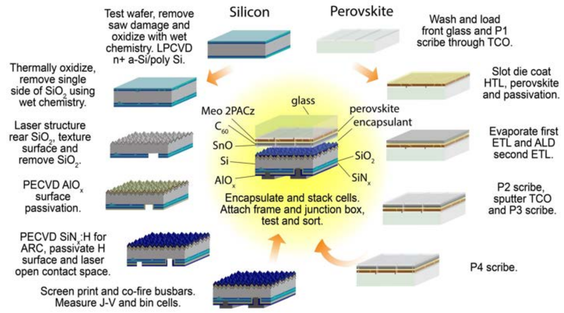
CONCLUSION

- This project is developing tools and best practices to enable tandems to become a commercial technology.
- EHE and TEA analysis show there are not major performance or cost differences for 2T vs 4T tandem configurations.
- Next steps: understand long-term outdoor performance of tandem modules.

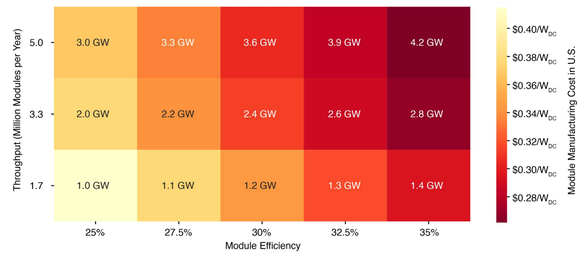
Common geometries for combinations of thin-film and Si wafer tandems for 2T, 3T, and 4T configurations. *(Alberi Roadmap 2024)*



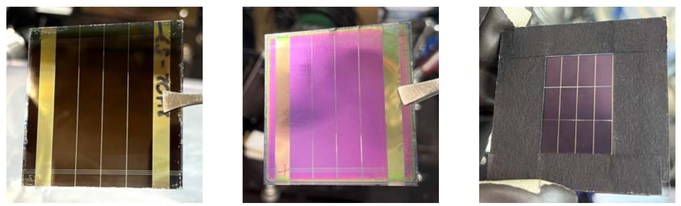
Technoeconomic analysis: Baseline process for fabricating a 4T MHP//Si module. *(Cordell 2024)*



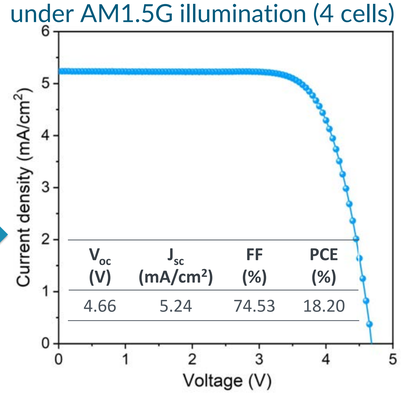
Comparison of 4T MHP//Si module manufacturing costs (U.S.) based on module efficiency and factory throughput. (Below 1GW production, production costs increase due to equipment under utilization.)



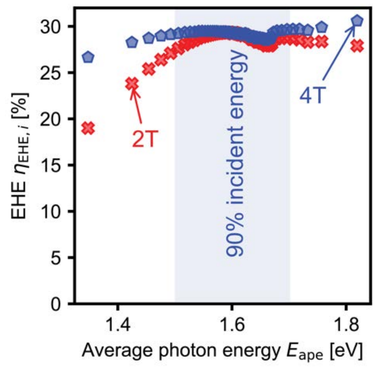
Images of MHP modules with transparent back contact for 4T tandems (50x50mm substrate, aperture areas 4–12 cm^2)



Representative performance for a MHP modules with transparent back contacts under AM1.5G illumination (4 cells)



Comparison of the energy harvesting efficiency EHE for 2T and 4T devices for a full year of in Golden, CO. *(Witteck 2023)* (based on 100 proxy spectra)



Additional project contributors: Institute for Solar Energy Hamelin

PROJECT NAME: Advanced Diagnosis and Accelerated Testing of Balance-of-System Components for Utility-Scale PV Installations

Last 5 digits of project number: **38524**
Principal Investigator (PI): **David Miller**
Lead Organization: **National Renewable Energy Laboratory**
PI Email: David.Miller@nrel.gov

BACKGROUND and OVERVIEW

- Degradation and failure of balance of systems components (e.g., connectors, cables, and rapid shutdown devices) threatens the availability, safety, and adoption of PV technology.
- The state of the industry was studied to identify the most problematic components, their typical failure modes, and their occurrence.

METHODS

- Topic-specific meetings followed the PVQAT TG10 survey to assess the present state of the industry.
- Degraded and failed connector and cable specimens were obtained from PV installations.
- Separate accelerated test studies were conducted on representative connectors and cables.
- Forensics based failure analysis was conducted to compare field- and chamber-aged specimens.

KEY MILESTONES

- A manuscript summarizing the state of the industry and the forensics examination of field cable connectors has been submitted.
- A manuscript summarizing the state of the industry and the accelerated testing of PV cable is presently in preparation.

CONCLUSIONS

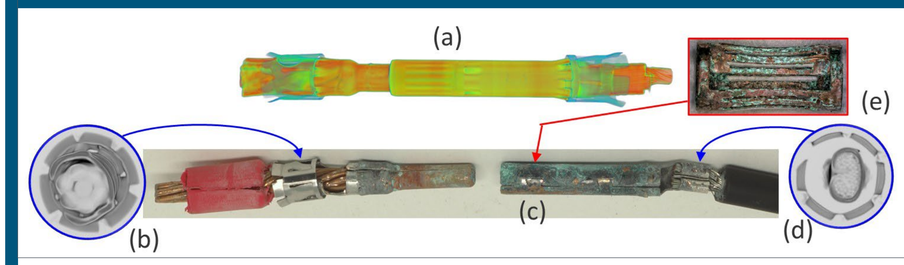
- Cable connectors were found to be generally less durable than PV cable.
- Scorched metal components may result from (TBD): design, manufacturing, uncapped ends, vibration/bending, and/or CTE-misfit (abrasion).
- From PVQAT, rapid shutdown devices are purportedly problematic, including fire-risk.
- We provided an outlet for long-standing concerns; the interest has motivated a new industry standard.

PHOTOVOLTAICS TRACK

Scorched metal pins were frequently observed on field degraded PV cable connectors in addition to several known degradation modes.

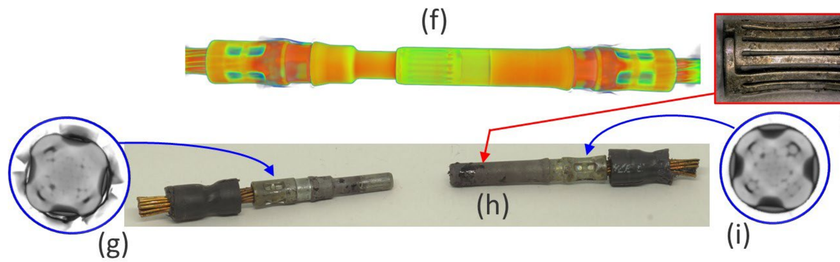
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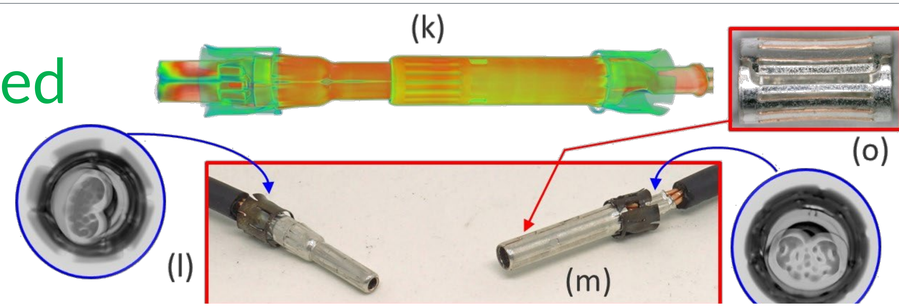
X-ray scans and visual appearance of connectors and springs after deconstruction.

PEI, CAN (ocean side)



Dallas, TX (subtropical)

Unaged



Presently common degradation modes: incompatible makes, improper assembly, uncapped ends, incomplete connection, improper sizing, and improper mechanical fastening.

Additional project contributors: Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Steven C. Hayden, Aubrey Jackson, Helio Moutinho, Jimmy Newkirk, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná, Weston Wall, Chuanxiao Xiao

PROJECT NAME: Development and Application of Voltage Loss Analysis for Advanced Thin Film PV

Last 5 digits of project number: **38525**
Principal Investigator (PI): **Darius Kuciauskas**
Lead Organization: NREL
PI Email: **Darius.Kuciauskas@nrel.gov**

BACKGROUND and OVERVIEW

- CdTe solar cell voltage reached 900 mV in 2013 and did not change since, limiting efficiency gains.
- We showed that about half of voltage losses occur in radiative voltage, due to band tails and near-bandgap defects, including carrier traps.
- Results focus R&D to reduce density of near-bandgap defects, which is possible with higher dopant activation and alternative gr. V dopants.

METHODS

- COMSOL device models integrate electro-optical, chemical, and surface analysis results.
- Absolute PL is used to measure ERE/PLQY, radiative voltage, and implied voltage.
- Time-resolved methods are used for charge carrier lifetimes, trapping, and mobility.
- AES and EBSD are used for Se-related bandgap fluctuations & crystallographic-dependent properties
- XPS is used for energy band alignments

KEY MILESTONES

- Absolute PL based V_{oc} loss analysis metrology for CdTe PV (absorbers with large electronic disorder)
- In progress: Facet-specific chemistry at key PV interfaces
- In progress: Transfer results (metrology, device models) to CdTe R&D labs, including CTAC

CONCLUSION

- **Physics:** Unintentionally, complexity introduced to the absorber (Se grading, >10^{18} cm^{-3} dopant density) increased electronic disorder, as described by the bandgap and electrostatic (defect) potential fluctuations γ>50 meV and Urbach energies E_u>25 meV. This reduced voltage entitlement (V_{OC}^{rad}) and created trap states, reducing mobility.
- **PV:** Results enabled several collaborations which increased V_{OC}^{rad}, primarily by modifying gr.V doping.
- **Metrology:** Voltage loss analysis methodology for CdTe was developed and implemented in device models.

PHOTOVOLTAICS TRACK

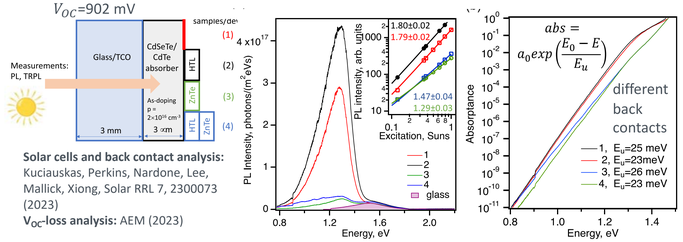
Reducing band tails enables CdTe solar cell efficiency above 23% and voltage above 900 mV, overcoming longstanding limitation

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Bulk recombination ("short lifetimes") no longer the largest loss pathway

Total:	$V_{OC} - V_{OC}^{SQ}$	= -247 mV	% total:
Radiative voltage losses:	$V_{OC}^{rad} - V_{OC}^{SQ}$	= -(99-129) mV	(40-52%)
BC recombination (band bending, N_t=10^{11} cm^{-3})		= -60 mV	(24%)
Remainder (front, bulk, contact selectivity)		= -(60-90) mV	(24-36%)



Solar cells and back contact analysis: Kuciauskas, Perkins, Nardone, Lee, Mallick, Xiong, Solar RRL 7, 2300073 (2023)
V_{OC}-loss analysis: AEM (2023)

Radiative voltage calculation:

$$I_{PL}(E) = \frac{2\pi\varepsilon^2}{h^3c^2}a(E)\frac{1}{\exp\left(\frac{E-\Delta\mu}{k_BT}\right)-1}$$

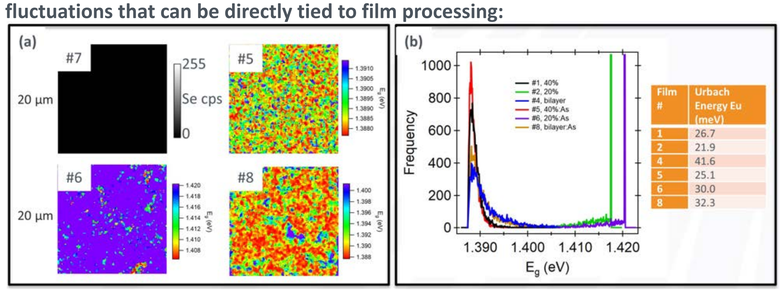
$$V_{OC}^{rad} = \frac{k_BT}{q}ln\left(\frac{q\int_0^\infty a(E)\phi_{Sun}(E)dE}{q\int_0^\infty a(E)\phi_{bb}(E)dE}+1\right)$$

≈ 1020-1050 mV

V_{OC}^{SQ} = 1149 mV (E_g=1.40 eV, EQE)

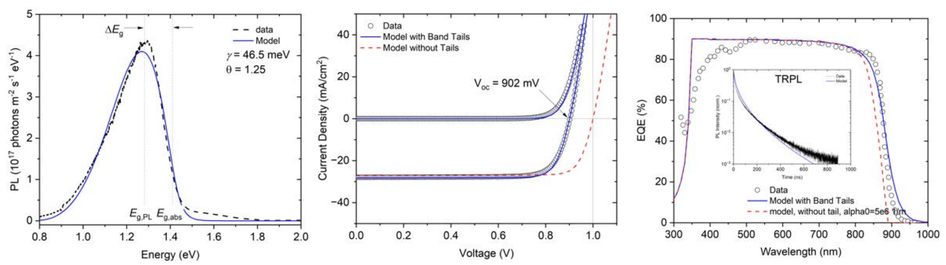
Shallow defects (band tails) can be as detrimental as deep defects (recombination); this new aspect needs to be included in device models and in CdTe solar cell R&D

Quantitative selenium maps from Auger electron microscopy reveal bandgap fluctuations that can be directly tied to film processing:

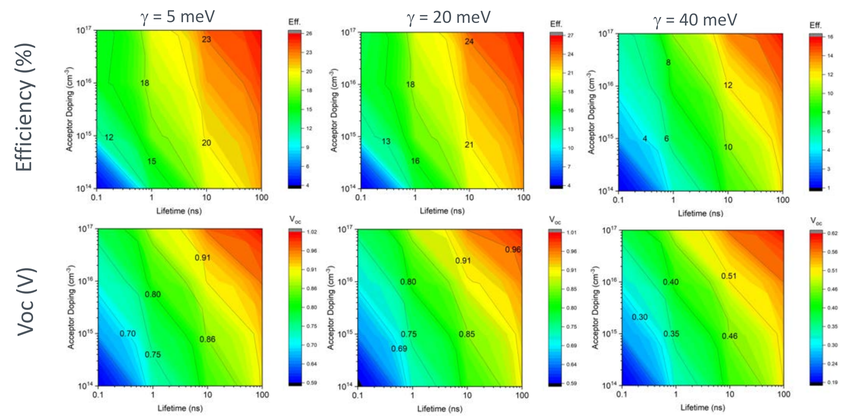


Film #	Urbach Energy Eu (meV)
1	26.7
2	21.9
4	41.6
5	25.1
6	30.0
8	32.3

COMSOL simulation of PL spectrum, EQE, TRPL, and JV using a single set of parameters. If band tails are not present, voltage is increasing from 900 mV to 1 V (red dashed):



Performance Limits with Band Tails



Project contributors: Darius Kuciauskas, Craig Perkins (NREL), and Marco Nardone (BGSU); collaborators from NREL and First Solar

PROJECT NAME: Electrically Detected Magnetic Resonance for Identifying Defects in Wide Range PV Devices and Materials

Last 5 digits of project number: **38526**
Principal Investigator (PI): **Paul Stradins**
Lead Organization: **National Renewable Energy Lab**
PI Email: pauls.stradins@nrel.gov

PHOTOVOLTAICS TRACK

Electrically Detected Magnetic Resonance technique (EDMR) identifies **performance-limiting defects** in *poly*-Si **passivated contact cells**

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BACKGROUND and OVERVIEW

- EDMR is a very sensitive technique and can be used for identification of atomic origins of performance- and reliability-limiting defects in PV.
- Unlike conventional EPR, the EDMR senses only the recombination-active defects in the device.
- EDMR enables characterization of defects in poly-Si/SiO_2 tunneling passivated contact, in Ga-doped *p*-Cz Si wafers, and in very high lifetime (> 20 ms) *n*-Cz Si wafers, also interface defects in solar cells.

METHODS

- EDMR setup was created at NREL with help from HZB and Penn State collaborators.
- Modified the existing E-500 EPR spectrometer at NREL for the EDMR application.
- New "passivated contact minicell" technology developed at NREL to accommodate small sample size required for the EDMR.
- Edge passivation by Nafion developed to limit the edge recombination in module fragments.

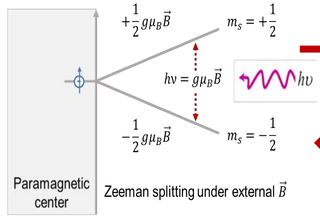
KEY MILESTONES

- Develop EDMR instrumentation at NREL (completed)
- EDMR on *n*-type passivated contact cell (completed)
- CW EDMR signal shown from O-precipitated and Tabula Rasa treated n-type wafer bulk (on-going)
- EDMR on n-type module fragment (TOPCon or SHJ) identifying the degradation mode
- LID and LeTID low-T EPR spectra with room temperature EDMR (on-going)

CONCLUSION

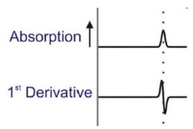
- The milestones address the technique development and application to cell performance and reliability (surface and contact passivation, n-Cz bulk, LeTID in p-Cz Si).
- EDMR technique and minicell preparation is successfully established at NREL.
- The minicell technology developed in this project also enabled novel laser power beaming Si module at 40% efficiency for 100 sun concentration.

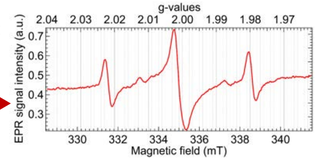
Electrically Detected Magnetic Resonance (EDMR)



- Change in the cell output is due to change in the recombination at magnetic resonance condition.
- EDMR is specific and sensitive to the performance-affecting paramagnetic defects.

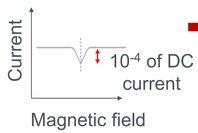
EPR detects spin-dependent microwave absorption

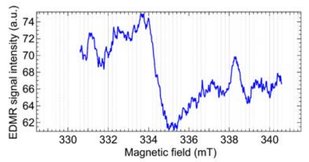




All paramagnetic defects

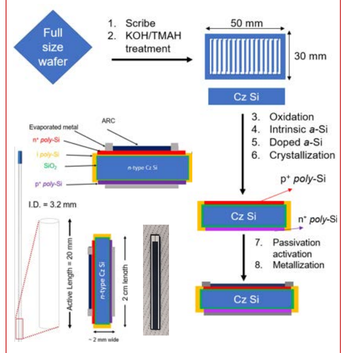
EDMR detects spin-dependent recombination





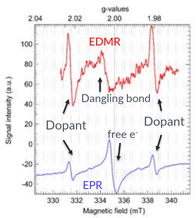
Only recombination-active paramagnetic defects

EDMR minicell replicates real poly-Si passivated contact cell



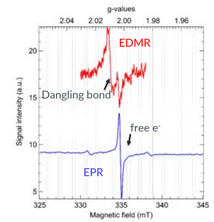
EDMR and EPR at T=10K and T=300K

EDMR at T=10K: dopants are recombination active, show hyperfine lines



10K EPR detects both frozen-out dopants and free electrons near n+ contact

Room T: EDMR detects only recombination active SiO_2/wafer interface defects

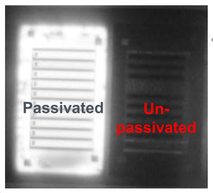


Room T: EPR detects all spin-active defects

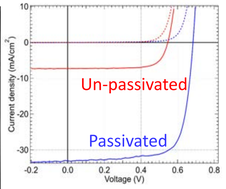
	Un-passivated	Passivated
iV_{oc}	0.652 V	0.703 V
J_0	3.08 E -13 (A/cm^2)	4.03 E -14 (A/cm^2)

EDMR is used to compare and identify interface defects in H-passivated and non-passivated poly-Si contact cells

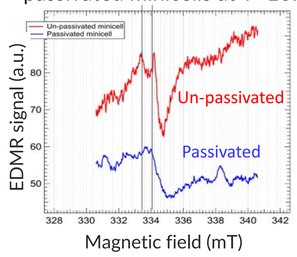
Photoluminescence from the EDMR minicells



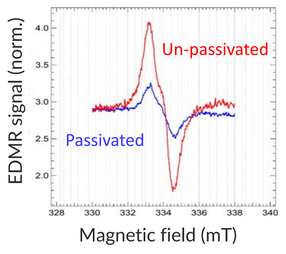
JV curves of 4cm^2 sister cells



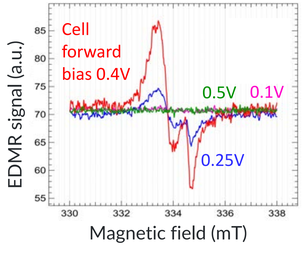
EDMR of passivated and Un-passivated minicells at T=10K



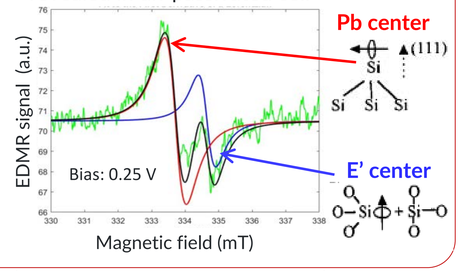
EDMR of passivated vs Un-passivated minicells at Room T



Bias dependence of the EDMR signal



Two recombination channels/defects revealed in un-passivated cell



Additional project contributors: Colorado School of Mines (all tasks), P. Craig Taylor (EPR consultant), Klaus Lips (Helmholtz Center, Berlin), Patrick Lenahan (Penn State University)

PROJECT NAME: American Made Solar Data Bounty Prize

Last 5 digits of project number: **40975**
Principal Investigator (PI): **Chris Deline**
Lead Organization: NREL
PI Email: **chris.deline@nrel.gov**

BACKGROUND and OVERVIEW

- Availability of high-quality PV site operations data is difficult to come by and often requires NDAs
- The Data Bounty Prize has now made available five high quality data sets from the winning contributions, to the research community and the public

METHODS

- Request for metadata and data from competitors divided into two possible tracks: <5 MW DC and >5MW DC.
- Submission of detailed site metadata and data following standardized templates and formats
- Analysis of submissions for quality and completeness
- Leverage existing PVDAQ cloud resources to provide a public dissemination platform.

KEY MILESTONES

- 2023-07-11. Prize announcement
- 2023-09-06. Initial round 1 metadata submissions from competitors
- 2023-12 Submission for Round 2 of full site time-series data covering a minimum of five years
- 2024-01-09 Scoring and announcement of winners.
  Data uploaded and available through OEDI site

CONCLUSION

- Previously difficult to obtain data is now readily available for the development of new analysis and research.
- Webinars are being conducted and recorded to aide the research community and public in how to easily access the data and understand the data and tool sets available for analysis.

PHOTOVOLTAICS TRACK

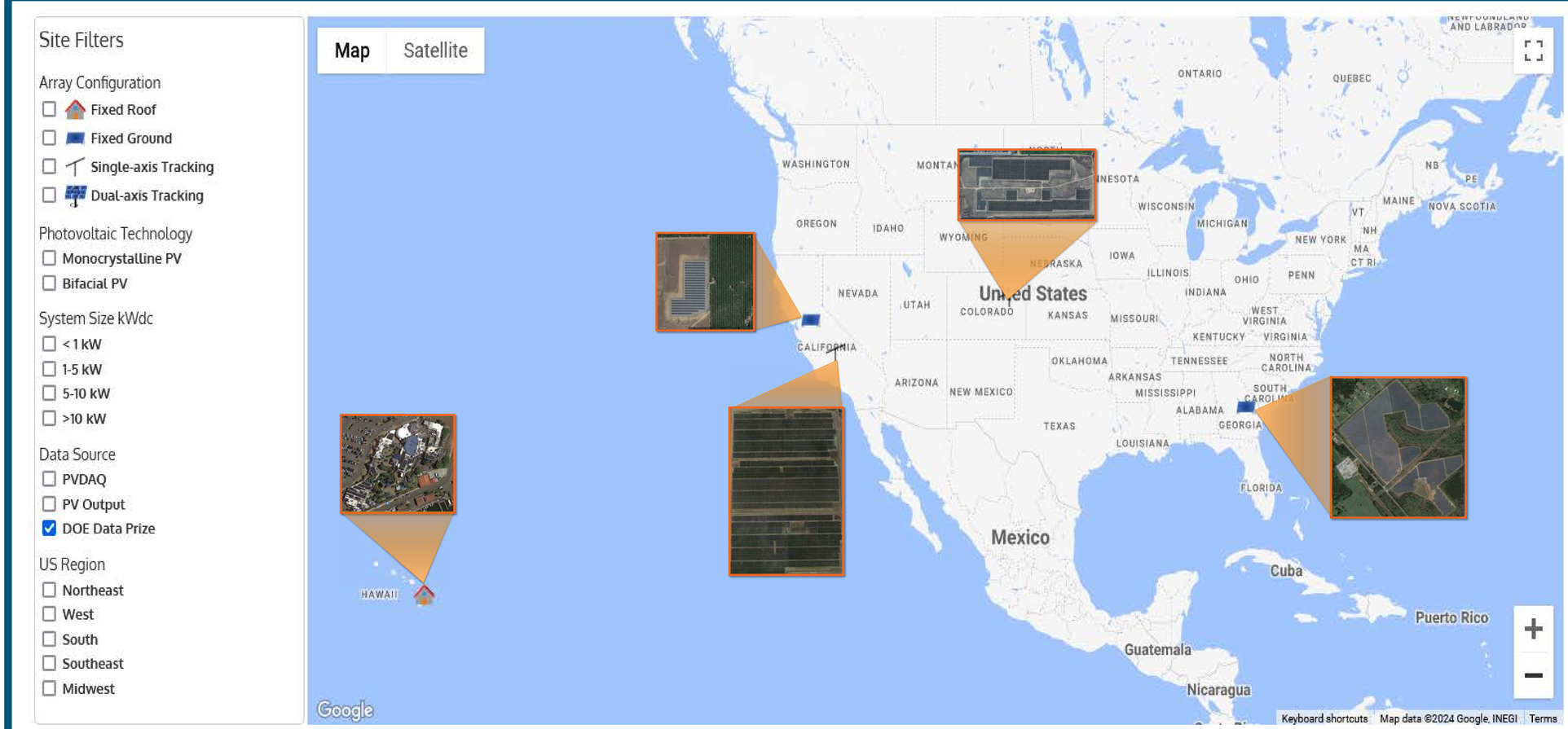
PV Solar Data Bounty Prize:

Publicly Accessible High Quality PV Site Operation Datasets to Support the Research Community

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Take a picture to Open the Data Repository



Additional project contributors: Robert White, Caleigh Issacks, Carlie Ortiz, Emmalee Benson, Silvana Ovaitt, Sofia Toropova, Julia Drummer, Noreen Gentry, and Anastasios Golnas

PROJECT NAME: Quantifying the Impact of Repowering and Reuse

Last 5 digits of project number: **52184**
Principal Investigator (PI): **Silvana Ovaitt**
Lead Organization: **NREL**
PI Email: **silvana.Ovaitt@nrel.gov**

BACKGROUND and OVERVIEW

- This project will provide guidance to the givers and receivers of repowering a solar plant, a lifecycle management practice of replacing modules before their technical lifetime, potentially enabling reuse. We will examine repowering in the context of US solar market dynamics, quantifying the economics, environmental impacts, and justice implications for multiple stakeholders.

METHODS

- PV ICE evaluates material, energy, and carbon impacts of PV deployed at any scale. For this project, the tool will be used for single-systems and linked with the System Advisor Model (SAM) for the economics of the 1st and 2nd life systems.
- Interviews and literature reviews at the beginning of the project will identify the key parameters.

KEY MILESTONES

- Develop the open-source framework to study repower and reuse economics and sustainability aspects with SAM and PV ICE.
- Identify and execute relevant case studies and key parameters for the US market,
- Share results in a journal publication and through an easy-to-understand video for 2nd-life owners, so they can decide if and when to pursue this pathway.

CONCLUSION

There is not much active repowering happening yet in the US, but it is frequently discussed. Most examples involve utilities evaluating repowering, and recipients of the second-life module that would benefit from cheaper and/or donated modules. Through this project, we will identify donor and receipient stakeholder needs and drivers for repowering and reuse, current practices, and explore possible scenarios quantifying the economics, environmental impacts, and energy justice implications.

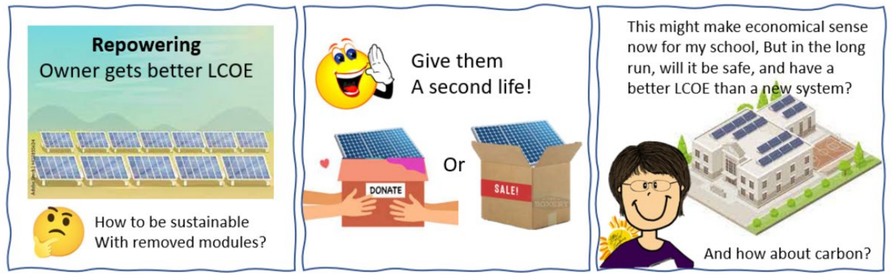
PHOTOVOLTAICS TRACK

Quantifying Repowering and Reuse: Guidance for 1st and 2nd life PV owners quantifying economics, environment impacts and energy justice with PV ICE & SAM

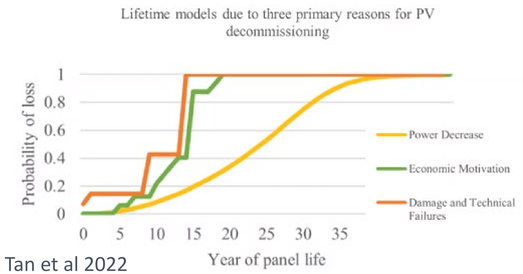
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Overview of the current understanding of repowering and reuse practices, and that we intend to evaluate with this project; economic and sustainability impacts



Data on US repowering is anecdotal; economics are a known important driver, and reliability issues are another motive. It is critical to understand which modules are viable for 2nd-life, technically, economically, and ethically.



Tan et al 2022
doi.org/10.3390/su14095336

"For a 1 MW system that was having reliability issues, the re-engineering costs amounted to $30k. The owner decided to repower at ~$0.49/W"
Henry Hiesleimar (DNV) anecdote at PVRW 2024

Repowering experience from Equitable Energy Solutions
PVCW 2024 Proceedings

PV module ages:
- Average: 11.75 years in service
- Median: 13 years in service
- Minimum: 1 & 2 years
- Maximum: 21

No system-level donations have reached the end of warranty.

Factors driving PV array donations to ESS
- Newer system with better efficiency/performance
- Financial incentives – IRA+adders, accelerated depreciation, more profit
- Rooftop limited – efficiency per surface area
- Re-roof, remodel, building demolition
- Component failure – mostly inverter

Project Impact – Quantifications not Hunches

This project will explore various repowering & reuse cases that are anecdotally discussed, providing quantifications of the main metrics for sustainability, economics and equity. Depending on where boundaries are drawn and project specifics, well-intentioned owners/developers hunches might not be as beneficial as the donors hope they will be.

Cases Impact on:	LCOE	Material Balance	Energy Balance	Capital Cost	Decarb Impact
Repowered Utility	Low	Better	Worse	Low	Good
Add to Utility	Low	Worse	Better	High	Best
LMI School New	Low	Worse	Mid.	High	Good
LMI School - Reused	High	Better	Mid.	Low	Poor

Additional project contributors: Heather Mirletz, Teresa Barnes, Brian Mirletz

PROJECT NAME: Back-Contact Interface Engineering for Higher Efficiency CdTe PV

Last 5 digits of project number: 08974
Principal Investigator (PI): James Sites
Lead Organization: Colorado State University
PI Email: james.sites@colostate.edu

PHOTOVOLTAICS TRACK

BACKGROUND and OVERVIEW

- Key problem is to find the best combination of back-contact layers for CdTe cells that have small contact barriers, low interfacial recombination, and high conductivity.
- The project strategy has been to design and compare various back-contact configurations from three institutions in the partnership.

METHODS

- Explore promising back buffer materials based on quasi-delafossites (e.g., AlGaOx), TeO_2, and polymeric materials (e.g. PTAA).
- Explore PERC-like architectures based on incorporation of passivation layers.
- Exploit transparent back contacts, enabling PL-based interrogation of near back interface carrier lifetimes.
- Develop characterization based on external radiative efficiency as measure of implied Voc.

KEY MILESTONES

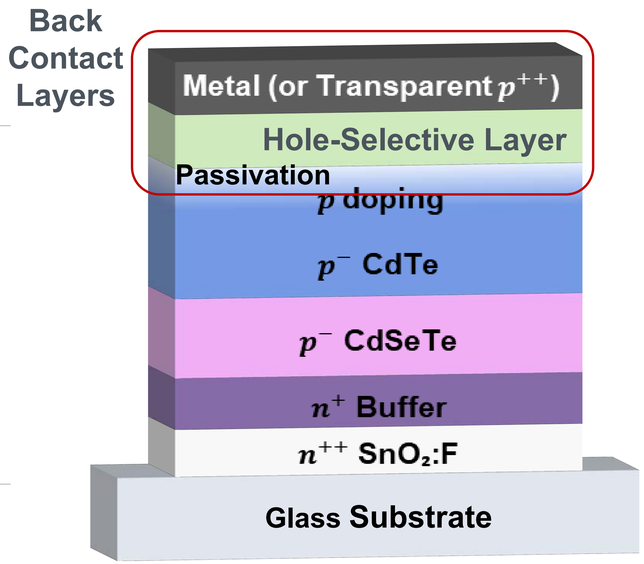
- Cell efficiencies near or above 20% for a variety of back-contact configurations; achieved V_{OC} > 900 mV.
- Carrier recombination lifetimes exceeding 20 ns along with high radiative efficiency of PL peak near the band gap.
- Bifaciality with 20 mA/cm^2 from the back while maintaining 24 mA/cm^2 from the front.

CONCLUSIONS

- Several approaches to the back-contact for CdTe cells have proven successful.
- Working as a team in parallel has allowed very useful comparisons and discussions of the different back contacts.
- The collaboration has especially benefited from the PL characterization at NREL and microscopy at UIC.

Several back-contact configurations at partner labs (First Solar, University of Toledo, and Colorado State University) have led to efficiencies at or near 20% for CdTe-based cells, as well as high carrier lifetimes, improved understanding, and significant bifaciality.

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Partner	Absorber	Doping	Rear Layer	External Contact	Efficiency	Comment
First Solar	CdSeTe/CdTe	As	Polymer/ZnTe	Al	19.8	907 mV
First Solar	Thin CdSeTe/CdTe	As	Polymer/ZnTe	TCO	19.1	80% Bifaciality
Toledo	CdS:O/CdSe/CdTe	Cu	CuSCN	Au	20.0	TEC 12D
Toledo	CdSeTe/CdTe	Bi	Polymer	Au	19.8	907 mV
Toledo	CdSeTe/CdTe	As	AlGaOx/SWNT	Au	19.7	PERC-like contact
CSU	CdSeTe/CdTe	Cu	Te	Ni	19.1	Low A-factor
CSU	CdSeTe/CdTe	As	TeO_2/Te	Ni	19.0	Sputtered TeO2
CSU	CdSeTe/CdTe	None	TeO_2/Te	Ni	18.8	No doping

CdTe cell structure and summary table of key cells from project partners.

Abstract: Three research groups working in coordination have built high-efficiency, polycrystalline CdTe cells with different back-contact designs, transparent for bifaciality in some cases. Two other groups have provided PL evaluation of recombination parameters and atomic-level microscopy of the contact layers and interfaces.

Additional project contributors: University of Toledo, First Solar, University of Illinois at Chicago, National Renewable Energy Laboratory

PROJECT NAME: Solar-Leap: A Democratized Tool to Manage Long-Term Impact of Environmental and Operational Stressors on Asset Performance Degradation

Last 5 digits of project number: **39640**
Principal Investigator (PI): **Hyekyung (Clarisse) Kim**
Lead Organization: **Argonne National Laboratory**
PI Email: clarisse@anl.gov

PHOTOVOLTAICS TRACK

Degradation models for solar inverters subject to different weather, ambient and operational stress conditions, with open-source tool to *characterize inverter failures* and *reduce 10.7% production downtime*.

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BACKGROUND and OVERVIEW

- **Challenge:** Asset Life Improvement (ALI) of SETO's 2030 Solar Cost Targets requires comprehensive understanding and effective management of dynamic climatic, ambient and operational stress conditions.
- **Solution:** This project develop (i) predictive degradation and failure models and (ii) support tools for mitigating the impact of stress conditions (e.g., extreme climate and unfavorable ambient environments) on PV assets.

METHODS

- (1) Develop an in-depth understanding of the long-term reliability implications of different extreme climate and related stress conditions. (2) Propose a decision support tool and mitigation strategies for the adverse effects of extreme climate and related stress conditions. (3) Collaborate with the industry to demonstrate the impact of the proposed methods on their assets and operations.
- **Key Enabler:** Access to multi-year field sensor data and maintenance records from industrial partners

KEY MILESTONES

- [12/2022] Construction of evolving inverter operational dataset with weather metrics.
- [06/2023] Identification of failure modes and extracted stressor indicators from the industrial data based on developed failure mode identification framework.
- [09/2023] Development of degradation models for solar inverters subject to multiple stress conditions that results in 10.7% reduction in production downtime.
- [04/2024] Validation of open-source decision support tool with 15+% reduction in production downtime.

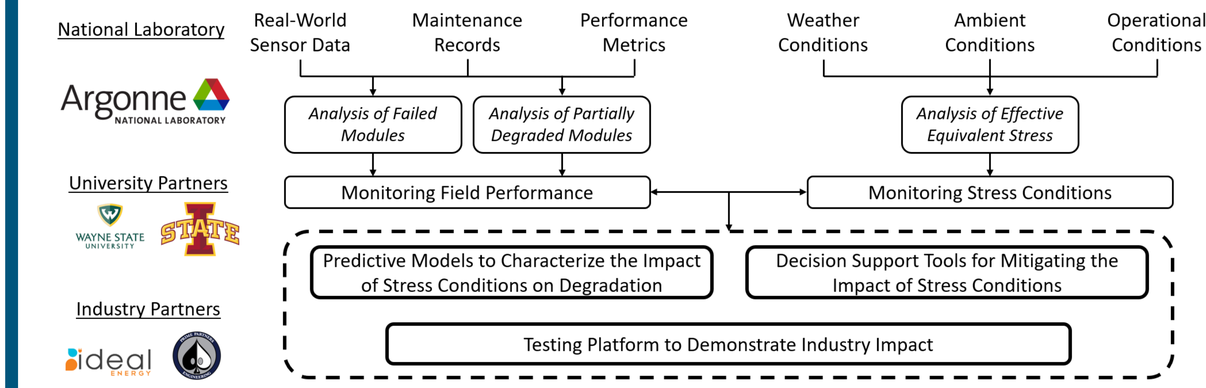
CONCLUSION

- Outcomes of the proposed models will be tested and validated through a comprehensive testing platform built on field data to showcase the accuracy of the predictive models and impact of stress mitigation strategies in terms of cost and reliability.
- Our partnership with Prime Partners Engineering and Ideal Energy enables us to explicitly address the challenges faced by minority owned businesses, and businesses serving under-privileged rural communities.

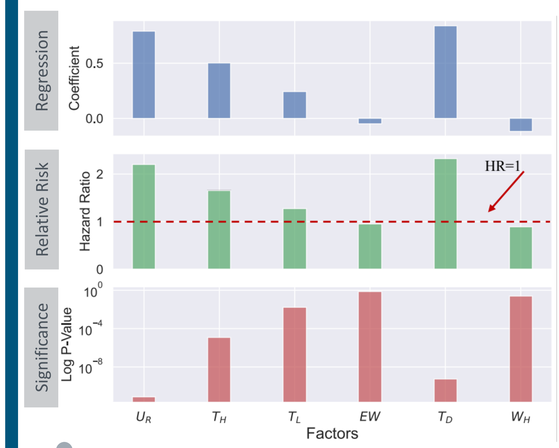
National Laboratory: Argonne National Laboratory

University Partners: Wayne State University, Iowa State University

Industry Partners: ideal ENERGY



Optimize Maintenance and Quantify Economic Impact (Simulation based on statistical distributions in models developed to predict inverter failures)	**Proposed Model** (w/o U_R in regime clusters)	**Benchmark Model** (w/o U_R stress factor)
# Successful Maintenances (Preplanned maintenance time occurs before the realization of failure)	34/39	31/39
Total Unavailable Days	136.63	153



Stress Factors

Domain knowledge-related

U_R: equivalent under-sizing rate

Weather-related

W_H: highest average wind speed among the top 1%

T_H, T_L: the average high/low temperature experienced by the top 1% of the days

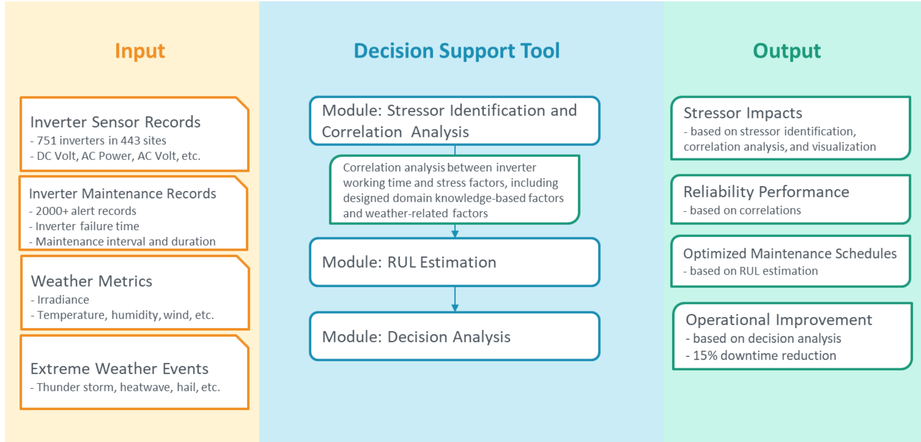
T_D: the average daily temperature difference in the top 1% of time

Extreme event-related

EW: average number of extreme weather events over the operating time

Stress Factors with High Impacts:

Under-sizing rate, Temperature, ...



Additional project contributors: Wayne State University, Iowa State University, Ideal Energy, Prime Partner Engineering, LLC.

PROJECT NAME: Innovative Interfacial Engineering for Simultaneous Enhancement in Efficiency, Stability, and Reliability in Perovskite Devices

Last 5 digits of project number: **09511**

Principal Investigator (PI): **Nitin Padture**

Lead Organization: **Brown University**

PI Email: **nitin_padture@brown.edu**

BACKGROUND and OVERVIEW

- Evolving internal residual stresses and applied external stresses during the operation of multi-layer perovskite solar cells (PSCs) drive interfacial failure, thereby compromising efficiency, stability, and reliability of the devices.
- Here we judiciously engineer the key PSCs interfaces using self-assembled monolayers (SAMs) and/or low-dimensional (LD) halide perovskites to increase the interfacial adhesion toughness (G_C) to simultaneously enhance efficiency, operational-stability, and mechanical-reliability of PSCs.

METHODS

- Iodine-terminated silane SAM was chosen and used to engineer the metal-halide perovskite (MHP)/electron-transport layer (ETL) interface in mesoscopic-rigid and planar-flexible *n-i-p* ('regular') PSCs. Additionally, the MHP/hole-transport layer (HTL) interface was modified using a rationally-designed LD perovskite.
- Iodine-terminated carbazole-based SAM was chosen and synthesized for use in *p-i-n* ('inverted') PSCs at the indium-tin oxide (ITO)/MHP interface.
- In all the cases, an increase in G_C due to SAMs and/or LD perovskite at the interfaces resulted in improvements in not only the operational-stability but also efficiency.

KEY MILESTONES

- Achieved >60% improvement in G_C over control interfaces.
- Achieved efficiency >23% (0.1 cm^2 area) and >20% (1.0 cm^2 area), and *T*80 life >5,000 h (extrapolated; 0.1 cm^2 and 1.0 cm^2 areas) due to SAMs/LD MHP in *n-i-p* mesoscopic-rigid PSCs.
- In *p-i-n* planar-rigid PSCs (0.1 cm^2 area) with SAMs, achieved efficiency >25% and *T*80 life >4,000 h (extrapolated) .
- Achieved efficiency >21% (0.1 cm^2 area) due to SAMs/LD MHP in *n-i-p* planar-flexible PSCs. Efficiency-loss <20% after bending to 5 mm radius achieved. Efficiency >21% (1.0 cm^2 area) not yet achieved. T80 life >4,000 h (1 cm^2 area) not yet achieved.
- Ongoing work on extending these concepts to 10 cm^2 rigid mini-modules, with the goal of achieving efficiency >20% and *T*80 life >5,000 h.

CONCLUSION

- The quantified demonstration of the impact of interfacial mechanical adhesion on the mechanical-reliability, operational-stability, and efficiency of rigid and flexible PSCs is an important accomplishment.
- This presents vast opportunities for the rational design and implementation of new approaches for improving the G_C of the various interfaces in PSCs.
- This work indicates that it is possible to align improvements of efficiency, stability, and reliability critical to the success of PSCs in which improving the interfacial adhesion toughness may be decisive.

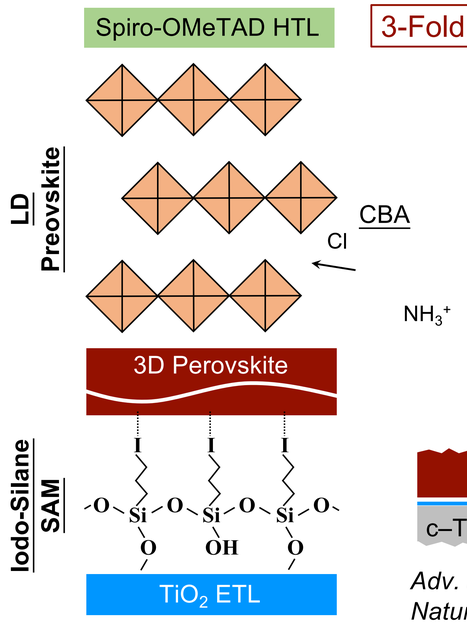
PHOTOVOLTAICS TRACK

Revealing and Utilizing Connections between **Interfacial Mechanical Adhesion**, **Efficiency**, and **Operational-Stability** in High-Performance Perovskite Solar Cells

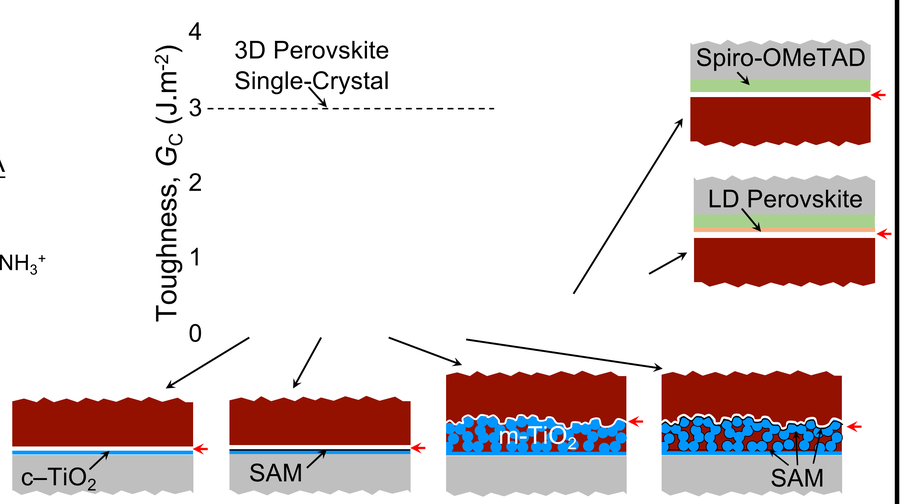
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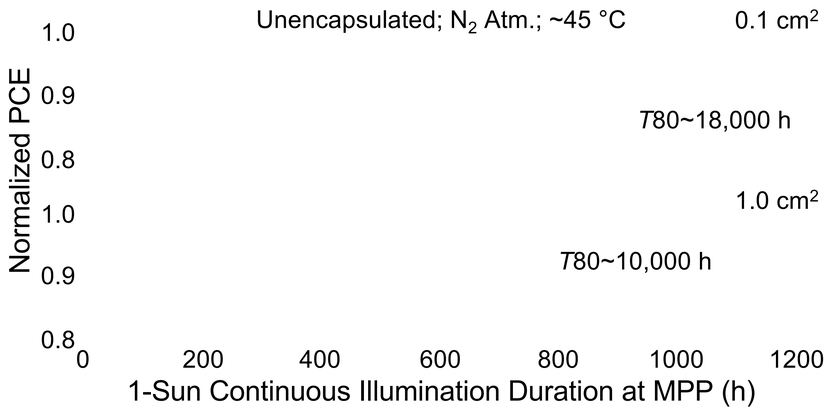
Mesoscopic *n-i-p* PSCs



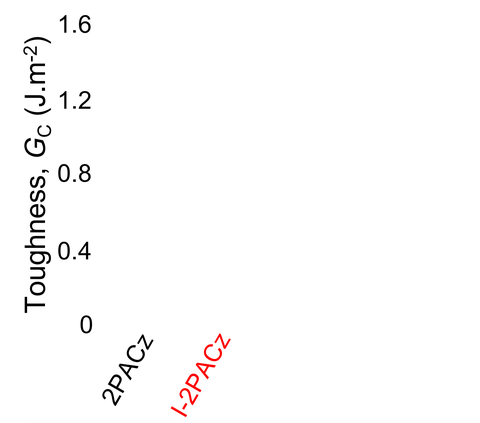
3-Fold Increase in G_C Results in Improved *T*80 and Efficiency



Adv. Mater., **34** (2022) 2205301;
Nature Energy, **8** (2023) 1319;
Adv. Mater, **36** (2024) 2308819

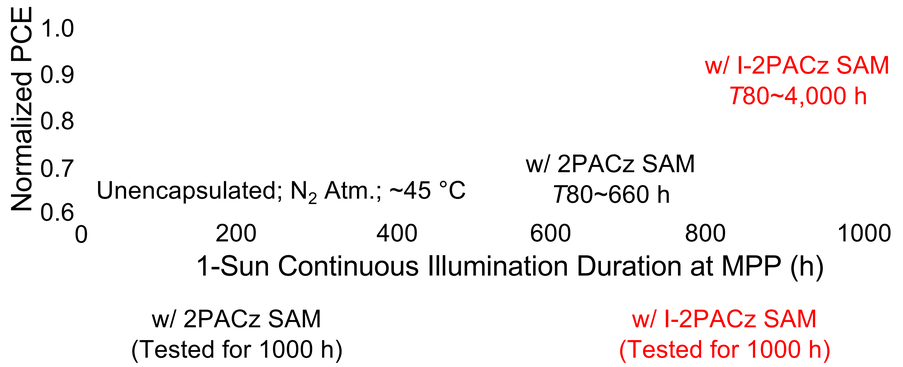


Planar *p-i-n* PSCs



2.6-Fold Increase in G_C Results in 6-Fold Increase in *T*80 and Efficiency Up To 25.44%

ACS Energy Lett., in final review (2024)



Enhanced G_C Suppresses Pore Formation and Interfacial Delamination

Additional project contributors: Brown University.: I.S. Yang, Z. Dai, A. Ranka, M. Layek, Y. Qi, D. Chakraborty. NREL: K. Zhu, J.J. Berry, R.C. Bramante, S. You
Yale University.: P. Guo, S. Li, D. Chen. University of Colorado - Boulder: S.R. Marder, S. Barlow, Y. Zhang

PROJECT NAME: Toward low-cost, efficient and stable perovskite thin-film modules

Last 5 digits of project number: **08970**
Principal Investigator (PI): **Yanfa Yan**
Lead Organization: University of Toledo
PI Email: **yanfa.yan@utoledo.edu**

BACKGROUND and OVERVIEW

- Fabricating efficient perovskite minimodules using scalable methods such as blade and slot die coating is challenging.
- Perovskite solar cells and minimodules can degrade during outdoor tests.
- There is no well-accepted model to predict field lifetime of perovskite solar cells and minimodules through indoor accelerated test

METHODS

- Developed perovskite inks that enabled the fabrication of efficient perovskite minimodules using scalable methods.
- Explored interface materials to improve the stability of perovskite solar cells and minimodules.
- Conducted indoor accelerated stability tests and outdoor stability tests.

KEY MILESTONES

- Fabricated efficient perovskite minimodules (up to 20%) using scalable methods such as blade and slot die coating.
- Perovskite minimodules retained 97% of their initial efficiencies after outdoor tests for more than ten months
- Provided evidence for linking the lab and field lifetime for perovskite solar cells.

CONCLUSION

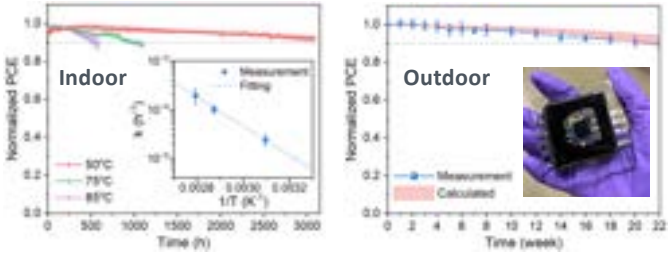
- Efficient perovskite modules can be fabricated using scaling methods.
- Perovskite solar cells and minimodules have demonstrated promising outdoor operational stability.
- Perovskite solar modules may help address SETO's 2030 cost targets.

PHOTOVOLTAICS TRACK

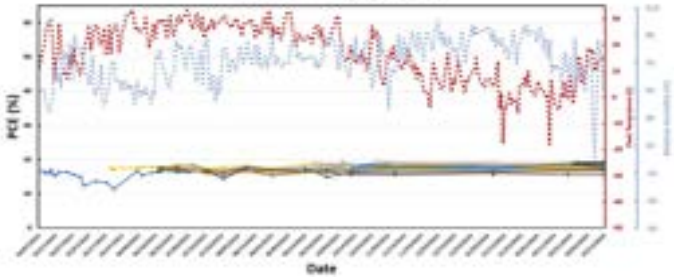
Perovskite **minimodules** retained **97%** of their initial efficiencies after **outdoor** testing for over **ten months**

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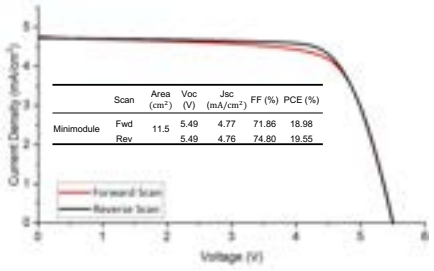
- **Link indoor (lab) and outdoor (field) lifetimes to accelerate stability evaluation of perovskite PV**



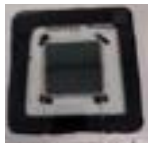
- **Minimodules retained 97% of their initial efficiencies after outdoor tests**



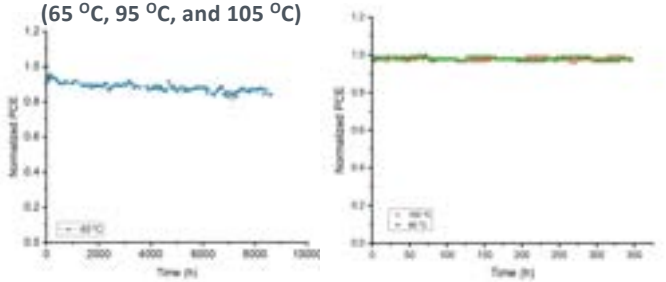
- **A representative perovskite minimodule fabricated by the team**



	Scan	Area (cm²)	Voc (V)	Jsc (mA/cm²)	FF (%)	PCE (%)
Minimodule	Fwd	11.5	5.49	4.77	71.86	18.98
	Rev		5.49	4.76	74.80	19.55



- **MPP tracking of minimodules tested at various temperatures (65 °C, 95 °C, and 105 °C)**



Additional project contributors: National Renewable Energy Laboratory (NREL), First Solar Inc. (FSRL)

PROJECT NAME: *In-situ* antimony doped polycrystalline CdTe films for simplified cell processing and maximized energy

Last 5 digits of project number: **09344**
Principal Investigator (PI): **William Shafarman**
Lead Organization: **University of Delaware**
PI Email: **wns@udel.edu**

PHOTOVOLTAICS TRACK

Approach to increase open circuit voltage of **CdTe** PV using novel **antimony doping** with *in-situ* vapor transport deposition process

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BACKGROUND and OVERVIEW

- To meet 25% efficiency goal CdTe photovoltaics will require higher open circuit voltage (V_{OC}).
- Models show enhanced doping needed for high carrier concentration. Record performance achieved with As-doping but low dopant activation may limit performance.
- Hypothesis: With atomic radius match of Sb to Te and demonstrated stability, Sb-doping can enable high doping efficiency and simplified processing compared to As or Cu dopants.
- Objective: Demonstrate that control of Sb-doping in CdTe:Sb and CdSeTe:Sb using commercially-relevant processes can lead to higher V_{OC} and efficiency and reduced post-deposition processing.

METHODS

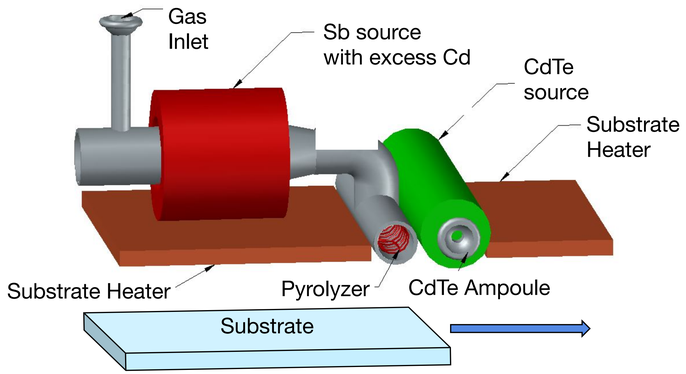
- Novel *in-situ* group-V doping of CdTe in an in-line vapor transport process with two-stage doping source incorporating control of critical process parameters and dopant pyrolysis.
- Develop scientific basis for doping using advanced characterization of defects and carrier dynamics with first-principles theory of defect formation.

KEY MILESTONES

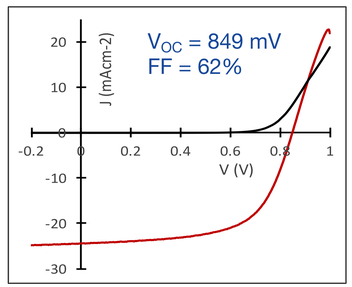
- 50% doping efficiency (carrier concentration / Sb concentration) and voltage deficit $W_{OC} \equiv E_g/q - V_{OC} \leq 600$ mV – achieved 20% doping efficiency, 10X greater than As-doped CdTe, and met W_{OC} goal.
- Density functional theory showed that Sb is a viable dopant and identified compensating defects.
- Bulk lifetime > 50 ns with reduced potential fluctuations shows promise of Sb-doping approach.

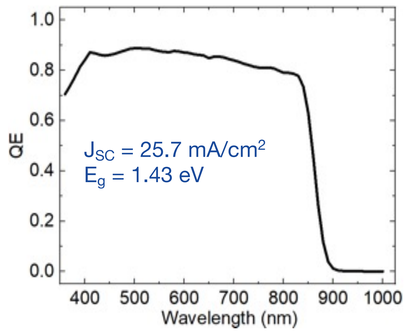
CONCLUSION

- Sb-doping provides path to improved performance of CdTe photovoltaics.
- Critical process controls have been determined but fundamental understanding of doping in CdTe is still needed.

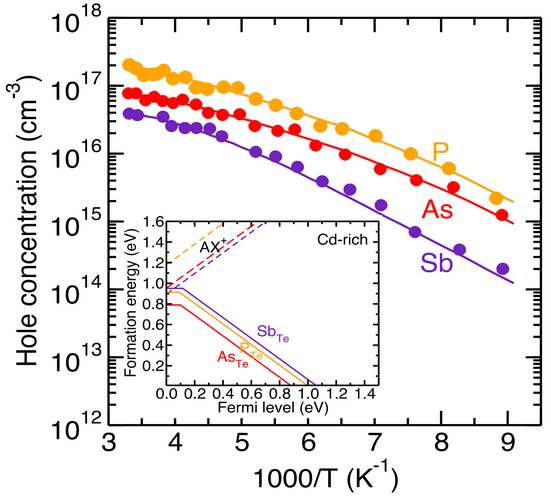


Vapor transport source provides independent control of Sb and Cd with pyrolyzer to form monatomic dopant species and overlapping flux with CdTe source.





Sb-doped CdSeTe solar cell with V_{OC} = 849 mV and voltage deficit W_{OC} < 600 mV. Optimization of back contact process expected to improve device efficiency.



Calculated hole concentration vs. temperature fits recent experimental data showing high hole concentrations in group-V doped CdTe.*

Inset shows calculated formation energies of group-V acceptors and their AX-centers, indicating that all ionization energies are ~100 meV and the AX-centers do not limit hole density.

* Nagaoka, et al., Phys. Rev. B 116, 132102 (2020).

Additional project contributors: Drexel University, The Ohio State University, National Renewable Energy Laboratory

UNIVERSITY OF DELAWARE INSTITUTE OF ENERGY CONVERSION

Robust PV PLR Estimation: Using Spatiotemporal Graph Neural Network Models in a Reliable System-Topology-Aware Learning Framework

Last 5 digits of project number: **09353**
Principal Investigator (PI): Roger French
Lead Organization: Case Western Reserve University
PI Email: **rxf131@case.edu**

PHOTOVOLTAICS TRACK

Leveraging spatio-temporal value dependencies for Autonomous PV dataset grading and Outlier Detection

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Dataset Link

BACKGROUND and OVERVIEW

Photovoltaic (PV) Systems rely on real time data monitoring to evaluate system performance and cost efficiency

- Levelized Cost of Electricity* (LCOE)
  - Power degradation and estimated lifetime
  - Must monitoring and evaluate systems
- Power Degradation & Estimated Lifetime
  - Require complete records of timeseries data
  - Statistical models for
    - Power & Performance Loss Rate (PLR)

METHODS

Time-series Data Imputation Framework (STGAE-Impute):

- **Data Ingestion:** Collects and transforms the raw input data from metering infrastructure of inverters to attributed data D_o
- **PV Data Augmentation:** Transforms D_o to augmented data D_A via a light-weighted imputation process
- **PV Data Corruption:** Injects missing data to D_A with specified missing patterns and configuration
- **PVplr-st-GAE Training:** Corrupted data Dc and the augmented data D_A serve as the input to the st-GAE model, trained by minimizing reconstruction loss between D_R and D_A

KEY MILESTONES

- Creation of Graph-based PV Performance analysis tools (PVplr-stGNN) **COMPLETED**
  - PVplr-stGAE/ PV-stGNN-PLR
- Validation of Graph Based Tools for Imputation / Trend Estimation **COMPLETED**
- Leverage Fleet level timeseries data for large scale graph machine learning (**IN PROGRESS**)
  - Graph Machine Learning 100,000+ timeseries
- Dissemination of Model Architecture and Pretrained Graph Models **COMPLETED**

CONCLUSION

st-GAE:

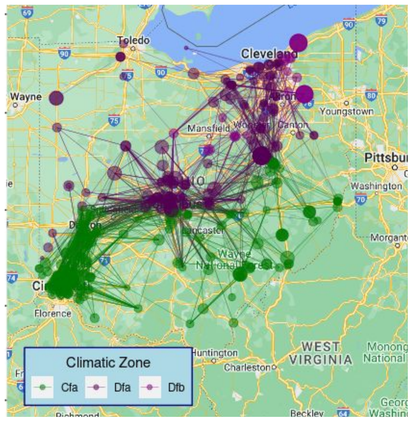
- Obtains **superior outlier detection accuracy**
- **Retains Raw Data** properties
  - ➔ Seasonality , Magnitude
- Graph-based Outlier Detection
  - ➔ **"Learned"** from **Fleet**
  - ➔ **Physics Informed Loss**
  - ➔ Data Similarity

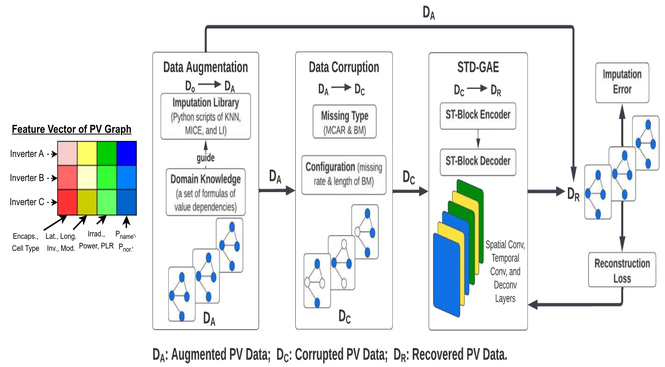
What IS a graph?

- Deep learning Method
- Allows for "message passing"
  - Sharing of information between Datasets
  - Amount of information dependent on how "similar" nodes are
- Transformers (NLP) and CNNs
  - Special Graphs
- Used to connect individual datasets

Why USE graphs?

- Coherence
  - Value Dependencies
    - Space / Time
    - Categorical Data
- Leverages entirety of large datasets
  - Knowledge Extraction





D_A: Augmented PV Data; D_C: Corrupted PV Data; D_R: Recovered PV Data.

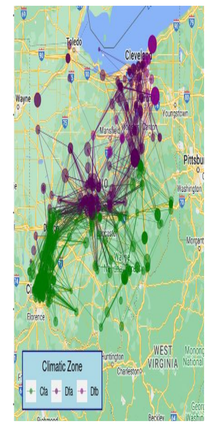
Multi-Channel stGNNs:

- Mirror the inputs of leading physics based models.
  - Irradiance channels:
    - DNI DHI GHI
  - Temperature:
    - Air Temperature, Module Temperature
  - Windspeed
  - Curtailment
- FAIRified metadata feature vectors
  - Value dependencies
- Observes spatio-temporal dependencies
  - Weather Patterns

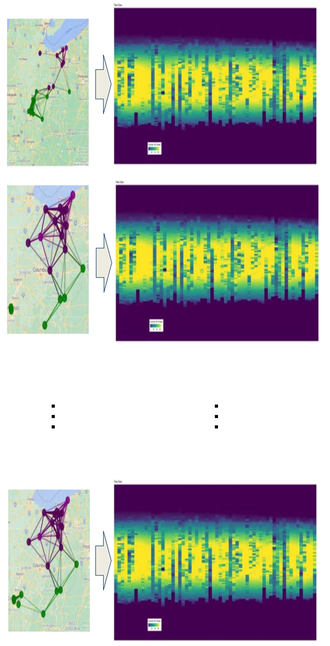
Site Similarity

- **Ensemble Domain Metrics**
  - Distance, Cell Technology, Climatic Zone, etc…
- Linear Regression of the coefficient on similarity matrices
  - Determines the contribution of each similarity metric
  - Allows for featurized studies of system parameters like cell type

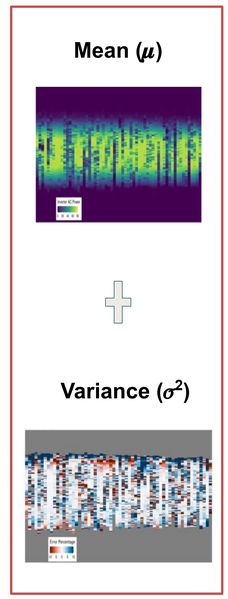
PV Fleet



Graph 'Conditional' Simulations



Final Power Prediction



Graph Models provide a framework for connecting different systems together, we can assist in learning the spatio-temporal dependencies by giving each node more information on the predictive values.

stGAE is data-driven - better represents real performance of system overall (absolute magnitude)

stGAE-detect

- represents real-time conditions
  - on performance of neighbors
  - + opt. weather inputs
- PV systems as labeled sensors
- vs satellite / physical sensors of empirical (steady state assumptions)

Additional project contributors: Raymond Wieser, Yangxin Fan, Xuanji Yu, Jen Braid, Daniel Gibbons, Adam Hoffman, Jean-Nicolas Jaubert, Nicholas Steffan, Ashwin Nair, Avishai Shaton, Laura Bruckman, Yinghui Wu, Roger French

PROJECT NAME: Accelerating Cycles of Learning of Advanced Silicon Architectures: Cell Processing Approaches and their Effect on Degradation Mechanisms

Last 5 digits of project number: **10250**
Principal Investigator (PI): **Laura Bruckman**
Lead Organization: **Case Western Reserve University**
PI Email: laura.bruckman@case.edu

BACKGROUND and OVERVIEW

- Novel materials/processes in advanced c-Si PV devices introduces potential for complex avenues of failure
- Identify/mitigate failure modes, complicated by internal and external stressors
- Deconvolute effects of environment, encapsulation
- Cell-level contributions to module failure are important
- Creation of reliable screening process spaces for industry to rapidly assess design and lifetime constraints

METHODS

- Apply accelerated aging schemes of various stressors and stress levels to different unencapsulated devices
- Stepwise non-destructive characterization to assess device-level performance losses.
- Advanced materials characterization to ascertain materials-level root causes for performance loss
- Input measured device/materials characteristics into netSEM, a statistical learning method by which degradation pathways can be inferentially modeled for lifetime prediction

KEY MILESTONES

- Completed characterization (stepwise, destructive) of samples undergoing relevant exposure types and exhibiting at least 25% loss in characteristic
- Modeled degradation pathways for exposures of each architecture and generated rank ordered list of degradation mechanisms (network model)
- Drafted prioritized review of degradation pathways applicable across device architectures
- Presented methodology and failure modes to members of PV industry and received feedback on rapid screening process

CONCLUSION

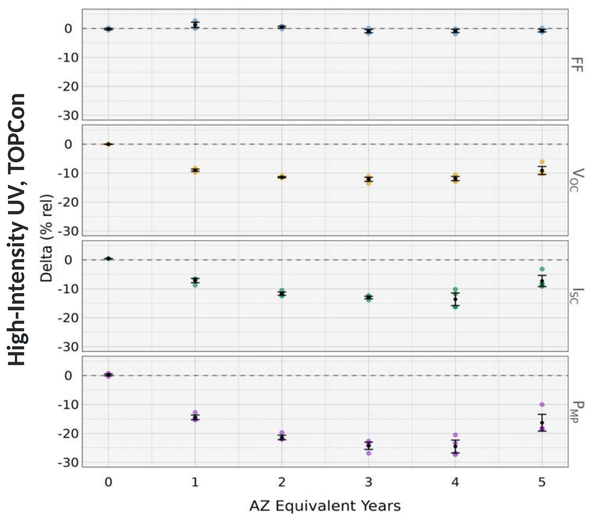
- Accelerated aging, characterization, and domain knowledge has informed the creation of degradation pathway models, providing data-driven insights in combination with physical modeling and experimental results
- Provides PV industry with a framework for evaluating technologies, creating a space for screening degradation to better inform materials choice and device design

PHOTOVOLTAICS TRACK

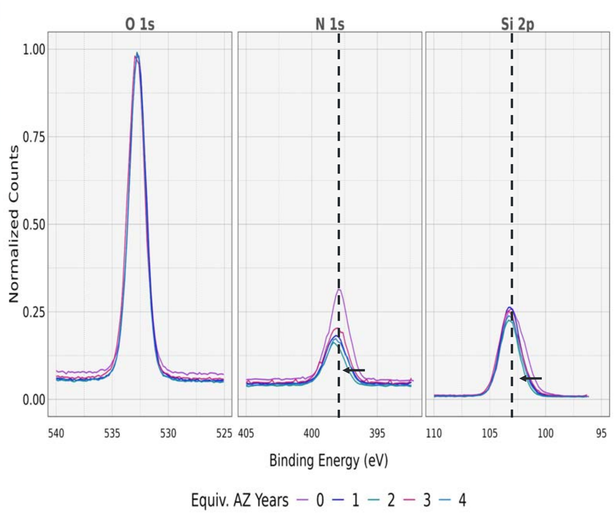
Develop rapid screening process for **unencapsulated PV architectures** informed by **material contributions to device performance loss** under exposure to varied stressors

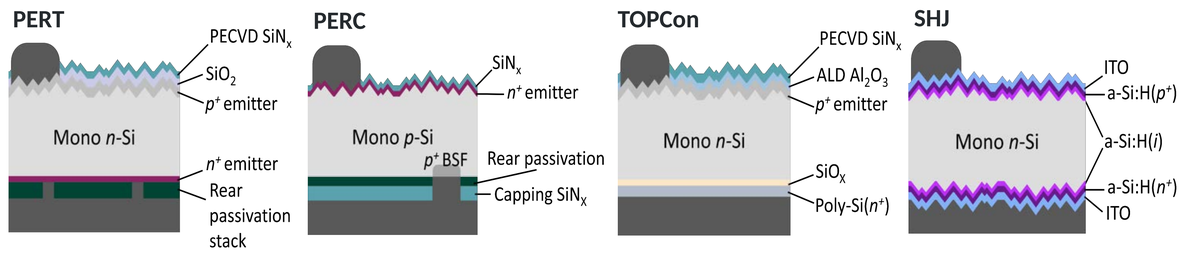
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Device-level Performance Loss

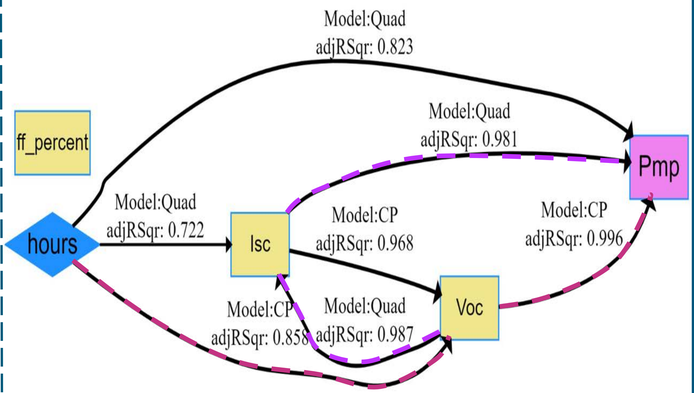


Materials-level Root Cause Analysis





Degradation Pathway Modeling and Lifetime Prediction



Degradation Pathway	Min. adj R^2
hours → Pmp	0.823
hours → Voc → Pmp	0.858
hours → Isc → Pmp	0.721
hours → Voc → Isc → Pmp	0.858

- Most probable degradation pathways are through V_{OC} , I_{SC} as these have highest minimum correlations
- No pathway through FF (evidenced by little/no change in graph at right)

Additional project contributors: University of Central Florida, Arizona State University

Low temperature printing for Next Generation Perovskite Tandem Solar Cells with Little to No Silver Content

Last 5 digits of project number: **11157**
Principal Investigator (PI): **Owen Hildreth**
Lead Organization: **Colorado School of Mines**
PI Email: **ohildreth@mines.edu**

PHOTOVOLTAICS TRACK

Novel Reactive Copper and Silver inks to enable low-cost, low-temperature metallization of perovskite tandem photovoltaic cells. Project will reduce silver consumption by 80% or completely replace with copper.

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BACKGROUND and OVERVIEW

- Problem: Perovskite tandem photovoltaic cells are temperature sensitive and are incompatible with traditional, low-cost metallization strategies.
- This project will develop a set of low-temperature reactive silver and copper inks to metallize perovskite tandem cells to reduce metallization costs while improving manufacturability.

METHODS

- Chemical compatibility of reactive silver and copper inks with perovskite tandem PV cells will be evaluated and ink composition adjusted as necessary
- Optimize ink and printing process for good electrical properties (media resistivity, contact resistance) and cell performance (efficiency, J_{sc}, V_{oc}, IV, line width)
- Demonstrate reliability with 100-hr stress test

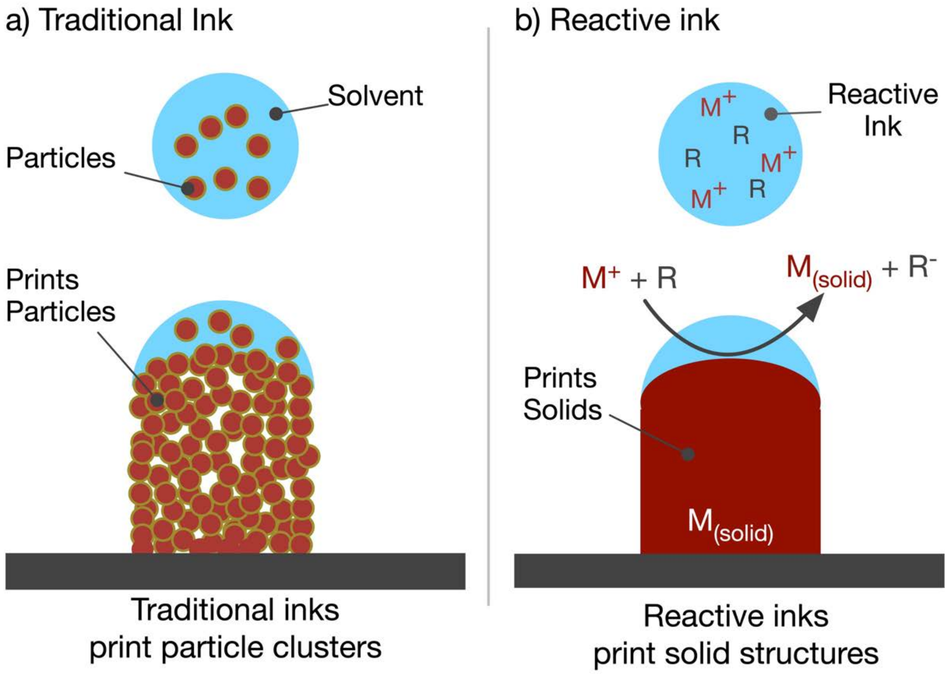
KEY MILESTONES

- Printed reactive silver/copper ink properties: line width ≤ 40 µm; resistivity ≤ 4 µΩ-cm; line resistance ≤ 4 Ω/cm
- Tandem cell efficiency with reactive ink metallization within 10% (relative) of the evaporated silver metallization baseline
- 80% reduction in silver metallization relative to low-temperature screen-printed pastes or complete replacement of silver with copper metallization

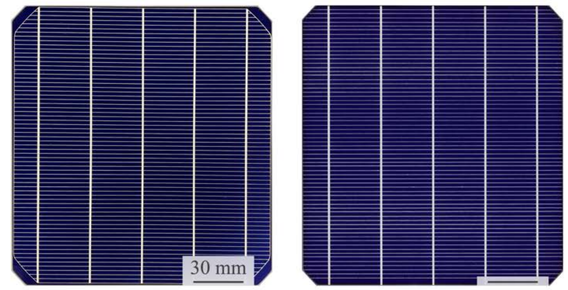
CONCLUSION

- Enable low-cost, high-quality metallization of perovskite tandem PV cells
- Improve manufacturability of perovskite tandem PV cells
- Reduce silver consumption by 80% or complete replacement with low-cost copper

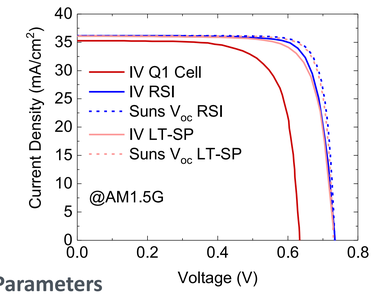
Reactive Inks Print Chemical Reactions Instead of Particles

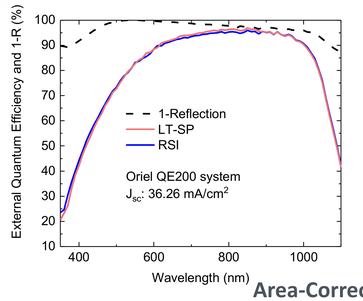


Example: Reactive Inks for SHJ



- Prior work developed reactive silver inks (RSI) for Silicon Heterojunction (SHJ) cells to reduce silver consumption by ~90%.
- This new project will develop reactive silver and copper inks to metallize perovskite tandem PV Cells





JV Parameters — **Area-Corrected**

	Finger Ag Content (mg/finger)	V_{oc} (mV)	J_{sc} (mA/cm²)	FF (%)	R_s (Ω cm²)	Efficiency (%)	J_{sc} (mA/cm²)	Efficiency (%)
LT-SP	3.38	730	31.48	78.11	1.45	18.07	36.2	20.6
RSI	0.30	734	30.54	80.4	0.87	17.99	36.1	21.3

Additional project contributors: Mariana Bertoni (Arizona State University); Zhengshan Yu (Beyond Silicon)

Investigations of Single-Crystal CdTe on Silicon to Enable Future PV Devices

Last 5 digits of project number: **10252**
Principal Investigator (PI): **Peter Dingus**
Lead Organization: **Uriel Solar Inc.**
PI Email: **peterdingus@urielsolar.net**

PHOTOVOLTAICS TRACK

High Quality Single-Crystal CdTe grown on Silicon Substrate by CSS at 16µm/min. CdTe Solar Cell with diffused/insitu As & In doping without post-growth halide treatments .

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BACKGROUND and OVERVIEW

- This project will focus on de-risking single-crystal CdTe solar cells grown on inexpensive silicon templates without post-growth halide treatments as a prototype to more stable, high efficiency CdTe solar cells.
- MBE growth of nucleating template on silicon substrate followed by high deposition rate close-space sublimation (CSS) to produce single-crystal CdTe.
- Doping by diffusion. CdTe homo-junction emitter.

METHODS

- MBE template nucleation layer by MEE on Si<211> and Si<100>
- MBE single-crystal 0.5µm ZnTe:As on Silicon
- 3µm-8µm single-Crystal CdTe by MBE/CSS
- Insitu & diffusion doping ZnTe:As and CdTe:As by MBE/RTP-oven
- Insitu & diffusion doping CdTe:In by MBE/RTP-oven

KEY MILESTONES

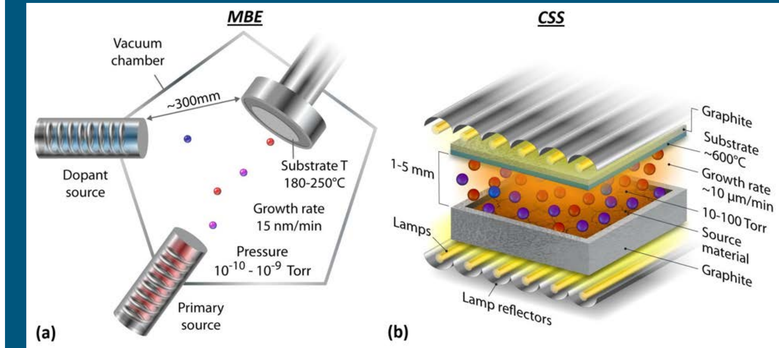
1. Molecular Beam Epitaxy used to deposit p-ZnTe with a carrier concentration cc≥5.0x10^{17}/cm3
2. Close-Space Sublimation used to deposit single-crystal CdTe (Thickness ≤15um) XRD FWHM ≤350”
3. p-CdTe with a carrier concentration cc ≥10^{16}/cm^3
4. n-emitter with a carrier concentration cc ≥ 10^{17} /cm^3

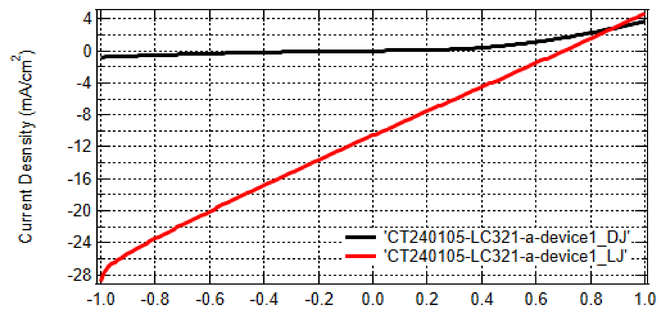
5.1 Close-Space Sublimation used to deposit single-crystal CdTe (Thickness ≤8um) XRD FWHM ≤350”

5.2 Epi-CdTe solar cell on Si Voc≥0.9V — Not yet demonstrated

CONCLUSION

- Epi-ZnTe/CdTe deposited on 12% mismatched Silicon
- CdTe single-crystal deposited at 16µm/min by CSS
- Diffusion Doping of n-type and p-type CdTe
- Good photocurrent with no post-deposition Halide heat treatment (no $CdCl_2$).
- High Voc with CdTe homo-junction.





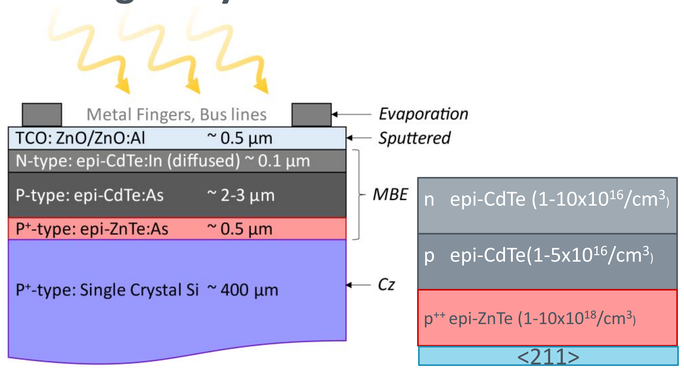
Device	Voc (mV)	Jsc (mA/cm²)	FF (%)
1	760	10.58	24.96
2	709	11.50	24.71
3	688	9.18	25.27

No TCO test structure (metal indium pads only)



Device area = 0.01 cm^2
Around indium pad

Single-Crystal CdTe:As on Silicon



MBE CdTe - Si<211> — In Situ CdTe:As, CdTe:In Doping

	FWHM – XRD (arcsec)	CC – Hall (cm-3)	Mobility – Hall (cm2/V.s)
N	79 CT220908	-3.2E17 CT220908	731 CT220908
P	87 CA230227	4E16 CA230227	83.5 CA230227

CSS CdTe - Si<211>—CdTe:As, CdTe:In Diffusion Doping

	FWHM – XRD (arcsec)	CC – Hall (cm-3)	Mobility – Hall (cm2/V.s)
N	110 CSS221207b	-3.4E17 CSS221207b	637 CSS221207b
P	171-258 CSS230313b	3.2E15 CSS230313b	59.4 CSS230313b

Additional project contributors: James Garnett (US), Eric Colegrove, Hongling Lott, Anthony Rice, Mathew Reese (NREL)

PROJECT NAME: Development of ~25% Efficient Double Side Screen Printed Poly-Si/SiO_x Passivated Contact Solar Cells

Last 5 digits of project number: **09350**
Principal Investigator (PI): **Ajeet Rohatgi**
Lead Organization: **Georgia Institute of Technology**
PI Email: **ajeet.rohatgi@ece.gatech.edu**

BACKGROUND and OVERVIEW

- Recombination in the diffused and metallized regions within the Si absorber are the major loss mechanisms in current low-cost Si solar cells.
- This project involves a comprehensive and challenging program to develop 24-25% efficient large-area commercial ready low-cost DS-TOPCon back junction (BJ) bifacial cells with screen-printed contacts on both sides.

METHODS

- Implementation of either thin homogeneous n-TOPCon on the entire front surface or selective area thick (≥100 nm) n-TOPCon underneath the front metal contact with dielectric passivated textured n-bulk in the field region.
- Conjunction with planar hole selective p+-poly-Si/SiOx passivated contact (p-TOPCon) on the rear surface, which will serve the function of the rear junction.

KEY MILESTONES

- High quality full area thin n-TOPCon on the textured front surface with metallized J_0 ~10 fA/cm² or metallized J_0 of ~5 fA/cm² for selective area n-TOPCon with J_{0}_field ~ 5 fA/cm²
- High quality p-TOPCon on the rear with metallized J_0 <10 fA/cm² with ~5% metal-Si contact area
- Optimized wafer resistivity/bulk lifetime to achieve bulk J_0 ~10 fA/cm²
- Validation of >24% selective DS-TOPCon cell efficiency

CONCLUSION

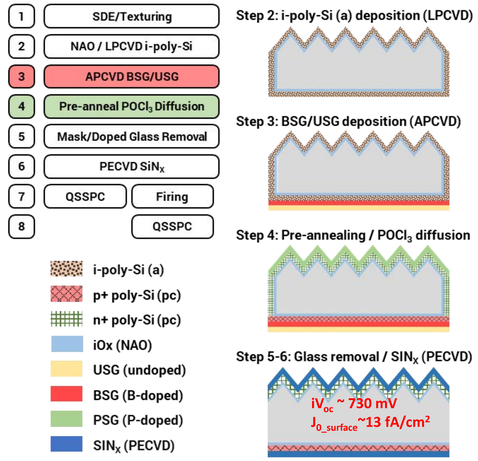
- Achieved total J_0 of ~11 fA/cm² for selective ex-situ doped thick n-TOPCon on for front and total J0 of ~20 fA/cm² for ex-situ doped p-TOPCon on the rear side.
- Developed a novel low-cost technology for producing asymmetric DS-TOPCon cell precursors with excellent iVoc of ~730 mV
- Demonstrated ~21.2% full area DS-TOPCon and ~22.5% selective DS-TOPCon cell
- Need to further the cell process optimization to increase cell efficiency (Final stage)

PHOTOVOLTAICS TRACK

Development of a Novel Low-Cost Technology For High-Efficiency (>24%) Screen-Printed Rear Junction Selective-Area Double Side TOPCon Si Solar Cells

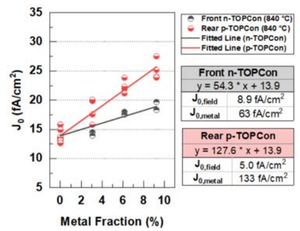
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Successful Development of a Process Sequence and Technology for Forming Full Area DS-TOPCon Precursor Involving a Single High Temperature Step Without Any Masking

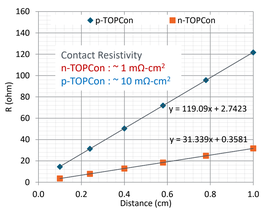


Characterization of Passivated and Metallized J_0 as well as Contact Resistivity of Tx-n-TOPCon and Planar p-TOPCon Layers in Our Current DS-TOPCon Cell Precursors

QSSPC for J_{0_Field} and J_{0_metal}

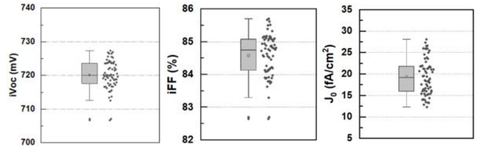


TLM For Contact Resistivity

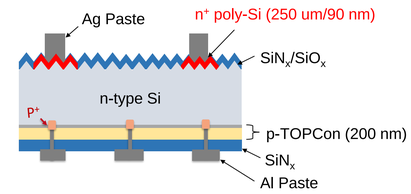


Properties	200nm Textured n-TOPCon		300nm Planar p-TOPCon	
	Passivated Full Area	Metallized Full Area	Passivated Full Area	Metallized Full Area
100% Jo (fA/cm²)	9	~60	~5	~130
Contact Resistivity (mΩ-cm²)	0.7-2.0		10-15	

iV_{oc}/J_0/iFF Values of Unmetallized Selective DS-TOPCon Cell Precursors-Compatible with 24% Efficiency

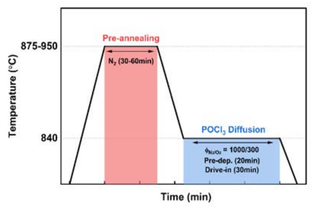


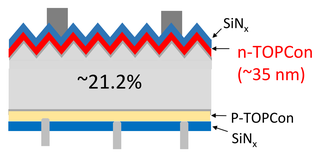
Successful Fabrication of ~22.5% Selective DS-TOPCon Cell



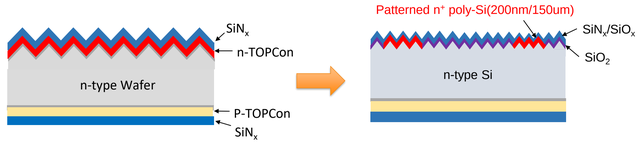
Voc(V)	Jsc(mA/cm²)	FF(%)	Eff(%)
0.693	39.5	82.1	22.5

Single Step Co-diffusion Process for DS-TOPCon Precursor, Resulting in ~21.2% Full Area Screen Printed DS-TOPCon Cells

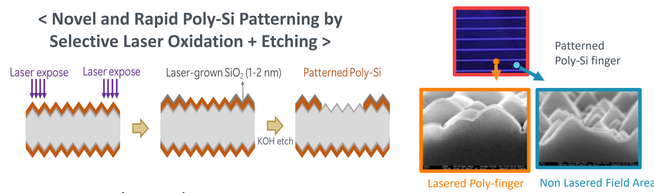




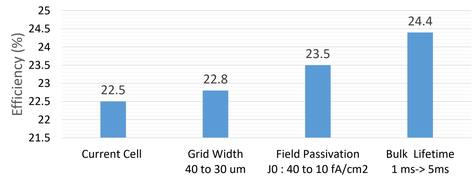
Successful Patterning of n-TOCon Fingers by Inject Printing and Selective Laser Oxidation



< Novel and Rapid Poly-Si Patterning by Selective Laser Oxidation + Etching >



Current Roadmap and Process Development to Raise the Efficiency From 22.5% to >24%



Additional project contributors: Solar Energy Research Institute of Singapore (SERIS)

PROJECT NAME: Development of Commercial-Ready Screen Printed ~23% PERC and TOPCon Cells by Replacing Ag Contacts with Novel Low-Cost Cu and/or Al Pastes

Last 5 digits of project number: **10497**
Principal Investigator (PI): **Ajeet Rohatgi**
Lead Organization: **Georgia Institute of Technology**
PI Email: **ajeet.rohatgi@ece.gatech.edu**

PHOTOVOLTAICS TRACK

Development of Ag Free Commercial-Ready Screen Printed ~23% PERC and TOPCon Cells With Novel Low-Cost Cu and Al Pastes

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BACKGROUND and OVERVIEW

- Ag metal contacts still account for ≥ 30% of the cost of solar cells and the supply of the Ag may become an issue as we move toward Terawatt scale PV.
- The goal of this project is to eliminate Ag contacts by novel low-cost copper (Cu) and/or Al screen printable pastes, which cost ≤1% of Ag paste, without compromising efficiency and reliability of p-PERC and TOPCon Si solar cells.

METHODS

- Development of advanced screen printable atmospheric Cu paste to replace Ag contacts on Si solar cells.
- Development of advanced screen-printable alloying and non-alloying Al pastes to replace Ag contacts on front and back of Si solar cells.
- Fabrication of ~23% p-PERC or n-TOPCon cells with screen printed Cu on n+ emitter or n-TOPCon in combination with alloy Al (or Al non-alloying) contact on p+ emitter (or n-TOPcon)

KEY MILESTONES

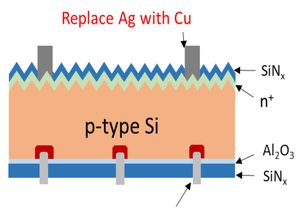
- Screen printed Cu grid width ~40 µm/contact resistance ≤ 5 mΩ-cm^2 / metal contact weighted $J_{0\text{-}metal}$ ~ 30 fA/cm^2 on diffused n$^+$ emitter and/or on n-poly-Si.
- Screen printed Al grid line width ~50 µm/ contact resistance ≤ 1 mΩ-cm^2 / metal contact weighted $J_{0\text{-}metal}$< 20 fA/cm^2 on diffused p+ emitter for the alloying Al paste.
- Fabrication and validation of commercial ready Ag free >21.5% p-PERC and/or >22.5% n-TOPCon cells with Cu and/or Al contact

CONCLUSION

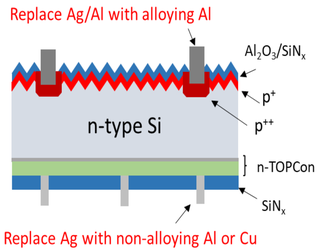
- Established the target values of all the contact parameter for Al and Cu contact that can lead to 22-23% Ag free p-PERC and TOPCon cells.
- Investigated the screen-printing parameters and firing temperature to optimized Cu paste printability and contact properties.
- Demonstrated contact resistivity ~ 5 mohm-cm^2 with grid width of ~70 um
- Achieved 20.2% p-PERC with Cu contact on n+

Proposed Cell Structures and Efficiency Targets for the Ag-free p-PERC and n-TOPCon cells

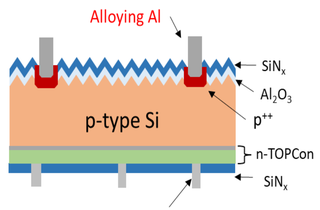
(a) ~22% p-base PERC



(b) ~23% n-base FJ TOPCon



(c) ~22.5% p-base BJ TOPCon



Device Modelling To Establish Required Screen-Printed Cu and Al contact Parameters For the Front and Back Layers To Achieve 22-23% p-PERC and n-TOPCon cells

Paste	Cu paste		Al (alloy)	Al (non-alloy)	Simulation	Cells
Layer	n+ emitter	N-TOPCon	p+ emitter or p-wafer	N-TOPCon	• Quokka 2D Modelling of 22-23% • Modeling of fabricated cells to quantify loss Mechanisms • roadmap to >24%	>22% p-PERC
Line Width (um)	<40	<60	<50	<100		
Contact Resistivity (mΩ-cm^2)	≤ 5	≤ 5	≤1	≤5		
$J_{0\text{-metal},100\%}$ (fA/cm^2)	≤700	≤200	≤600 (line), ≤6000 (dot)	≤1000 (dot)		22-23% n-TOPCon
Weighted Jo-metal	~ 20 (2.5%)	~20 (10%)	~15 / (3, 0.3%)	10 (1%)		
Final Delivery >22.5% Ag free P-PERC or n-TOPcon with Cu and/or Al contacts						

Additional project contributors: BERT Thin Films (Thad Druffel) and TOYO Aluminum (Dhamrin Marwan)

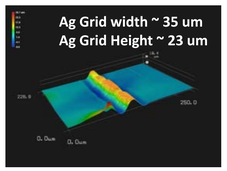
Successful Demonstration of >20% PERC Cell with Screen Printed Cu on n$^+$ Emitter and Local Al BSF on the back.

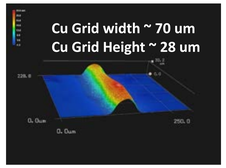
Cu contacted p-PERC cells



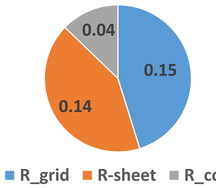
Ag contacted p-PERC cells





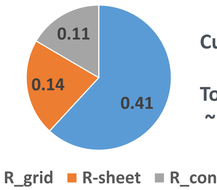


Detailed Analysis and Comparison of Rs Components of Ag and Cu contacts to n$^+$ emitter of p-PERC Cells



Ag Contacts on n$^+$

Total Rs (front) ~ 0.3 Ohm-cm^2



Cu Contacts on n$^+$

Total Rs (Front) ~ 0.8 Ohm-cm^2

p-PERC Cells with Screen Printed Ag or Cu on n$^+$ Emitter

n+ contact	Firing	Voc(V)	Isc(A)	Jsc(mA/cm^2)	FF(%)	Eff(%)
Cu Contacted	Co-Firing	0.602	8.53	35.7	45.7	9.0
Cu Contacted	Two-step Firing	0.660	9.50	39.8	77.2	20.2
Ag contacted	Co-Firing	0.674	9.88	40.4	81.2	22.1

PROJECT NAME: Maturing Critical Structural Connections – Solar PV Module Mounting & Rack Assemblies #38532

Principal Investigator (PI): Gerald Robinson
Lawrence Berkeley National Laboratory
gtrobinson@lbl.gov

BACKGROUND and OVERVIEW

- Module mounting and rack critical structural connections are subjected to highly dynamic loading.
- The small and unique fastener stacks used are not represented in code and standards + supporting testing methods.
- **Core objective:** Contribute to maturing of solar PV critical structural connections.

METHODS

- **Develop Classification system** – common language (https://so.lbl.gov/solar-pv-critical-fastened-joints)
- **Failure surveys** – quantify & characterize.
- **Codes & Standards** Gaps
- Transferable Knowledge
- **Model wind loading** – CFD of structure to FEA of joint.
- **Lab testing** – simulate dynamic loading
- **Guidance Document**: good practices in fastened joints tailored to Solar PV structures.

KEY MILESTONES

- Significant contributions to:
  - **ASCE** – Solar Structures Committee – Method of Practice (MOP)
  - **UL – 2703** (in progress)
- Modeling discoveries – testing needs to inform.
- Significant code/standards gaps.
- Systems-level testing can inform simpler product-level testing.

CONCLUSION

- Critical to understand systems-level interactions: two way street between joint performance and rack performance.
- First generation fastened joint guidance will be published in the MOP and strength testing in UL. 2703. Work continues here.
- Test rack is 1st ever systems level means to strength test connections.

PHOTOVOLTAICS TRACK

Critical Structural Connections in Solar PV Rack Assemblies are Subjected to Dynamic Loading Conditions

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Failure Modes



Failure Effects



Classification System



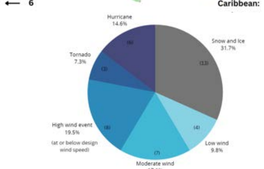


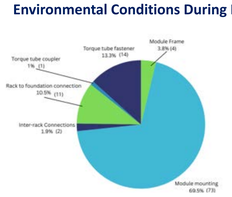
Survey Results



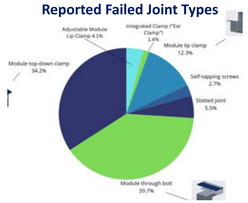


Environmental Conditions During Failure





Reported Failed Joint Types

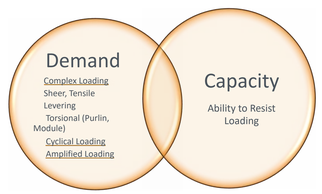


Reported Failed Module Mounting Type



Postulated Failure Causes

Codes & Standards Gaps





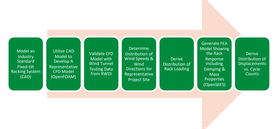
Prevalence of "Suspect" Hardware – No Traceability & compliance with Fastener Quality Act (FAQ) – https://indfast.org/about-us/fastener-quality-act/

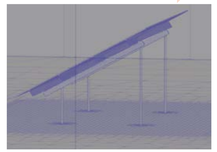
Self Apparent Code Gaps

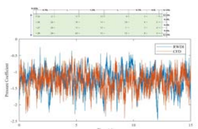
Transferable Knowledge

1. ASCE Solar Structures Committee – The Method of Practice (MOP
2. UL 2703 Active Working Committee
3. SEIA Standards Development (https://www.seia.org/initiatives/standards-development)
4. IEC S82/1740/NP -Evaluation of Photovoltaic (PV) Module to Mounting Structure Interface – Spring 2024

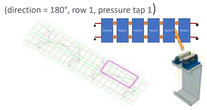
Modeling



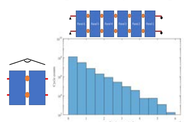




Comparison of time series of pressure coefficients from experiments and CFD
(direction = 180°, row 1, pressure tap 1)



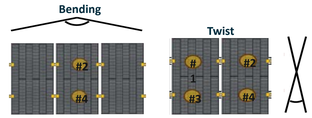
Estimating structural responses using FEA



Determining Joint Duty Cycles for a Given Wind Profile

Systems Level Testing

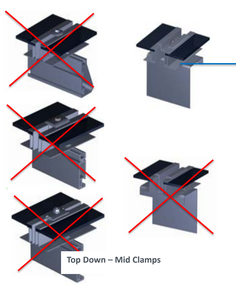




Test Modes; Bending & Twist



Design of Experiment (DOE)



Test Parameters
1. # of Clamps
2. Top-Down Clamp Pretension Value
3. Length of Clamp
4. Smooth vs. Serrated Clamp Lip
5. Height of Clamp
6. Module Frame Height
7. Coatings

Top Down – Mid Clamps



Test Parameters
1. # of Through Bolts
2. Through-Threaded Bolt - Pretension Value
3. Through-Threaded Bolt – Clamp Length
4. Through-Lock Bolt
5. Electrical Bonding Device (WEEB)
6. Belleville washers
7. Loctite

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Berkeley Civil & Environmental Engineering

PROJECT NAME: Understanding Defect Behavior in CdTe Solar Cells using First Principles Simulations and Graph Neural Networks

Last 5 digits of project number: **11158**

Principal Investigator (PI):
Arun Mannodi Kanakkithodi

Lead Organization: **Purdue University**

PI Email: **amannodi@purdue.edu**

PHOTOVOLTAICS TRACK

Crystal graph neural networks combined with density functional theory enable accelerated discovery of low energy defect structures in CdTe solar cells

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BACKGROUND and OVERVIEW

- Density functional theory (DFT) is invaluable for calculating defect formation energies in semiconductors, but is quite expensive.
- DFT combined with crystal graph-based neural networks (GNNs) helps make on-demand defect predictions, create libraries of low energy defects, and explain + drive experimental measurements.

METHODS

- Perform high-throughput DFT computations for native defects, dopants, and defect complexes across Cd/Zn-Te/Se/S/O binaries and alloys, using both semi-local GGA and nonlocal hybrid HSE06 functionals.
- Dynamically train ALIGNN* models on DFT data, make predictions on ~ 10^6 possible hypothetical defects.
- Project uses python packages, Jupyter notebooks.

KEY MILESTONES

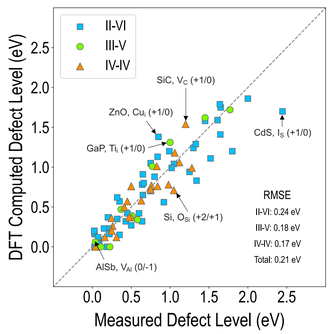
- Benchmarking DFT, initial discussions with experimentalists to guide computations.
- Generate dataset of > 20,000 defect structures, computed formation energies and defect levels.
- Release optimized GNN models + defect library + user-friendly tools via nanoHUB**.
- Correlate with results from collaborators.

EXPECTED RESULTS

- This work will help identify all consequential defect structures across Cd/Zn-Te/Se/S/O compositions + improve atomistic defect predictions in general.
- DFT-GNN-experiment framework can be easily extended to any material class and application.

DFT-computed Defect Formation Energies and Defect Levels

Defects in $CdSe_{0.25}Te_{0.75}$ (Cd-rich conditions)



DFT+GNN Framework for Defect Predictions

Dynamic DFT-GNN model for native defects + dopants/impurities (As, Cu, Cl, O, P, Sb) + complexes in Cd/Zn-Te/Se/S/O compounds

→ Library of low energy defects + tools on nanoHUB for predicting defect properties

→ Interface with XRD, XANES, and DLTS/DLOS measurements → improve performance

Simulated XAS of low energy defects → linear fit to measurement → resolve components

References

ALIGNN*: npj Comput Mater. 7, 185 (2021).
nanoHUB:** https://nanohub.org/resources
Initial DFT-GNN work: Accepted in APL Machine Learning; preprint: https://arxiv.org/abs/2309.06423

Students currently involved in project: Md. Habibur Rahman, Maitreyo Biswas, Sabria Nesmith (Purdue University)
Additional project contributors: Dr. Mariana Bertoni (ASU), Srisuda Rojsatien (ASU), Dr. Dmitry Krasikov (First Solar)

Studying Perovskite Solar Cells in Reverse Bias to Accelerate and Investigate Degradation Due to Electrochemistry and Halogen Migration

Last 5 digits of project number: **09513**
Principal Investigator (PI): **Michael D. McGehee**
Lead Organization: **University of Colorado Boulder**
PI Email: **Michael.McGehee@Colorado.edu**

BACKGROUND and OVERVIEW

- Perovskite solar cells (PSCs) are subject to a variety of degradation processes under various stressors (light, moisture, oxygen, heat)
- A shading event that covers a portion of a module will force subcells into reverse bias to pass current
- The degradation of PSCs in reverse bias is caused by the electrochemical reactions between halides and other species within the device

METHODS

- Enhancing the breakdown strength of PSCs in reverse bias by engineering ion-blocking barrier layers to prevent ion migration (ALD SnOx)
- Using inorganic metal oxide transport layers to enhance the dielectric strength of the solar cell
- Reducing surface defects (pinholes, cracks, voids) through careful fabrication processes
- Preventing the redox reactions within the solar cell will also improve the reverse bias stability

KEY MILESTONES

- **(Completed)** Characterize mechanisms for breakdown and electrochemical processes in reverse bias (tunneling vs. hotspots)
- **(Completed)** Identify and develop exceptionally impermeable contacts and implement them in reverse bias (ALD SnOx barriers)
- **(Incomplete)** Demonstrate that aging cells in reverse bias can rapidly predict longer-term stability at forward bias under 1-Sun illumination at elevated temperatures

CONCLUSION

- The tunneling of holes at moderate reverse biases triggers the flow of current in the device
- The formation of localized hotspots occurs at pinholes in our devices which lead to catastrophic damage after passing reverse current
- We have developed a robust ion-blocking barrier layer via the use of Ozone-treated ALD-SnOx
- We are currently developing a complete device architecture that we believe will demonstrate the enhanced breakdown strength based on the material properties of the transport layers and contacts.

PHOTOVOLTAICS TRACK

Addressing the Instability of Perovskite Solar Cells in Reverse Bias

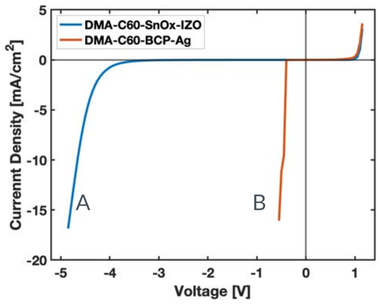
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NREL Transforming ENERGY

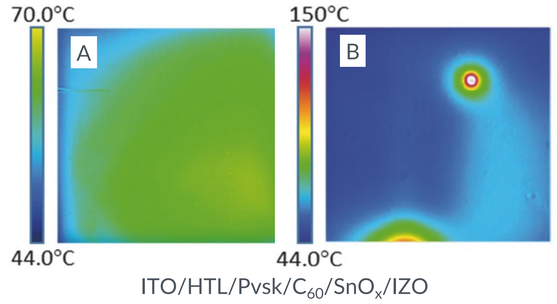
University of Colorado **Boulder**

PSCs pass current in two ways during reverse bias:

Tunneling of Holes vs. Formation of Hotspots



Thermography During Reverse Bias

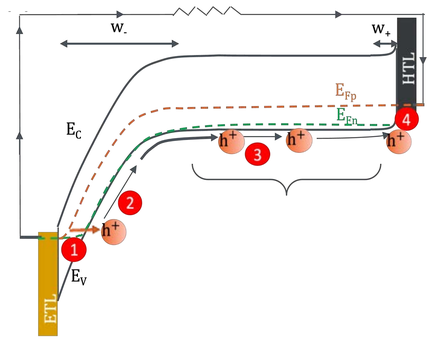


ITO/HTL/Pvsk/C_{60}/SnO_x/IZO

When the current increases abruptly, localized hotspots are observed. We attribute this behavior to dielectric breakdown in regions where there is a pinhole in the perovskite. When the current increases exponentially and the heating is uniform, we believe that holes tunnel into the perovskite and travel across the device.

https://doi.org/10.1002/aenm.201702365

A: The flow of holes induces redox reactions



Devices pass current via an ion-shuttling redox reaction with perovskite as the electrolyte.

Where a halide (likely iodide) is oxidized:

$$X_X^- + h^+ \leftrightarrow X_i^0 + V_X^+ + e^-$$

And a metal (likely Sn, In, or Pb) is reduced:

$$M_X^+ + e^- \leftrightarrow M_i^0 + V_M^- + h^+$$

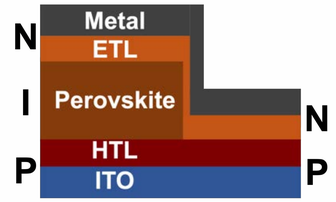
It might be challenging to prevent these redox reactions from occurring. The key to preventing permanent degradation might be ensuring that the reaction products (e.g. I2) do not leave the perovskite film.

https://doi.org/10.1002/aenm.202002614

B: Breakdown occurs in perovskite pinholes if the ETL & HTL are not robust

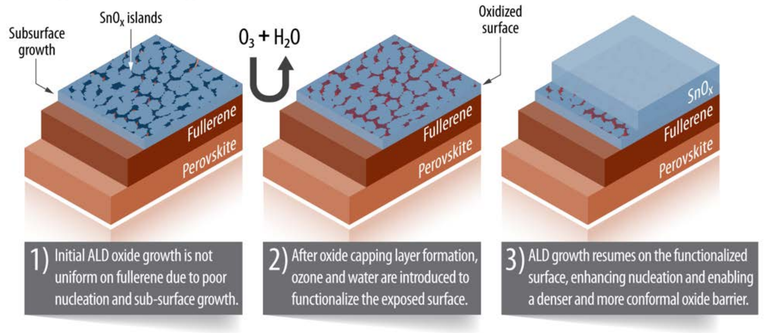
When perovskites are solution processed there are lots of pinholes. The devices still work well because the ETL and HTL layers prevent massive shunting from destroying the fill factor. However, these regions undergo dielectric breakdown in reverse bias. Massive current densities result in metal melting and perovskite decomposition. Manuscript in preparation.

Defect Cross Section



Using ALD to make impermeable tin oxide barriers inside the cell

Using ozone improves the nucleation of ALD SnOx precursor on fullerene, resulting in a homogenous closed film with enhanced mechanical robustness.

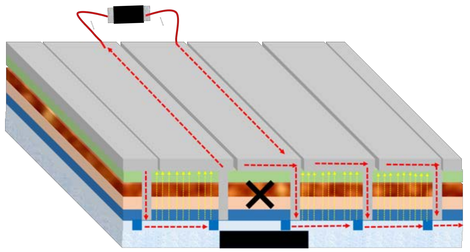


https://doi.org/10.1016/j.joule.2023.10.009

The SnOx eliminates dielectric breakdown. We hope to prevent degradation due to loss of I2, but think that the I2 is still escaping through pinholes in the SnOX layer that result from us not fabricating our devices in a clean room.

We strongly recommend using bypass diodes to protect cells

The breakdown voltage of perovskite-Si tandems is high and it is easy to run current through metal ribbons to bypass diodes. However, in monolithic perovskite panels, a very large number of bypass diodes would be needed and the voltage drop when running the current to the side of the panel would be too high.



Cost of Bypass Diode : $0.25/pc

https://doi.org/10.1002/solr.202100239

Additional project contributors: Daniel Morales, Samuel Johnson, Isaac Gould, Axel Palmstrom

PROJECT NAME: Patterns and Value of Co-Adoption of Solar and Related Technologies

Last 5 digits of project number: **09363**
Principal Investigator (PI): **Kenneth Gillingham**
Lead Organization: **Yale University**
PI Email: **kenneth.gillingham@yale.edu**

PHOTOVOLTAICS TRACK

New important **synergies between residential rooftop solar PV and other clean energy technologies** quantified and underpinned by behavioral theories

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BACKGROUND and OVERVIEW

- Residential clean energy technologies can have synergies when coadopted. This project quantifies such synergies and explores contributing behavioral factors
- This project has four themes, each focusing on different mechanisms and technologies: 1) PV and battery energy storage, 2) PV and electric vehicles, 3) behavioral theories for PV and storage, and 4) behavioral theories for PV and other technologies
- Implications for policymakers and other stakeholders can help facilitate energy transitions

METHODS

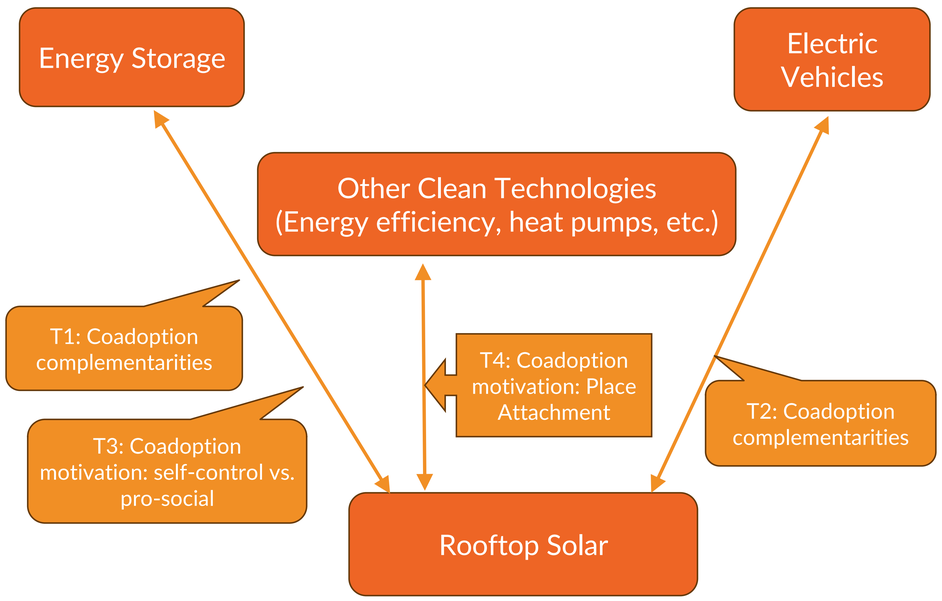
- Themes 1 and 2 involve econometric studies identifying causal co-adoption relationships in administrative data, allowing us to quantify the synergies
- Theme 3 introduces a field experiment on two treatments: "Self-sufficiency and control" and "Fossil-fuel-free and solar use" to help us understand motivations for PV+storage
- Theme 4 analyzes how the strength of interviewees' attachment to the place they live ("Place Attachment") affects coadoption by factor analysis and logit regression

KEY MILESTONES

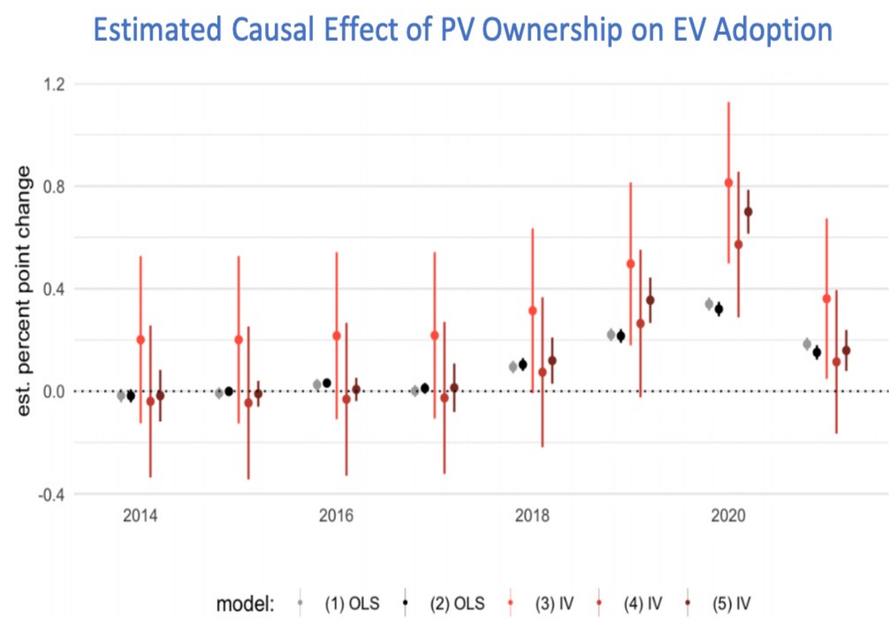
- Theme 1 quantified how outages affect the synergy between PV and energy storage. The results were presented in multiple venues and submitted to a journal
- Theme 2 quantifies PV+EV synergies
- The first wave of treatments for Theme 3 is completed and being analyzed, while the second wave is underway
- Theme 4 has already led to novel evidence of place attachment

CONCLUSION

- Battery storage increases consumer valuation of solar. Incentivizing storage has a small spillover effect on total solar adoption
- Having solar quadruples EV adoption
- Power outages greatly influences the coadoption of solar and energy storage
- Place attachment affects both solar adoption and solar + storage adoption



Schematic of the basic concept of the project.



Using rich address-level data, we quantified the lift from having PV on getting an electric vehicle.

Additional project contributors: Bryan Bollinger (NYU), Brian Keane (SmartPower), Bob Wall (SmartPower), Stefano Carattini (GSU), Chris Pike (ACEP), Jaime Hansen (Information Insights) and Hal Hershfield (UCLA)

Mitigating the Performance Degradation of Si TOPCon Solar Cells by Analyzing their Structural and Electronic Dynamics From Femtoseconds to Gigaseconds

Project No: 11155
PI: Gergely Zimanyi
University of California, Davis
zimanyi@physics.ucdavis.edu

co-PI: David Young
NREL

BACKGROUND and OVERVIEW

* The PV industry is about to choose the next generation of solar cells. The leading candidates are TOPCon and Heterojunction (HJ) cells. We propose that the degradation rate should be one of the factors considered in this choice.
* Our work analyzes the degradation mechanisms of TOPCon and HJ cells. This analysis empowers us to propose fabrication changes how to suppress degradation.

METHODS

* We developed the SolDeg platform to model and analyze the structural dynamics of solar cells from femtoseconds to gigaseconds. SolDeg uses Molecular Dynamics, based on interatomic potentials that we developed with artificial intelligence. Results are validated by DFT. Building on this, we use the Nudged Elastic Band method to determine the energy barriers that control the long-time dynamics.
* NREL fabricates TOPCOn stacks, performs accelerated degradation studies, and uses SIMS, EBIC and TEM methods to characterize and analyze the TOPCon stacks.

KEY MILESTONES

* Determination of correlation between interface texture and pinhole formation in TOPCon stacks.
* Determination how texturing the interface shifts the J0([H])-minimizing [H]opt.
* Determination of mechanism of SiOx layer thickness growth.
* Determination of mechanism of degradation/re-generation cycle of J0 at intermediate times t<100hrs.
* Determination of degradation dynamics for long times: t>100hrs.

CONCLUSION - GOALS

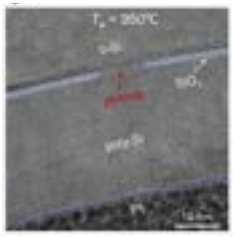
The main goals of the project are:

* To reduce degradation on the short time scale (<10hrs), thereby increasing the efficiency of the as-sold TOPCon cells by at least 0.2%.
* To reduce degradation rate on the long-time scale (>100 hrs) by at least 0.2%/yr in the first year.

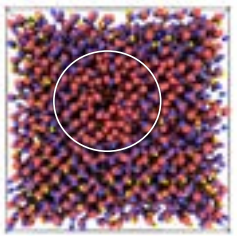
PHOTOVOLTAICS TRACK

Pinhole formation is a key driver of TOPCon cell degradation. We found optimal hydrogen concentration that minimizes this degradation. We will study effects of texture, light and mechanism, all to reduce degradation.

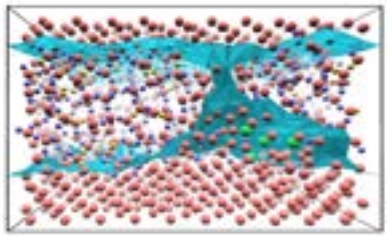
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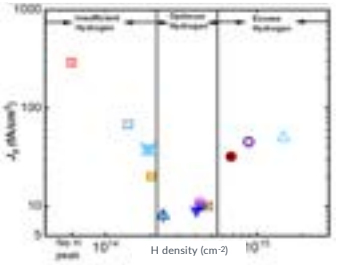
Pinholes pierce SiOx layer in TOPCon cells, degrading their performance



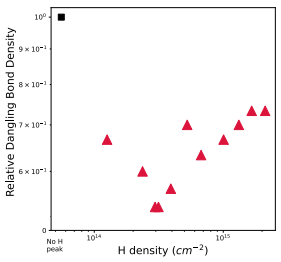
Our SolDeg platform successfully modeled the formation of pinholes. Hydrogen helps formation of pinholes.



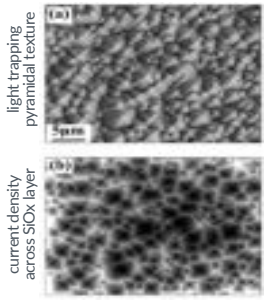
Sideview of pinhole. Teal surface is where the oxygen (blue) concentration x equals 0.5 within the SiOx layer.



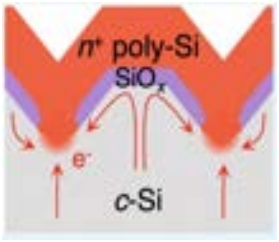
Kang et al. 2020 found that the recombination current J_0 showed a dramatic minimum as a function of [H].



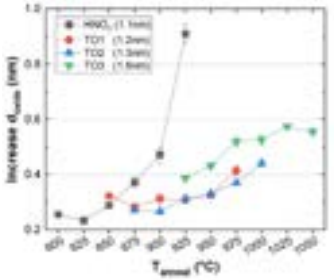
Our SolDeg study also found the J_0 minimum and discovered that it is driven by pinhole formation at large [H].



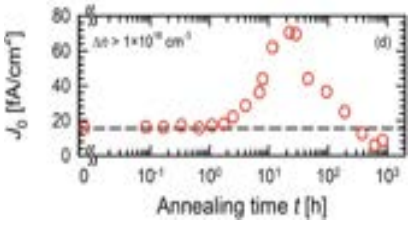
Pinhole formation shows a strong correlation with texture



Pinholes form at bottoms of inverted pyramids. There is no theory of this.



In parallel, the thickness of the remaining SiOx layer increases.



NREL found that J_0 showed a dramatic maximum at intermediate times.

PROJECT NAME: Integrated Approach to Ancillary PV Component Reliability Assessment

Last 5 digits of project number: **09349**
Principal Investigator (PI): **F. Patrick McCluskey**
Lead Organization: **University of Maryland**
PI Email: **mcclupa@umd.edu**

BACKGROUND and OVERVIEW

- Reliability of the inverter is critical to the PV system. Standard approaches to reliability assessment have severe drawbacks. Frequent redesign limits the usefulness of methods based on historical parts data. Difficulty in directly monitoring all the components with sensors and analyzing large data sets, limits condition monitoring.
- This project develops an integrated approach to assess inverter reliability in PV systems. It combines the best of historical data mining/analysis techniques; fundamental PoF assessment; and sensor-based condition monitoring.

METHODS

- Complementary approaches to reliability assessment were developed and integrated in a digital twin.
  - Field environmental and degradation data were collected, classified and analyzed using AI/ML.
  - Inverter external stresses were converted to internal component stresses
  - PoF degradation modeling was conducted and is being incorporated into the digital twin
- An H-ANPC test-bed inverter and its digital twin were developed, characterized, and validated.

KEY MILESTONES

- ✓ Milestone 1.1.2: Field degradation and failure data were collected, classified and analyzed using AI/ML.
- ✓ Milestone 1.2.1: Inverter external stresses were converted to internal component stresses
- ✓ Milestone 1.3.1: H-ANPC test-bed inverter was created
- ✓ G/NG Milestone: Digital twin of H-ANPC inverter was developed and validated for no degradation.
- EOP 1: Digital twin model validated against field and test-bed degradation data: (Final Milestone)
- EOP 2: Technology Transfer to PV Manufacturers (Final Milestone)

CONCLUSION

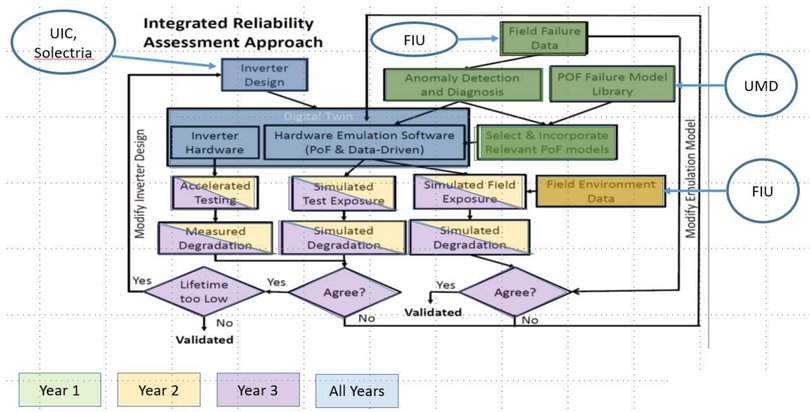
- Through completion of the milestones, a digital twin approach for reliability assessment that integrates AI/ML analysis of field data, stress transformation, and PoF modeling of component failure has been created, demonstrated, and validated.
- This approach and related tools provide manufacturers with the ability to reduce the design and development time, and increase the reliability of PV inverters.

PHOTOVOLTAICS TRACK

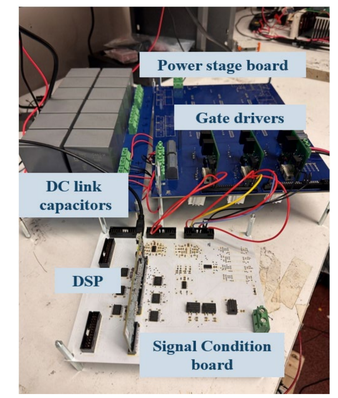
AI/ML of field degradation data has been combined with inverter stress modeling and component degradation modeling using reliability physics to create a digital twin validated against a test bed H-ANPC inverter that can be used to conduct reliability assessment.

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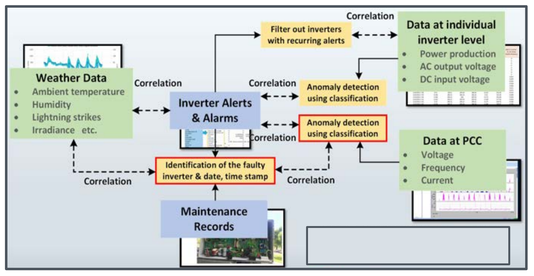
Typical PV String Inverter Used in FL



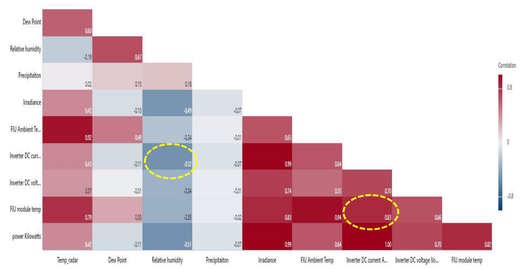
Summary of Overall Integrated Approach



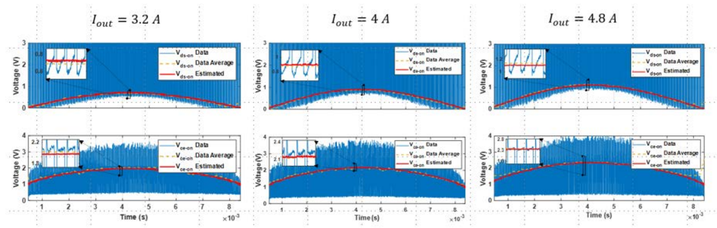
Test bed SiC H-ANPC Inverter



Machine Learning Approach to Field Data Analysis



Classification of Failure Drivers



Validation of Digital Twin for Test bed SiC H-ANPC Inverter

Additional project contributors: Sudip Mazumder (UIC), Arif Sarwat (FIU), Miles Russell (Solectria), Matt Ursino (Solectria). 4 graduates, 6 PhD students, 1 post-doc, 1 undergraduate).

Single Axis Tracker Reliability and Performance Improvement

Last 5 digits of project number: **38350**
Principal Investigator (PI): **Dan Riley**
Lead Organization: **Sandia National Labs**
PI Email: **driley@sandia.gov**

PHOTOVOLTAICS TRACK

BACKGROUND and OVERVIEW

- The project seeks to improve single axis tracker (SAT) reliability, models, performance, and standards.
- The project work proceeds through 4 separate tasks, focused on fault detection, modeling, diffuse energy collection, and standard generation.

METHODS

- We will generate fault data in a SAT system to gather fault time series, then analyze the data for fault signatures.
- We will model SAT systems and generate algorithms for improved tracking on variable terrain and in diffuse conditions.
- We will provide assistance to SAT standards organizations.

KEY MILESTONES

- Generate fault time-series data sets.
- Develop and publish algorithms for detecting specific faults from SAT time series data.
- Develop and publish algorithms for detecting sky conditions from sky imagery and tracking to collect more diffuse energy in cloudy conditions.
- Develop and publish algorithms for improving tracking on complex terrain to increase energy at low sun angles.

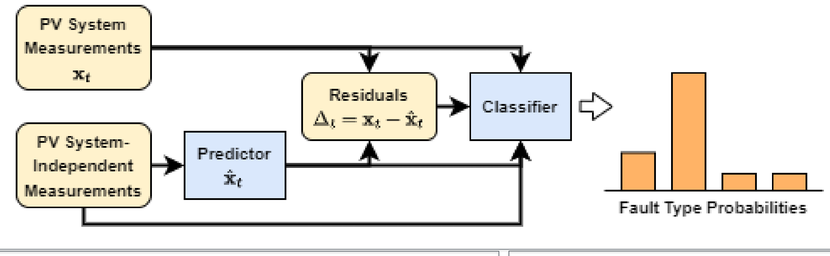
CONCLUSION

- Additional diffuse energy is difficult to collect and significant improvement may come from reduced tracker actuation.
- Significant additional energy can be obtained on complex terrain by optimizing tracker rotation angles during backtracking.
- Some physical signals provide great insight to tracker faults.

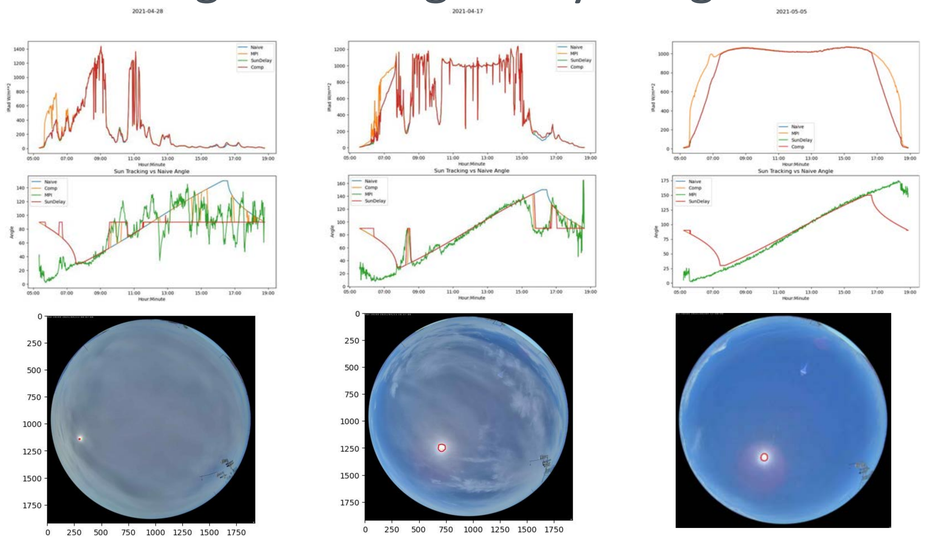
Single Axis Tracker (SAT) PV systems may generate **additional energy** through smart tracker controls and early fault detection. Data collection, planning, and **new algorithms** are required to unlock additional potential.

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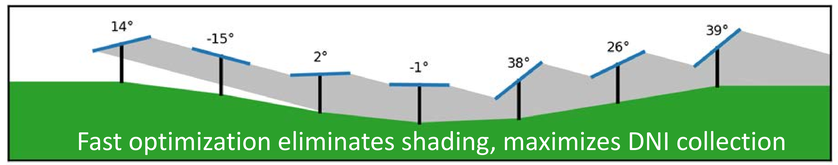
Fault detection from time series data methods

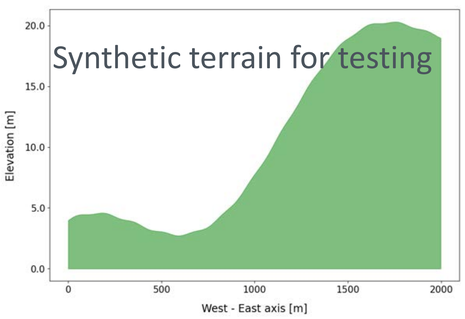


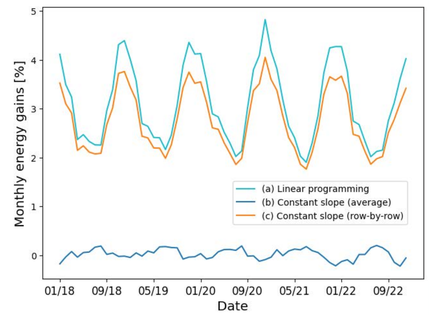
Diffuse energy collection by altering tracking according to sky images



Complex terrain backtracking optimization for additional energy







Additional project contributors: Kevin Anderson, Emma Cooper, Brandon Byford, Taos Transue, Ben Pierce, Marios Theristis

PROJECT NAME: High speed, Roll-to-Roll Production of Durable, Low-Cost, Bifacial Perovskite Photovoltaic Modules

Last 5 digits of project number: **8972**
Principal Investigator (PI): **Thomas Tombs**
Lead Organization: Energy Materials Corporation
PI Email: **tom.tombs@enmatcorp.com**

PHOTOVOLTAICS TRACK

High-speed, US manufacturing of Perovskite PV will produce high performance modules that can be profitably sold at a lower price per Watt than Silicon PV manufacturing costs in Asia

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BACKGROUND and OVERVIEW

- **Perovskite PV can be manufactured at high speed with low energy, low depreciation cost, simplified supply chain, and without today's hidden costs from material transportation and inventory imbalances**

Single Factory

High-speed Print | Assemble in glass | Locally Produced

METHODS

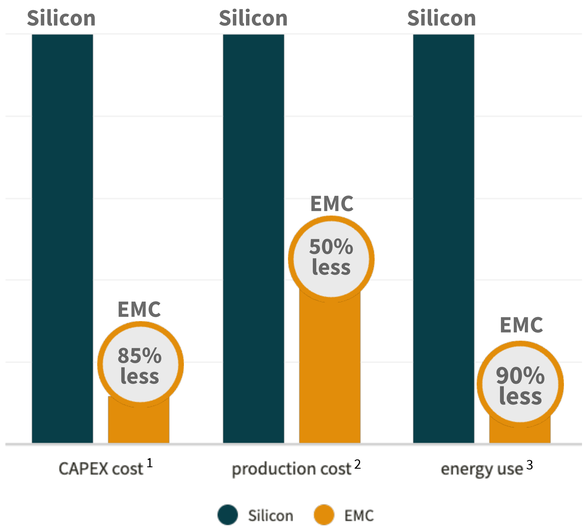
- Demonstrated high speed production of Perovskite PV devices on roll-to-roll pilot equipment
- Transparent electrode made on roll-to-roll equipment surpasses performance of commercially available ITO on PET at 50x lower cost
- Cell interconnects made using high speed methods do not degrade in accelerated tests

KEY MILESTONES

- 16 minimodules up to 100 cm^2 in size have undergone outdoor testing at 2 third party sites with the earliest at 17 months of continuous outdoor exposure
- Passed accelerated tests: 1000 damp heat test, and IEC 61215-1:2021
- 100 cm^2 packaged minimodules have a PCE loss of <2% compared to 1 cm^2 cells
- Cost estimates validated with supplier quotes

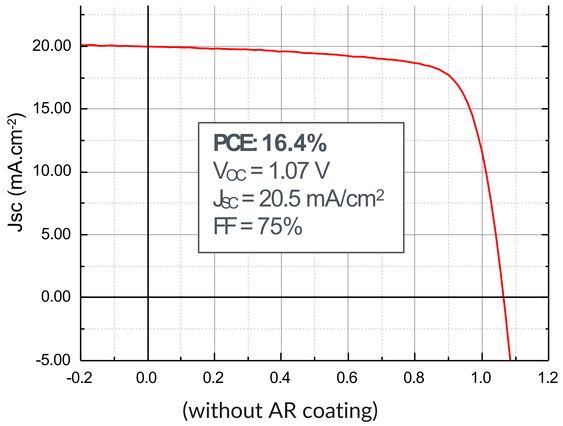
CONCLUSION

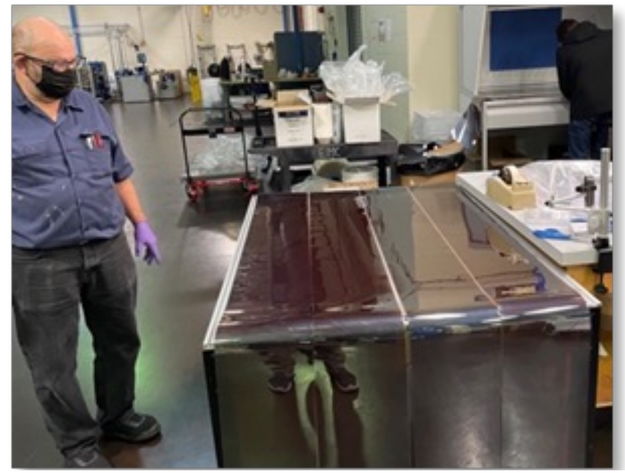
- Manufacturing of all PV layers can be made at high speed, including the transparent conductor
- Roll-to-roll manufacturing can be scaled to extremely high capacity at low CapEx/W and much faster than PV technologies that rely on high-vacuum deposition
- Single-junction Perovskite modules made in the US can be profitable



- Sustainable local manufacturing for local demand
- No trade, import requirements
- Low energy needs
- Independence from international suppliers
- Simple logistics
- Low equipment cost per Watt
- Low production costs

High performance PV devices are made by solution depositing Perovskite ink using roll-to-roll pilot equipment running at >20 m/minute





Uniform Perovskite device layers on flexible substrate are routinely made using pilot equipment at >20 m/minute. EMC has coated >24,000 m^2 of functional layers on roll-to-roll equipment in the last 6 months

Additional project contributors: NREL, Eastman Kodak, University of Louisville, Swift Coat

ENERGY MATERIALS CORPORATION

PROJECT NAME: Developing PID Susceptibility Models for Bifacial PV Module Technologies

Last 5 digits of project number: **09345**
Principal Investigator (PI): **Hubert Seigneur**
Lead Organization: **University of Central Florida**
PI Email: seigneur@ucf.edu

BACKGROUND and OVERVIEW

- n-PERT, TOPCon, and PERC bifacial modules have shown quickly occurring PID polarization
- Module makers advertise that UV light can annihilate the accumulated charge in the dielectric
- However, there is no certainty that sufficient UV light will arrive at the module rear
- We investigate through experimentation / modeling the mechanism and extent of PID polarization on bifacial modules using newer cell architectures

METHODS

- PID polarization susceptibility with respect to materials, cell architecture, module construction
- PID polarization susceptibility with respect to the mounting configuration
- Acceleration factor based on voltage bias
- Activation energy for PID polarization
- Field inspection of PV plants for PID polarization
- A weather/empirical model, an electrochemical model, and a semiconductor model

KEY MILESTONES

- 95% uptime for the outdoor testbed (**Completed**)
- PID polarization is occurring in bifacial technologies and whether mounting configuration is influencing PID with 80% confidence (**Completed**)
- Linear relationship between leakage I and V bias to validate using V bias for acceleration (**In progress**)
- Activation energy of PID polarization (**In progress**)
- Develop & validate models to confirm the physics and predict leakage I and P loss (**In progress**)

CONCLUSION

- Provides tools to predict power loss more accurately and reduce uncertainty in LCOE
- Assess the relevance of PID standard testing protocols performed in chambers
- Report to IEC 62804-2 standards committee on the use of voltage for acceleration
- Inform industry of PID polarization sensitivity related to different technologies, of mechanisms, and on the influence of the mounting configuration

PHOTOVOLTAICS TRACK

PID polarization can occur and persist in the field on the rear surface of PERC bifacial modules resulting in 5-10% power loss.

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Simulated ground (-1500V) | Open Rack (-1500V) | Open Rack (-3500V) | Open Rack (+1500V) | Simulated Roof (-1500V)

N

Figure (Top):
Electroluminescence (EL) images of the degraded PERC bifacial modules rear side that are superimposed on the layout of the outdoor PID testbed racks according to their installation position. The surface underneath the rack is altered to study different mounting configurations. Per rack and per technology, there are 4 biased modules (test) and 1 unbiased module (control).

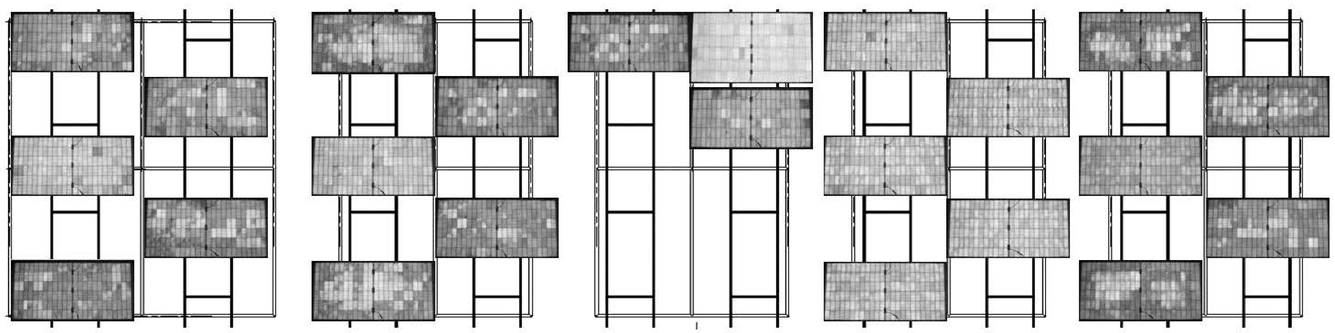
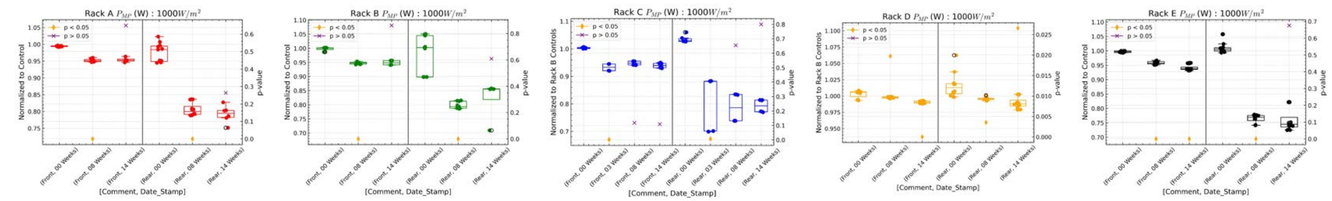


Figure (Bottom):
Corresponding maximum power data from indoor IV measurements of both the module front and rear sides. Results are shown for 1000 W/m² and 25°C and normalized to the baseline after light soaking. The statistical significance is captured in the P value. The rear side degradation is severe reaching 20-30%. The rear side degradation is also stable in the field because there is not enough incident UV light on the rear to prevent or recover it.



Biased modules darken significantly more than control. This configuration was designed to simulate modules close to the ground

Biased modules again darken significantly more than control. The open rack results in less severe degradation with respect to the simulated ground

Major darkening after first round of bias. Seems to improve afterward. Silicon technology 2 is largely unchanged.

Similar intensity on all modules, biased and control. The positive bias does not show any effect on the EL images

Some darkening of control. Biased modules show severe darkening around module perimeter with darkening moving toward the center over time

Additional project contributors: National Renewable Energy Laboratory, Arizona State University, University of North Carolina Charlotte, Pordis LLC, First Solar, SOLV Energy LLC, Orlando Utilities Commission

PROJECT NAME: Forecasting Perovskite Photovoltaic Device Performance Using Dark-Field Imaging and Machine Learning

Last 5 digits of project number: **09351**
Principal Investigator (PI): **Hugh Hillhouse**
Lead Organization: **University of Washington**
PI Email: **h2@uw.edu**

PHOTOVOLTAICS TRACK

Machine learning models with chemical reaction features successfully predict the degradation of low-bandgap and high-bandgap perovskites

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BACKGROUND and OVERVIEW

- Perovskite solar cells have shown promising efficiencies at lab-scale, but their instability hinders commercialization
- There is a lack of adequate analysis on the performance degradation rates of perovskite solar cells
- Developed t_{80} lifetime forecasting models using accelerated tests on lab-scale perovskite films and sub-cells and investigated their performance degradation

METHODS

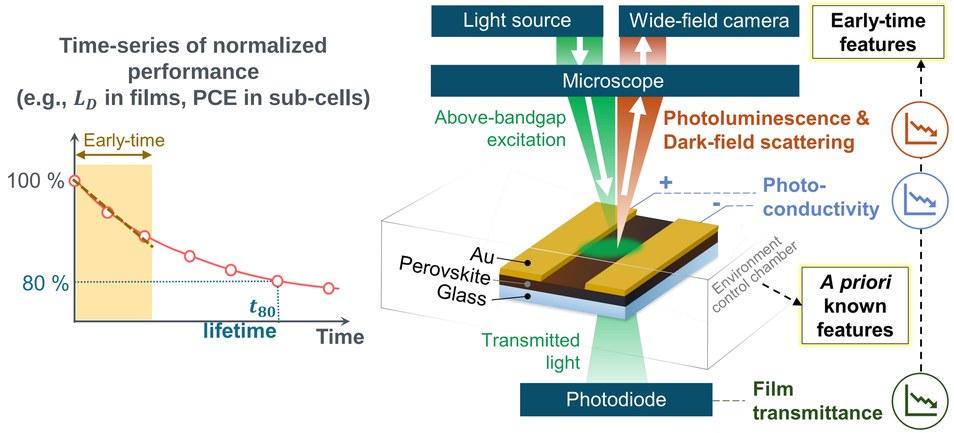
- Develop an accelerated testing protocol involving simultaneous widefield imaging, and conductivity and transmittance probing to track perovskite degradation
- Build physicochemical and experimental features that can explain the trends in performance decays in low- (1.25 eV) and high- (1.65 eV) bandgap perovskites
- Build robust machine learning (ML) models that can accurately predict the t_{80} lifetimes in perovskite films and sub-cells

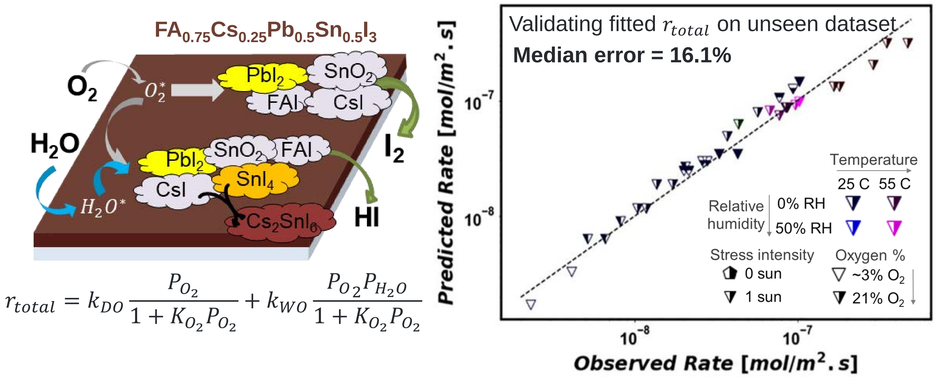
KEY MILESTONES

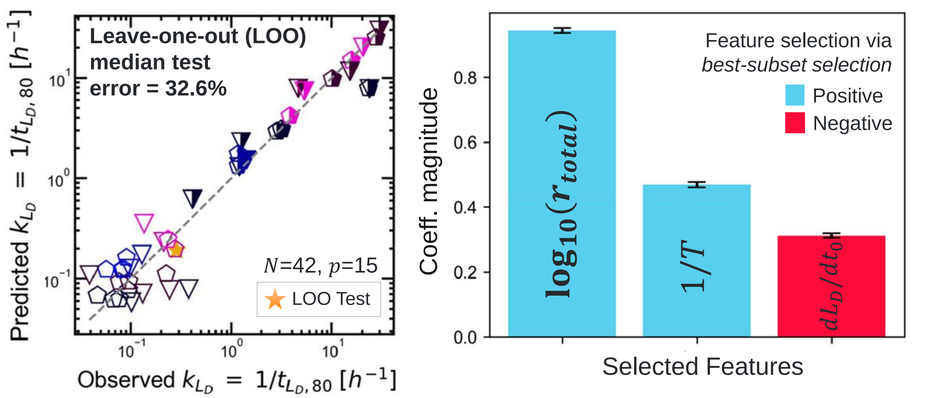
- Built evaluable *chemical reaction rate* expressions for perovskite degradation *for the first-time* with a *validation error of ≤20%* in our efforts to prepare physics-informed features for ML
- Achieved *≤40% error* in the prediction of t_{80} lifetimes of the carrier diffusion length (L_D) of low-bandgap perovskite films
- Achieved *≤30% error* (*goal*: 40%) in the prediction of t_{80} lifetimes in the photo-conversion efficiencies (PCE) of the low-bandgap perovskite sub-cells

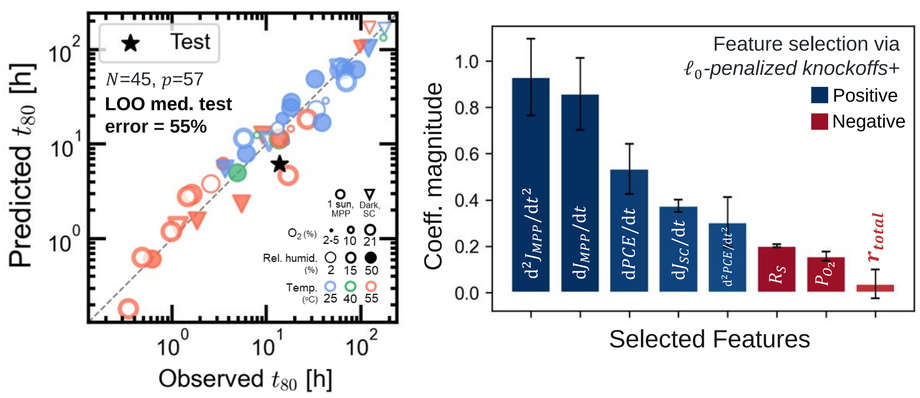
CONCLUSION

- Understanding the chemical degradation mechanisms in perovskite thin films helps develop physicochemical features that enhance prediction accuracies in t_{80} forecasting ML models
- The chemical reaction features and the t_{80} forecasting models shown here lay the groundwork for commercial ML models to make lifetime predictions in PV modules









PROJECT NAME: Extending Component Lifetime And Improving Inverter Reliability (ECLAIIR)

Last 5 digits of project number: **09826**
Principal Investigator (PI): **Wayne Li**
Lead Organization: **EPRI**
PI Email: **wli@epri.com**

PHOTOVOLTAICS TRACK

Retrofitting of PV Inverters for Prediction of Failure: Lessons Learned from **Case Study at Utility Scale PV Plant** and **Accelerated Lifetime Testing**

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BACKGROUND and OVERVIEW

- Inverters have been identified as the largest source of corrective maintenance and downtime.
- Very few research explored the component level failure on the inverter
- This project aims to identify improving inverter reliability by improving the service lifetime of components.
- This project also aims to develop service lifetime estimates and predictive maintenance practices for inverters.

METHODS

- Retrofitting of string inverters (3 different OEMs) is performed with temperature, humidity, acoustics, and electrical sensors.
- Accelerated lifetime testing of the retrofitted inverters in the environmental chamber in a laboratory setting.
- Field deployment of the retrofitted inverters.
- Monitoring of the lab and filed-based inverter to detect the failure signature from different components.
- Technical and Economic evaluation of the performance after retrofitting.

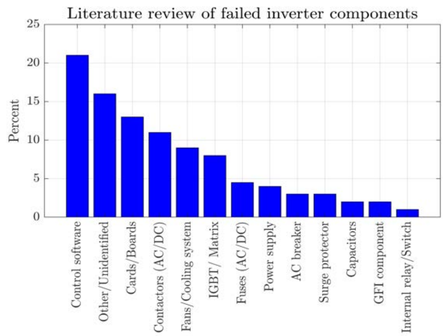
KEY MILESTONES

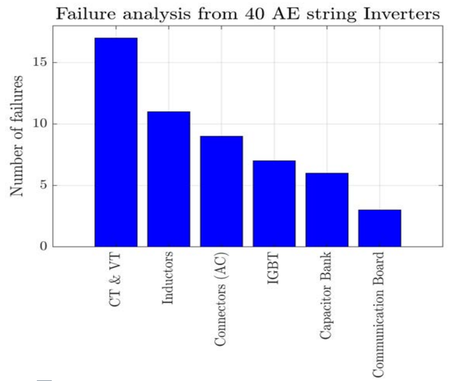
- Identification and procurement of sensors, inverters, and monitoring platform (completed)
- Retrofitting of inverters and validation using monitoring platform (completed)
- Field deployment and commission of the retrofitted inverters and monitoring platform (completed)
- Accelerated lifetime testing started (completed)
- Identification of pre-fault signature from lab-based testing
- Identification of causes of failure of inverters.
- Development of a predictive maintenance approach

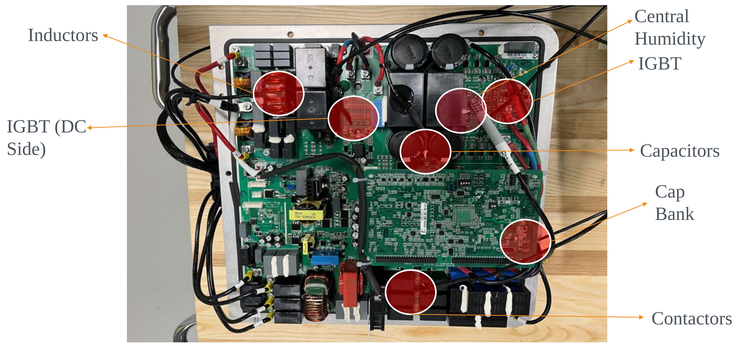
CONCLUSION

- Retrofitting of inverters enables the monitoring of crucial components responsible for the primary failure of inverters.
- Retrofitting and predictive maintenance strategy provides a valuable tool for PV plant owners to rectify inverter issues before failure occurs, thus reducing inverter downtime.
- These tools help OEM and PV plant owners to enhance the service lifespan of components, thus improving inverter reliability.

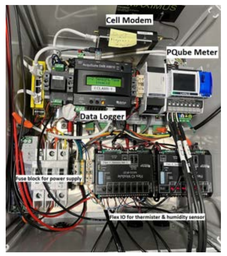
Identification of components that require monitoring based on literature review and failure inspection of the inverter from the host site → Instrumentation & Development of Data Monitoring System → Field Deployment/Lab Testing & Preliminary Results







Instrumentation of Inverter



(a)



(b)

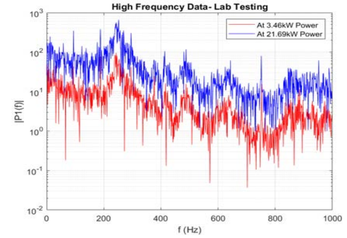


(c)

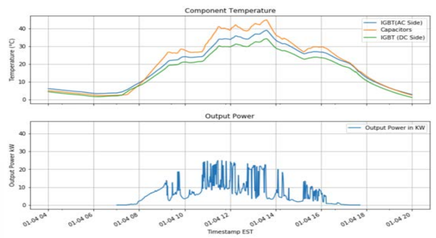
Data Monitoring Package consisting of a) data logger for thermistor and electrical sensors b) Acoustics sensors with signal conditioning box , and c) Data logger for acoustics sensors



Field Installation of data box and inverters



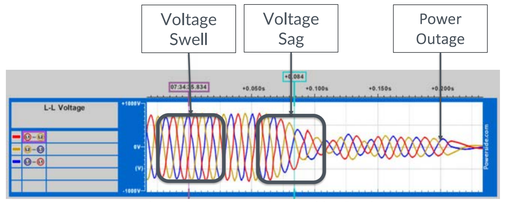
Preliminary data from acoustics sensor



Components temperature during power production in a day

Total number of alarms: (January-2024)	10
Critical:	6
➢Voltage Sag:	4
➢Interruption:	2

Number of events triggered by Pqube meter in a month for an inverter



snapshot of an event triggered by Pqube meter

Additional project contributors: Rabin Dhakal (EPRI) – *Presenter*, Deriva Energy, RETC & TEAMSESCO

Completing the Feedback Loop: Linking Data, Manufacturers, and Insurance Markets

Last 5 digits of project number: **09827**
Principal Investigator (PI): **Adam Shinn**
Lead Organization: **kWh Analytics**
PI Email: **adam.shinn@kwhanalytics.com**

PHOTOVOLTAICS TRACK

BACKGROUND and OVERVIEW

- Today's value chain is siloed: pain experienced downstream in the value chain is not formally communicated upstream to manufacturers or financiers.
- To support a 50yr service life for solar assets, this project aims to develop a feedback loop, communicate field insights, and develop insurance incentives for reliability and resiliency best practices.

METHODS

- Natural Language Processing of O&M Service Logs using PVOPS open-source software.
- Engagement up and down the value chain with stakeholders such as asset managers, financiers, O&M service providers, and manufacturers.
- As an insurance stakeholder, we aim to encourage behaviors that bring about reliability and resiliency, akin to offering "safe driver discounts" through our insurance products.

KEY MILESTONES

- Collect 50,000 O&M log records *[complete]*
- Characterize top 10 failures from logs *[complete]*
- 20 stakeholder touchpoints *[13/20 complete]*
- Webinar *[scheduled: May 2nd]*
- Publish "safe driver discounts" case studies *[BP2]*

CONCLUSION

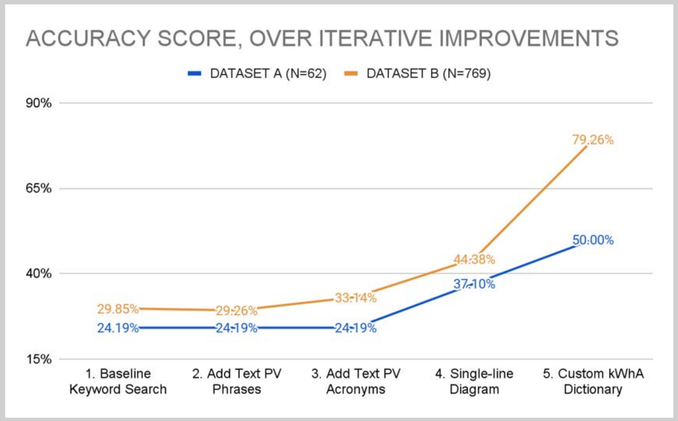
- We are halfway through this 3-year effort
- O&M logs lack consistency in equipment terms
- Applying PV domain knowledge is crucial for gleaning insights from unstructured O&M log data
- Upstream stakeholders value knowing what is working in the field and what isn't
- Reliable/resilient best practices can be incentivized through the up-front cost of insurance
- Justifications behind "safe driver discounts" are ideally rooted in data

By enriching O&M work order data, we unlock valuable insights, and work toward incentivizing reliability and resiliency

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Take a picture to connect to the feedback loop

Figure 1. Accuracy Score, over iterative improvements
By comparing our labelling approach to two pre-labelled datasets from industry O&M providers, we can quantify labelling accuracy.



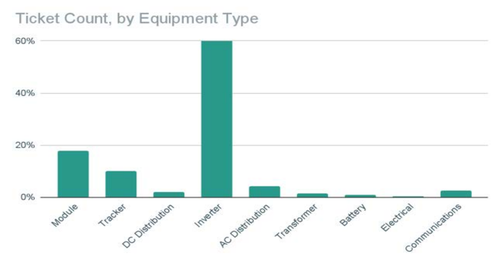
Approach

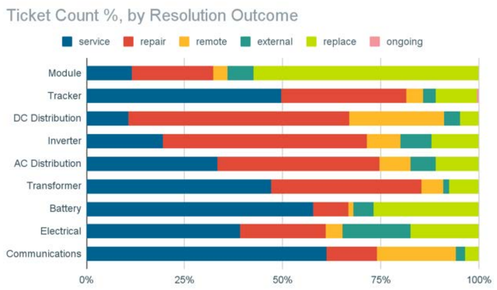
- Working with unstructured O&M log data, we apply labels to tickets to make the data useful for analytics purposes
- In this exercise, we compare our labelling results to pre-labelled data sets from two industry O&M providers
- Through multiple iterations of applying PV domain-expertise, we find that our labelling accuracy significantly improves

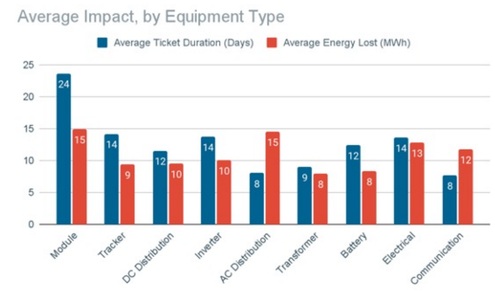
Table 1. Data Summary

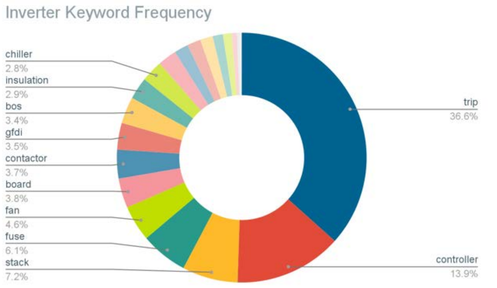
Log Count	Capacity	Systems	System-Years	Start	End
87,229	14.4 GW DC	909	2,928	2005	2023

Figures 2-5. Breakdown of Equipment: ticket frequency, impact, duration, resolution, and inverter sub-component keywords









Additional project contributors: Charity Faith Sotero, Nikky Venkataraman

Disclaimer: The views expressed herein do not necessarily represent the views of the U.S.Department of Energy or the United States Government.

PROJECT NAME: Coherent CdTe/ZnTe heterostructures for highly efficient CdTe bifacial PV devices

Last 5 digits of project number: **11154**
Principal Investigator (PI): **Pierre F Poudeu**
Lead Organization: **University of Michigan**
PI Email: ppoudeup@umich.edu

PHOTOVOLTAICS TRACK

Coherent CdTe/ZnTe interfaces are expected to minimize carrier's defect scattering enabling **enhancement** in the **PCE** of CdTe PV devices

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BACKGROUND and OVERVIEW

- One major source of performance losses in CdTe-based solar cells is the poor carrier transport across the *CdTe/ZnTe/TCO contact* interfaces
- Develop scalable process for growth of *coherent* $CdTe/Cd_{1-x}Zn_xTe/ZnTe$ interfaces
- Demonstrate a significant (>50%) improvement in the carrier's collection efficiency compared to CdTe/ZnTe interface fabricated through traditional methods

METHODS

- Compositionally graded $Cd_{1-x}Zn_xTe$ interlayer will be fabricated directly from the as-deposited CdTe thin film absorber layer through partial substitution of Cd^{2+} by Zn^{2+} ions
- Cross-sectional high-resolution STEM will be deployed to investigate the lattice coherency at the $CdTe/Cd_{1-x}Zn_xTe/ZnTe/$ interfaces
- Photoluminescence (PL) and time-resolved PL (TRPL) will be used to evaluate improvement in charge carrier's collections efficiency

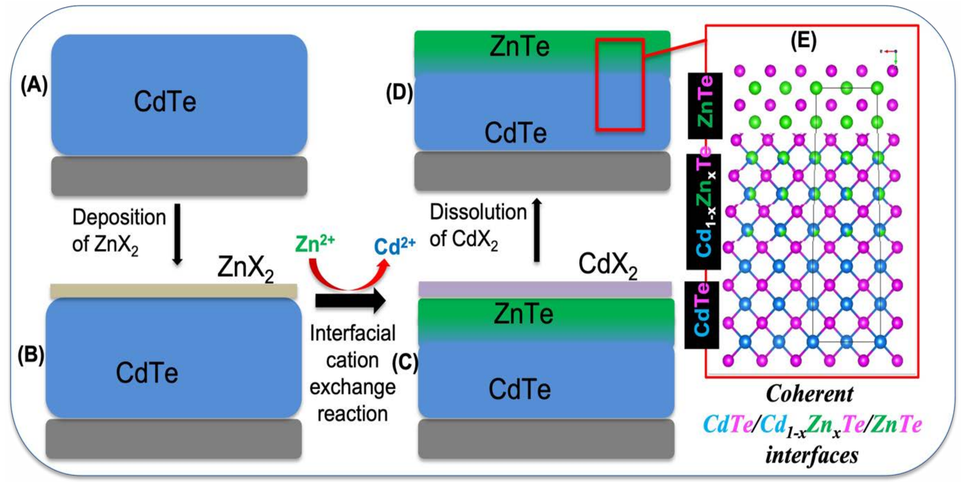
KEY MILESTONES

- Successful fabrication and characterization of coherent heterostructures with 50% or greater reduction in structural defects over at least 100 nm of interface length compared to FSLR's standard bifacial back contacts
- Coherent interfaces show improved PL and 10x improvement on TRPL signal, Measured from the rear of the cell, compared to FSLR's standard bifacial back contact

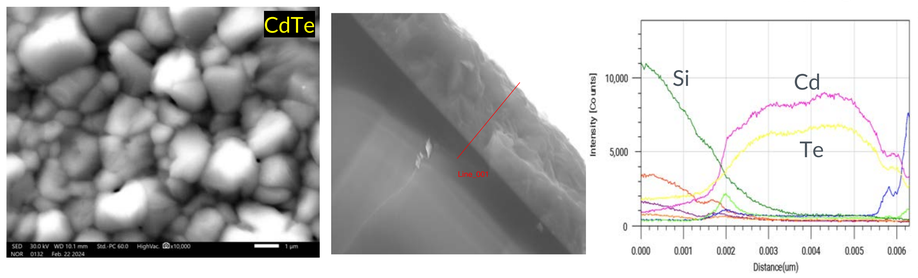
CONCLUSION

- One can anticipate a significant reduction of defects scattering of charge carriers across the CdTe/ZnTe interfaces
- Improved band alignment and carrier lifetime can be expected
- Major enhancement in the power conversion efficiency (PCE) and bifaciality of CdTe thin film solar cells.

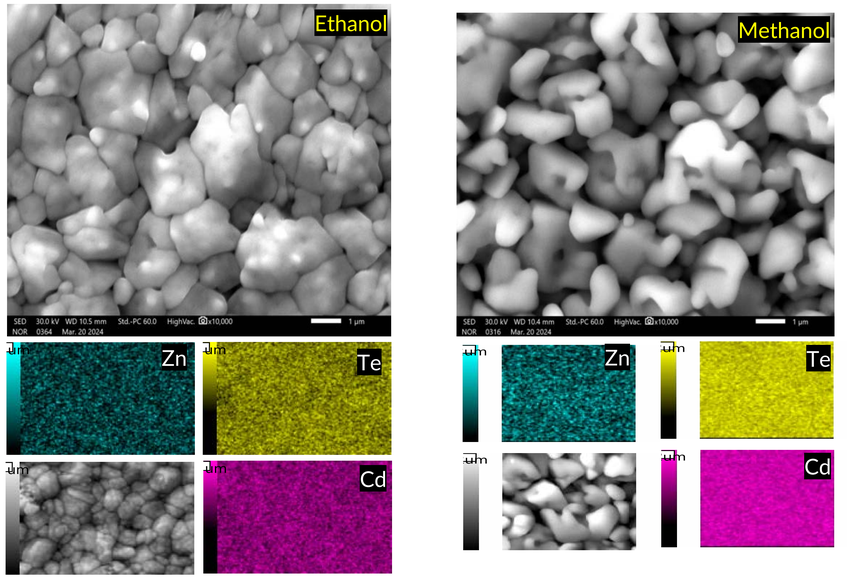
Innovative fabrication approach to coherent ZnTe/CdTe heterojunction



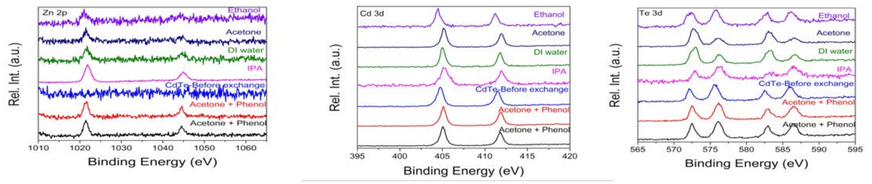
SEM of original CdTe film and cross-sectional composition mapping



SEM of $ZnCl_2$/CdTe heterostructure in various solvents



XPS of $ZnCl_2$/CdTe heterostructure in various solvents



Additional project contributors: First Solar

PROJECT NAME: Center for Co-Design of Durable, Reproducible, and Efficient Perovskite Tandems (ADDEPT)

Last 5 digits of project number: **10503**
Principal Investigator (PI): **Tonio Buonassisi**
Lead Organization: **MIT**
PI Email: **buonassisi@mit.edu**

BACKGROUND and OVERVIEW

- ADDEPT is a national center (started 9/23), employing a "co-design" strategy for perovskite-based tandems that prioritizes durability and reproducibility on par with efficiency.
- We aim to demonstrate 97% power retention over an accelerated stress test that simulates 25 years of field operation, employing laser-scribed test structures and hotspot detection.

METHODS

- Strengthen foundations: realistic accelerated stress tests, environmental controls, chemistry
- Leverage high-throughput experiments, AI/ML, and simulation to accelerate learning.
- Build strong industry partnerships to guide academic R&D, test concepts faster at scale, and offer paths to market.

KEY MILESTONES

- BP1 (9/23–5/24) is our set-up phase: Met operational GNG's focused on equipment, personnel, IP, protocols, industry engagement.
- Held an online workshop on accelerated stress testing protocols & hardware (>80 attendees).
- Formulated principles to guide transfer of recipes from spin coating to meniscus-coating, to accelerate scale-up.
- Developing common capabilities for accelerated stress testing & environment control (hardware & software); obtained preliminary results.

CONCLUSIONS

- BP1 (set-up) is wrapping up on schedule. Focus now shifts to performing to research in a systematic and collaborative manner.
- We welcome enquiries at: buonassisi@mit.edu

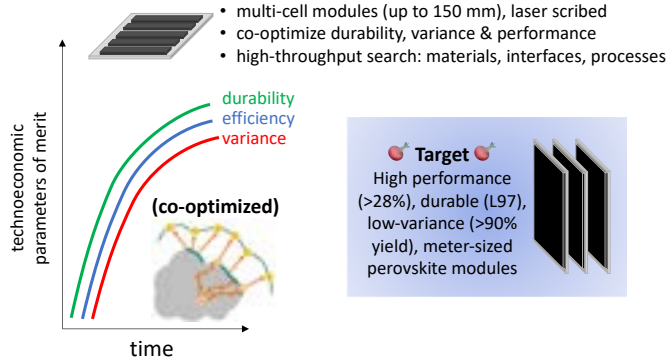
PHOTOVOLTAICS TRACK

ADDEPT: creating perovskite modules co-optimized for durability, efficiency, and reproducibility

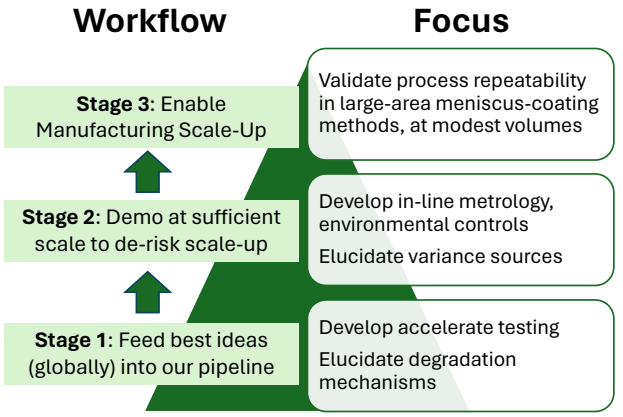
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Co-Optimization Approach leverages high-throughput experiments & data-driven methods to accelerate learning

Approach



Stage-Gated Workflow tests and validates the best innovations with increasing scale, toward full module



Additional project contributors: Quinn Burlingame, Lynn Loo, Barry Rand (Princeton), David Fenning (UCSD), Moungi Bawendi, Vladimir Bulovic, Tonio Buonassisi (MIT), Skylar Bagdon (Verde), Adam Lorenz (CubicPV)

PROJECT NAME: Increasing the Efficiency and Resilience of PV Systems at Northern Latitudes

Last 5 digits of project number: **38527**
Principal Investigator (PI): **Laurie Burnham**
Lead Organization: Sandia National Laboratories
PI Email: lburnha@sandia.gov

PHOTOVOLTAICS TRACK

BACKGROUND and OVERVIEW

- Given the rapid growth of solar across northern regions, snow shading is a growing concern: a single snowstorm can impact >40% of the contiguous US and energy losses for a PV plant can range from 1 to 12 percent annually, with monthly losses as high as 100 percent. In addition, snow creates prolonged, repetitive and uneven stress on modules, cells and systems.
- Sandia has installed > 14 experimental systems, representing different design and component choices, at the MI RTC to compare their performance and reliability in winter.
- In addition, we have developed models and methods for estimating performance losses. Including inverter-based snow detection and advanced snow-shedding models.

METHODS

- **Field experimentation** is focused on 3 areas: 1) module architectures and system designs that promote snow shedding; 2) advanced control algorithms that increase the efficiency of single-axis trackers in winter; and 3) a comparative reliability analysis of different module technologies. **Model development** includes advanced snow-shedding estimation tools based on module parameters such as orientation, cell stringing and frame architecture. **Snow loss estimations** are possible, as we have shown, based on time-series inverter data, and provide valuable information for PV plant design choices.

KEY MILESTONES

- Snow-shedding rates for experimental systems quantified and compared
- Snow-shedding algorithm for single-axis trackers demonstrated to increase efficiency in winter
- Advanced snow-shedding model developed and validated
- Method developed and validated for measuring snow losses at multiple utility-scale sites

CONCLUSION

- Projected increases in snowstorm severity necessitate new approaches to maximize PV plant availability and robustness.
- This project has significantly advanced the resilience of PV systems in snowy regions of the US.

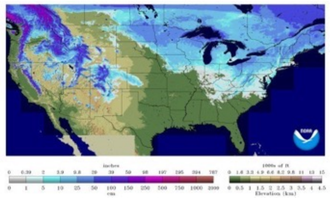
This project supports high-fidelity **field research** to increase the **efficiency, reliability** and **availability** of PV systems **in winter.**

For more information

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SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. DEPARTMENT OF ENERGY
National Nuclear Security Administration
Sandia National Laboratories

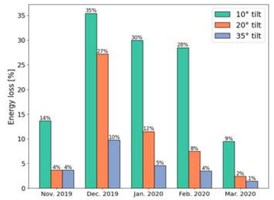
Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND2024-XXXX

Why This Work Matters



1. Snow is ubiquitous

Snow occurs in every state; this map shows snow depth for a single day.



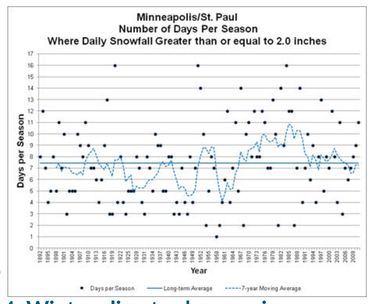
2. Power losses are significant

Snow shading of modules causes significant power losses



3. Snow takes PV offline

Blizzards sweep across the US, causing zero solar generation; and one storm can impact > 50% of US



4. Wintry climates have unique stressors: snow is repetitive and always accompanied by cold temperatures



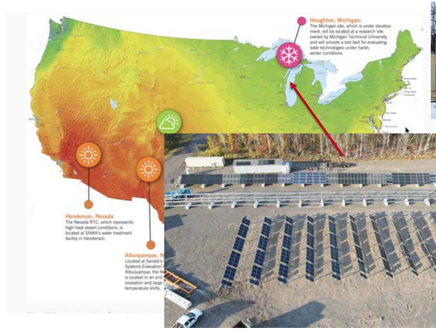
5. Design optimization

Many PV systems are not designed for winter performance and will hold snow for a long time.

6. US PV Capacity

Some of the fastest-growing states for solar are in the north. As of 2021, **31%** of all operable **US PV capacity** was located **above 40° N** (*U.S. EIA,, Annual Generator Report*, EIA-860A/860B)

The MI Regional Test Center







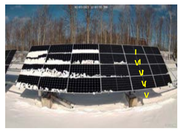
- Site commissioned in 2021
- 14 experimental systems
- Fixed tilt
- Single-axis trackers
- Multiple orientation

Experimental Systems





Comparison of steel-framed vs aluminum-framed modules



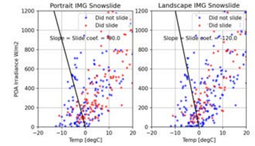


Portrait vs landscape

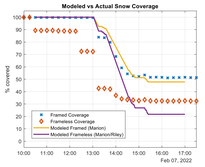


Snow-strip applied to modules on right aim to reduce frame friction.

Model Development

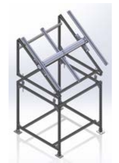


Coefficients show that portrait slides faster than landscape



Frameless shed snow 50% faster than framed modules





Reliability under snow, cold and wind load

Additional project contributors: D. Riley, N. Jost, E. Cooper (Sandia); A. Dyreson, A. Chutani (Mich Tech); C. Pike, H. Toal (Univ AK, Fairbanks)

PROJECT NAME: Precursor Engineering of All-Inorganic Perovskite Absorber and Rapid Photonic Annealing for Large-Area Highly Stable Perovskite Solar Modules

Last 5 digits of project number: **10242**
Principal Investigator (PI): **Dawen Li**
Lead Organization: The University of Alabama
PI Email: **dawenl@eng.ua.edu**

PHOTOVOLTAICS TRACK

With eco-friendly solvent engineering on all-inorganic perovskite , PSCs based on slot-die coating demonstrated PCE > 19% and maintain over 90% of its original PCE after one month. Rapid UV-LED annealing and sintering has been applied to SnO_2 (ETL), NiOx (HTL), and perovskite absorber.

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BACKGROUND and OVERVIEW

- What is they key problem that this project solves? The objective of this technology development is to address instability that reduces lifespan and the lengthy annealing times that limit the throughput capability for high-speed printing.
- How will/does the project address that key problem? We address instability issues by sandwiching all-inorganic $CsPbI_3$ perovskite with metal oxides. All stacking layers will be slot-die coated followed by rapid UV-LED photonic annealing, a technology innovation that is fully compatible with high-speed printing.

METHODS

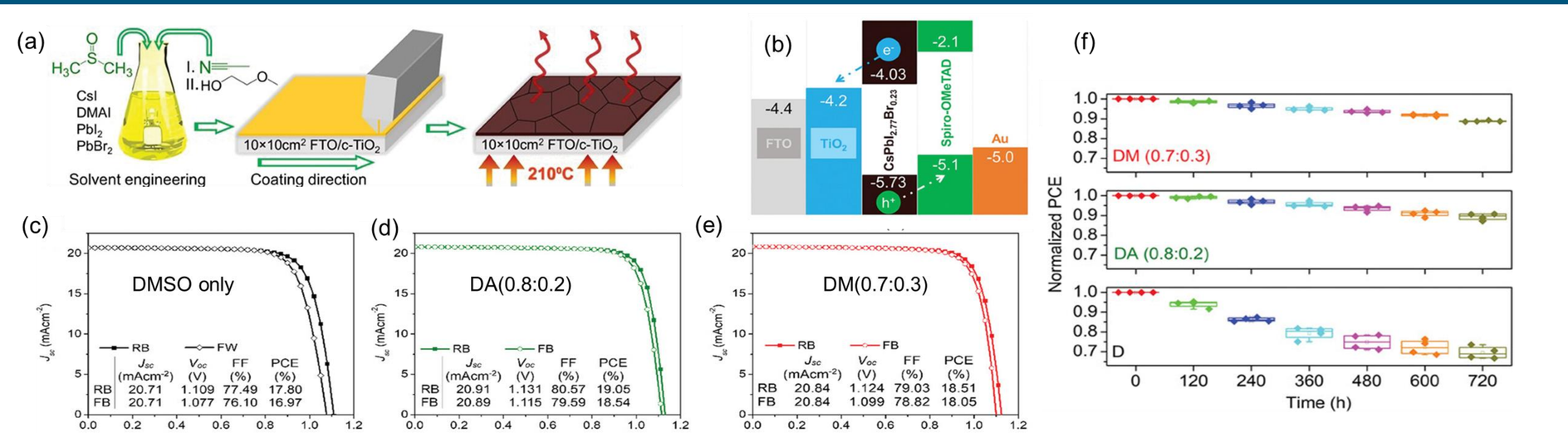
- Eco-friendly solvent engineering for all-inorganic $CsPbI_xBr_{3-x}$ perovskite ink.
- Rapid photonic annealing for each stacking layer to achieve high-performance PSCs.
- Slot-die coating of each stacking layer and make perovskite solar modules (PSMs).

KEY MILESTONES

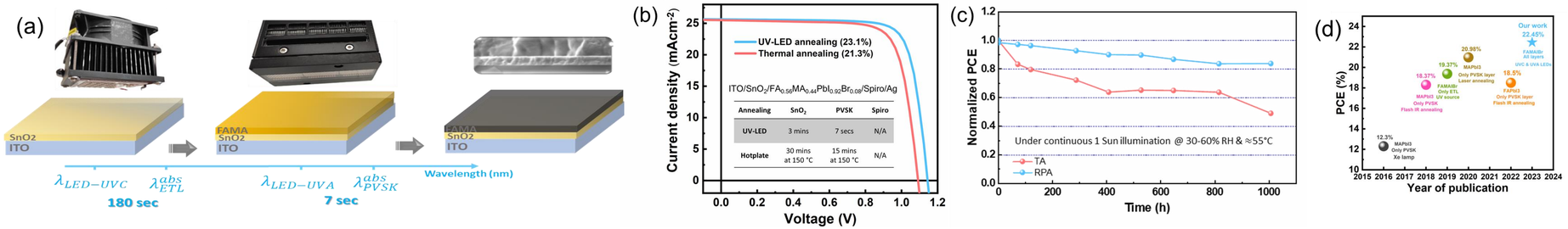
- Solvent engineering for all-inorganic perovskite ink (completed).
- Photonic annealing for NiOx in p-i-n structure and SnO_2 in n-i-p architecture has been accomplished. However, it is difficult to put NiOx on the top of perovskite absorber.
- Perovskite solar modules with PCE close to 20% (not completed).

CONCLUSION

- Based on solvent engineering, PSCs with slot-die coating of all-inorganic $CsPbI_{2.77}Br_{0.23}$ perovskite demonstrated PCE > 19%.
- With rapid UV-LED annealing of SnO2 (180 secs) and FAMA perovskite (7 secs), PCE of over 23% has been accomplished.
- Female and minority students have participated in the project.



(a) Schematic illustration of all-inorganic perovskite film creation, (b) PSC structure, (c) champion efficiency with DMSO solvent only, (d) PCE with DMSO to acetonitrile (ACN) ratio (DA) of 0.8:0.2, (e) PCE with DMSO to 2-methoxyethanol (2-ME) ratio (DM) of 0.7:0.3, (f) Stability characterization.



Additional project contributors: Prof. Qilin Dai, Dr. Mohsen Ameri, Dr. Seid Yimer Abate, Yifang Qi, Qiqi Zhang

PROJECT NAME: Hot-Swap and Modular PV + Battery Energy System to Achieve Strong Resilience and Fast Restoration from Natural Disasters for Vulnerable Communities

Last 5 digits of project number: 10427
Principal Investigator (PI): **Yuan Li**
Lead Organization: Florida A&M University
PI Email: **yuanli@eng.famu.fsu.edu**

PHOTOVOLTAICS TRACK

Develop **hot-swap and modular** PV and battery system to achieve fast restoration from natural disasters for vulnerable communities

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Community outreach is ongoing. We have a workshop planned in Spring 2025. If you are interested in participating and being part of our outreach network, please reach to us at eozguven@eng.famu.fsu.edu.

BACKGROUND and OVERVIEW

- We develop compact size and light-weight modular PV inverter and advanced control technology for operating under fault conditions
- We employ automatic fault detection, alarming, and isolation for hot-swap operation during faults
- We include investigation of inverter modules, power plants, and local vulnerable communities for a comprehensive solution

METHODS

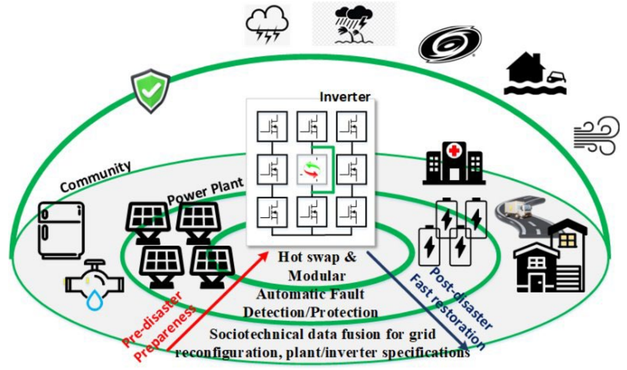
- Develop hot-swap and modular inverter
- Implement advanced data analysis, algorithm for fault detection and protection
- Assess vulnerable community use case and use data fusion methods for resilience and restoration constrains/requirements identification
- Simulate, validate and evaluate modular PV + battery storage systems

KEY MILESTONES

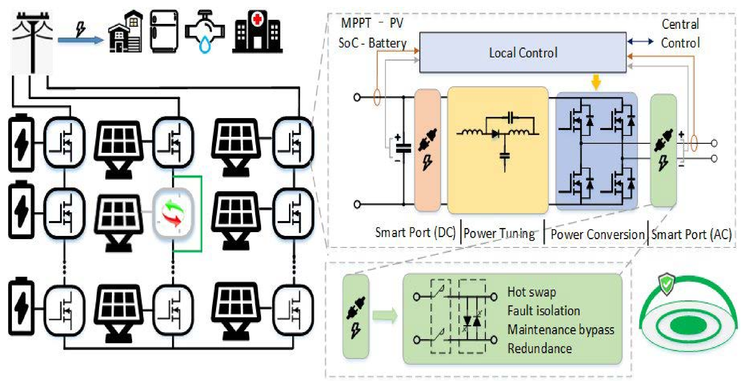
- A 33-kW 277-V single phase modular inverter with 10 hot-swap submodules
- Uninterrupted operation and smooth transition during faulty submodule's hot swap operation
- Mechanical hot-swap time < 5 minutes for 2-person manual operation without any heavy equipment (or according to OSHA standards).
- Leakage current < 10 mA, parasitic capacitance < 10 nF, (or according to NEC codes).

CONCLUSION

- By developing the hot-swap modular inverters with advanced fault detection and control methods, the system should offer community-based disaster preparedness and restoration pathways
- Grid code compliance needs to be further investigated and control algorithms should be validated experimentally



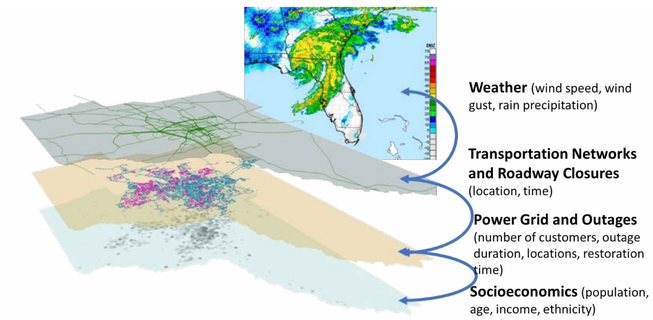
Fast recovery for vulnerable communities



Modular PV inverter for hot-swap operation



FAMU-FSU College of Engineering students visit 20-MW solar farm



Multi-network Resilience using Sociotechnical Data



DEI plan: community outreach activities – FAMU day at the Capitol





DEI plan: community outreach activities – Open House

Additional project contributors: Northeastern University, NREL, City of Tallahassee

Development of Efficient and Stable Perovskite Solar Cells with SnO_2 as an Electron Transport Layer

Last 5 digits of project number: **39486**
Principal Investigator (PI): **Hongmei Dang**
Lead Organization: **University of the District of Columbia**
PI Email: **hongmei.dang@udc.edu**

PHOTOVOLTAICS TRACK

BACKGROUND and OVERVIEW

Perovskite solar cells (PSCs) have achieved power conversion efficiency beyond 25%, however long-term stability is the most pressing issue impeding their applications. Recent efforts have been devoted to develop SnO_2 as a stable and efficient electron transport layer (ETL) to overcome the essential limitations of TiO_2 ETL. To date, a few researchers have attempted to enhance performance of PSCs by optimization of SnO_2 fabrication processes. In this project, we developed a spin-coating technique as a simple and effective process to fabricate SnO_2 films. Four types of SnO_2 precursor solutions were studied and the optimal precursor solution was developed. The precursor solution concentration, spin coating rate and annealing were investigated. Their impact on SnO_2 film properties were characterized by SEM EDX and XRD. Further, the gold was deposited on various SnO_2 films to investigate device electrical properties and obtain the optimal SnO_2 films.

METHODS

One group of the precursor solutions was diluted in 2:1 volume of SnO_2 and DI water and the other precursor solutions was not diluted and all of solutions were stirred with 800rpm at room temperature for 2 hours. Then the precursor solutions were spin coated on the FTO substrates with 3000 rpm, 4000 rpm and 5000 rpm for 30 seconds. The samples were then annealed in the annealing furnace at 200°C for one hour. SnO_2 films were characterized via SEM, EDX and XRD. Gold was deposited by thermal evaporation on various SnO_2 films to form devices. Current-voltage (I-V) measurement was conducted to characterize device electrical properties.

KEY MILESTONES

- ❖Developed SnO_2 ETL with pinhole free, dense, uniform and full-coverage films.
- ❖Perovskite layer needs to be fabricated to form the minimum 10% efficiency.
- ❖Thermal stability testing needs to be completed.

CONCLUSION

The spin coating process were applied to fabricate SnO_2 films and Au was deposited on SnO_2 to form Au/SnO_2 devices. SEM demonstrated that formed SnO_2 are pinhole free, dense, uniform and full-coverage films and Sn/O ration is close to 50% and XRD showed good crystalline structure, which are expected results in the milestones. Increase in spin coating rate and diluted precursor solutions can reduce thinness of SnO_2 films. Au/SnO_2 devices presents diode IV behaviors, indicating SnO_2 without pinholes and preventing Au from directly contacting FTO. Formed SnO_2 films reach the milestones and promote efficient charge extraction and reduce the shunt issues, leading to improved efficiency of perovskite solar cells.

- ❖**SnO_2 films with pinhole free, dense, uniform and full-coverage.**

Grain size of SnO_2 films is 50-70nm. Ration of Sn/O is close to expected 50%.

Sharp XRD Spectrum and good crystalline structure.

Au/SnO_2 presents diode IV behaviors, preventing Au from directly contacting FTO.

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Fabrication processes impact on SnO_2 films

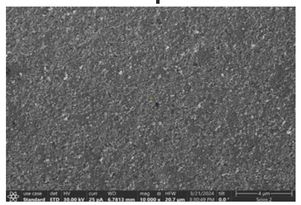


Figure 1 (a)

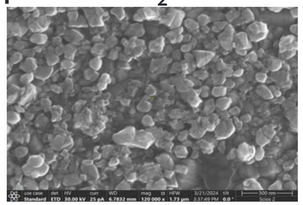


Figure 1 (b)

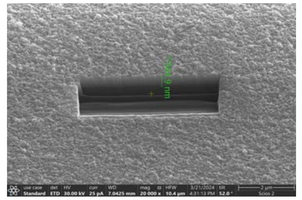


Figure 1 (c)

Figure 1 (a) (b)(c) surface and cross-sectional images of diluted SnO_2 films by spin coating with 3000rpm

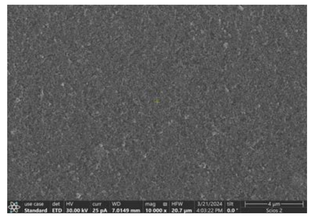


Figure 2 (a)

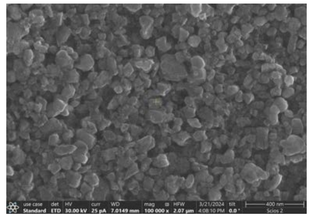


Figure 2 (b)

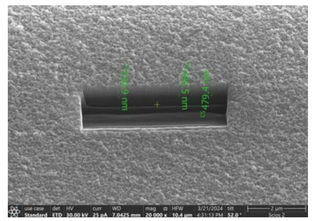


Figure 2 (c)

Figure 2 (a) (b)(c) surface and cross-sectional images of diluted SnO_2 films by spin coating with 4000rpm

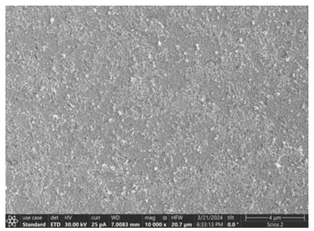


Figure 3 (a)

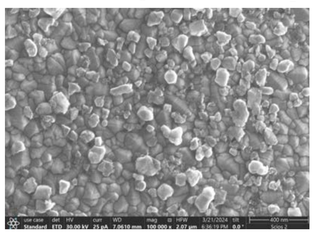


Figure 3(b)

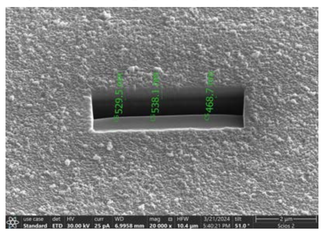


Figure 3 (c)

Figure 3 (a) (b)(c) surface cross-sectional images of diluted SnO_2 films by spin coating with 5000rpm

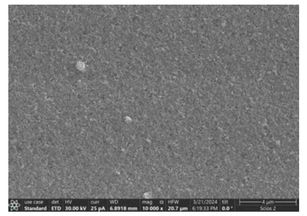


Figure 4 (a)

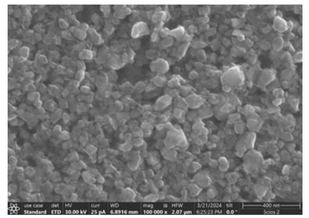


Figure 4 (b)

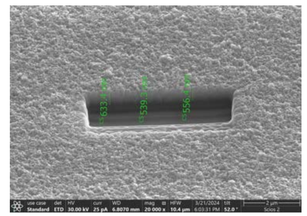


Figure 4 (c)

Figure 4 (a) (b)(c) surface cross-sectional images of non-diluted SnO_2 films by spin coating with 3000rpm

Element Name	Atomic Conc.	Sn/O ratio
Tin	26.34	40%
Oxygen	66.47	
Indium	2.41	
Carbon	3.34	



SEM images demonstrate that diluted and non-diluted precursor solutions form SnO_2 with pinhole free, dense, uniform and full-coverage films. The diluted precursor solutions may be able to reduce SnO_2 thickness, but diluted samples show the similar grain features with non-diluted samples and gain size is approximately 50-70nm.

The spin rate increases the grain size to about 100nm and the mechanism is unclear. Increase in spin coating rate reduces thinness of SnO_2 film as expected and 469nm thickness was obtained with spin coating rate of 5000rpm. The ration of Sn/O and ration is close to expected 50%. Annealing improves the ratio of Sn/O. XRD perks are sharp, showing good crystalline structure. Au/SnO_2 presents diode IV behaviors, indicating SnO_2 without pinholes and voids preventing Au from directly contacting FTO. Next, we will fabricate perovskite solar cells based on SnO_2 ETL

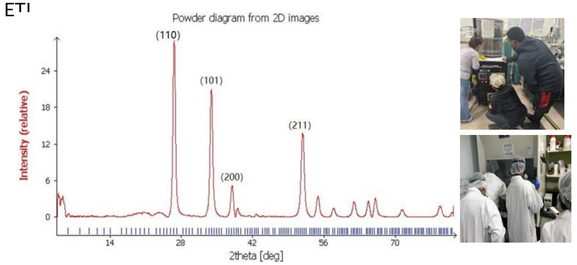


Figure 4 XRD of SnO_2 film

Figure 5 Students working on thermal evaporation of Au

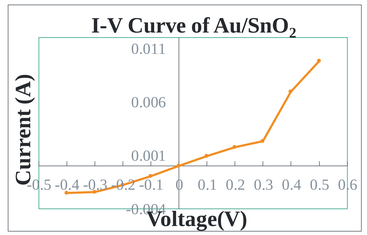


Figure 6 I-V curve of Au/SnO_2

Additional project contributors: Akhil Prio Chakma, Tewelde Semere, Dr. Kate Klein and Dr. Xueqing Song

PROJECT NAME: Metal-Complex Inks for Low- Cost Photovoltaic Material Metallization

Last 5 digits of project number: **10501**
Principal Investigator (PI): **Sneh Sinha**
Lead Organization: Electroninks Inc.
PI Email: **sneh@electroninks.com**

PHOTOVOLTAICS TRACK

High performance metal-complex conductive Ag and Cu inks to significantly lower the cost of solar cell metallization.

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BACKGROUND and OVERVIEW

- Solar cells require metallic electrodes to extract the photo-generated charge carriers from the semiconductor usually applied on the front and rear side using various metallization technologies like printing, electroplating, or evaporation.
- This project seeks to explore the use of a new type of non-particle-based, screen-printable Ag and Cu pastes for PV metallization, called metal-complex inks, that can reduce costs and the amount of Ag per cell and ultimately provide a chemical pathway to transition to Cu metallization.

METHODS

- The new inks developed would help in lowering the finger resistivity and precious metal usage by screen printing thin, dense metal films compared to traditional pastes along with reducing the firing temperature thereby preserving the passivation.
- The project aims to explore new metal complex inks based on metals such as Ni, Cu and Ni/Cu alloys along with commercially available Ag based metal complex inks developed by Electroninks Inc.

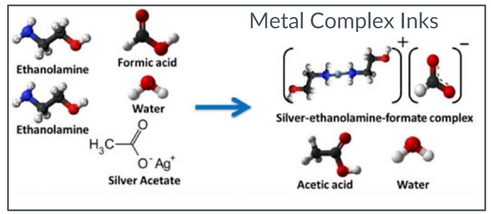
KEY MILESTONES

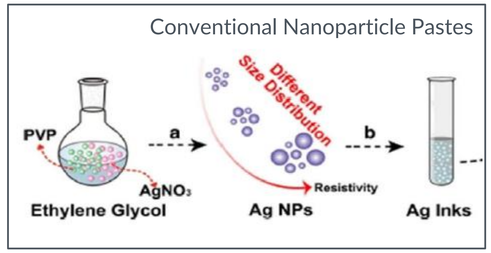
- Silicon Solar cells have been successfully metallized using commercially available EI-909 ink and screen printing.
- The printed lines were characterized for electrical resistivity, contact resistivity, morphology, adhesion and PL under the metal and in the field areas.
- Full Solar Cell characterization on Silicon Heterojunction and TOPCON is in progress.
- EI is currently developing metal complex copper ink for screen printing on silicon cells

CONCLUSION

- Contact Resistance is an important parameter for overall solar cell performance to ensure maximum power from the system. Contact resistance losses take place at the interface between the silicon solar cell and deposited metal
- The eventual goal of the project is to reduce the overall cost of ownership of inks for solar cell manufacturers leading to possible reduction in overall cost of the solar cell.

Metal Complex Inks vs Conventional Inks



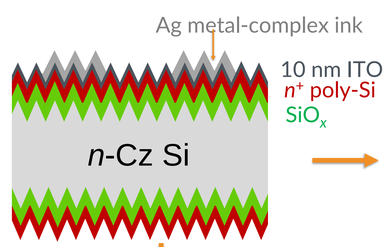


EI's Core Technology, Differentiation, Advantages

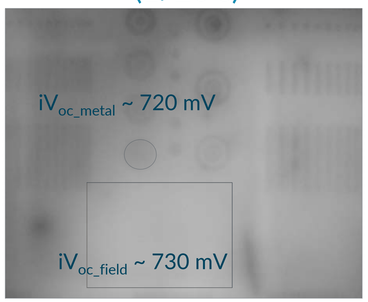
1. **Metal Complex Inks**
   - Molecular metal solution (**Ag, Ni, Cu & alloys**)
   - Highly conductive films at relatively low cure profile (thermal, NIR, UV)
2. **No traditional binders/surfactants**
   - Superior environmental stability and reliability
     No impurities in final film
3. **Low Cost and Cost of Ownership**
   - No metal particle as starting material
   - Customers use far less material for same or better performance

Metallizing ITO (10 nm)/Poly-Si/SiO2 Contacts using EI-909 (Screen Printable Silver Complex Ink)

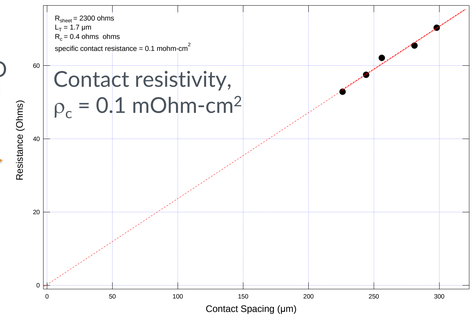
Architecture of Cell



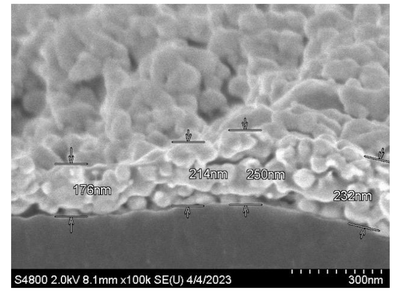
Photoluminescence Image (1/20 s)



Contact Resistivity



Cross Sectional SEM



Observations from Initial Experiments

- ρ_{metal} = 3-7 µΩ-cm (~2-4 x ρ_{Ag})
- non-uniform coverage especially over the pyramid tips
- The metal-complex inks do not aggressively etch the poly-Si surface
- The low-temperature annealing conditions preserve the field passivation (< 300 ˚C)
- J_o is preserved under the metal
- J_o is preserved in the field region
- $J_{o_metal} - J_{o_non\text{-}metal} < 1$ fA/cm^2

Next Steps

- Need to improve screen-printing uniformity
- Need to improve direct contact to poly-Si
- Cu-based metal-complex inks are under development

Team Members: EI: Mitchell Smith, Melbs Lemieux, Brett Walker
NREL: David Young, William Nemeth, Markus Kaupa, Matthew Page, Thien Truong

electroninks

PROJECT NAME: Project Performance Assessment of Photovoltaic Panels Using Impedance Spectroscopy

Last 5 digits of project number: **10253**
Principal Investigator (PI): **Sung Yeul Park**
Lead Organization: University of Connecticut
PI Email: sung_yeul.park@uconn.edu

PHOTOVOLTAICS TRACK

Development and Validation of a new PV degradation detection method using Light Intensity Modulated Impedance Spectroscopy

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BACKGROUND and OVERVIEW

- Accurate measurement of degradation in photovoltaic (PV) panels to ensure their reliability.
- Utilizing Light Intensity Modulated Impedance Spectroscopy (LIMIS) for PV panel characterization.
- Implementing a 10W LIMIS for initial testing and a scaled-up 250W LIMIS testbed for comprehensive evaluation.
- Providing a more sensitive and accurate method for detecting PV panel degradation than other testing methods.

METHODS

- LIMIS is a new PV characterization method, which is to apply modulated light intensity using a LED light and to measure the PV response in impedance.
- Developed a 10 W LIMIS testbed for 10 W PV panel characterization.
- Identified the impact of load impedance on the characteristics of a PV panel.
- Developed a parameter extraction algorithm that operates effectively in the mid-frequency region.
- Developing a 250 W testbed for a 200 W PV panel.
- Established the optimal distance between LED panels and a PV panel based on irradiance distribution.
- Plan to modulate LED using a SiC based buck converter to obtain 200 W PV panel characteristics.

KEY MILESTONES

Completed Milestones:
- 1.1.1 Validation of the 10W LIMIS LED modulation, with less than 10% variance.
- 1.1.2 Demonstrated repeatability of extracted circuit parameters.

Milestones Yet to be Completed:
- 1.1.3 Identify a thermal cycling protocol that results in at least 20% change in one or more parameters extracted from LIMIS measurement
- 1.1.4 Identification of a mechanical impact protocol that results in significant change (at least 20%)
- 1.2.1 Verified uniform light intensity across the 250W LIMIS system, with point-to-point variation less than 10%
- 1.2.2: Validation that 250W and 10W LIMIS extracted parameters from 10W panels agree within 15%.
- 1.2.3: Assessment of degraded 250W modules using LIMIS, IV, and IR measurements

CONCLUSION

- Validated 10W LIMIS System: Ensures sensitive initial detection of panel degradation.
- Scaled-Up 250W LIMIS Testbed: Allows for broader application in commercial PV panel assessment.
- Degradation Impact Protocol Development: Enhances understanding of mechanical degradation effects.
- Consistency Across Panel Sizes: Proves LIMIS applicability for both small and full-scale panels.
- Improves PV Panel Longevity: Early degradation detection leads to better maintenance.

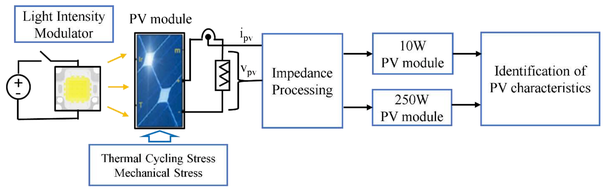


Fig. 1 Block diagram of LIMIS

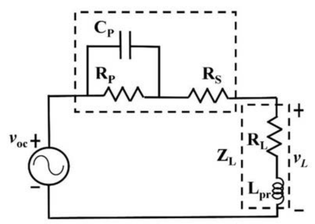


Fig. 2 Equivalent Circuit Diagram of PV panel with Load

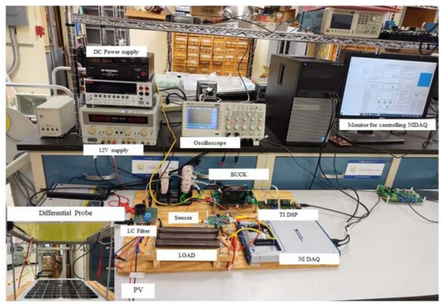


Fig. 3 10W LIMIS Testbed

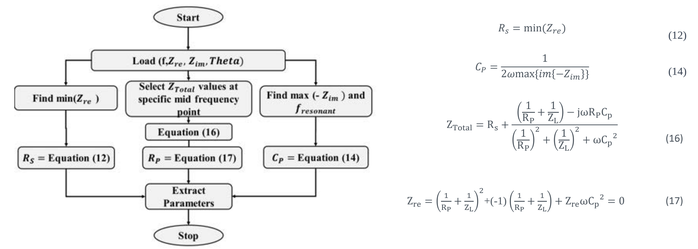


Fig. 4 Flowchart of Parameter Extraction

$$R_s = \min(Z_{re}) \quad (12)$$

$$C_P = \frac{1}{2\omega \max\{im\{-Z_{im}\}\}} \quad (14)$$

$$Z_{Total} = R_s + \frac{\left(\frac{1}{R_P} + \frac{1}{Z_L}\right) - j\omega R_P C_p}{\left(\frac{1}{R_P}\right)^2 + \left(\frac{1}{Z_L}\right)^2 + \omega C_p^2} \quad (16)$$

$$Z_{re} = \left(\frac{1}{R_P} + \frac{1}{Z_L}\right)^2 + (-1)\left(\frac{1}{R_P} + \frac{1}{Z_L}\right) + Z_{re}\omega C_p^2 = 0 \quad (17)$$

Table I: Comparison of load resistance with respect to FRA and calculation

Frequency (kHz)	Real part of Z_{R_L} (Ω)		
	From FRA (Ω)	From calculation (Ω)	Difference (%)
79.4	205	205.41	<1%
63.0	204	204.78	<1%
50.1	204	204.86	<1%
39.8	205	204.98	<1%
31.6	205	205.01	<1%
25.1	205	205.23	<1%

※ FRA: Frequency Response Analyzer

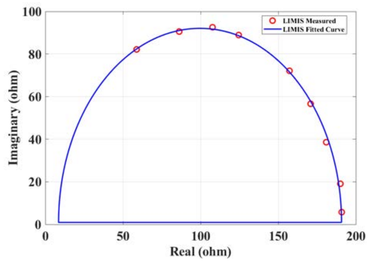


Fig. 5 Nyquist Plot of PV IS

Table II: Comparative analysis proposed algorithm with other algorithm for LIMIS data processing

Parameter	Extracted value using FRA test	Extracted value using proposed method	Difference between FRA and proposed algorithm (%)	Extracted values using low and high frequency-based algorithm considering R_L	Difference between FRA and low and high frequency-based algorithm considering R_L (%)	Extracted values using low and high frequency-based algorithm considering Z_L	Difference between FRA and low and high frequency-based algorithm considering Z_L (%)
Rs (Ω)	3.67	3	18%	1.67	54%	2	45%
Rp (kΩ)	87	93	7%	30.31	65%	65	25%
Cp (nF)	0.22	0.21	5%	0.28	30%	0.28	30%

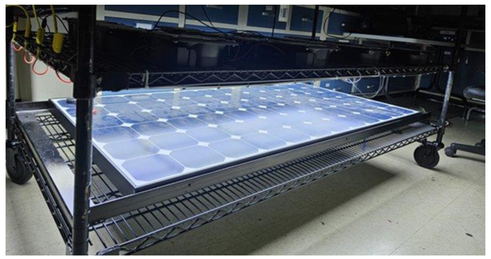


Fig. 6 250 W LIMIS Testbed

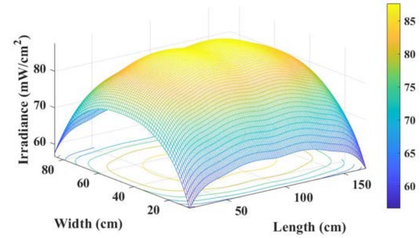


Fig. 7 Simulation result of irradiance distribution at height of 17.17cm

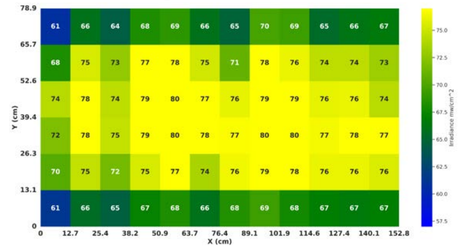


Fig. 8 Heat map of irradiance distribution measured at height of 17.17cm

PROJECT NAME: Multi-Functional Semiconducting Ligand Design for Intrinsically Stable and Scalable Perovskite Solar Cells

Last 5 digits of project number: **09519**
Principal Investigator (PI): **Letian Dou**
Lead Organization: Purdue University
PI Email: dou10@purdue.edu

BACKGROUND and OVERVIEW

- Perovskite solar cells have high efficiency, comparable to Si solar cells, but poor environmental stability.
- Designing new organic molecules as ligands can build intrinsically robust interfacial layer to improve both the efficiency and stability of perovskite solar cells.
- The newly designed ligand materials can be scaled up and incorporated to large-area perovskite devices.

METHODS

- Establish molecular dynamics (MD) simulations and training of machine learning classifiers to predict structural stability
- Employ organic synthesis approach to build novel conjugated organic ligands to form new 2D perovskite materials, denoted as OSiPs.
- Study the stability of OSiPs by characterizing ion diffusion, applying multiple external stress.
- Build OSiPs-interlayer based perovskite devices with high efficiency, stability, and scalability

KEY MILESTONES

- Developed high-throughput MD to screen ligand chemistries **(> 10,000 structures)** for stable integration into the perovskite.
- Synthesized **18** new ligands with high purity, with yield >10%.
- Fabricated solar cell devices with polymeric HTL and surface passivation and achieved **24.6%** PCE. More than 10 devices have achieved over **23%** PCE.
- Achieved <20% efficiency lost for **500h** damp-heat test and **2000h** MPP tracking.
- Achieved over 23% PCE and 21.41% PCE for **blade-coating** PSCs with 0.05 cm^2 and **0.5 cm^2**, respectively.

CONCLUSION

- A series of organic semiconducting ligands with tailored energy alignment are successfully synthesized with excellent yield (>20% overall yield) and purity (>99%)
- High-throughput MD simulation is an effective way to screen large quantity of potential ligand candidates
- Solar cells with greatly enhanced power conversion efficiency, mechanical adhesion, and device stability have been achieved.

PHOTOVOLTAICS TRACK

Incorporating organic-semiconducting ligands at the perovskite-polymeric hole transporting interface delivers >24.6% efficiency with high stability

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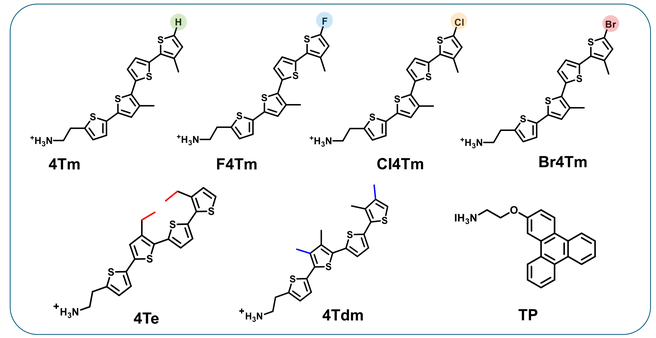
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High-throughput MD Framework

Highest Power Conversion Efficiency (PCE) =24.6%

Record efficiency of PTAA based n-i-p devices

Novel Conjugated Ligand Design

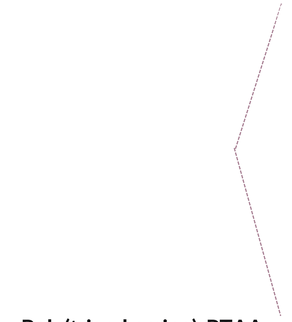


Uniform Coating and Interfacial Adhesion

Encapsulation and Damp-Heat Stability

84%

Perovskite Solar Cells with OSiPs



Blade-Coating Perovskite Film for PSCs with OSiP

Additional project contributors: National Renewable Energy Laboratory, University of California, San Diego, University of Kentucky

PROJECT NAME: PV Foundry: Increasing Manufacturing Innovation and Capabilities in the US

Last 5 digits of project number: **08975**
Principal Investigator (PI): **Zachary Holman**
Lead Organization: **Arizona State University**
PI Email: zachary.holman@asu.edu

PHOTOVOLTAICS TRACK

Empowering all US **solar innovators** with custom **silicon heterojunction** and **TOPCon** solar cells, including **for tandems**

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BACKGROUND and OVERVIEW

- Solar researchers in the US who are inventing new materials or processes for silicon cells, or who are making silicon-based tandems, need partially processed, custom-sized silicon cells.
- This project maintains baseline processes for silicon heterojunction (SHJ) and TOPCon solar cells that are customized for such innovators.

METHODS

- Fabrication and measurement of SHJ (ASU) and TOPCon (GA Tech) solar cells
- Process improvements, materials testing, and statistical process control to maintain and improve cell technology
- Customization of cells for use in tandems, including small cell sizes and layer tuning
- Provision of cells to researchers

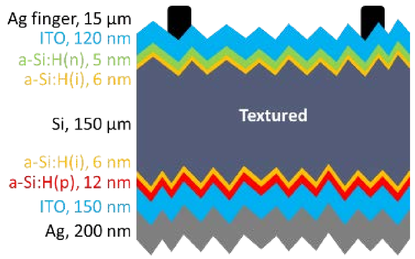
KEY MILESTONES

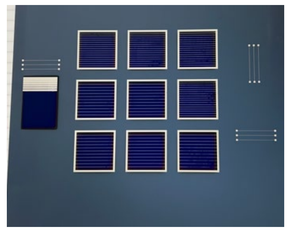
- Average one-sun SHJ cell efficiency >21.5% and tuning for use in tandems
- Average one-sun TOPCon cell efficiency >22.0% and tuning for use in tandems
- >20 customers or partners using the ASU and GA Tech PV Foundry capabilities or cells

CONCLUSION

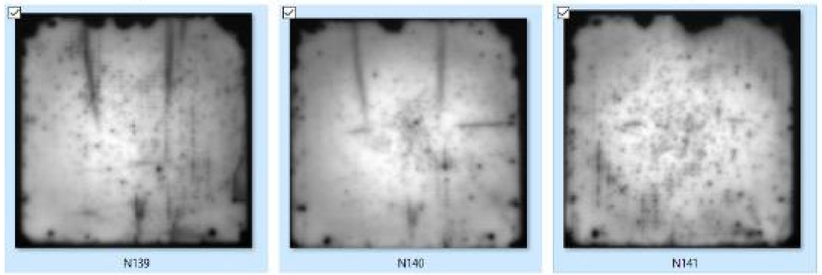
- Cells delivered to many customers, including bottom cells for incorporation into tandems
- Implemented laser-enhanced contact optimization (LECO) process in TOPCon for V_{oc} enhancement
- Implemented new cleans and PECVD process for >15 ms lifetime on FZ wafers for SHJ cells

SHJ

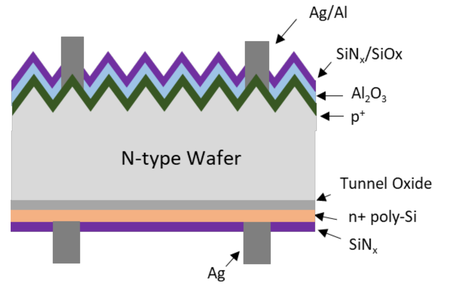


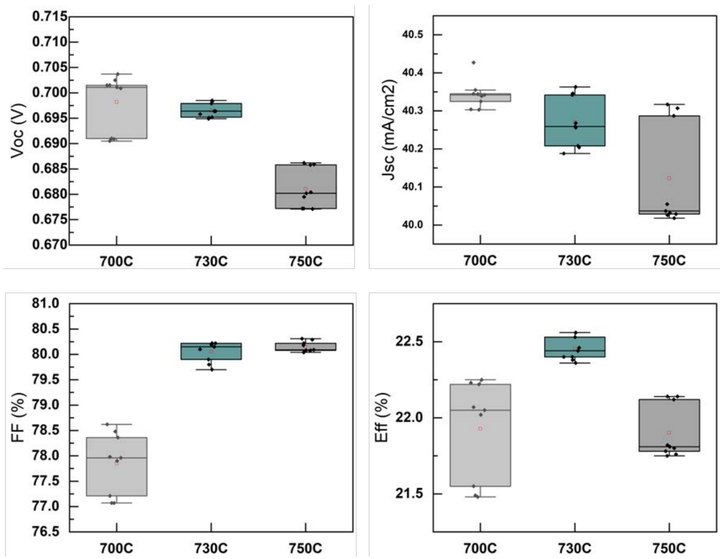


	Avg Lifetime Comparison (in msec)		
Tool	Sample 1	Sample 2	Sample 3
P5000	1.9	2.3	2.2
Octopus	2.7	2.9	2.7



TOPCon





Additional project contributors: Georgia Institute of Technology

Passivated and Conductive Back Contacts for Bifacial CdTe PV

Last 5 digits of project number: **09829**
Principal Investigator (PI): **André D. Taylor**
Lead Organization: **New York University**
PI Email: **adt4@nyu.edu**

PHOTOVOLTAICS TRACK

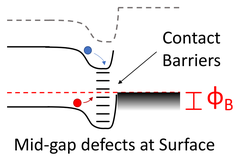
2D MXenes make excellent back contacts for Cd(Se,Te) and enable **high transparency** and **high conductivity** bifacial contacts

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BACKGROUND and OVERVIEW

- CdTe is the most widely deployed thin-film technology but effective bifacial contacts remain elusive
- MXenes have many properties that make them effective back contacts
- Project is to evaluate potential of MXenes to enable bifacial back contacts



METHODS

- Devices and test structures grown in collaboration with CdTe Core @ NREL
- MXenes grown in collaboration with Drexel University
- Robust characterization to determine contact barrier heights, surface passivation, and bifacial performance
- Leverage best-known-methods for passivation and conductive transparent contacts with MXenes to make bifacial contacts

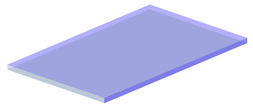
KEY MILESTONES

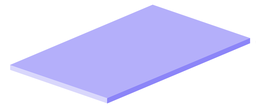
- **18% $Ti_3C_2T_x$ contacted device** (no additional metallization)
- **200 W / m^2 bifacial device** with 1 sun frontside illumination + 10% rear illumination (20% equiv.)
- 5 MXenes evaluated as back contact candidates

CONCLUSION

- MXenes reduce back contact barrier at rear surface of Cd(Se,Te)
- Cannot passivate intrinsically defective polycrystalline CdTe surface, but can work with complementary passivation strategies due to low-temperature deposition and flexible solvent
- Part of an effective bifacial contact
- Many more MXenes worth exploring!

Copper-doped devices





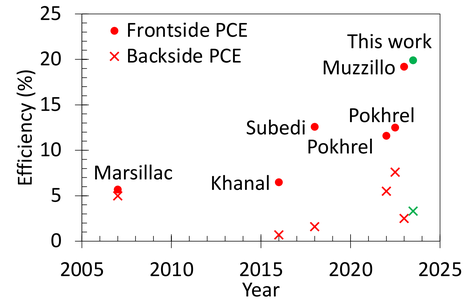
$AlGaO_x$ / ***X*** / CFL Au

Arsenic-doped bifacial devices on First Solar absorbers

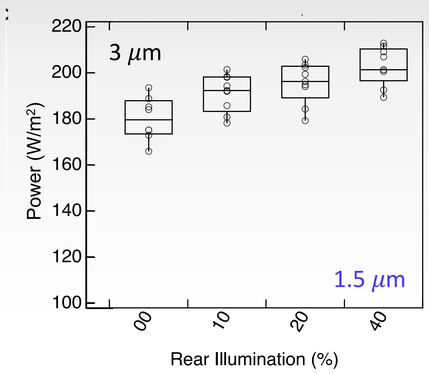
Cracked film lithography
Macroscale lateral conductivity

$Ti_3C_2T_x$
Microscale lateral conductivity

$AlGaO_x$
Improved band alignment



Vary device thickness



Additional project contributors: Ed Sartor (NYU), Teng Zheng (Drexel), Matt Reese (NREL)

PROJECT NAME: Recycling of end-of-life solar panels using near-critical fluids and O_3

Last 5 digits of project number: **10496**
Principal Investigator (PI): **Bala Subramaniam**
Lead Organization: **University of Kansas**
PI Email: **bsubramaniam@ku.edu**

PHOTOVOLTAICS TRACK

Food-grade solvents and acoustic vibrations efficiently remove interlayer adhesive from CdTe cells to achieve delamination of glass panels.

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BACKGROUND and OVERVIEW

- State-of-the-art method for recycling CdTe cells involves crushing glass and semiconductor materials.
- Delamination of the panels is achieved using aromatic solvents that are deleterious to human health and the environment. The process requires hours to days.
- Subsequent processes to reclaim Cd and Te involves treating the mixture with harsh chemicals (e.g., hydrogen peroxide) to leach the elements.

METHODS

- **Goal:** To develop economically and environmentally sustainable critical metals recovery technologies using benign solvents and reagents for recycling solar panels at TRL 3 (at KU) and TRL 5 (at INL) levels
- Investigate choice of solvent(s), swarf geometry, vibration frequency, medium properties, batch time, etc. on delamination time and glass purity
- Oxidize the semiconductor materials with ozone and extract the elements at ambient temperature

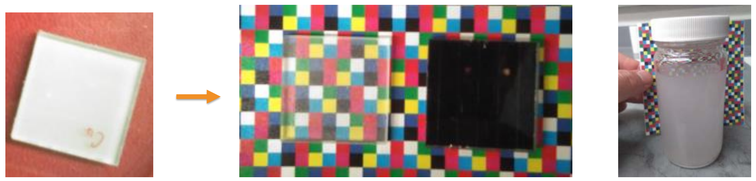
KEY MILESTONES

- Key parameters for efficient delamination at bench scale identified (KU)
- Scaled-up delamination throughput to > 1000 cm^2 total swarf area per hour to be demonstrated at Idaho National Laboratory (INL).
- Semiconductor materials in multiple swarfs to be oxidized using ozone to leach > 95% of Cd and Te.

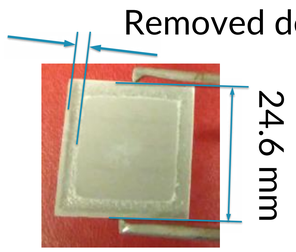
CONCLUSION

- Compared to aromatic and/or chlorinated solvents reported in literature, aliphatic solvents such as pentane and hexane are more benign and show higher affinity to dissolve in and swell the polyolefin adhesives.
- In a warm aliphatic solvent (50–60 °C), suitable acoustic vibrations can accelerate adhesive removal.
- Removal rate is dependent on applied vibration frequency which requires further optimization.

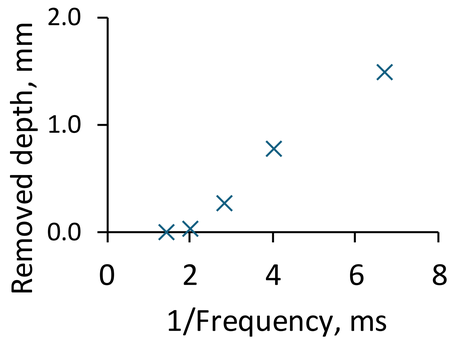
Polyolefin interlayer removed using suitable solvent and acoustic vibrations to achieve delamination

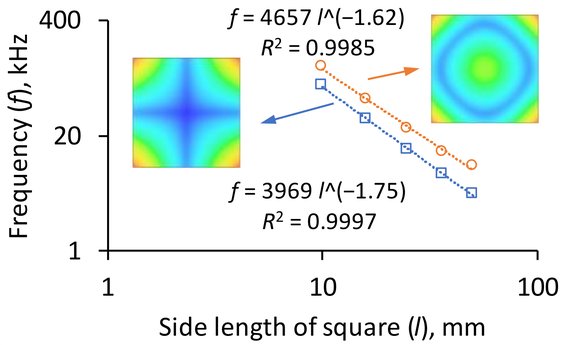


The extent of adhesive removal at various single vibration frequencies shows a linear trend (below) while adhesive removal with two superposed frequencies yielded no clear trend (right)

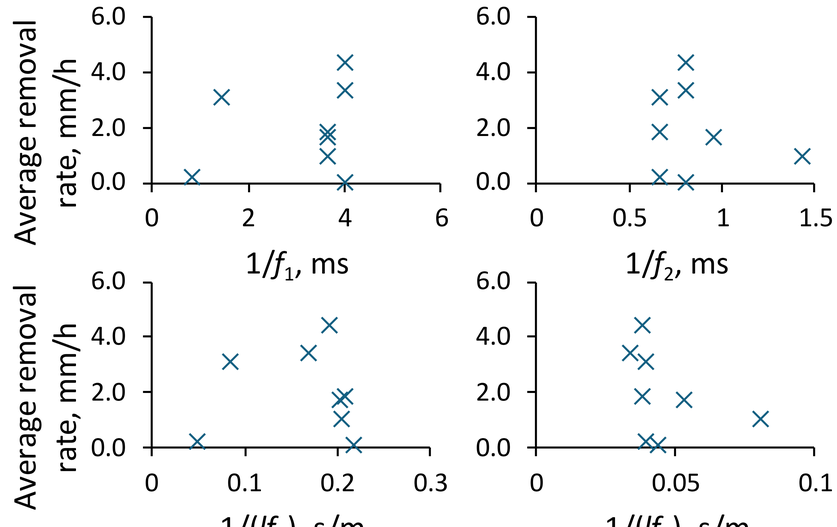


Partially removed polyolefin interlayer





Numerical simulations suggest that the optimal delamination frequencies decrease with larger swarf dimensions. This favors both process scalability and economics.



Additional project contributors: Idaho National Laboratory (INL), First Solar (FS)

Tool for Reliability Assessment of Critical Electronics in PV (TRACE-PV)

Last 5 digits of project number: **09348**
Principal Investigator (PI): **Zheyu Zhang**
Lead Organization: **Clemson University/Rensselaer Polytechnic Institute (RPI)**
PI Email: zhangz49@rpi.edu

PHOTOVOLTAICS TRACK

Create an open-source tool verified by the field data of **54 inverters** and empowered by HPC—allowing for **60,000x speedup** without sacrificing accuracy—to quantify **PV inverter reliability**

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BACKGROUND and OVERVIEW

- Field data show that PV inverters contribute most to O&M events, responsible for between 43% and 70% of service calls
- Goal of this project is to develop a Tool for Reliability Assessment of Critical Electronics in PV (TRACE-PV), which can (i) predict inverter lifetime, (ii) provide an understanding of the physics-to-failure mechanisms that manifest, and (iii) assess the Levelized Cost of Energy (LCOE)

METHODS

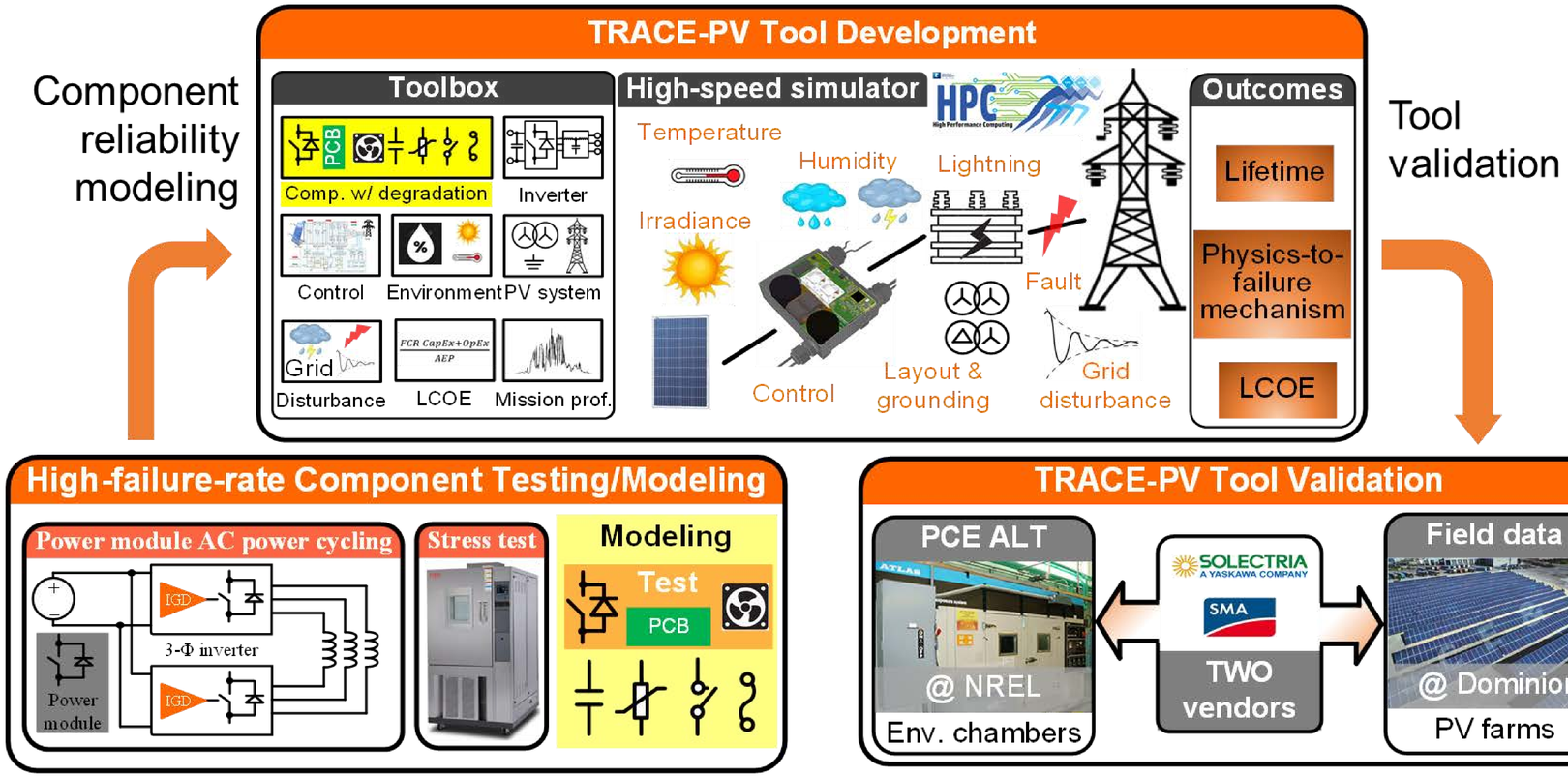
- Identification of high-failure-rate components based on field data and failure modes and effects analysis (FMEA)
- High performance computing (HPC) empowered faster-than-real-time reliability simulation considering mission profile, PV system, and grid dynamics for yearlong high-fidelity stressors across identified components
- Components' lifetime modeling through reliability testing considering degradation and statistical variation
- Integration and demonstration of TRACE-PV tool
- Field data acquisition and analytics for tool validation

KEY MILESTONES

- FMEA completed and six components identified: IGBT module, capacitor, cooling fan, PCB, MOV, & contactor
- Three custom reliability testing platforms established for IGBT (AC power cycling), fan (RH & T), & PCB (RH & T)
- Four reliability models derived and validated w/ > 0.9 R^2 score; two remaining ones (IGBT & PCB) to be completed
- HPC-empowered simulator demonstrated w/ 60,000x speed up and maintained accuracy over the benchmark
- Field data collected for 54 PV inverters in Cayce, SC
- Open-source TRACE-PV tool to be integrated & validated

CONCLUSION

- Still need to produce an integrated TRACE-PV tool and validate the model based on field data
- Completed tool will allow (i) PV inverter manufacturers to assess lifetime and understand reliability bottlenecks to improve the next-generation designs; (ii) utility/PV farm operators to fairly quantify PV inverter reliability, assess online remaining useful life of inverters under operation, and schedule maintenance in advance accordingly; and (iii) the PV community to further develop the standard for reliability testing



Additional project contributors: Clemson – Shuangshuang Jin, Johan Enslin, Ramtin Hadidi; NREL – Peter Hacke, Jin Tan, Ram Thiagarajan, Yeongrack Son, Shuan Dong; Yaskawa Solectria – Matt Ursino, Miles Russell; Purdue – Xiaonan Lu; Dominion Energy – Joe Hodges

PROJECT NAME: Interface Engineering using Vapor Transport Deposited Perovskite Films for Solar Cells

Last 5 digits of project number: **09514**
Principal Investigator (PI): **Russell J. Holmes**
Lead Organization: **University of Minnesota**
PI Email: **rholmes@umn.edu**

PHOTOVOLTAICS TRACK

Moderate vacuum vapor transport deposition is used to synthesize $APbI_3$ (A=MA, FA) thin films and efficient $MAPbI_3$-based photovoltaic devices

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BACKGROUND and OVERVIEW

- Conventional solution processing of perovskites presents challenges with solvent vapor handling
- Vapor-based methods can help to resolve this issue – Insight is needed into factors that limit device performance (especially for moderate vacuum methods)
- Demonstrate viability of vapor transport deposition (VTD) for construction of perovskite photovoltaic devices

METHODS

- Film synthesis via vapor transport deposition by either co-deposition ($MAPbI_3$) or sequential deposition (α-$FAPbI_3$) of organohalide and PbI_2
- Characterization of film composition and morphology by XRD, SEM, and Rutherford Backscattering
- Integration into devices that are otherwise solution processed with known high performing transport layers

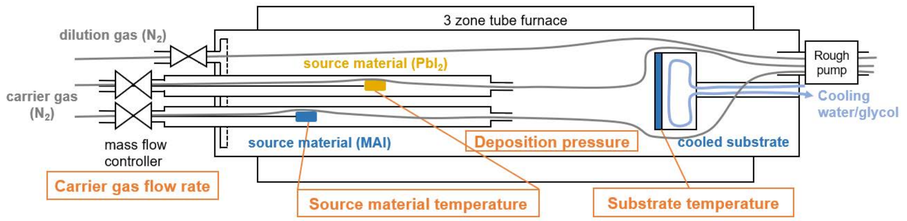
KEY MILESTONES

- Constructed a model for process parameter selection for co-deposition
- Demonstrated control over film composition and morphology with changes in processing conditions (co-deposited $MAPbI_3$)
- Demonstration of efficient VTD-processed $MAPbI_3$-devices using conventional solution-processed transport layers
- Successful synthesis of standalone films of α-$FAPbI_3$ using sequential deposition in VTD

CONCLUSION

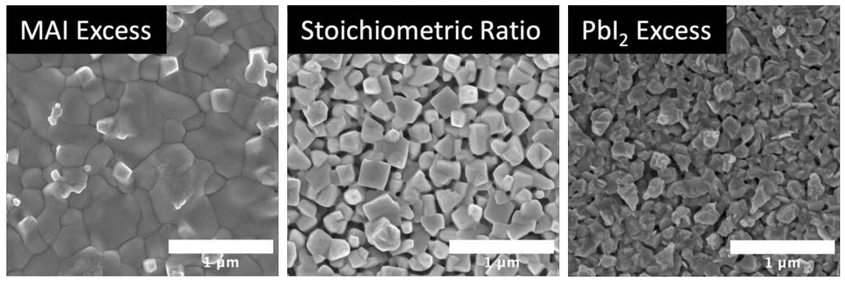
- Moderate vacuum VTD can be used to access a variety of perovskite chemistries via co-deposition or sequential deposition
- Morphology and composition can be tuned via processing conditions
- Optimum devices based on co-deposited $MAPbI_3$ require PbI_2 excess
- Work is ongoing to fully elucidate the kinetics of film formation for α-$FAPbI_3$ in VTD

Vapor Transport Deposition System



PbI_2 Temperature and Flow Rate	MAI Temperature and Flow Rate	Chamber Pressure	Transport Zone Temperature	Substrate Temperature
355°C, 5 sccm	140°C, 5 sccm	0.1-10 Torr	360°C	60°C

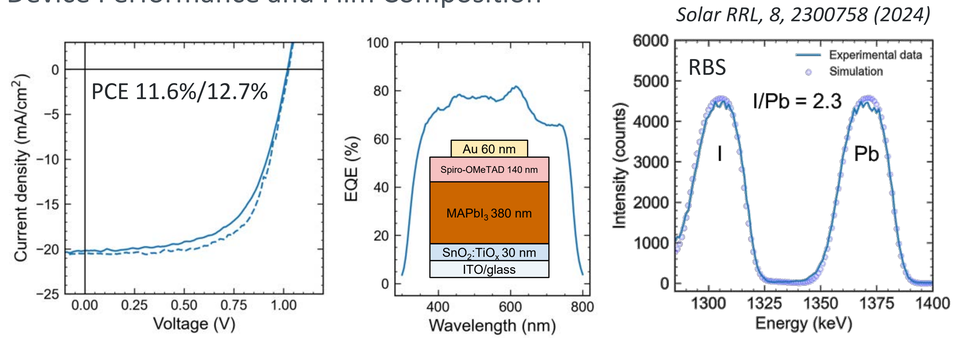
Tuning $MAPbI_3$ Film Morphology and Composition



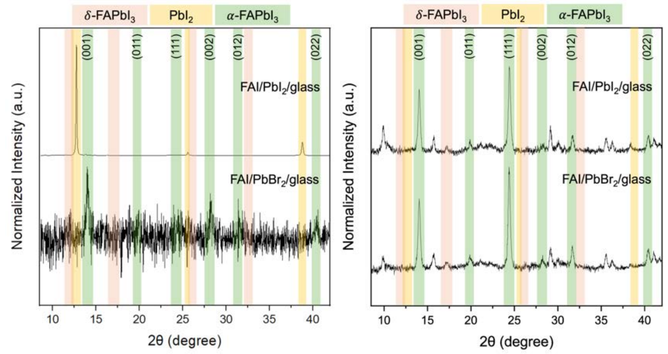
SEM images showing top view $MAPbI_3$ films with varying compositions. Nominal film composition determined via XRD.

Device Performance and Film Composition

Solar RRL, 8, 2300758 (2024)



Synthesis of α-$FAPbI_3$ by VTD



Synthesis of $FAPbI_3$ requires the inclusion of additional halides or, reduction in dilution gas to increase partial pressure of FAI

Additional project contributors: UMN (W.-J. Hsu, E.C. Pettit), M.I.T. (V. Bulović, T. Kadosh, S. Srinivasan)

PROJECT NAME: RAPID Printing of Highly Efficient and Stable Perovskite Films for Solar Cell Applications

Last 5 digits of project number: **09523**
Principal Investigator (PI): **Adam Printz**
Lead Organization: **University of Arizona**
PI Email: **aprintz@arizona.edu**

BACKGROUND and OVERVIEW

- Metal halide perovskites are materials with promising optoelectronic properties, but defects at grain boundaries can cause material instabilities
- Nucleation inhibition through confined growth techniques have increased grain size, but have been limited to batch techniques
- Scalable printing of films from confinement could address shortcomings and enable tunable control over nucleation and subsequent growth

METHODS

- Develop reduced area printing by ink drawing (RAPID), which confines ink and enables temperature control during printing
- Assess film quality through optical microscopy, scanning electron microscopy, x-ray diffraction, fluorimetry, and profilometry; assess device power conversion efficiency
- Determine film and device stability by measuring film stresses and performance after accelerated aging and thermal cycling

KEY MILESTONES

- Optimization of RAPID processing parameters on glass substrates done in batch, showing grain size increase by an order of magnitude compared to spin-coated films
- Batch print devices with >15% power conversion efficiencies on glass (in progress)
- Printing on flexible substrates at speeds of at least 1 m min^{-1} (pending)
- Increase in PCE retention (50%) of unencapsulated devices compared to spin coated under accelerated aging conditions (pending)

CONCLUSION

- RAPID has been used to produce large domain perovskite with different processing windows and different ink formulations
- Further work is necessary to optimize the printing conditions for photovoltaic devices, but we are implementing Bayesian optimization to expedite this process
- Project success will result in an alternative approach to scalable printing that removes the need for post-processing

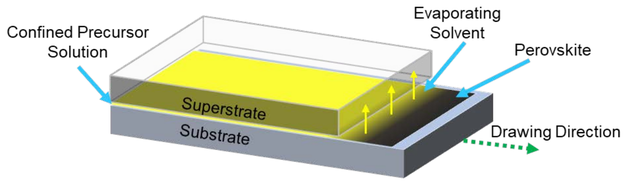
PHOTOVOLTAICS TRACK

Restricted area printing by ink drawing (RAPID) is a scalable printing approach that can produce thin film metal halide perovskites with **large domain features**

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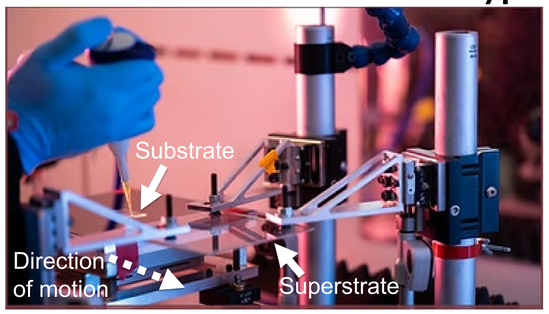
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Confined Volume Printing: RAPID



Schematic of restricted area printing by ink drawing (RAPID). The ink is confined by a substrate and superstrate and the solvent evaporates rapidly once the substrate moves out from confinement.

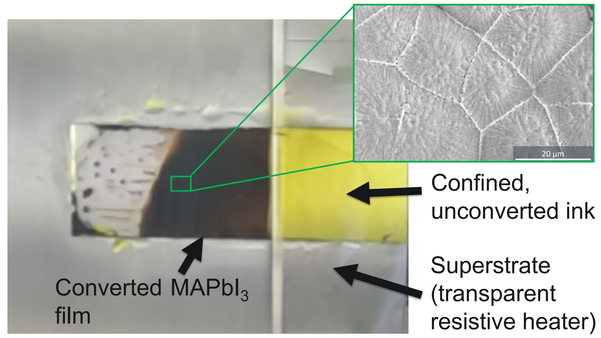
RAPID 150-mm Wide Prototype



Photograph of the RAPID printer prototype. The substrate moves under the stationary superstrate that is held in parallel to keep contact with the ink as it moves. The ink is being deposited by hand in this photograph, but this approach is also compatible with continuous ink deposition.

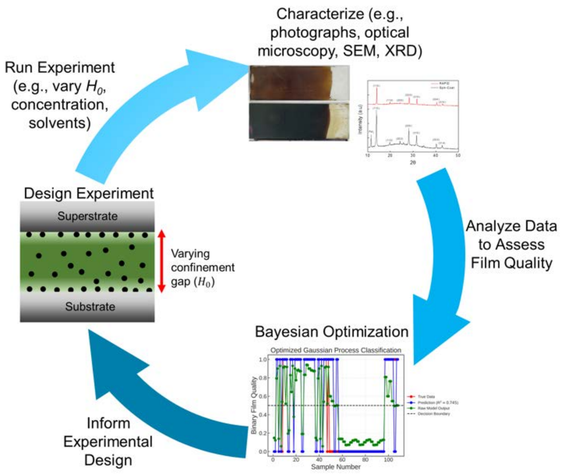
Additional project contributors:

Fast Film Conversion Results in Large Domains



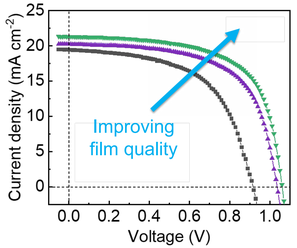
Printing of $MAPbI_3$ out of dimethylformamide (DMF) using RAPID printing in ambient conditions, showing solvent evaporation immediately after exiting confinement. In this film, large domains are visible by SEM and no formation of PbI_2 was observed.

Current Efforts in Improving Film Quality

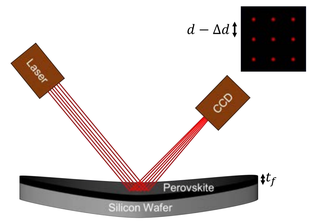


Future Work

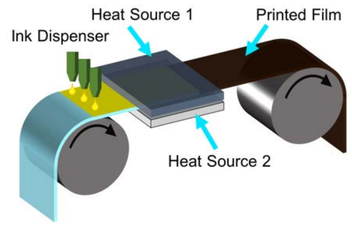
Device Fabrication/Optimization



Evaluating Internal Film Stresses



Roll-to-Roll Printing



Advance perovskite cell development and stability using in-line electrochemical methodologies

Last 5 digits of project number: **10238**
Principal Investigator (PI): **Dr. Erin L Ratcliff**
Lead Organization: The University of Arizona
PI Email: **ratcliff@arizona.edu**

BACKGROUND and OVERVIEW

- Reactive ion defects in perovskite materials limit device performance and long-term stability.
- Many spectroscopy and microscopy characterization approaches cannot detect defects below 10^{16} cm^{-3} and/or cannot provide energy resolution
- This project demonstrates the development of a low-cost, *operando*, non-destructive electrochemical sensor that quantifies defect densities and energetics; amenable to manufacturing and failure analysis

METHODS

- Electrochemistry and spectroelectrochemistry are used to reproducibly quantify defect densities from 10^{17} to below 10^{14} cm^{-3}
- Assessment of different energetic defects
- Defect evolution during degradation
- Benchmarked on device-relevant stacks from First Solar
- Integration of the electrochemical probe onto a robot for in-line processing.

KEY MILESTONES

- Reproducible quantification of near valence and near conduction band reactive defects for MA-free perovskites and benchmark with independently prepared perovskite stacks.
- Correlate long-term stability to time-dependent changes in reactive defect densities and energetics using accelerated aging conditions.
- Demonstrate in-line processing capability by automatic multi-point probing of film quality.

CONCLUSION

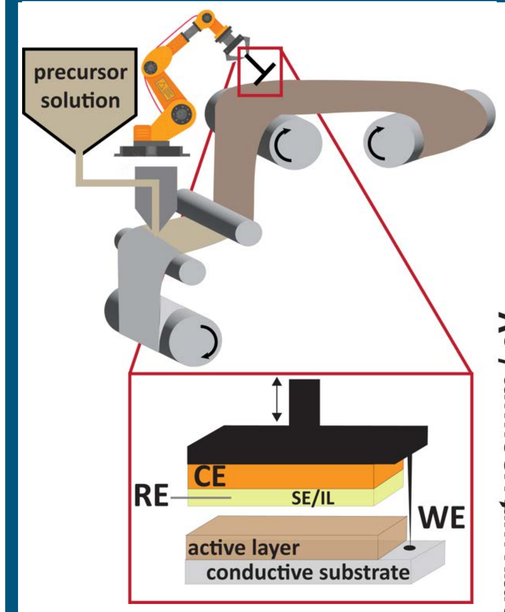
- Device performance and long-term stability are more reliably assessed by quantifying reactive defects in perovskite stacks compared to PL probes.
- Low-cost, reliable and *operando* quality control and guide tool for US solar industry to assess engineering strategies for large area modules with commercially relevant efficiencies.
- Patent-pending technology; further collaborations with device/module manufacturers proposed.

PHOTOVOLTAICS TRACK

Solar cell device efficiencies and long-term stabilities are reliably assessed through **defect quantification** in semiconductor stacks.

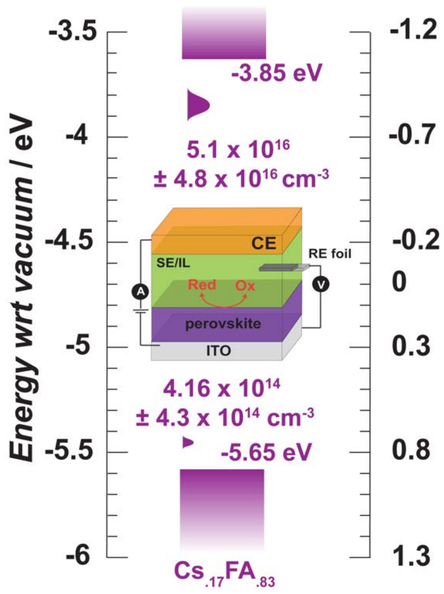
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Take a picture to **download** the **paper and patent**

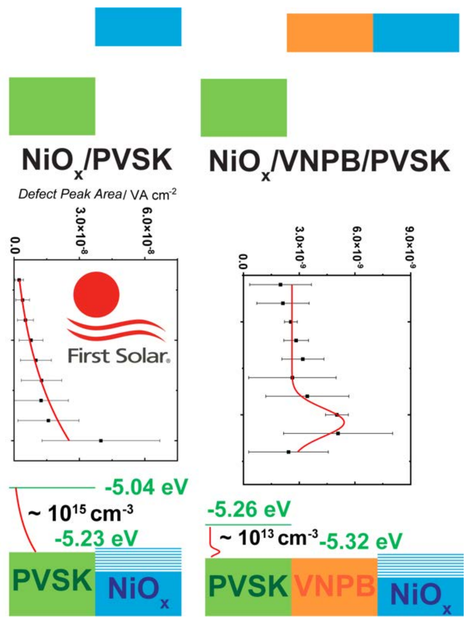


An in-line probe for rapid defect characterization of layer quality and durability during manufacturing.

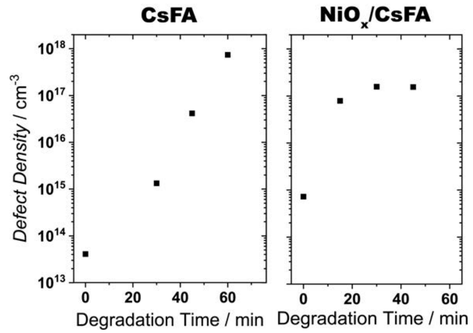
Reproducible donor and acceptor defect characterization in lead halide perovskites.



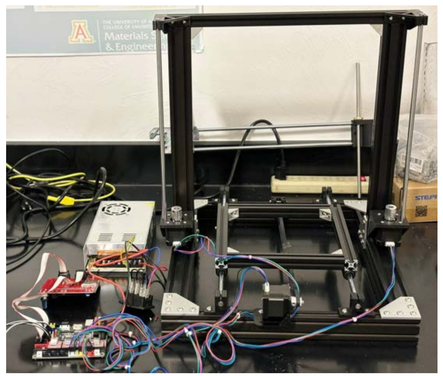
Benchmarking defect characterization technique on device-relevant external perovskite stacks.



Long-term stability assessment using perovskite stacks under aged conditions.



Automatic probe capability.



Additional project contributors: Dr. Michel De Keersmaecker, Dr. Juan Tirado, Dr. Mriganka Singh, Eli Williams

De Keersmaecker, M.; Ratcliff, E. L.; Armstrong, N. R. Device and Methods for Characterization of Semiconductor Films. International patent No. PCT/US2022/033102, December, 22, 2022.
De Keersmaecker, M.; Ratcliff, E. L.; Armstrong, N. R. Defect Quantification in Metal Halide Perovskites Projecting Photoluminescence and Photovoltaic Performance. US patent No. 63/584,557, September, 22, 2023.

PROJECT NAME: Planar Transformer Systems for Modular Power Electronics in Long-haul, Low-Cost PV Systems

Last 5 digits of project number: **10239**
Principal Investigator (PI): **Mike K. Ranjram**
Lead Organization: **Arizona State University**
PI Email: **Mike.Ranjram@asu.edu**

BACKGROUND and OVERVIEW

- Emerging utility-scale modular PV systems dramatically reduce balance of system costs.
- These ubiquitously employ high-frequency, miniaturized transformers in each module.
- We developed and verified a new approach for these transformers to simplify their manufacture, improve their isolation capability, lower their cost, and reduce their volume and/or loss.

METHODS

- Critical design discrepancies in the state of the art were identified and corrected.
- Established planar magnetic winding cost model to improve BOS estimation.
- Created and validated isolation and core loss testbeds for accurate characterization.
- Developed planar transformer design framework for simple-to-manufacture, non-interleaved designs.

KEY MILESTONES (All Complete)

- Demonstrated planar transformers having 1.5x greater isolation capability at >4x lower cost compared to the state of the art.
- Benefits are demonstrated in a miniaturized design (~40% lower volume) and a high-performance design (~12% lower loss, >60kV withstand voltage).
- Surveyed PCB manufacturers to develop PCB winding cost model.
- Confirmed accuracy of developed square-wave, high-frequency core loss testbed.

CONCLUSION

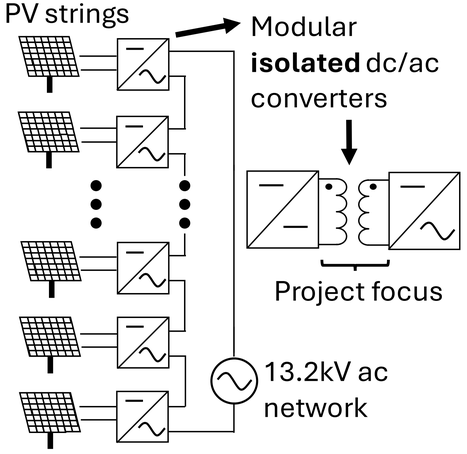
- Our demonstrated planar transformer systems exceed project goals, enabling ultra-low cost, low complexity, and low volume and/or loss with improved isolation capability while using commonly-stocked PCB materials.
- Next steps are to demonstrate deployment in a miniaturized converter module, and to develop and characterize partial discharge compliant designs under wide temperature operation.

PHOTOVOLTAICS TRACK

Demonstrated **medium voltage planar transformers** for solar PV inverters with **1.5x greater isolation capability** and **>4x lower cost** compared to the state of the art.

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Three publications on cost modeling (available), core loss tester validation (submitted), and planar transformer systems (submitted)

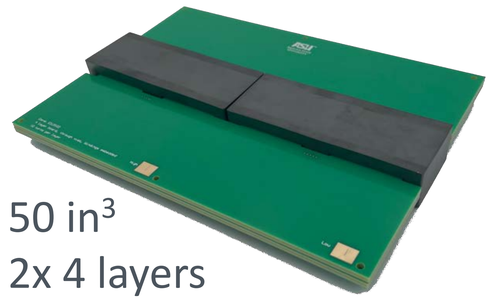


Miniaturized



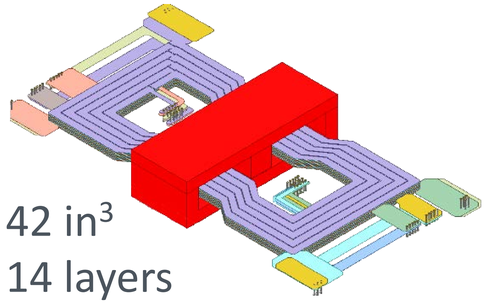
25 in^3
2x 4 layers

High Performance



50 in^3
2x 4 layers

Prior Art

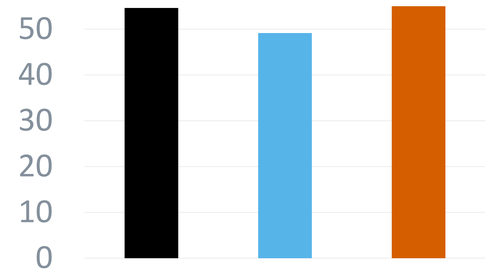


42 in^3
14 layers

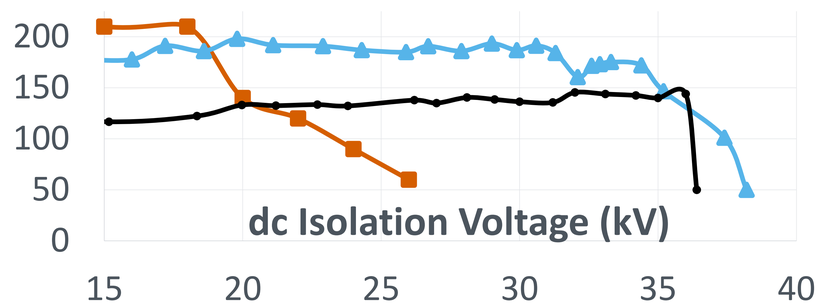
Standard materials and manufacturing

Exotic PCB requirements

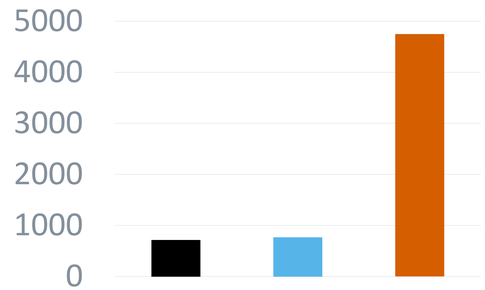
Loss (W)



Isolation Resistance (GOhm)



Cost per Unit ($)



The work in this project was performed with doctoral students Htat "Ted" Min and Emmanuel Havugimana at Arizona State University.

PROJECT NAME: In-situ hydrogen microstructural characterization of Si heterojunction passivation: Addressing V_{OC} degradation and mitigation pathways

Last 5 digits of project number: **10249**
Principal Investigator (PI): **Dr. Ujjwal Das**
Lead Organization: **University of Delaware**
PI Email: **ukdas@udel.edu**

PHOTOVOLTAICS TRACK

Hydrogen evolution from p-type a-Si:H and its interface with surface passivating intrinsic a-Si:H plays the most critical role in V_{OC}-degradation in Si HJ structure

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BACKGROUND and OVERVIEW

- Si heterojunction (SHJ) has excellent surface passivation
  - Record high efficiency = 26.8% and open circuit voltage (V_{OC}) ≈ 750 mV
  - But exhibited higher rate of V_{OC}-driven degradation, unlike other Si cells
- This project aims to identify the critical interface degradation and decipher the mechanism (kinetics) of the V_{OC}-degradation in SHJ

METHODS

- Accelerated stress exposure of SHJ component structures to heat, light and their combinations
- In-depth ex-situ characterization of implied V_{OC} (iV_{OC}); ToF-SIMS and FTIR studies to identify degrading interface(s) and/or layer(s)
- In-situ FTIR under heat and light stresses to decipher H-migration / evolution kinetics and correlate them to iV_{OC} degradation

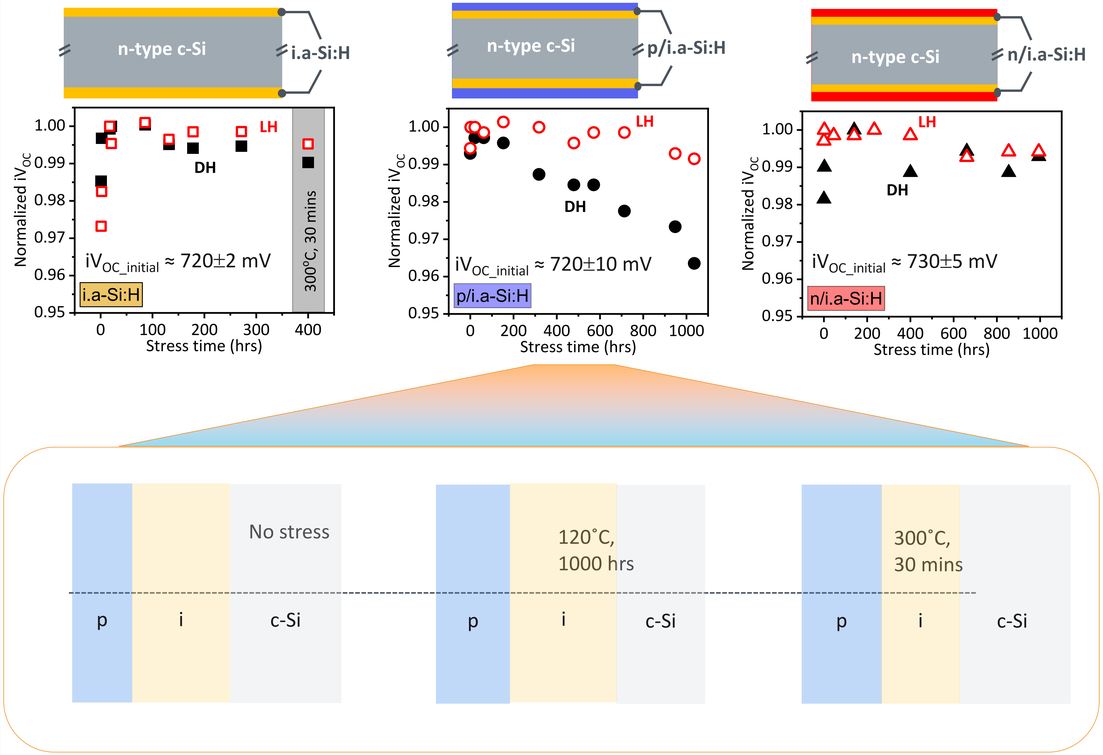
KEY MILESTONES

- Initial iV_{OC} > 740 mV of SHJ passivation structure with intrinsic and doped amorphous Si layers – *achieved iV_{OC} = 730 ± 5 mV*
- SHJ cell V_{OC} > 730 mV – *achieved 700 mV, limited due to ITO sputter damage*
- Identify V_{OC}-degrading critical interfaces – *achieved by ex-situ ToF-SIMS*
- Decipher heat and light-induced H-migration kinetics and correlate to the iV_{OC} degradation – *achieved by in-situ FTIR measurements*

CONCLUSION

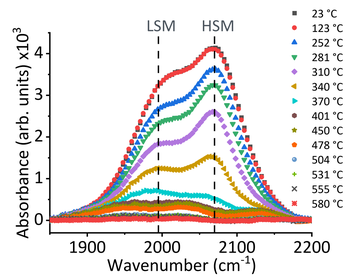
- iV_{OC} > 730 mV demonstrates state-of-the-art SHJ passivation
- In-situ FTIR experiments under heat stress suggest an activated process for H-evolution and associated interface degradation with an activation energy of 0.4 – 0.6 eV
- P-type a-Si:H layer and its interface with intrinsic a-Si:H play the most critical role in V_{OC} degradation, offering focus for mitigation strategies

Identifying V_{OC}-degrading critical interfaces (layers)

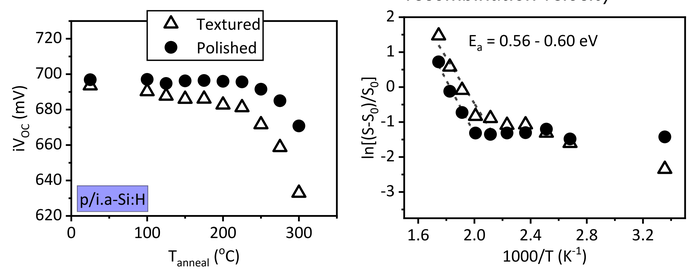


Correlating H-evolution and V_{OC} (SRV) degradation kinetics

Fractional loss of hydrogen



Fractional increase of surface recombination velocity



Additional project contributors: Prof. **Andrew** V. Teplyakov, Tasnim Kamal Mouri , Margaret Zeile, Tyler Parke, Marissa Pina, John R. Mason, and Dhamelyz Rosana Silva Quinones

PROJECT NAME: Photovoltaics Supporting Community and Cultural EcoSystem Services (PV-SuCCESS)

Last 5 digits of project number: **10385**

Principal Investigator (PI): **Brian Ross**

Lead Organization: **The Great Plains Institute**

PI Email: **bross@gpisd.net**

BACKGROUND and OVERVIEW

In state and local permitting, large- and community-scale solar development is often treated as an industrial land use – degrading local and regional natural systems, conflicting with the community's land use or economic priorities, and undermining rural character.

Resulting regulation and permitting can slow deployment, result in permit denials, diminish environmental outcomes, and miss opportunities for community co-benefits.

METHODS

This project will deliver and implement data-driven, field-tested, stakeholder-informed decision tools for communities, regulators, and developers for evaluating ecosystem service impacts and co-benefit opportunities in the development and management of large-scale ground-mounted solar facilities.

KEY MILESTONES

- Conduct field research on biophysical ecosystem services on solar farms and create predictive models.
- Conduct social research on cultural ecosystem services in host communities and Tribal nations.
- Engage distinct jurisdictions (host community, state agency, Tribal Nation) on ecosystem priorities to guide the development of decision tools.
- Create an ecosystem framework decision toolset to enable solar projects to capture priority co-benefits and create buy-in from host communities and regulators.

CONCLUSION

- The project builds in implementation pathways for the scientific research to be used by permitting authorities, and opportunities for ultimate users to shape both research and development of decision tools.
- The decision tools will enable developers, regulators, and host communities to consider large-scale solar development as an opportunity to benefit local and state ecosystems and align with host community priorities.

PHOTOVOLTAICS TRACK

Establish a **scientific foundation** for measuring cultural and physical **ecosystem co-benefit potential** associated with solar site selection and site design. Create a **decision-tool framework** for Midwestern ecosystems that **reflects host community, state agency, and tribal nation priorities**.

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Access the PV_SuCCESS web page



Assessing Cultural Priorities



Field Research and Modeling



Finding #2:

Soil Depth

The soil depth, also known as rooting depth, defines the capacity of the site to infiltrate water. Soil depth measures from the soil surface to the first impervious layer past which water (and roots) cannot infiltrate. Soil depth in the modeling ranged from 0.5 to 1.5 meters, with deeper depths possible, but modeling showed little impact beyond 1.5 meters. Soil depth is the second most important element of the site in terms of stormwater management and water quality risk or opportunity. The PV-SMaRT research estimated a 78 percent increase in runoff as soil depth decreases from 1.5 to 0.5 meters.

Soil depth cannot be easily improved on a site, as the impervious layer would have to be plowed or broken through or additional soil added to the site. Soil depth can, however, be diminished in some development scenarios, where extensive grading, soil removal, or cut-and-fill techniques alter the rooting depth of the site. Solar projects currently evaluate soil depth from the standpoint of engineering the pile system to support the arrays but not in evaluating infiltrative capacity.

Considering the infiltrative capacity of the site would be a new concept for most permitting processes. Such a measure would contribute to evaluating sites as green infrastructure for watershed benefit. The PV-SMaRT runoff calculator incorporates soil depth into the design storm runoff estimates or site-specific curve numbers.

Creating Decision Tools

Additional project contributors: University of Minnesota, Argonne National Laboratory, Midwest Tribal Energy Resources Association, Minnesota Clean Energy Resources Teams, MN Department of Commerce (and other MN agencies), WI and IL Depts. Of Natural Resources, Xcel Energy, Center for Watershed Protection

ENHANCING HARDENING AND RESILIENCE OF SOLAR TRACKERS UNDER STRONG WINDS

Last 5 digits of project number: **10426**
Principal Investigator (PI): **Yanlin Guo**
Lead Organization: **Colorado State University**
PI Email: **Yanlin.Guo@colostate.edu**

PHOTOVOLTAICS TRACK

Resilience of solar trackers under strong winds will be enhanced through **cost-effective aerodynamic mitigators**, accurate **wind nowcasting** and **digital twin** simulations.

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BACKGROUND and OVERVIEW

- **Goal:** to improve the hardening and resilience of single axis solar trackers under extreme winds

Current work involves tasks to develop:

- A wind nowcasting model to better inform tracker stow
- Efficient models to simulate wind response of trackers
- Cost-effective aerodynamic mitigators for trackers to reduce wind damage risk

Future work includes tasks to develop:

- A smart sensing system to collect field data that can be used to validate the design of aerodynamic modifiers
- A digital twin model that integrates wind nowcasting, sensing data and numerical models to improve tracker's emergence response under high winds

METHODS

The methods of the **current work** are divided into two parts.

Part I:

- Develop fluid-structure-interaction models to simulate tracker response under winds
- Design aerodynamic mitigators using developed models
- Validate aerodynamic design in wind tunnel testing

Part II:

- Collect extreme wind data from different sources
- Develop a machine learning model to nowcast wind

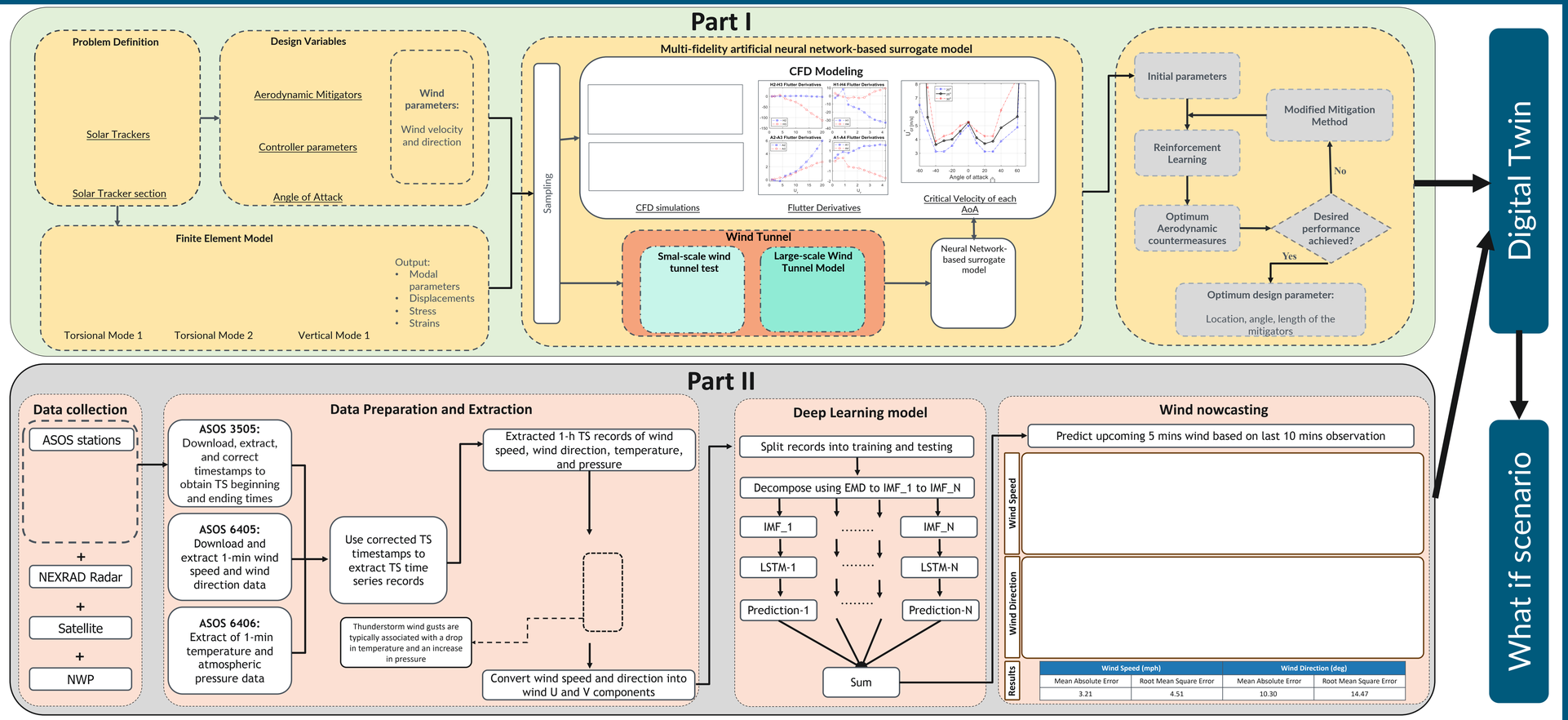
KEY MILESTONES

- Accurate wind nowcasting (IP)
- Field deployment of wind and structural response sensing system (IP)
- Wind tunnel validation on identified aerodynamic measure combinations (IP)
- Trackers with aerodynamic designs installed in field (NS)
- Validation of digital twin in wind tunnel (NS)
- User customizable spreadsheet tool for financial analysis of hardening measures (NS)

* IP: In-progress; NS: Not started.

CONCLUSION

- The aerodynamic mitigators will lead to decreased wind-induced damage and maintenance costs.
- The accurate wind nowcasting will allow more effective wind stow strategies.
- Digital twin allows simulation of what-if scenarios, thus can enhance decision-making in emergency response.
- The new technologies has the potential to drive down the cost of solar energy production in a holistic way, through improving the wind performance of the structural system (passive) and enhancing emergence response (active).



Additional project contributors: Teng Wu (Sub-PI), University at Buffalo; James Elsworth (Sub-PI), NREL; Scott Dana, NREL

PROJECT NAME: Agrivoltaic Systems for Diversified Agriculture

Last 5 digits of project number: **10439**
Principal Investigator (PI): **Ethan Schoolman**
Lead Organization: **Rutgers University**
PI Email: **ethan.schoolman@rutgers.edu**

BACKGROUND and OVERVIEW

- Diversified agriculture means farms or farm groups that exhibit ecological diversity at field and landscape scales
- The complexity of diversified cropping systems and lack of examples of dual-use solar in peri-urban areas presents a high barrier to entry to the agrivoltaic space
- Advancing agrivoltaics in diversified agricultural landscapes requires significant advances in technical understanding and translation to on-farm practices

METHODS

- Conduct crop trials at agrivoltaic installations at three Rutgers research farms
- Study crop performance, soil health, and energy production during crop trials
- Model economic benefits/costs for farms and explore perceptions of agrivoltaics among community members
- Use research sites as venues for new technical assistance, outreach, and educational programs

KEY MILESTONES

- Yearly reports on crop performance and soil health trends across treatment and control plots
- Shading and energy production modeled at each array, for comparison with actual energy produced
- Enterprise budgets developed for key crops within agrivoltaic systems (hay, soy, tomatoes)
- Community perceptions of agrivoltaics explored
- Technical assistance workshops on agrivoltaics held with farmers, landowners, and solar developers
- Regional network of land-grand universities organized

CONCLUSION

- Foundational research will directly address the questions and concerns of operators of farms that are part of diversified agricultural landscapes
- New Technical Assistance Program for Agrivoltaic Systems will prepare a cohort of early adopters of agrivoltaics in New Jersey
- Regional land-grant university network will speed diffusion of lessons learned through Rutgers project

PHOTOVOLTAICS TRACK

Examine **crop performance, soil health, energy production, and socioeconomic dimensions** under dual-use solar, and **develop outreach programs** to advance agrivoltaics regionally.

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Take a picture visit the **Rutgers Agrivoltaics Program site**



Buckwheat cover crop at Snyder Farm, Sept. 6, 2023



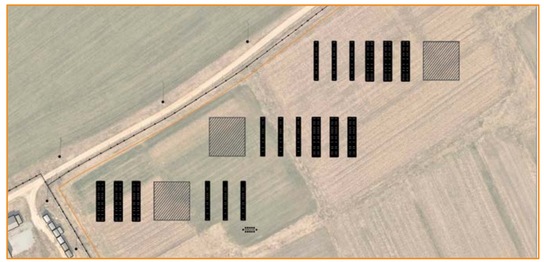
RAREC from the air, March 2023



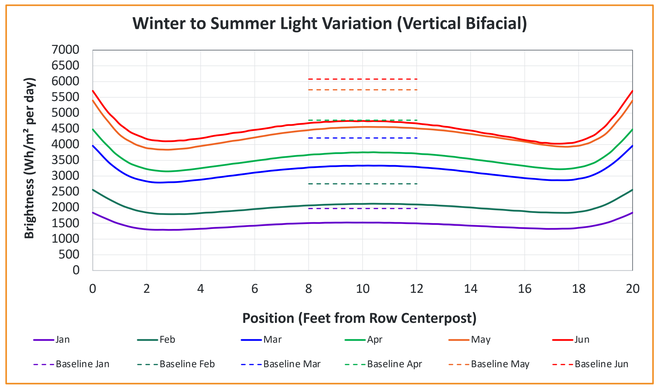
Cook Animal Farm under construction, Feb. 2, 2024



1. Cook Animal Farm
   - Vertical bifacial "solar fence" array
   - 3.1 acres in a perennial forage crop
   - 170 kW
2. RAREC: Rutgers Agricultural Research and Extension Center
   - Single-axis tracker array; single- and double-wide panel rows
   - 2.9 acres in specialty crops and soy
   - 255 kW
3. Snyder Farm
   - Single-axis tracker array; single-wide panel rows
   - 1.4 acres in a perennial hay crop
   - 95 kW



RAREC experimental design:
- Three blocks for growing specialty crops or soybeans
- Each block has 2 treatment conditions (single-wide or double-wide panel rows) and a control



Additional project contributors: American Farmland Trust, Delaware State University, National Renewable Energy Laboratory

PROJECT NAME: PV Packaging Designed for Circularity

Last 5 digits of project number: **10498**
Principal Investigator (PI): **David Fenning**
Lead Organization: **UC San Diego**
PI Email: **dfenning@ucsd.edu**

BACKGROUND and OVERVIEW

- The need for new approaches to recycling is urgent to manage end-of-life panels and support the industry's sustainability.
- We seek to develop a reversibly cross-linking interlayer polymer (ReCLIP) to interface between the module layers.
- Temperature can temporarily alter the ReCLIP's properties, allowing easy separation without damaging the materials.

METHODS

- Initial phases of the project focus on refining and developing of the ReCLIP, ensuring compatibility with PV materials.
- The project will progress to integrate ReCLIP into silicon modules to test separation of the layers after accelerated degradation.

KEY MILESTONES

- Synthesis scaled to > 5g of the functional polymer in R&D lab setting.
- Successful demonstration of both crosslinking and de-crosslinking of the ReCLIP material.
- Deposition of ReCLIP as a thick film
- Creation of a data library providing the project with the necessary thermomechanical properties of encapsulants for baseline comparison.

CONCLUSION

- The project aims to enable easier, more efficient recycling of solar panels, contributing to the solar industry's sustainability and the global push for circular economy practices.
- By achieving synthesis and demonstrating reversible crosslinking of the ReCLIP, we move closer towards simplifying disassembly and recycling.

A **Re**versibly **C**ross-**L**inking **I**nterlayer **P**olymer (**ReCLIP**) provides a path to PV circularity

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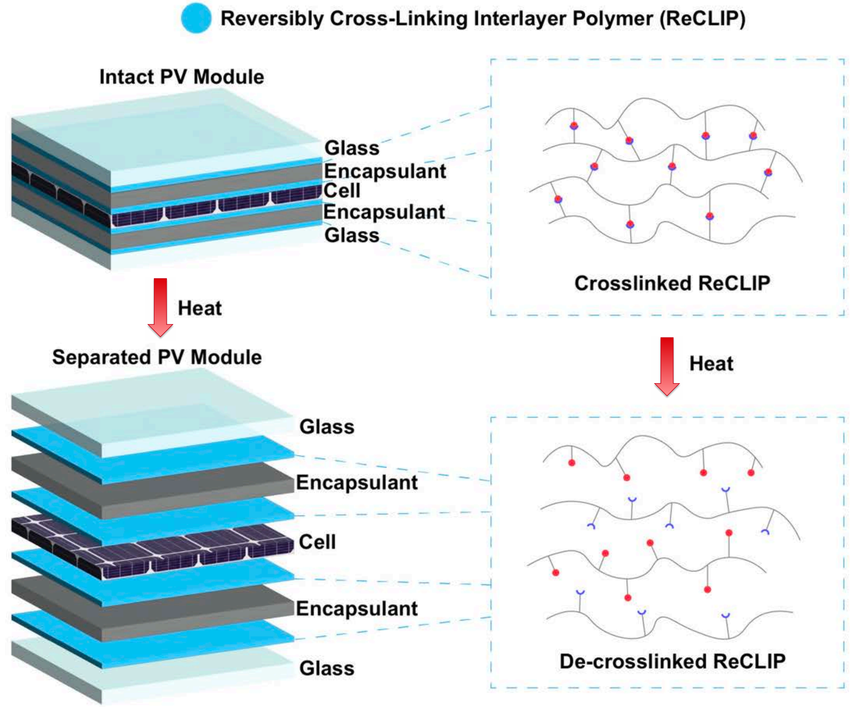


Fig 1: Concept for ReCLIP use in a PV Module. ReCLIP operates as a "lock-and-key" chemistry with a de-crosslinking reaction temperature tuned above terrestrial operating temperatures. Target interfaces will be tested within the project pristine and after accelerated tests.

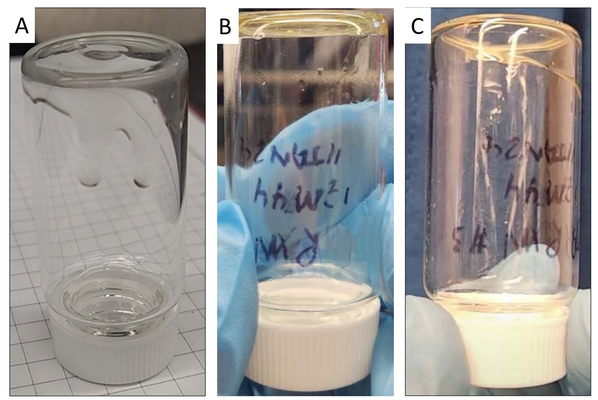


Fig 2: ReCLIP (A) Uncrosslinked, (B) Crosslinked at low temperature, (C) De-crosslinked at temperatures above terrestrial operation

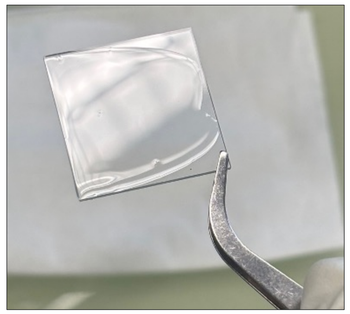


Fig 3: Blade-coated ReCLIP thick film

Additional project contributors: UC San Diego: Ayush Tiwary, Zack Moreau, Dr. Adit Nyayachavadi, Dr. Rachel Blau, Prof. Darren Lipomi

Porous Aromatic Frameworks (PAFs) as Multifunctional Adsorbents for Selective Metal Recovery from Spent Photovoltaic (PV) Materials

10499

Prof. Jeffrey Long
Institute of Decarbonization Materials,
University of California, Berkeley
jrlong@berkeley.edu

PHOTOVOLTAICS TRACK

Porous Aromatic Frameworks (PAFs) for Selective Capture of Ag(I) from Spent PV Waste

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BACKGROUND and OVERVIEW

- Net zero emission targets require massive deployment of renewable photovoltaic (PV) energy sources
- PV solar cells compositionally contain <0.1 % silver (Ag) but Ag make around ~50 % of total panel cost
- By 2050, estimates suggests generation of ~80 Mt of PV solar panel waste (Value ~15 Billion USD)[1]
- Urgent need to design technology for circular economy and environmental protection purpose

METHODS

- Rationally designed and synthesized chemically robust porous aromatic frameworks (PAFs) functionalized with polythiol functional groups (PAF-1-3S)
- The polythiol functional groups were rationally chosen based on strong interactions with soft Ag(I) ions driven by Hard-Soft Acid-base principle[2-4]
- Successful extraction of silver has been realized from spent PV waste chips confirmed by Inductively coupled plasma emission spectroscopy (ICP) analysis

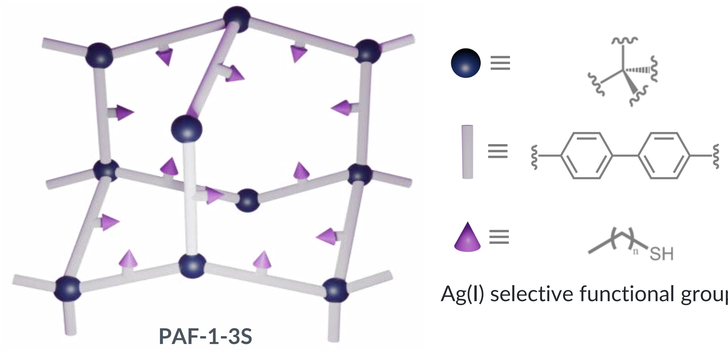
KEY MILESTONES

- Designed PAF shows high functional group loading (~ 2.5 mmol/g), and high surface area
- PAF-1-3S exhibits high uptake capacity, fast kinetics for Ag(I) ion capture
- Selective capture of Ag(I) from spent PV waste solution has been realized
- Next milestones will target the design of PAFs for the selective capture of relevant ions (Cu(II)) and toxic metal ions (Pb(II)) for circular economy and environmental protection purpose

CONCLUSION

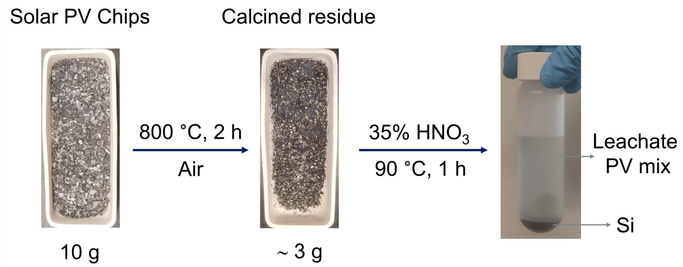
- Through rational design approach, a polythiol functionalized PAF has been synthesized. The thiol functional groups enable selective and fast capture of Ag(I) ions from spent PV waste leachate
- The next steps in the project would be to explore recycling pathways for cost-effectiveness
- This work will help inform the development of recycling technology for PV solar cells and enable sustainable development goals

Porous Aromatic Framework (PAF-1-3S)



Schematic representation of porous aromatic framework (PAF-1-3S) network exhibiting potential porosity. **PAF-1-3S was functionalized with polythiol functional groups owing to favorable interactions between S and Ag based on Hard-Soft Acid-Base principle**.

Extraction of Ag from PV Waste Chips

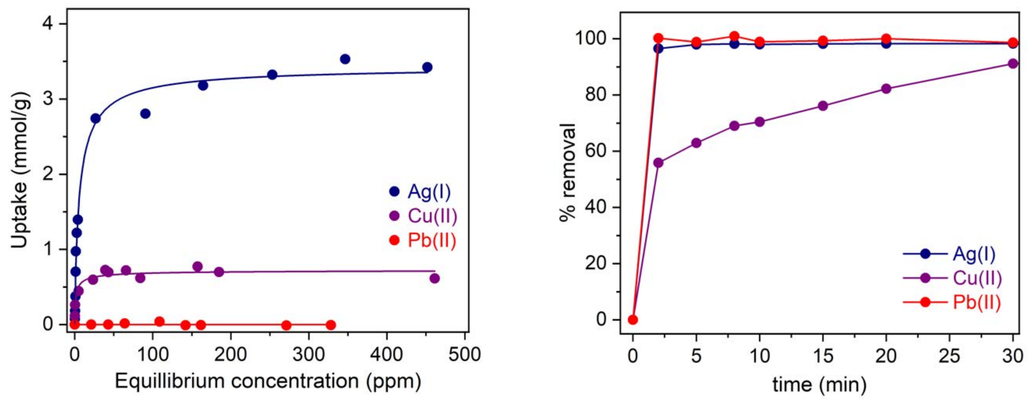


Illustrating strategy for leaching of spent photovoltaic solar panel chips (ITRI, Taiwan). **Ag(I) ions were successfully leached with >99% yield**.

References: (1) Heath *et al. Nat. Energy* **2020**, *5*, 502-510; (2) Uliana, UC Berkeley, Ph. D. Thesis, **2022**; (3) Yuan *et al. J. Am. Chem. Soc.* **2020**, *142*, 1574-1583; (4) Yang, *et al. Angew. Chem. Int. Ed.* **2022**, *61*, e202112511.

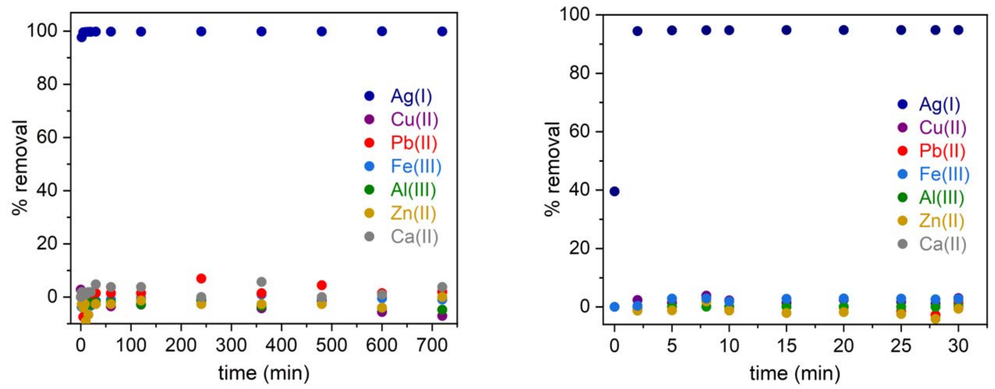
Shivani Sharma, Hsinhan Tsai, Ethan Pezoulas

Single Component Metal Ion Adsorption



Adsorption isotherms (left) for Ag(I), Cu(II), and Pb(II) at room temperature. **Uptake trend Ag(I) >> Cu(II) >>> Pb(II) indicates strong interaction of thiol functional groups with Ag(I) ion**. Adsorption kinetics (right) for Ag(I), Cu(II), and Pb(II) by PAF-1-3S. **PAF-1-3S shows favorable kinetics for Ag(I) ~ Pb(II) >> Cu(II)**.

Selective Ag(I) Capture in PAF-1-3S



Selective removal of Ag(I) with PAF-1-3S by exposure to ideal PV leachate solution (left) (pH~7) and real PV waste solution (right) (pH~1). **PAF-1-3S selectively adsorbs Ag(I) in the presence of multiple competing ions. This maybe due to favorable interactions between Ag(I) and thiol functional sites**

PROJECT NAME: Tandems for Efficient and Advanced Modules using Ultrastable Perovskites (TEAMUP)

Last 5 digits of project number: **10502**
Principal Investigator (PI): **Michael McGehee**
Lead Organization: **University of Colorado-Boulder**
PI Email: **michael.mcgehee@colorado.edu**

BACKGROUND and OVERVIEW

- TEAMUP is a diverse PV consortium, with members strategically chosen to target >28%-efficient perovskite/silicon multijunction modules with stable operation in field conditions.
- TEAMUP brings together the researchers from world-class research labs and leading US companies to manufacture both 2 and 4-terminal tandems.
- The project started on October 1, 2023. Subcontracts were executed in January 2024.

METHODS

- Optimizing the perovskite composition and deposition, contacts, module design and fabrication with a lens for understanding and improving stability at the tandem module scale. This will be complemented by outdoor testing and energy yield calculations. Modules will be tested outside through PACT and facilities at UC Merced. Acceleration factors will be measured and lifetimes in real world conditions will be predicted.
- Key problems targeted are preventing halide oxidation, PbI_2 formation and blisters, use of stable self-assembled monolayers, and scribe stability.

KEY MILESTONES

- Analysis of scribe losses, design of outdoor testing, build and qualification of in-house light and heat stability testing for tandem cells and modules, design of mechanically robust layers (completed).
- Hold a meeting with the MIT-led consortium and write a roadmap for perovskite PV development.
- >24% efficient 2T (225 cm^2) and 4T tandems (100 cm^2) after 500 hours at 1-sun and 65C in ambient and >28% efficient 2T and 4T (1100 cm^2) tandems after 10,000 hours equivalent operation (ongoing).

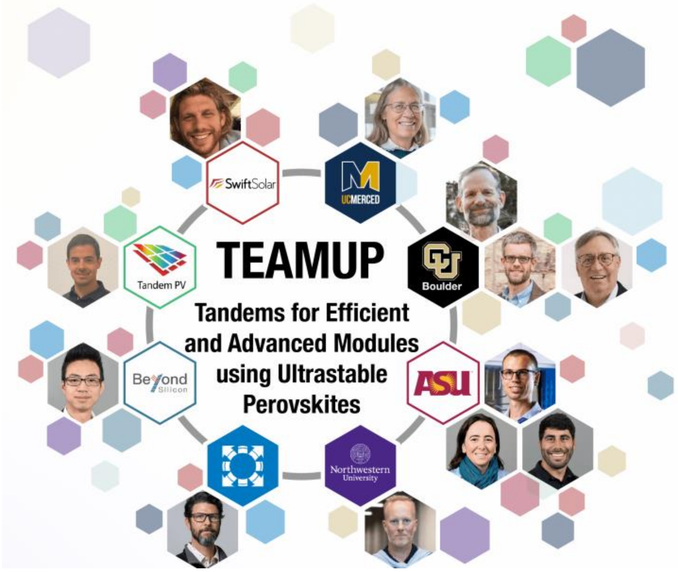
CONCLUSION

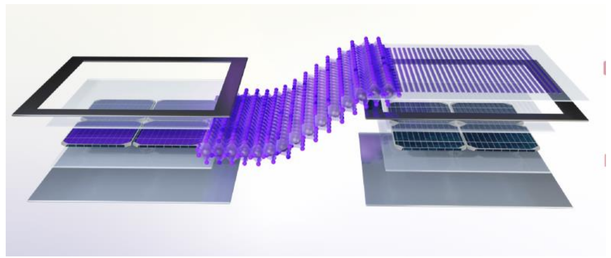
- The industry partners are focused on related but distinct device configurations and processes. They have advanced pilot lines to achieve the SETO 5-year goal of 28%-efficient 1100-cm^2 tandem modules with degradation rates of <1% over 10,000 hours under conditions equivalent to field operation.
- The university and national laboratory teams provide expertise and capability in materials selection, device design, advanced thin-film deposition, and characterization.

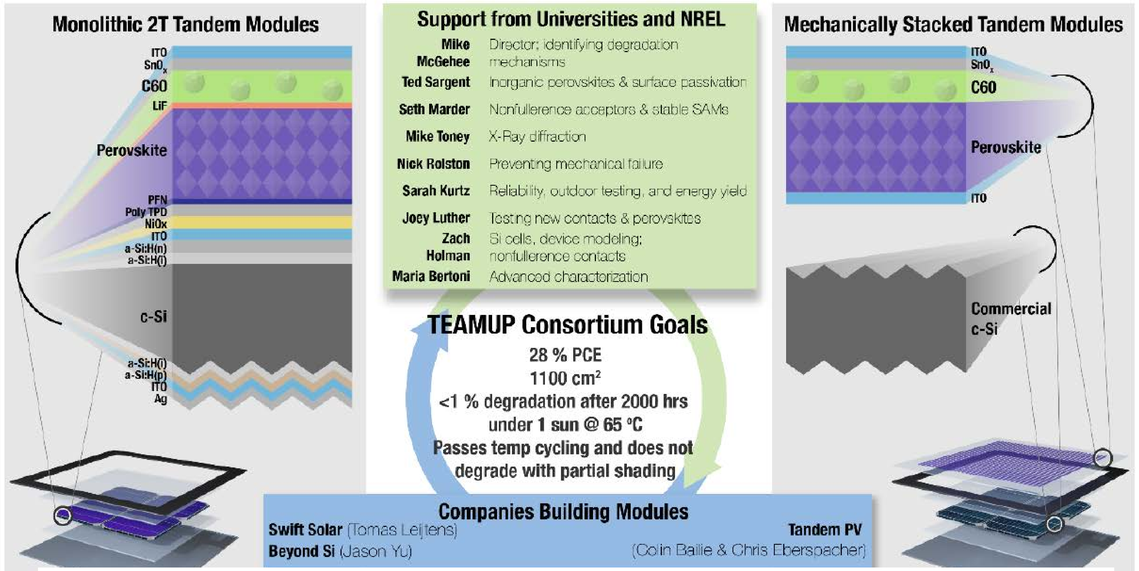
PHOTOVOLTAICS TRACK

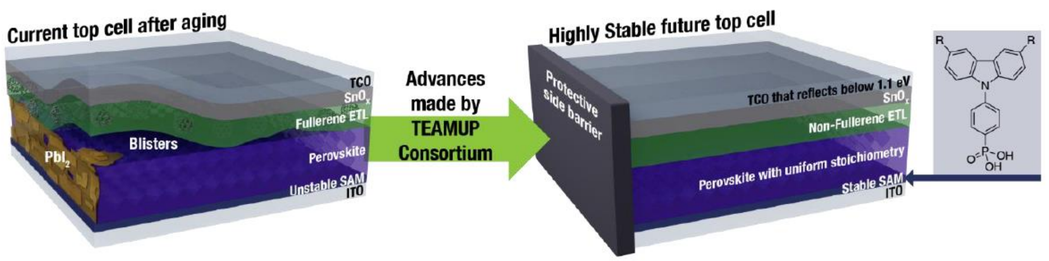
Addressing the scientific challenges to *accelerate the commercialization* of stable perovskite-silicon tandem solar modules

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Additional project contributors: Applied Materials, Dow, Endurans, Maxeon, NTact, Sinton Instruments

PROJECT NAME: Improving perovskite solar module stability by understanding and mitigating scribe-induced chemo-thermomechanical degradation

Last 5 digits of project number: **11152**
Principal Investigator (PI): **Nicholas Rolston**
Lead Organization: **Arizona State University**
PI Email: **nicholas.rolston@asu.edu**

BACKGROUND and OVERVIEW

- This project aims to solve the gap in stability observed between perovskite solar cells and modules from laser scribing-based degradation
- This project studies the effect of thermal cycling over the laser scribing area of perovskite solar modules and to develop design criteria to overcome mechanical and chemical limitations

METHODS

- This work will use mechanical measurements (through quantifying fracture energy and film stress) and changes in optoelectronic behavior in perovskite solar modules under thermal cycling (-40 °C to 85 °C) to identify the main causes in failure and identify the relative contributions of mechanical stress, delamination, and chemical corrosion.

KEY MILESTONES

- Key milestones include (all ongoing): baseline measurements of thermomechanical and operational stability of perovskite solar cells and modules, understanding and modeling delamination-based and corrosion-based mechanisms of laser scribing, and strategies to validate improvements against chemo- and thermomechanical induced degradation

CONCLUSION

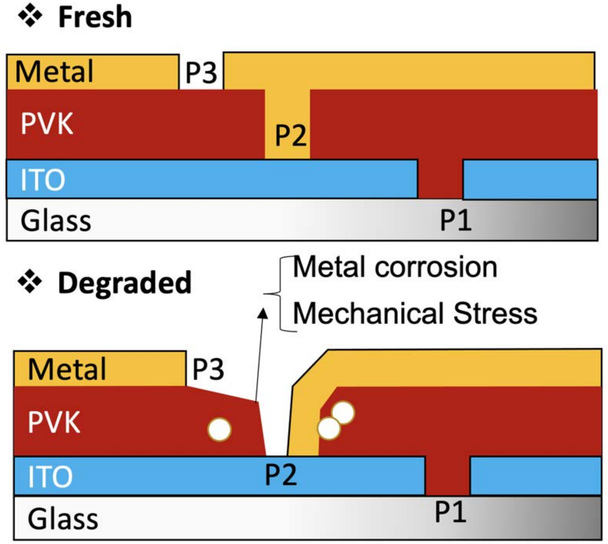
- The milestones will study and quantify mechanical and chemical degradation involving delamination of the electrode near the P2, effect of packaging materials, and chemical-based failure from corrosion.
- This project will implement strategies to drastically reduce perovskite module degradation to pass the IEC 61215 thermal cycling test while maintaining >95% of efficiency after 200 thermal cycles

PHOTOVOLTAICS TRACK

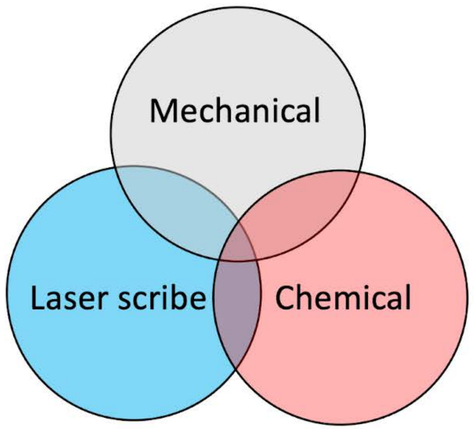
Decoupling the *thermomechanical and chemical degradation* of laser scribes to improve the operational stability of perovskite solar modules

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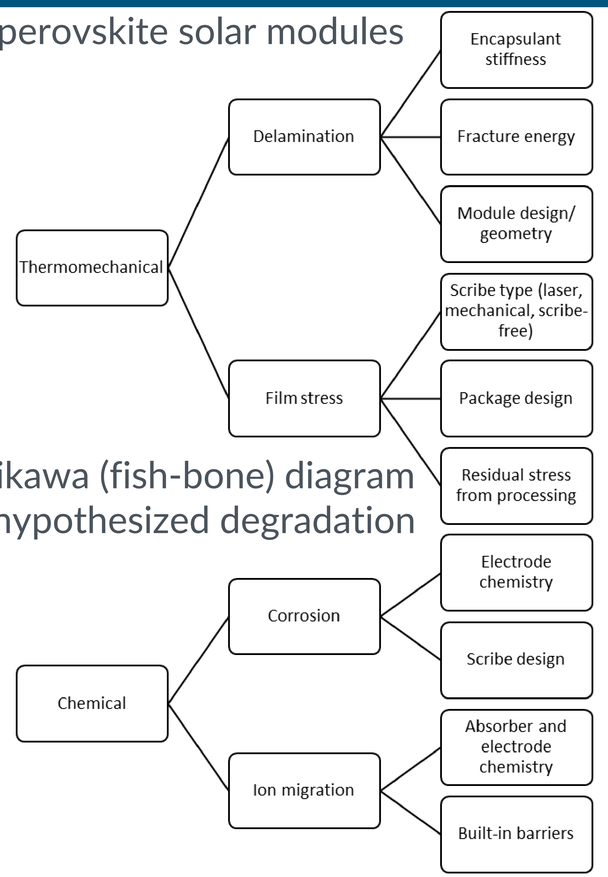
Our approach is to provide understanding and design criteria to deploy stable perovskite solar modules



Schematic of laser scribe-based degradation mechanisms in perovskite solar modules



This work will study the intersection between mechanical and chemical degradation modes with laser scribing



Ishikawa (fish-bone) diagram of hypothesized degradation

Additional project contributors: Wanyi Nie (University at Buffalo), Perovskite PV Accelerator for Commercializing Technologies (PACT)

PROJECT NAME: Self-Leveling Inks for Printing Ultra-uniform Perovskite Solar Modules by Flexography

Last 5 digits of project number: **11153**
Principal Investigator (PI): **Will Scheideler**
Lead Organization: Dartmouth College
PI Email: **william.j.scheideler@dartmouth.edu**

BACKGROUND and OVERVIEW

- Rapid direct patterning of perovskites simplifies module integration and eliminates scribe damage
- Current coating methods are comparatively slow and film defects serve as degradation sites limiting long-term stability.
- Self-leveling inks can compensate / heal nonuniformities occurring during printing and improve homogeneity of large area films.

METHODS

- High-speed flexography provides a scalable method for uniform large area deposition.
- Bayesian optimization can optimize ink and printing parameters for uniformity objective.
- Scanning PL + large area microscopy quantify printed film uniformity
- Fluid ink characterization allows for precise design of self-leveling inks.

KEY MILESTONES

- Train Bayesian Optimization (BO) model using initial data to design experimental conditions
- Characterize Marangoni coefficient and design inks for expanding leveling process window
- Iterate via BO to optimize areal PL uniformity for boosting large area performance and stability
- Integrate printed 'scribes' into mini-modules with enhanced lifetime

CONCLUSION

- BO model guides ink/process optimization towards uniformity objectives
- Fluid mechanics of leveling drive ink design for expanding process windows
- Initial data show printed 'scribes' reduce damage to perovskite at module interconnections
- Module performance and stability can leverage improved spatial uniformity

PHOTOVOLTAICS TRACK

Advance the **uniformity and stability** of perovskite modules by minimizing weakpoints from scribing and coating defects

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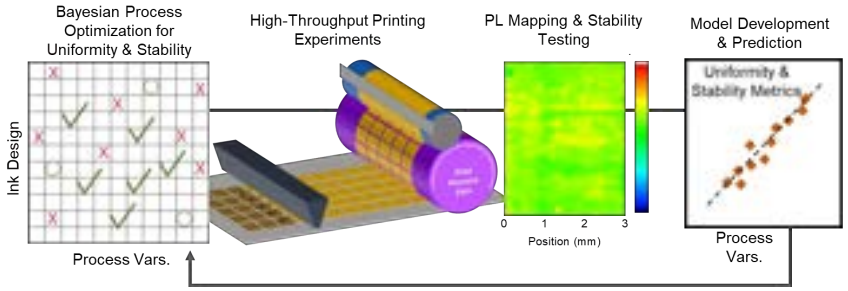


Figure 1: *Scheme for Bayesian optimization of ink and process variables via high-throughput experiments, PL mapping, and models to predict uniformity / stability with self-leveling inks.*

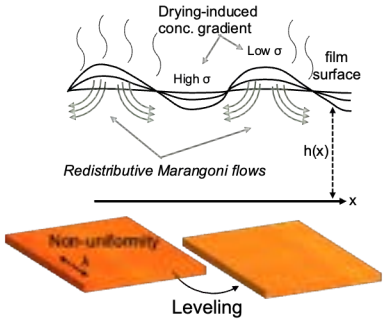


Figure 2 (left): *Leveling assisted by Marangoni flows with perovskite films (Saffman Taylor artifacts) below.*

$$\tau_{level} \approx \frac{3\eta\lambda^4}{16\pi^4\gamma h^3}$$

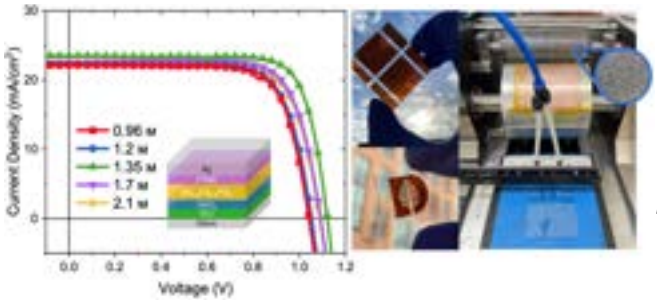


Figure 3 (left): *J-V curves for flexo printed (60 m/min) PVSK cells on glass. Images of patterned PVSK films and lab-scale flexo printer w/ inline drying.*

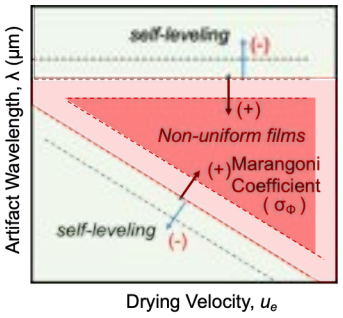


Figure 4 (left): *Process window describing the potential for leveling as a function of wavelength and drying– red marks a non-leveling regime.*

Additional project contributors:

PROJECT NAME: PVInsight

Last 5 digits of project number: **38529**

Principal Investigator (PI): **Bennet Meyers**

Lead Organization: **SLAC National Accelerator Lab**

PI Email: **bennetm@stanford.edu**

BACKGROUND and OVERVIEW

- Most distributed rooftop PV systems have lower data quality, are not well modeled, and are lacking reliable environmental data
- We aim to develop data science tools to enable cost-effective, fleet-scale operations and maintenance for all PV systems

METHODS

- Develop a novel approach to fleet-scale probabilistic modeling of power production, suitable for large scale fault detection and forecasting
- Make algorithms available in parallelizable, scalable, cloud computing environments
- Build a public-facing validation hub with curated datasets for testing and comparing statistical algorithms

KEY MILESTONES

- Released V1.1.1 of `solar-data-tools` (SDT)
- Developed parallelization system design with Dask
- Developed datasets, test environments and prototype of PV Validation Hub
- First paper published on smooth, periodic Gaussian copula method and applications to PV fleet analysis
- Release V1 of fleet probabilistic model software package (`spcqe`)
- Test Dask-based parallelization framework with cloud deployment support on AWS and GCP

CONCLUSION

- Pave the way for technology transfer of advanced statistical algorithms for data analysis from the academic sphere to industry
- Provide practical tools for industry for fleet-scale performance analysis for unlabeled data with no meteorological data
- Establish clear metric for validation of algorithms
- Make use of efficient “white box” machine learning

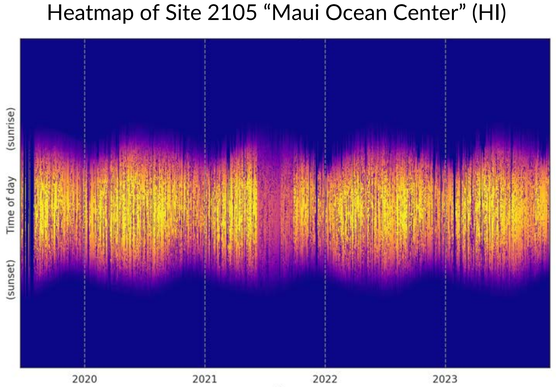
PHOTOVOLTAICS TRACK

Released an **open-source** Python library of tools for **automated, model-free, signal processing-based** data quality and loss factor analysis of **unlabeled** PV data

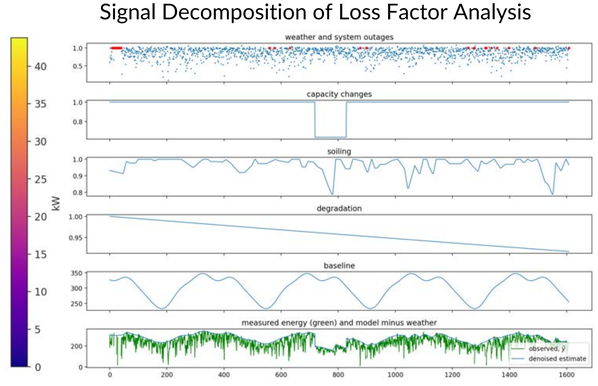
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Heatmap of Site 2105 “Maui Ocean Center” (HI)

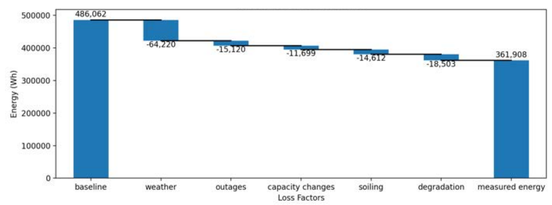


Signal Decomposition of Loss Factor Analysis

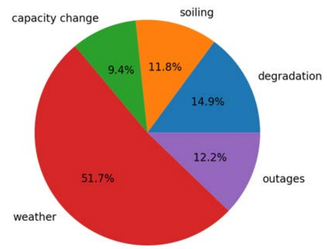


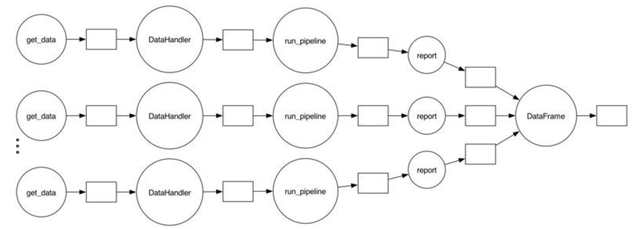

```
------------------
DATA SET REPORT
------------------
length              4.41 years
capacity estimate   41.86 kW
data sampling       5 minutes
quality score       0.97
clearness score     0.15
inverter clipping   True
clipped fraction    0.02
capacity changes    True
data quality warning True
time shift errors   False
time zone errors    False
```

System Loss Factor Waterfall



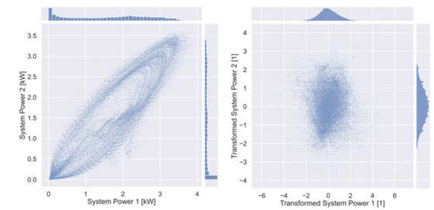
System Loss Breakdown



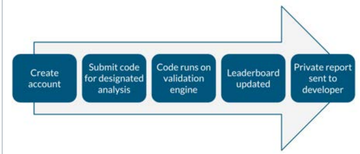


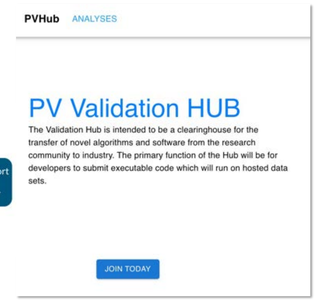
Parallelization: Running SDT pipeline on many files

Fleet modeling: Capturing correlations between nearby PV systems



PV Validation Hub: Curated datasets and online platform for validating common PV





Additional project contributors: Michael Deceglie (NREL), Sara Miskovich (SLAC), Kirsten Perry (NREL), Mehmet Oghut (Stanford), Aramis Dufour (Stanford), Duncan Ragsdale (SLAC), Mitchell Victoriano (SLAC)

PROJECT NAME: Understanding Defect Activation and Kinetics in Next Generation CdTe Absorbers

Last 5 digits of project number: **08754**
Principal Investigator (PI): **Mariana Bertoni**
Lead Organization: **ASU**
PI Email: bertoni@asu.edu

PHOTOVOLTAICS TRACK

Shown **Carrier Compensation** in Cu:CdTe and As:CdSeTe Induced by **Chlorine Defect Complexes**

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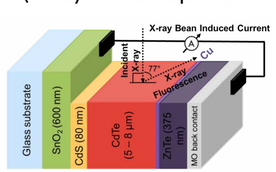
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BACKGROUND and OVERVIEW

- Low lifetimes and doping levels drive the low voltages in CdTe. The two crucial processes to improve V_{oc} are (1) $CdCl_2$ annealing and (2) dopant activation.
- The objective of this project is to unravel the interplay between defect activation and defect passivation in CdTe processing using correlative X-ray Microscopy.

METHODS

- We measured correlatively on a pixel-to-pixel basis the chemical composition (x-ray fluorescence), structure (x-ray absorption and diffraction), luminescence (x-ray exited optical Luminescence and electrical properties (x-ray beam induced current) across the absorber.



KEY MILESTONES

- Measured diffusion of dopants into the absorbers (Cu and As). (Published)
- Measured Current collection associated with defect activation (Pub. Submitted)
- Reported presence of active and inactive species in CdTe absorbers (Published)
- Observed liquid flux formation during $CdCl_2$ process (Pub. under preparation)
- Reported Se diffusion during solar cell aging (Pub. Submitted)

CONCLUSION

- We report for the first time the complex formation of the dopants with chlorine. The dopants sit where they are expected but the inevitable introduction of Cl during $CdCl_2$ is what produces unwanted compensation.
- This work has helped inform better processing practices (T, t, [Cl]), changes in precursors, dopants, etc.

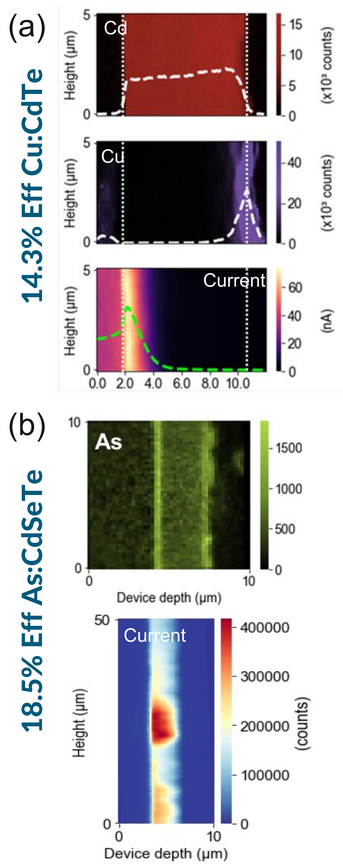


Figure 1. (a) X-ray Fluorescence Cd, Cu and X-ray Beam Induced Current (b) X-ray Fluorescence As and X-ray Beam Induced Current, (c) XBIC Sum Experimental vs. Modeled. Note the difference is due to extra donors that need to be added to the model

What kind of defects are these donors ?

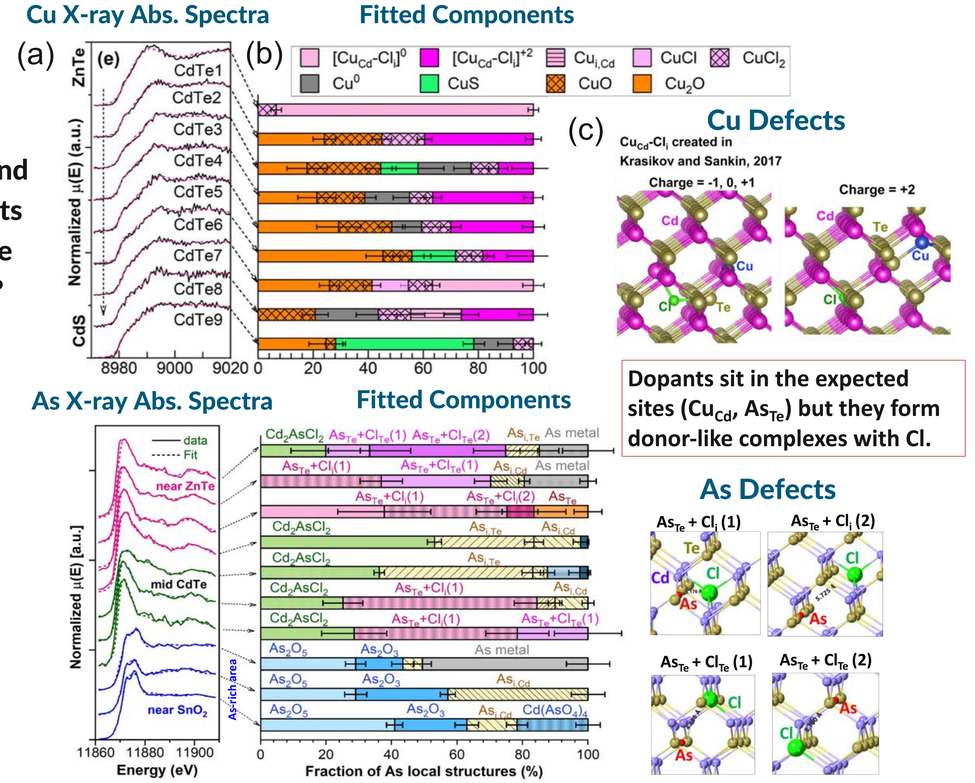


Figure 2. (a) X-ray Absorption spectra for Cu (top) and As (bottom) across the depth of the absorber, (b) Fitting of the spectra utilizing a library of DFT calculated defects and phases; (c) Donor defects found (pink)

Additional project contributors: Dan Mao (First Solar), Maria Chan (Argonne Nat. Lab.), Eric Colegrove (NREL)

PROJECT NAME: Sonic Wafering of III-V Substrates for High Efficiency Cells: A path to <$0.5/W

Last 5 digits of project number: **08973**
Principal Investigator (PI): **Mariana Bertoni**
Lead Organization: **ASU**
PI Email: bertoni@asu.edu

PHOTOVOLTAICS TRACK

Sonic Lift-off of III-V devices with no Damage and Equal Performance to Baseline, and Reusability of Substrate

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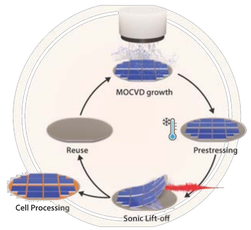
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BACKGROUND and OVERVIEW

- The higher cost of III-Vs cells has confined their application to space power systems and specialized applications. The implementation of III-Vs in emerging markets such as UAV and low-earth orbit satellites (LEO) have accepted cost structures of $100-300/W. However, terrestrial deployments (e.g. VIPV) or portable integrated markets (e.g. IoT) - expected to grow up to 10 GW/year - require cell manufacturing costs well below $100/W.

METHODS

- We use a novel and proprietary acoustic technology to lift-off III-V single junction devices from GaAs wafers, enabling reuse of these wafers for subsequent growth, with minimal re-polishing



KEY MILESTONES

- Achieved Sonic Lift-off of GaAs wafer with RMS roughness < 2µm and > 90% yield
- SLO of inverted and upright devices with equal performance to control
- No SLO induced damage on devices
- Reconditioned surfaces after SLO for multiple reuses
- Showed 3 reuses on 2” GaAs wafers and 2 reuses on 3” wafers.

CONCLUSION

- From discussions with stakeholders even the sonic lift-off of a device from its original substrate one time is an attractive proposition to significantly reduce CMP and hazardous waste associated costs.
- By reusing the substrate three times we have shown cell manufacturing costs compatible with $10/W, and a path to $0.5/W.
- This project helped validate the technology behind a start-up (CS) and has seeded projects between CS and space solar manufacturers.

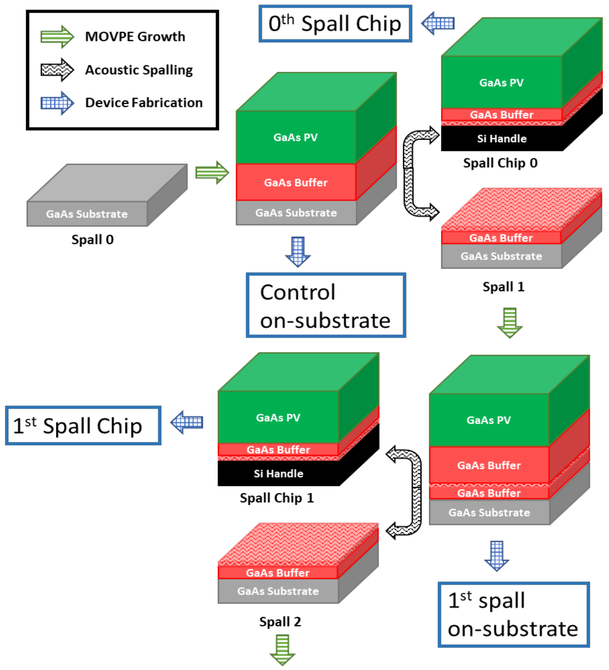


Figure 1. Schematic of the workflow

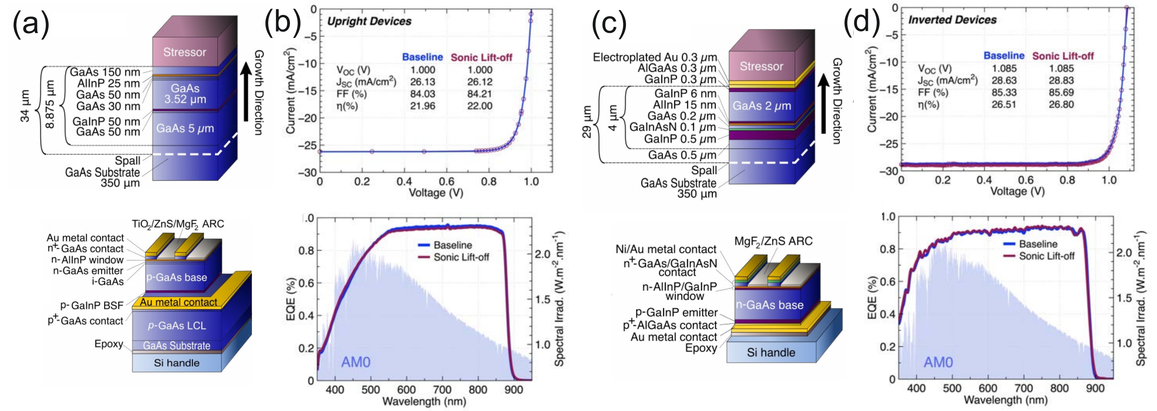
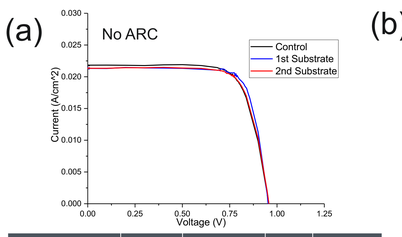


Figure 2. Schematics of as-grown cell stack a) upright device and upright device after processing, and c) inverted device and inverted device after processing; IV curve and EQE of 0th spall chip vs. control for (b) upright devices and (d) inverted devices.



Best Devices	V_{oc} (mV)	J_{sc} (mA/cm²)	FF (%)	Eff. (%)
Control	956	21.8	75.1	15.6
1st substrate	954	21.5	78.1	16.0
2nd substrate	958	21.4	76.2	15.6

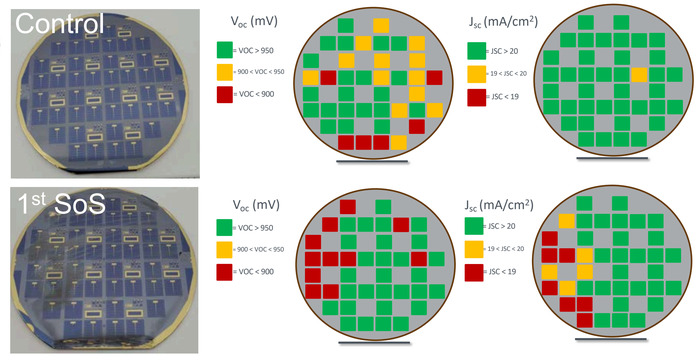


Figure 3. (a) IV curve of 1st and 2nd spall on-substrate vs. control, (b) optical images and device performance mapping for control and 1st spall substrate.

Additional project contributors: Seth Hubbard (RIT), Myles Steiner (NREL), Emily Warren (NREL), Lara Bathurst (Crystal Sonic Inc.)

PROJECT NAME: The Role of Hydrogen in the Performance and Long Term Stability of High Efficiency Silicon Cells and Modules

Last 5 digits of project number: **09346**
Principal Investigator (PI): **Mariana Bertoni**
Lead Organization: **ASU**
PI Email: bertoni@asu.edu

PHOTOVOLTAICS TRACK

Explained V_{oc} **Degradation** for SHJ Fielded Modules from **Interface Degradation** Models and Correlated Loses to **Hydrogen Evolution**

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BACKGROUND and OVERVIEW

- As the understanding of packaging related issues improves and the bill of materials get better, variations at the cell level will become the dominant response of the module, and a model capable of forecasting such performance will be game changing to investors, project developers and plant owners. This project seeks to understand and model the effect and evolution of hydrogen in the different layers of SHJ and TOPCon solar cells and their critical interfaces to explain the degradation of their respective modules.

METHODS

- T1 – Bottom-up Approach: parametrizing hydrogen diffusion through individual layers and materials
- T2 – Top-down Approach: validation through accelerated and fielded mini-modules
- T3 – Ab-initio Modeling: microscopic insights into defect states and H migration
- T4 – Defect-Device-Degradation Modeling

KEY MILESTONES

- Shown the importance of interface degradation in overall module performance and created models for the interface degradation that explain fielded data (not a packaging issue).
- Establish the importance of understanding next generation cells to understand next generation modules.
- Developed the fundamental understanding behind the role of light and humidity in the degradation of the a-Si/ITO interfaces.
- Shown the loss of Hydrogen at the a-Si/Si interface experimentally and how >50% H moves into the TCO by MD.

CONCLUSION

- We have created a model that can predict the degradation of SHJ fielded modules based on its surface recombination velocity behavior and its connection to hydrogen motion.
- This model can be used in the future to evaluate bankability of a project and help manufacturers design better materials and stacks for long term performance.
- Similar work is being undertaken with our project partner Qcells on TOPCon cells and structures.

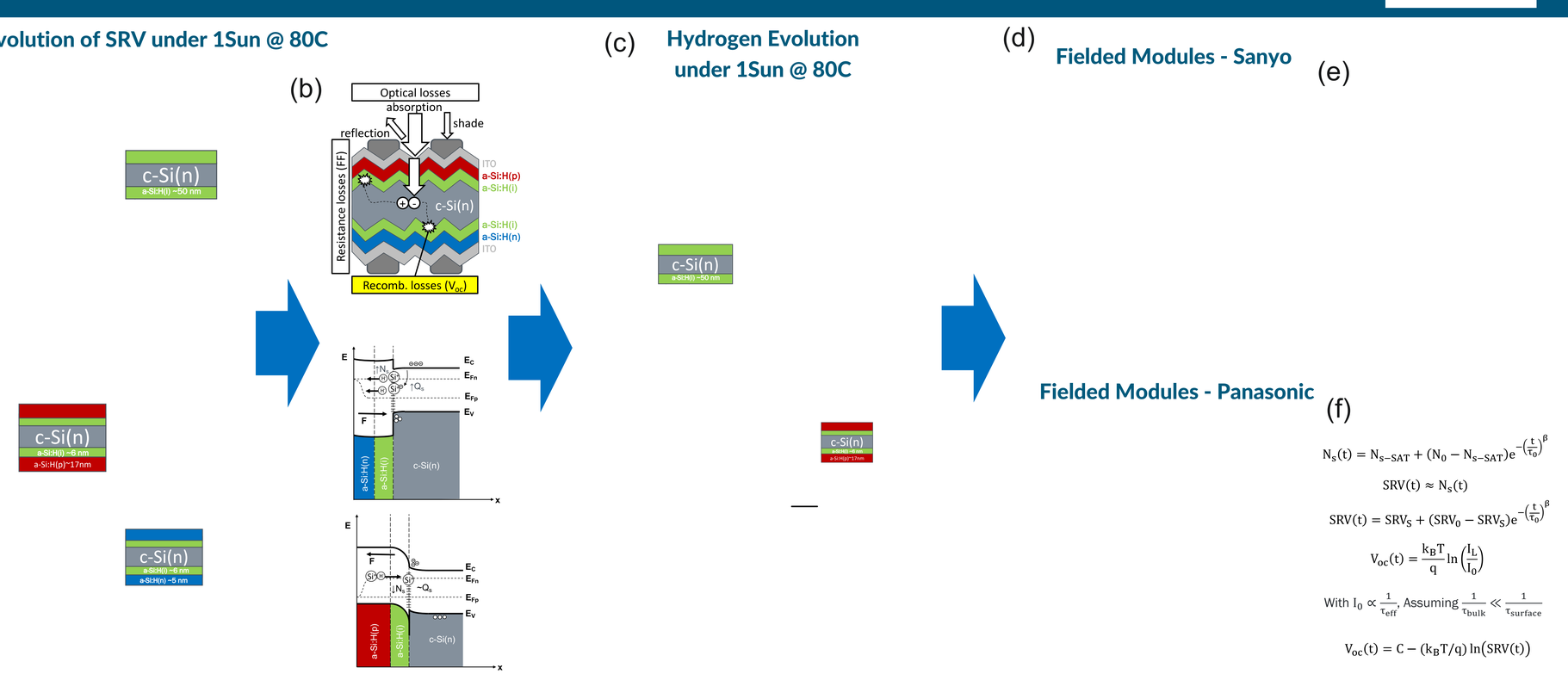


Figure 1. (a) Evolution of SRV and interface defect density for structures of SHJ exposed to 80C and 1 Sun, (b) device model based on charge and defect density at the interface, (c) Hydrogen evolution before and after exposure, (d) Fielded modules data for two generations of SHJ vs. fit with Voc model developed from (a, f), (e) ERE measurements of core outs before and after fielding.

Additional project contributors: Zachary Holman (ASU), David Fenning (UCSD), Julia Medvedeva (MS&T), Dirk Jordan (NREL), Max Koentopp (Qcells)

PROJECT NAME: PV Connector Reliability Across the US Solar Sector

Project numbers: **38531 and 39035**
Principal Investigators (PIs): **Laurie Burnham and Bruce King**
Lead Organization: **Sandia National Laboratories**
PI Email: **lburnha@sandia.gov**

PHOTOVOLTAICS TRACK

BACKGROUND and OVERVIEW

- PV connectors are a leading cause of module failure, arc faults and fires; they are also significant contributor to plant performance losses and O&M costs, increasing the levelized cost-of-energy (LCOE).
- No centralized reporting mechanism for connector issues exists; also much of the data is confidential, so full extent of the problem not documented.
- Sandia and team are engaging with asset owners and EPCs to collect field data, gather intelligence, and estimate economic losses attributable to connector degradation and failure.

METHODS

- **I. Field inspections.** Sandia researchers collect data and harvested connectors from PV plants, differing in age, size, climate, etc.).
- **II. Connector characterization and field analysis.** Fielded connectors are screened at Sandia for design and installation integrity and electrical performance.
- **III. Forensics.** Down-selected connectors undergo forensics analysis at EPRI to identify compositional and morphological variation in metallurgy and associated failure modes.
- **IV. Techno-economic analysis.** Utilizing a "PV O&M Cost Model," NREL has analyzed O&M expenses to quantify the impact of connector degradation on a plant's LCOE.

KEY MILESTONES

- Document plant-level differences in connector performance and reliability and correlate with installation practices and connector type.
- Correlate resistance and other factors (e.g., installation error and operating climate) with degradation mechanism.
- Calculate impact of connector issues on LCOE.
- Develop set of best practices based on above.

CONCLUSION

- PV connector failures are a significant problem for the US solar industry, resulting in fires, plant shutdowns and plantwide replacements.
- This project has identified multiple failure mechanisms and their impact on LCOE.
- End-of-project results are to include publications on best installation and O&M practices.

The **threat to PV plant reliability** posed by poorly-installed, designed and manufactured **PV connectors** is substantiated and **quantified** by site inspections, lab forensics and TEA .

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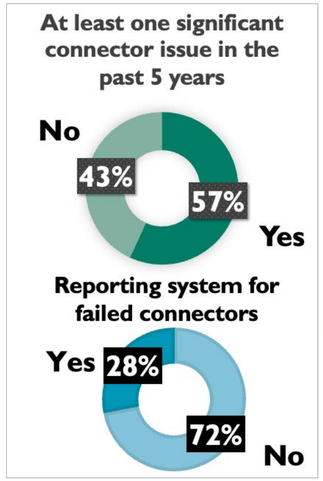
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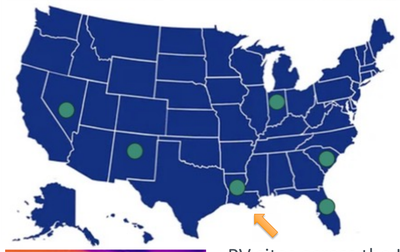
For more information

I. Site inspections

1. Preliminary survey sent to 31 asset owners and EPCs Indicate that connector failures are widespread., yet most connector problems are not reported, unless they are catastrophic.

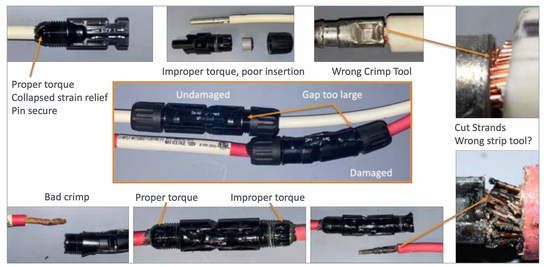



Example of a mated connector pair that reached temperatures hot enough to melt the polymer sheath


PV sites across the US that have contributed data and failed connectors to this project.

2. Follow-up site inspections reveal a multitude of poor installation practices that are likely to cause accelerated connector degradation and safety, including UV exposure, mechanical stress, and mismatch.

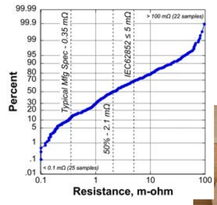




Close-up of a high-current, field-made home-run (string-level) connector highlights a complex installation process and the opportunity for multiple installation errors.

II. Module characterization

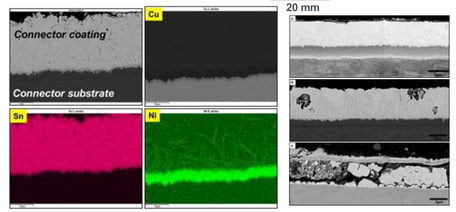
- >16,000 connectors
- 8 states (CA to NJ)
- 3 m'frs/5+ models
- 90% exceed m'fr specs for electrical resistance; 30% exceed IEC standards.




Set-up for measuring electrical resistance (m-ohm) of harvested connectors.

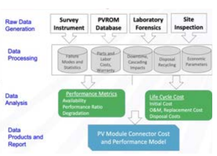
III. Metallurgical Forensics





Variations in metallic composition and structure of the pin and socket are seen across different manufacturers.

IV. Techno-economic Analysis





Additional project contributors: Steven DiGregorio (Sandia); Andy Walker, Vignesh Ramasamy, Jal Desai (NREL); Wayne Li, Tapasvi Lolla (EPRI)

PROJECT NAME: Project name goes here and here

Last 5 digits of project number: **XXXXX**
Principal Investigator (PI): **First and Last Name**
Lead Organization:
PI Email: example@website.solar

BACKGROUND and OVERVIEW

- What is they key problem that this project solves?
- How will/does the project address that key problem?
- No smaller than size 28 type font

METHODS

- What are the key actions that will/are being/have been completed as part of the project.
- No smaller than size 28 type font

KEY MILESTONES

- What are the key milestones of the project? (please note which milestones have been completed and which have yet to be completed).
- No smaller than size 28 type font

CONCLUSION

- How do the milestones address the projects key problem?
- What impact has your project had?/What is the project's anticipated impact?
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CONCENTRATING SOLAR-THERMAL POWER TRACK

Main finding (*or objective if your project has just started*) goes here, translated into plain English. **Emphasize** the important words.

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Additional project contributors:

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SYSTEMS INTEGRATION TRACK

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MANUFACTURING AND COMPETITIVENESS TRACK

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STRATEGIC ANALYSIS AND INSTITUTIONAL SUPPORT TRACK

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WORKFORCE AND EQUITABLE ACCESS TRACK

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Additional project contributors:

PROJECT NAME: Understanding Defect Activation and Kinetics in Next Generation CdTe Absorbers

Last 5 digits of project number: **08754**
Principal Investigator (PI): **Mariana Bertoni**
Lead Organization: **ASU**
PI Email: bertoni@asu.edu

PHOTOVOLTAICS TRACK

Shown **Carrier Compensation** in Cu:CdTe and As:CdSeTe Induced by **Chlorine Defect Complexes**

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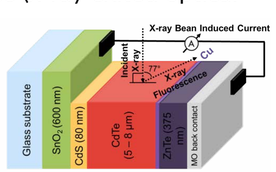
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BACKGROUND and OVERVIEW

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METHODS

- We measured correlatively on a pixel-to-pixel basis the chemical composition (x-ray fluorescence), structure (x-ray absorption and diffraction), luminescence (x-ray exited optical Luminescence and electrical properties (x-ray beam induced current) across the absorber.



KEY MILESTONES

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- Reported presence of active and inactive species in CdTe absorbers (Published)
- Observed liquid flux formation during $CdCl_2$ process (Pub. under preparation)
- Reported Se diffusion during solar cell aging (Pub. Submitted)

CONCLUSION

- We report for the first time the complex formation of the dopants with chlorine. The dopants sit where they are expected but the inevitable introduction of Cl during $CdCl_2$ is what produces unwanted compensation.
- This work has helped inform better processing practices (T, t, [Cl]), changes in precursors, dopants, etc.

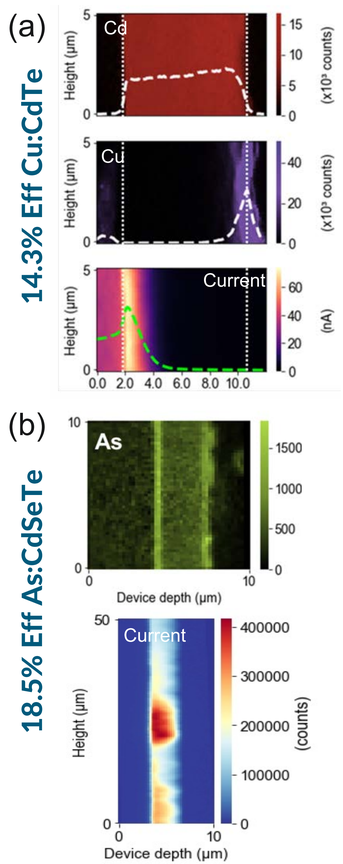


Figure 1. (a) X-ray Fluorescence Cd, Cu and X-ray Beam Induced Current (b) X-ray Fluorescence As and X-ray Beam Induced Current, (c) XBIC Sum Experimental vs. Modeled. Note the difference is due to extra donors that need to be added to the model

What kind of defects are these donors ?

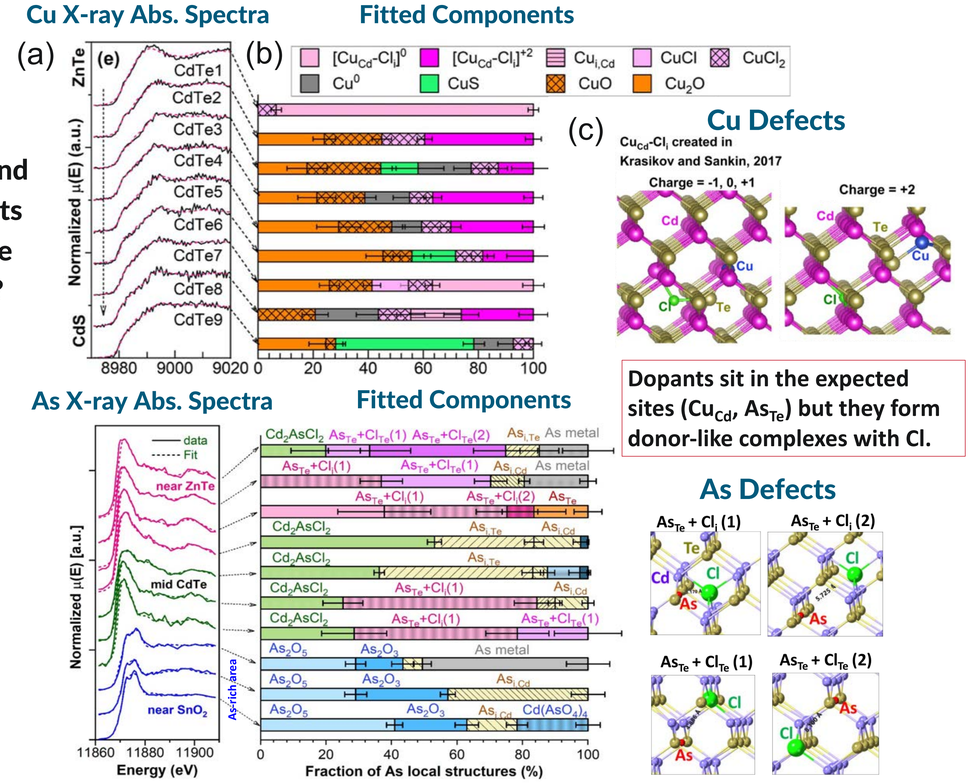


Figure 2. (a) X-ray Absorption spectra for Cu (top) and As (bottom) across the depth of the absorber, (b) Fitting of the spectra utilizing a library of DFT calculated defects and phases; (c) Donor defects found (pink)

Additional project contributors: Dan Mao (First Solar), Maria Chan (Argonne Nat. Lab.), Eric Colegrove (NREL)

PROJECT NAME: Total Characterization of Perovskite Films for Enhanced Stability

Last 5 digits of project number: 38045
Principal Investigator (PI): Kevin Stone
Lead Organization: SLAC National Accelerator Laboratory
PI Email: khstone@slac.stanford.edu

PHOTOVOLTAICS TRACK

Perform **detailed structural characterization**, including the **amorphous component**, in perovskite thin films and relate to **material stability**.

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BACKGROUND and OVERVIEW

- Phase stability is a prerequisite for device durability
- Metal halide perovskite films of nominally similar composition can show large differences in performance and stability
- A more complete structural understanding of the perovskite layer is needed for predicting crystalline phase stability

METHODS

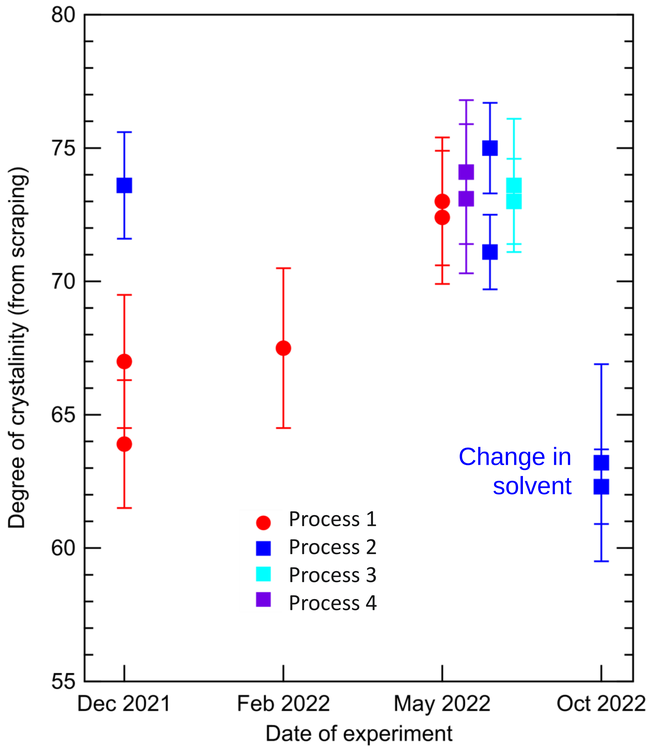
- Using advanced X-ray characterization approaches to understand the detailed structural aspects of perovskite thin films
- Quantification and description of the non-crystalline component of films
- Arrhenius behavior from accelerated aging studies to derive activation energies for degradation mechanisms

KEY MILESTONES

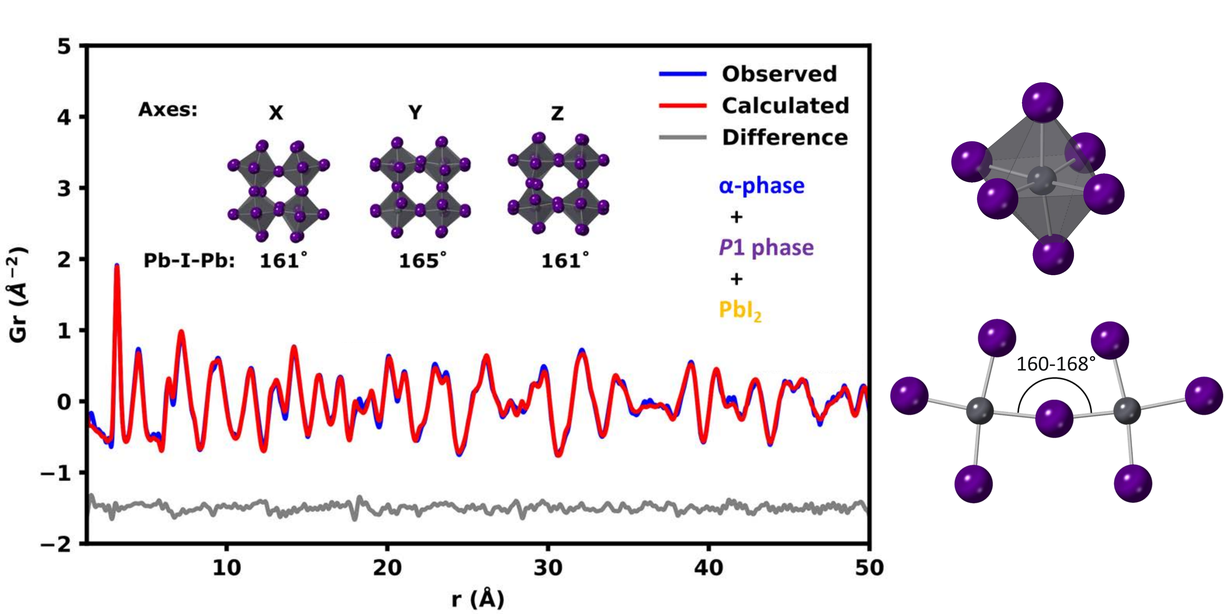
- Standardized method to quantify the degree of crystallinity in perovskite thin films
- Determined activation energies for degradation of crystalline material under accelerated aging conditions
- Characterized the structure of the amorphous component of the perovskite thin film

CONCLUSION

- We have quantified and characterized a previously unknown amorphous component which is widespread in perovskite films
- Detailed structural descriptions of films can be correlated to activation energy of the degradation of the perovskite crystalline phase



Degree of crystallinity determined for films made from different processing conditions over approximately one year



Pair Distribution Function measurements and analysis. The structure revealed by X-ray total scattering measurements is best fit by a combination of the crystalline α-phase, a small fraction of crystalline PbI_2, and a non-crystalline short range ordered phase of distorted but corner sharing PbI_6 octahedra.

Additional project contributors: NREL, CubicPV

PROJECT NAME: Next-generation perovskite photovoltaics

Last 5 digits of project number: **09512**
Principal Investigator (PI): **Vladimir Bulović**
Lead Organization: **Massachusetts Institute of Technology (MIT)**
PI Email: **bulovic@mit.edu**

PHOTOVOLTAICS TRACK

Defect Passivation and Interfacial Engineering of Perovskite Solar Cells

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BACKGROUND and OVERVIEW

- Interfacial engineering is the key to achieving highly efficient and stable perovskite solar cells.
- Defect passivation is the key to reducing non-radiative recombination at interfaces.
- Managing the oxidation states of tin-oxide electron transport layer is the key to the improved SnOx/perovskite interface.

METHODS

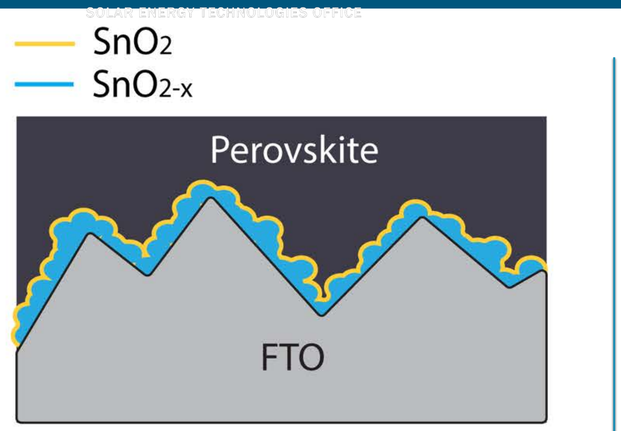
- Low temperature crystalline thin film tin-oxide is deposited using chemical bath deposition.
- PL spectroscopy is used to investigate the concentration and processing (thermal annealing) induced changes in carrier dynamics.
- Cross-sectional TEM and EDX are used to investigate interfacial passivation.

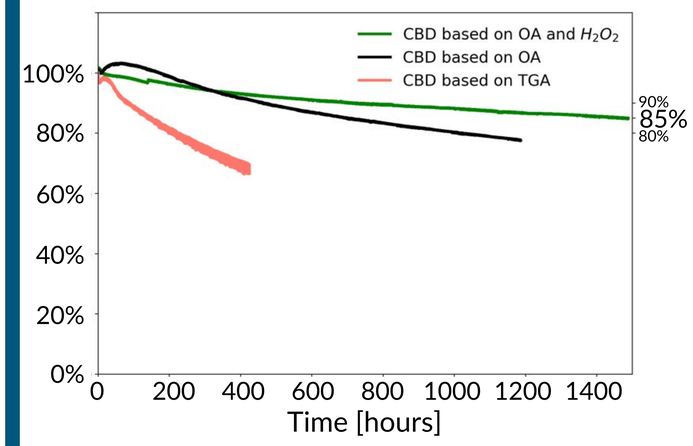
KEY MILESTONES

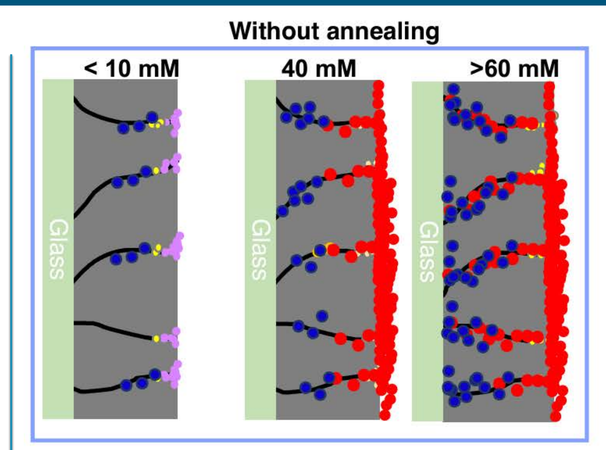
- Chemical linker enabled conformal and densely packed nanoparticle thin films on textured FTO substrates.
- Devices achieved PCE of 24.6% and maintained 85% of its initial efficiency after 1500h at MPPT.
- Ionic salt passivation (without forming 2D perovskite) has a larger processing window and better reproducibility.

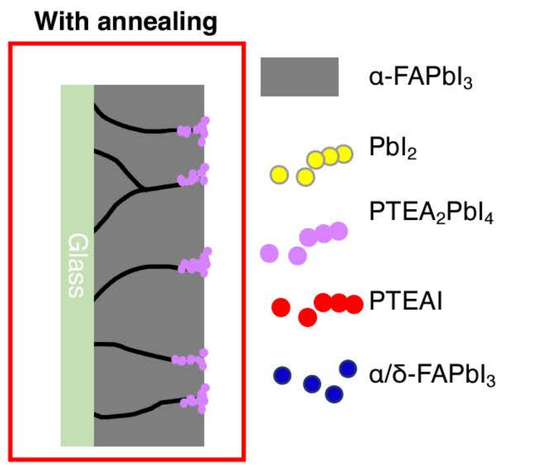
CONCLUSIONS

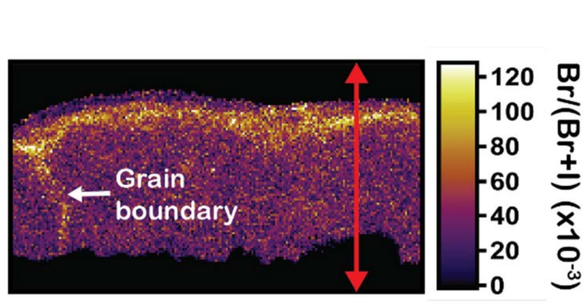
- Interface is crucial for efficient and stable perovskite solar cells.
- The long-term stability of the perovskite PV devices is significantly improved.

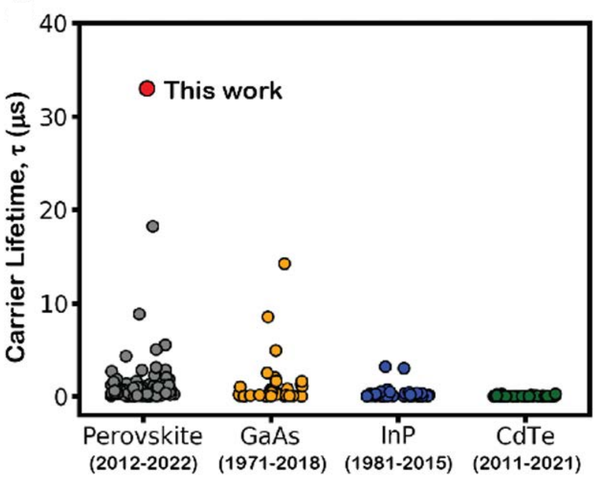












Additional project contributors: Moungi Bawendi

PROJECT NAME: Learning-Assisted Preventive and Corrective Maintenance of PV Systems: Predicting Heterogeneous Failures from Heterogeneous Data

Last 5 digits of project number: **09883**
Principal Investigator (PI): **Yue Zhao**
Lead Organization: Stony Brook University
PI Email: yue.zhao.2@stonybrook.edu

PHOTOVOLTAICS TRACK

BACKGROUND and OVERVIEW

- Enhance PV assets' corrective and preventive maintenance with a much more comprehensive picture of PV asset failures and hidden issues provided by trained predictors, thereby reducing the PV assets' O&M budget.
- Detection, classification, and prediction of heterogeneous PV system failures via machine learning from heterogeneous PV monitoring data sets.

METHODS

- Data procurement & cleaning
- SolarQuant opensource software
- Unsupervised/self-supervised learning for solar asset anomaly detection and classification:
  Cross-measurement and cross-inverter prediction
- Supervised learning for incipient failure prediction
- Fusion of different prediction mechanisms
- Predictor training for transferability and adaptation

KEY MILESTONES

- New performance anomalies detected that are not among the baseline anomalies observed by the existing asset monitoring practice (completed)
- Prediction significant incipient asset failures (to be completed)
- Prediction of rare events (to be completed)
- Transferability of learned predictors across PV systems (to be completed)
- O&M cost reduction (to be completed)

CONCLUSION

- The anomaly detection and failure prediction solutions enable the asset managers to a) be aware of hidden problems by detecting incipient failures so that loss of energy are minimized, and b) better optimize preventive maintenance scheduling and improve maintenance efficacy.
- The project has identified a wide variety and a large number of hidden anomalies that a) went unnoticed by the asset managers of Ecogy Energy, and b) if resolved, would lead to significant PV performance improvement / loss reduction. The project results are anticipated to reduce the PV asset's O&M budget by 20%.

A **wide variety** of malfunctions of PV systems, which are otherwise **unnoticed** by asset managers, can be successfully detected based on **unsupervised** learning from **heterogeneous** data sets.

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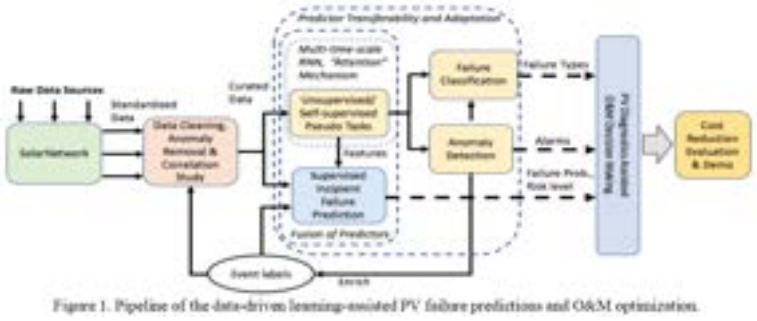
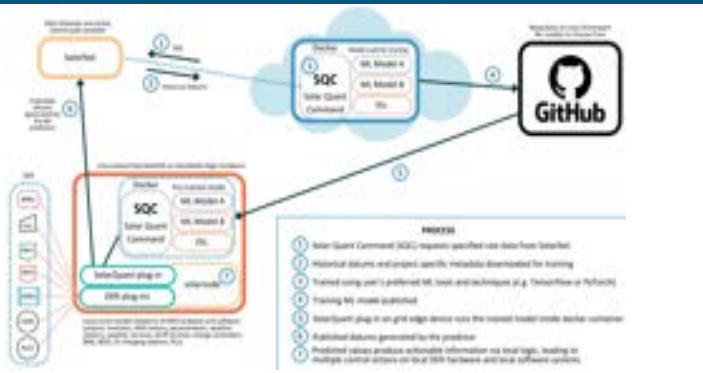
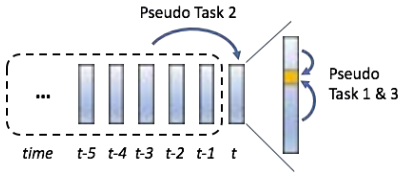


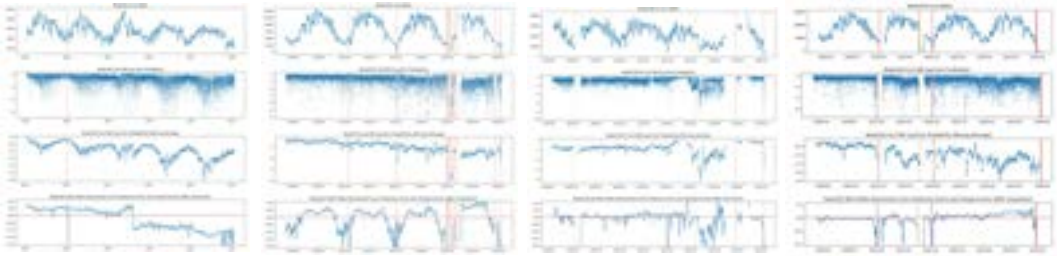
Figure 1. Pipeline of the data-driven learning-assisted PV failure predictions and O&M optimization.



SolarQuant opensource software: a zero friction ecosystem for DER data-driven machine learning.



Unsupervised/self-supervised pseudo tasks for training PV anomaly detectors and learning features.



Gainesville, FL | Washington, DC | Wilmington, DE | Washington, DC

Detected anomalies: sustained low performance, seasonal abnormal behaviors, sustained abnormality that precede system outages.

Additional project contributors: John Gorman (Ecogy Energy), Philip Court (Ecogy Energy), Arun Veeramany (PNNL), Meghana Ramesh (PNNL)

PROJECT NAME: Informing Wildlife Conservation Strategies and Best Practice for Solar Facilities

Last 5 digits of project number: **10382**
Principal Investigator (PI): **Timothy Randhir**
Lead Organization: University of Massachusetts, Amherst
PI Email: **randhir@umass.edu**

PHOTOVOLTAICS TRACK

Avian reproduction and **pollinator insect activity** varies between PV solar sites of different **landscape contexts** and **site characteristics** in the Northeastern United States

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BACKGROUND and OVERVIEW

- PV solar sites are embedded along landscape gradients, yet how landscape and site-level characteristics influence wildlife is unknown, limiting effective management.
- The project monitors insects and avian nest success in PV solar sites in northeast that have ambitious renewable energy goals that require vast and rapid expansion of PV solar, to develop an Integrated Decision Model (IDM), for reaching relevant stakeholders.

METHODS

- The project combines traditional surveys of insect activity and avian nest monitoring with emerging technologies for automated monitoring.
- The field work, conducted over the course of two field seasons (2023 and 2024) will contribute directly to the development of an IDM.
- The IDM will be developed with feedback from a diverse Stakeholder Advisory Committee (SAC) to enable uptake by stakeholders interested in evaluating the role of site and landscape factors on wildlife.

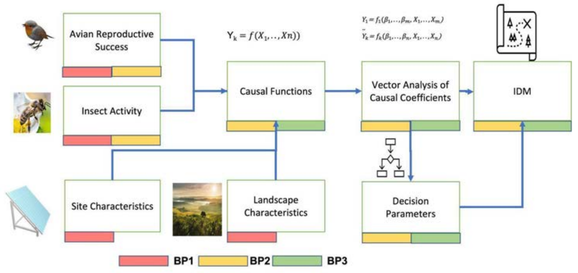
KEY MILESTONES

- Nest survival estimates for ten PV solar sites quantified
- Indices of insect biodiversity quantified for ten PV solar sites based on traditional method surveys
- Outreach activities reaching diverse audiences reached
- Site or landscape features that most heavily influence avian nest success and indices of insect biodiversity will be identified through modeling
- An Integrated Decision Model will be developed from field data and input from SAC

CONCLUSION

- This work assesses avian nest success and insect activity and biodiversity in solar PV sites in the northeastern US.
- The IDM will not only be based on field data from two years and two ecologically important wildlife groups (birds and insects), but also based on input from a diverse SAC (which includes members from industry and environmental conservation organizations). Stakeholder input throughout project is key to promoting uptake of recommendations.

Conceptual model of the technical scope of the project



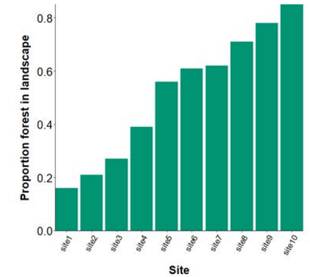
Geographic spread of 10 solar sites in Massachusetts and New York



Example of solar site surrounded by forest



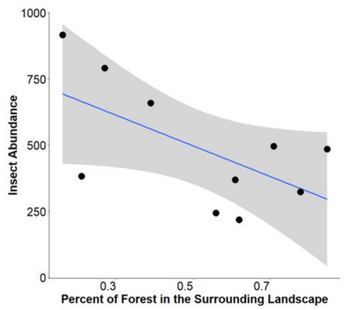
Gradient of landscape-level forest cover in each solar site

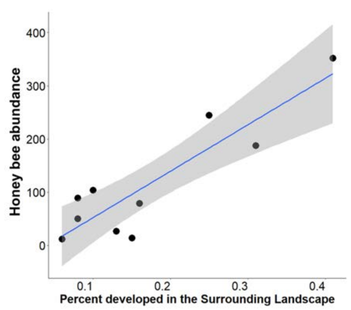


Honey bees were the most frequently observed insect in the first field season



Preliminary results: less insect activity in solar sites with more forest cover, possibly because there are more honey bees in more developed landscapes (inversely correlated with forest)

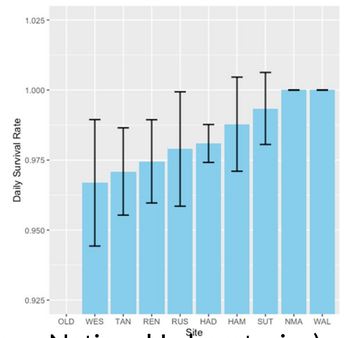




There are many potential avian nest predators in solar sites, both on the ground and aerial



Preliminary results: avian nest success varies considerably between solar sites



Additional project contributors: Laura L. Figueroa (UMass), David I. King (U.S. Forest Service/UMass), Yuki Hamada (Argonne National Laboratories), Amanda Klehr (DNV/UMass), Cory Gessert (DNV), Alexis Laskowski (UMass), Grace Shiffrin (UMass)

PROJECT NAME: Stabilizing Formamidinium-Cesium Mixed Cation Perovskites

Last 5 digits of project number: **09520**
Principal Investigator (PI): **Jinsong Huang**
Lead Organization: **UNC Chapel Hill**
PI Email: **jhuang@unc.edu**

PHOTOVOLTAICS TRACK

The underlining degradation mechanisms of a most stable perovskite under stressors of heat, UV, and visible light have been discovered, and solutions to them have been found.

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BACKGROUND and OVERVIEW

- A huge gap between indoor and outdoor stability was identified in perovskite solar cells
- No perovskite minimodules with aperture area >15 cm^2 demonstrated an efficiency above 15% after ten weeks of outdoor testing
- Understanding degradation mechanisms of perovskite under UV-light and photo-thermal conditions is lacking;
- The bottom perovskite is more defective than top side.

METHODS

- Lead chelation molecules (LCMs) passivated the surface defect and reduce the amorphous region of bottom perovskites, enabling record module stability;
- Strong bonding HTMs suppressed the cation migration of perovskite at ITO/HTM/perovskite interface , enabling record outdoor stability;
- Most 2D perovskites were found to react with FA+ at high temperature and under light. High pK_a value ammonium cations reduced the reaction of FA^+ in perovskite at photo-thermal condition;

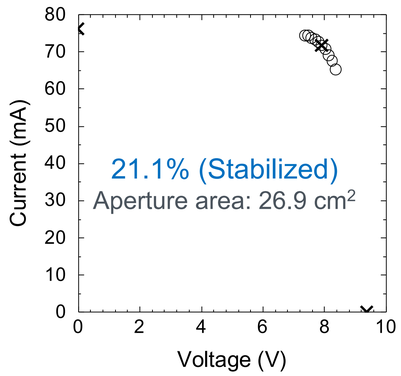
KEY MILESTONES

- Identify the primary degradation mechanisms of perovskite (Photo-thermal, UV-light)
- Perovskite solar cells with $PEAMA^+$ ion showed T_{90} lifetime >1500 hr after light-soaking test at ~90ºC
- Minimodule with aperture area of 50 cm^2 showed less than 10% efficiency loss after 2000 hours indoor light-soaking stability test;
- Perovskite minimodules maintained an efficiency >15% after 25 weeks outdoor stability test.

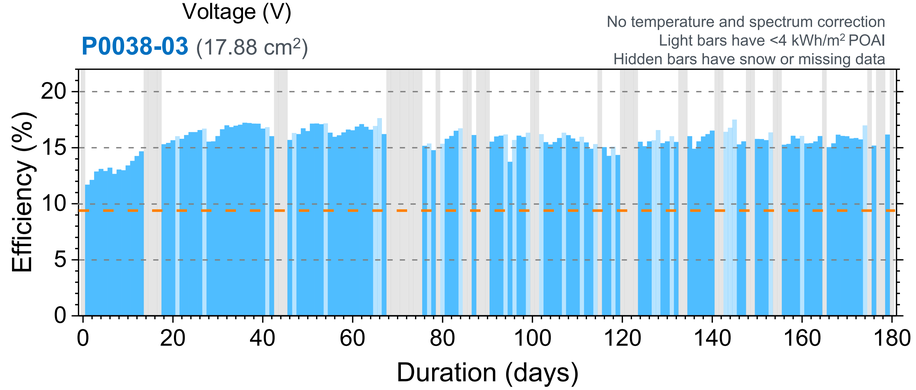
CONCLUSION

- Understanding of degradation mechanism is critical in enhancing the stability of perovskite minimodules;
- Both material defects and material chemistry need to be taken into considerations to stabilize perovskites under operational conditions.
- We found that the bottom interface to be the bottleneck of device stability.
- Further studies are needed to further stabilize perovskite modules to 30-year lifetime.

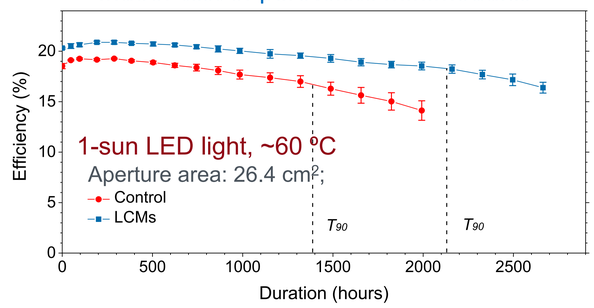
Outdoor test of perovskite minimodules



(Aperture area: 17.88 cm^2)



Indoor test of perovskite minimodules



High temperature photo-stability of PSCs

1-sun LED light, **~90ºC**
Active area: 0.08 cm^2

Additional project contributors: CubicPV Inc., National Renewable Energy Laboratory (NREL)

PROJECT NAME: Hydrophobic Carbon Nanosheets as Passivation Layer for Perovskite Solar Cell with High Efficiency and Stability

Last 5 digits of project number: **09525**
Principal Investigator (PI): **Wei Wei**
Lead Organization: **Wichita State University**
PI Email: **wei.wei@wichita.edu**

PHOTOVOLTAICS TRACK

Demonstrated the potential of **hydrophobic carbon** nanosheets as passivation layer for perovskite solar cell that could reach >22% efficiency

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BACKGROUND and OVERVIEW

- Low stability and poor durability under operative conditions (i.e. humid environment) represents an apparent barrier for perovskite solar cells (PSCs)' market uptake.
- This project addresses the durability challenge by employing hydrophobic carbon nanosheets as counter electrodes to PSCs.

METHODS

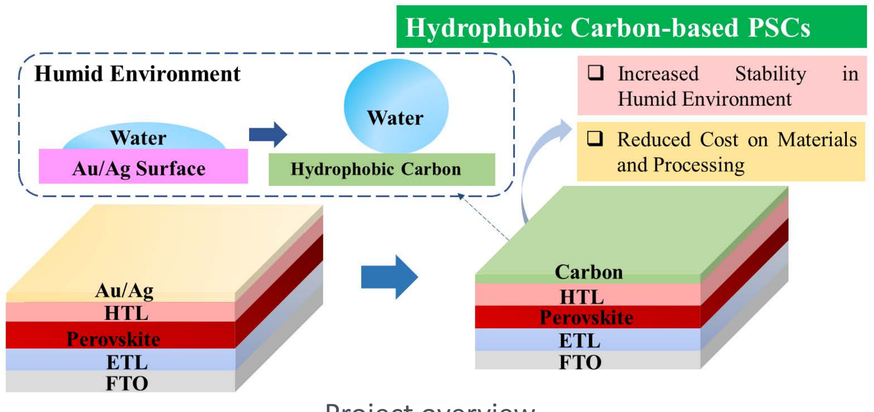
- Hydrophobic carbon will increase PSC's durability due to the hydrophobic feature.
- Design and build a scalable reaction system for mass production of hydrogenated carbon materials.
- Solution-processing capability of PSC components incentivizes the development of low-cost and large-scale manufacturing of PSCs.
- Establish fully slot die coated PSC architecture.

KEY MILESTONES

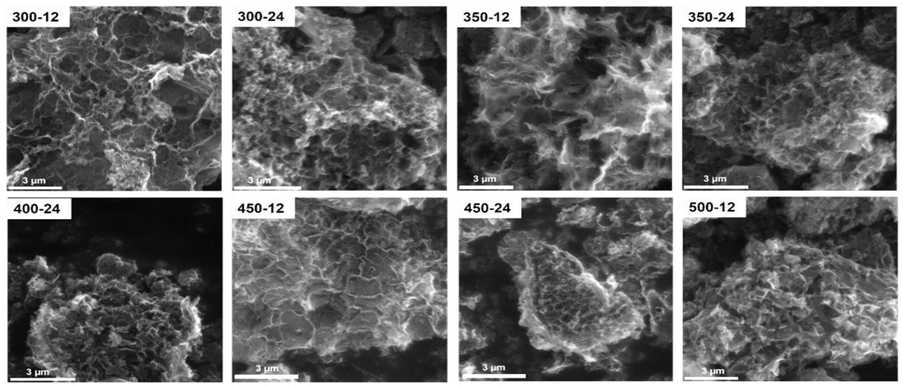
- The project built a scalable method for mass production of hydrogenated carbon materials.
- The project demonstrated hydrophobic carbon nanosheets-based PSCs with PCE of 22.35%, I_{sc} of 23.58 mA/cm^2, V_{oc} of 1.26V, and ff of 0.74.
- The device's stability was demonstrated to remain at 90% efficiency for 2000 hours.
- The project shows the potential of developing a fully slot die-coated perovskite solar module.

CONCLUSION

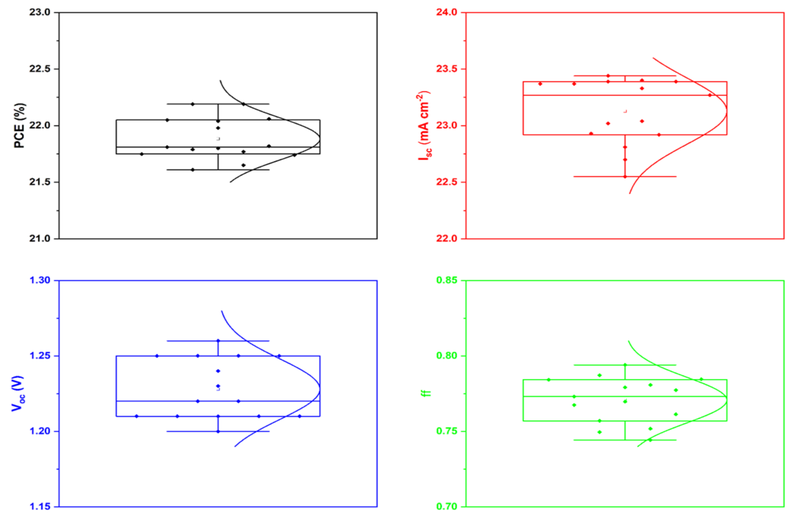
- Provides a new concept to design electrode materials for PSCs with high durability and efficiency.
- Reduces the cost of PSCs through the simplification of fabrication condition and carbon materials.
- Promotes the wide commercialization of PSC technologies in solar electricity.



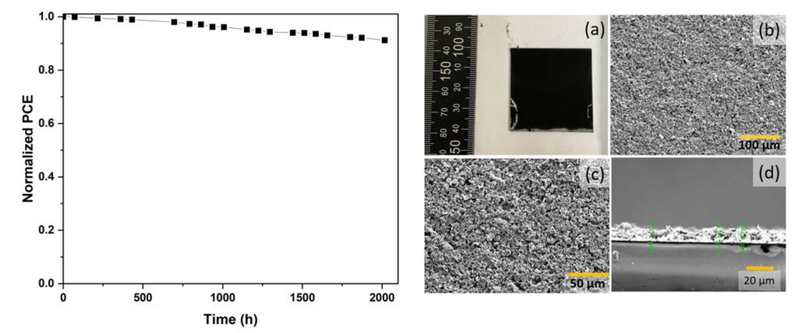
Project overview.



SEM images of carbon nanosheets that are produced from different reaction conditions.



PCE, I_{sc}, V_{oc}, and ff obtained from 15 devices.



Device stability and carbon films by slot die coating.

Additional project contributors: Hui Wang, University of Louisville

LASER RECYCLING OF SILVER FROM SILICON SOLAR CELLS

Last 5 digits of project number: **10244**
Principal Investigator (PI): **Prof. Mool C. Gupta**
Lead Organization: **University of Virginia**
PI Email: **mgupta@virginia.edu**

PHOTOVOLTAICS TRACK

Recovery of silver from waste silicon module using laser ablation method generating bulk form and high-value Ag nanoparticles.

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BACKGROUND and OVERVIEW

- The project addresses the environmental challenge of disposing end-of-life solar modules.
- Utilizing advanced laser techniques to efficiently recover precious metals from these waste streams, including the recovery of silver in high-value nanoparticles and in bulk form with high purity, promoting sustainability and reducing landfilling.

METHODS

- Experimental setup and execution of laser-based production of silver nanoparticles from discarded solar modules.
- Characterization of obtained nanoparticles using SEM and EDS. Finding the optimal processing conditions to obtain high purity, and high yield of nanoparticles.
- Mitigation of silicon impurities in fabricated silver nanoparticles.
- Application of laser debonding for the recovery of bulk silver.
- Implementation of laser ablation process automation through machine learning and Image processing.

KEY MILESTONES

List of Completed Milestones

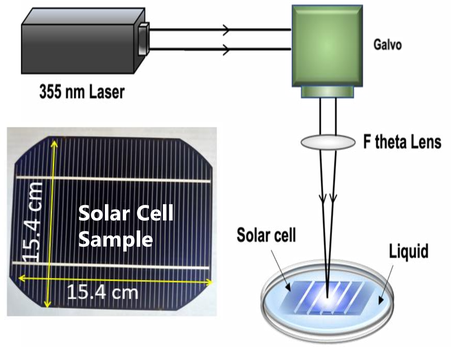
- Experimental setup for laser fabrication of Ag nanoparticles
- Fabrication of Ag Nanoparticles and role of laser parameters
- characterization of Ag nanoparticles: Composition, morphology, size, impurity etc.

List of Ongoing Milestones

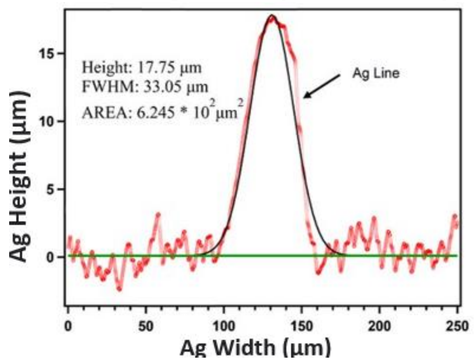
- Automation of the laser ablation process
- Optimization of the process and increase in throughput of recovered silver
- Cost analysis, economic impact, and commercialization.

CONCLUSION

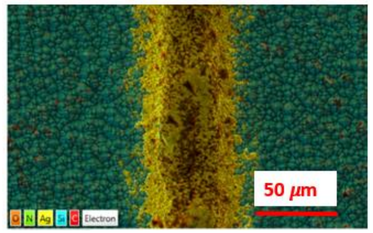
- Demonstrated recovery of silver from solar cells in bulk form and in high value nanoparticle form.
- Optimized process conditions to achieve high purity (up to 93 wt%) and high-speed (up to 3 g/minute) recovery of silver nanoparticles and silver in bulk from (1 m/sec) without the usage of any hazardous chemicals
- The method represents a significant step forward in the environmentally friendly and cost-effective metal recovery form end of life solar cells.



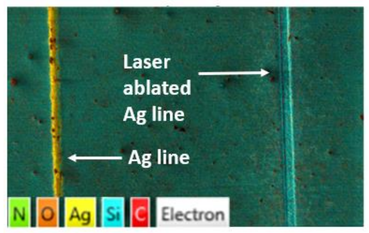
Schematic diagram of experimental setup



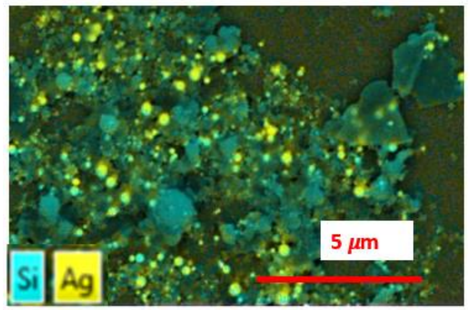
Height profile of the silver electrodes: approx. 90 mg of silver present in the form of electrodes



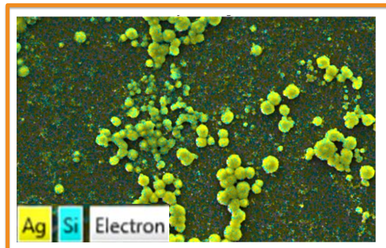
EDS image of silver electrodes before ablation



EDS image showing complete removal of silver on the laser scanned area

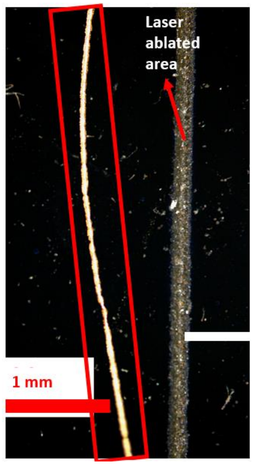


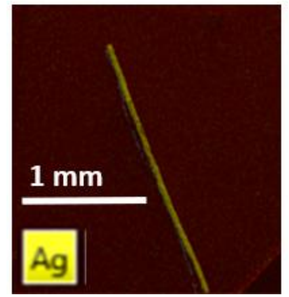
Optimized conditions for the purification of silver: Silver is size-wise and morphologically different from silicon nanoparticles making the separation easier.



Elements	Wt%
Ag	93.5%
Si	6.5%

Silver nanoparticles recovered from waste solar cells with purity up to 93 wt %





EDS image of collected Silver electrode after laser debonding

Laser debonding to separate Silver electrodes with the original purity

Additional project contributors: Mahantesh Khetri, PhD student ECE department, University of Virginia

PROJECT NAME: Monolithic Encapsulation of Perovskite Solar Cells with Transparent Conductive Composites for Long-Term Stability

Last 5 digits of project number: **10241**
Principal Investigator (PI): **Nicolas Gaillard**
Lead Organization: **University of Hawaii**
PI Email: **ngaillar@Hawaii.edu**

PHOTOVOLTAICS TRACK

Transparent Conductive Composites - **Novel** **Encapsulation** Scheme for organic photovoltaics show potential as a **dual functioning** transparent **electrode** and **barrier system**.

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BACKGROUND and OVERVIEW

- The electrically insulating nature of traditional barrier systems limits operational scope.
- The transparent conductive composites (TCC) is a unique strategy to improve the functional capabilities of traditional barrier systems by permitting out-of-plane conductivity and optical transparency while providing gas diffusion barrier properties to act as a dual functioning transparent electrode and barrier system for organic devices.

METHODS

- TCC conductivity and transparency measured intermittently during 1,000 hrs. exposure to outdoor climate for durability testing.
- Processing effects of TCC on perovskite solar cell (PSC) characterized by JV measurement as synthesized and after TCC lamination.
- A TCC encapsulated PSC was subjected to 1,000 hrs. quasi-MPP testing (~1 Sun, 40-50% R.H., 50 ˚C) and performance benchmarked intermittently.
- TCC tested for WVTR - multilayer stacks investigated for improved barrier property.

KEY MILESTONES

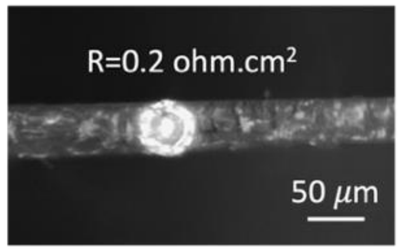
- TCC maintained T_{AVG}% (~85%) and conductivity (~0.1Ω-cm^2) after 1,000hrs outdoor exposure.
- TCC encapsulated IZO/TCC/IZO/PSC devices showed virtually no loss in power conversion efficiency (PCE) compared to uncoated sample.
- A TCC encapsulated TCC/IZO/PSC device reached T90 after 1,000hrs of testing.
- WVTR of 0.084 g/m^2/day was measured on an inorganic IZO/Ag/IZO multilayer/laminate stack, compared to the 1.48 g/m^2/day for laminate only.

CONCLUSION

- The facile room-temperature monolithic integration of TCCs onto a photovoltaic device show potential as a next generation dual functioning transparent electrode and barrier system. Improvements needed for beyond 1,000 hours of operation.
- By implementing a multilayer architecture, the barrier properties can be enhanced, and the TCC system has the potential to transform traditional barrier systems for optoelectronic devices.

Free-standing TCC

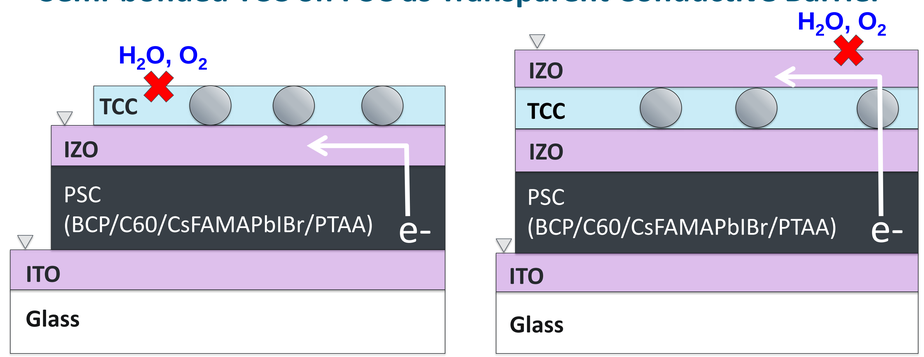


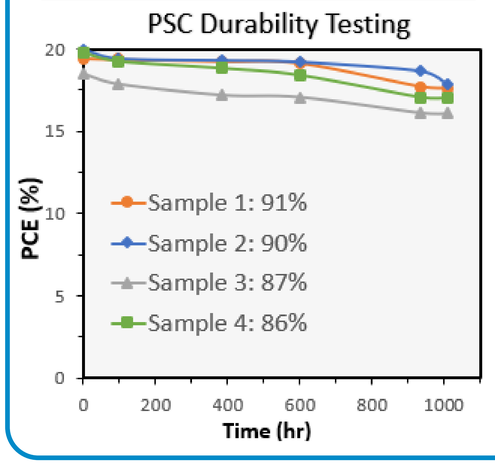


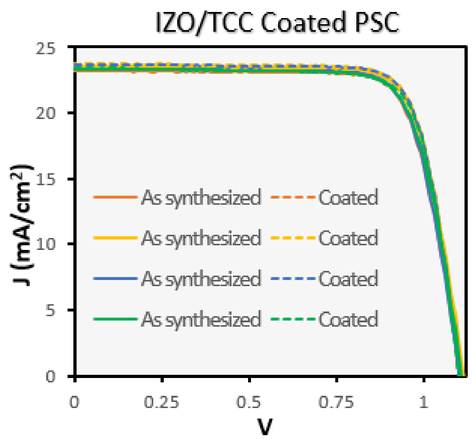
1000hrs. Outdoor Testing

Condition	Ω-cm²	T_{AVG} %
As Prepared (T0)	0.078	85
Aged (T1,000)	0.073	84

Semi-bonded TCC on PSC as Transparent Conductive Barrier







WVTR TCC and Laminate 25˚C 100% R.H.

Sample	Permeability (g-mm/m²/d)	WVTR (g/m²/d)
50μm TCC	2.04E-3	5.74
500μm TCC	1.91E-3	1.37
Laminate	1.88E-3	1.48

WVTR Inorganic Multilayer

Sample	WVTR (g/m²/d)	Test
IZO/Ag/IZO/ Laminate	0.0883	25 ˚C 45% R.H
IZO/Ag/IZO/ Laminate	0.0838	25 ˚C 90% R.H

Additional project contributors: K. Outlaw-Spruell, J. Xu, Q. Jiang, K. Zhu

PROJECT NAME: PV and Energy Storage GRid Integration: Open Datasets (PERIOD)

Last 5 digits of project number: **11159**
Principal Investigator (PI): **Yiwei Ma**
Lead Organization: EPRI
PI Email: **yma@epri.com**

PHOTOVOLTAICS TRACK

Publicly available and **easy-to-use** datasets from PV-plus-storage plant in the SE U.S. to enable continued research and education

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BACKGROUND and OVERVIEW

- This project aims to prepare and publicly release easy-to-use dataset from a utility-scale DC-coupled PV-plus-storage plant in southeastern U.S.

METHODS

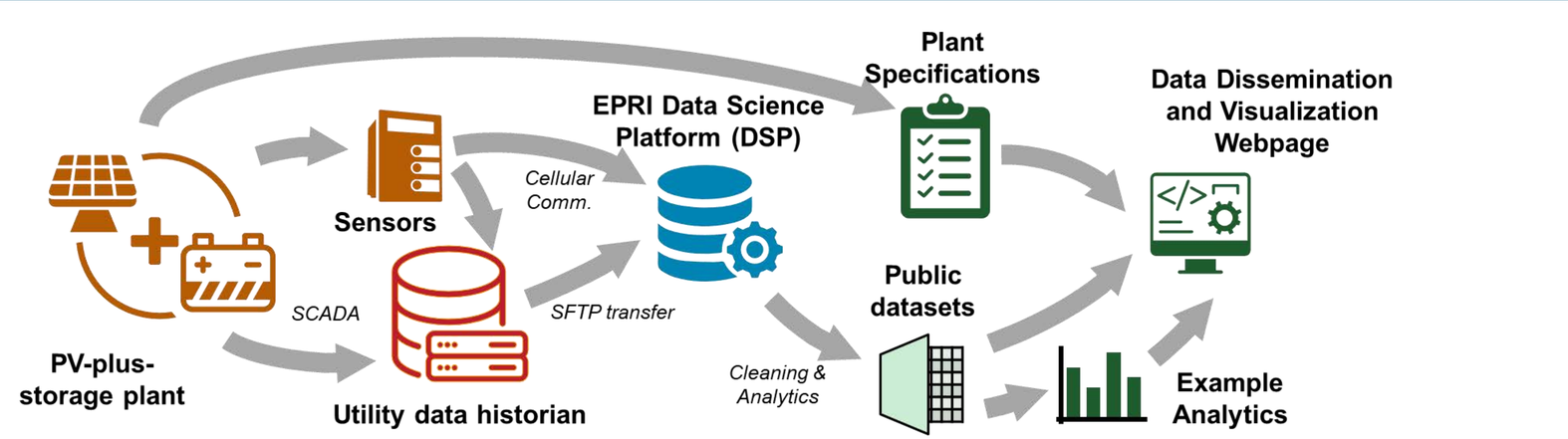
- Configure the PV-plus-storage plant in various operating modes and collect operational time-series data.
- Post-process erroneous and missing data
- Prepare separate datasets, organized by research areas of focus and temporal resolutions
- Perform data analysis to demonstrate potential applications of the data
- Publicly release the datasets, example analysis, and anonymized plant specification.

KEY MILESTONES

- Data collection and cleaning
- Data dissemination
- Data analysis and example applications
- Diversity, Equity, and Inclusion

CONCLUSION

- The proposed open access datasets, to be available by mid-2025, will enable follow-up research and education on the performances of combined PV-plus-storage plants, and potentially accelerate the development and adoption of such plants, especially in southeastern U.S,

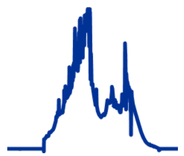




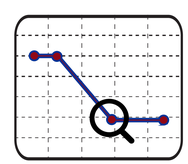
Open Datasets:



Battery Efficiency and Longevity



PV Profile and Performance Ratio



Impact of Smart Inverter Functions

...

Additional project contributors: Aminul Huque, Danny Fregosi, Joe Thompson, Rabin Dhakal, Sagnika Ghosh (Tennessee State University)

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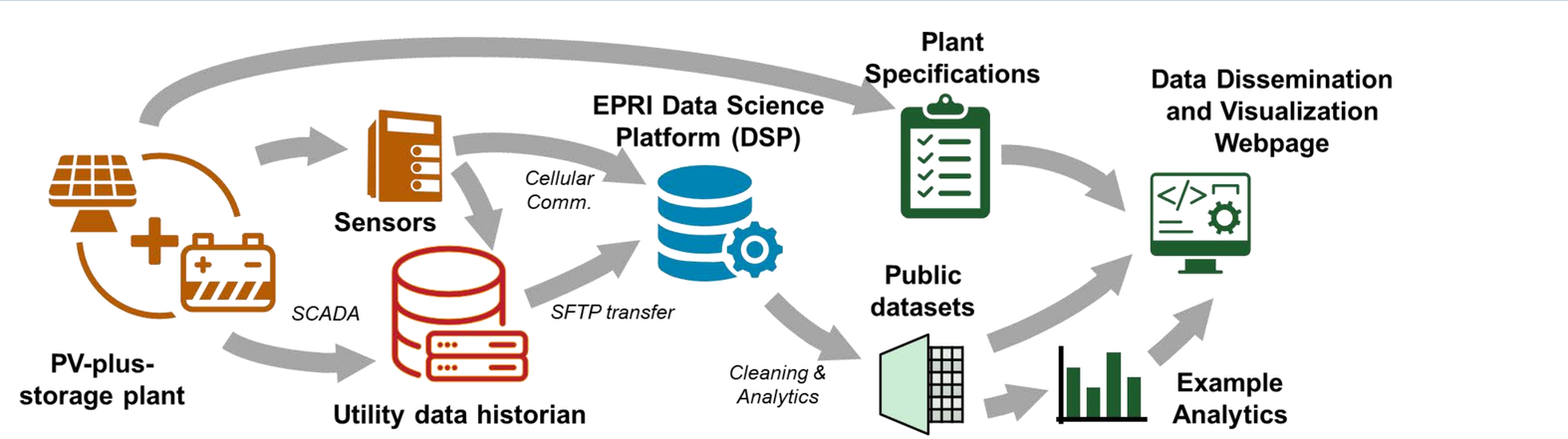
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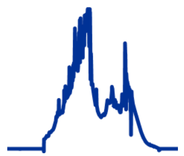




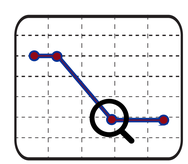
Open Datasets:



Battery Efficiency and Longevity



PV Profile and Performance Ratio



Impact of Smart Inverter Functions

...

Additional project contributors: Aminul Huque, Danny Fregosi, Joe Thompson, Rabin Dhakal, Sagnika Ghosh (Tennessee State University)

PROJECT NAME: Agrivoltaics: Unlocking Mid-Market Solar in Rural Northern Climates

Last 5 digits of project number: **10442**
Principal Investigator (PI): **Christopher Pike**
Lead Organization: **University of Alaska Fairbanks**
PI Email: **cpike6@Alaska.edu**

BACKGROUND and OVERVIEW

- High-latitude communities often face food insecurity, limited access to affordable energy, and dramatic climate change effects
- Understand the effects of Northern solar arrays and crops on each other at an 8.5 MW solar PV array in Alaska
- Provide stakeholders with economic, electrical, and agricultural results from agrivoltaics testbed to support decision making

METHODS

- Survey collected stakeholder's perceived benefits and barriers of northern agrivoltaics
- Over two growing seasons, team will measure soil moisture and temperature, photosynthetically active radiation, wind speed, and yield of crops grown between rows of solar panels and in control plots
- Assess impact of farming activities on array with albedo, soiling, temperature, energy production, and module degradation

KEY MILESTONES

- Agrivoltaics survey completed by 80 farmers, solar developers, electric utilities, tribal organizations, non-profits, land owners, and researchers; results inform a techno-economic analysis to guide future mid-market solar PV and agriculture projects
- Community programming includes weekly social media posts, presentations, and open house site events
- Preparing site with soil amendments, overseeing two growing seasons, and completing analysis of solar and plant physiology data.

CONCLUSION

- Rural households in Alaska spend nearly 27% of their annual income on energy expenses, and around 95% of Alaska's non-subsistence food supply is imported.
- If an agrivoltaic model works in Alaska, it could be a major breakthrough for increasing food and energy security in the state.

PHOTOVOLTAICS TRACK

A collaborative team is unlocking agrivoltaics in **northern, rural climates** by monitoring vegetables, forage crops, and berries between the rows of **Alaska's largest solar PV array**.

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Celebrating the 8.5 MW Houston Solar Farm with a ribbon cutting.







The 8.5 MW solar array with planned plot locations between array rows, control plot to be located outside of array.

Additional project contributors: Alaska Center for Energy and Power, Institute of Agriculture, Natural Resources and Extension, Alaska Pacific University Spring Creek Farm, Renewable IPP, CleanCapital

Agrivoltaics
Unlocking Mid-Market Solar in Rural Northern Climates

PROJECT NAME: Automating Detection and Diagnosis of Faults, Failures, and Underperformance in PV Plants

Last 5 digits of project number: **08976**
Principal Investigator (PI): **Wayne Li & Danny Fregosi**
Lead Organization: EPRI
PI Email: WLi@epri.com dfregosi@epri.com

PHOTOVOLTAICS TRACK

Anomaly Detection **Outperforms** **Commercial Solution by 4X** at detecting string and tracker outages in real time

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Take a picture to **download** the **validation datasets**

BACKGROUND and OVERVIEW

- Faults in strings, combiners, and trackers significantly decrease capacity in utility PV plants.
- Early detection of these faults is crucial for improving plant efficiency.
- A new physics-based anomaly detection algorithm has been developed, utilizing standard monitoring data from utility-scale plants.
- The algorithm has been tested and validated for 10+ utility scale plants

METHODS

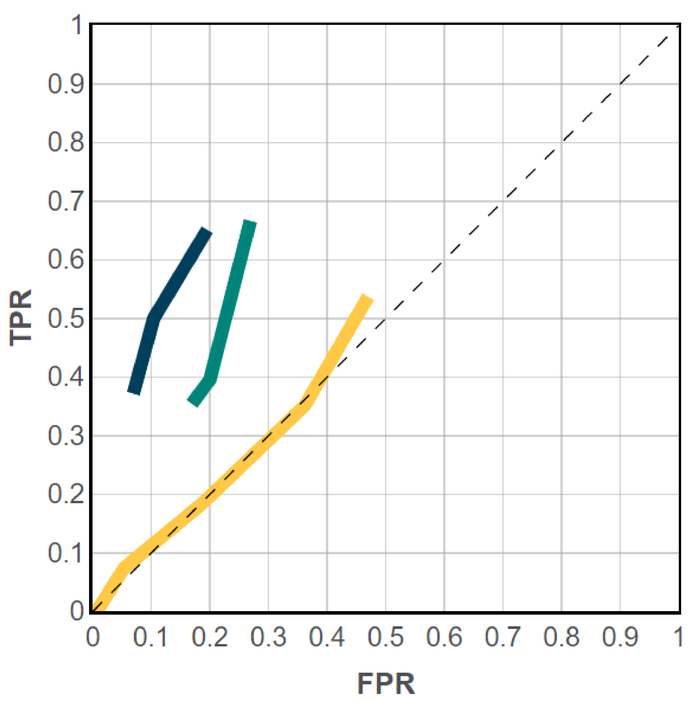
- Integration of intelligent data filtering and machine learning for initial site setup.
- Implementation of physics-based models for predicting performance.
- Use of machine learning for accurate anomaly detection.
- Validation through aerial infrared data from nine utility-scale plants, ensuring the algorithm's reliability across different weather conditions and fault types.

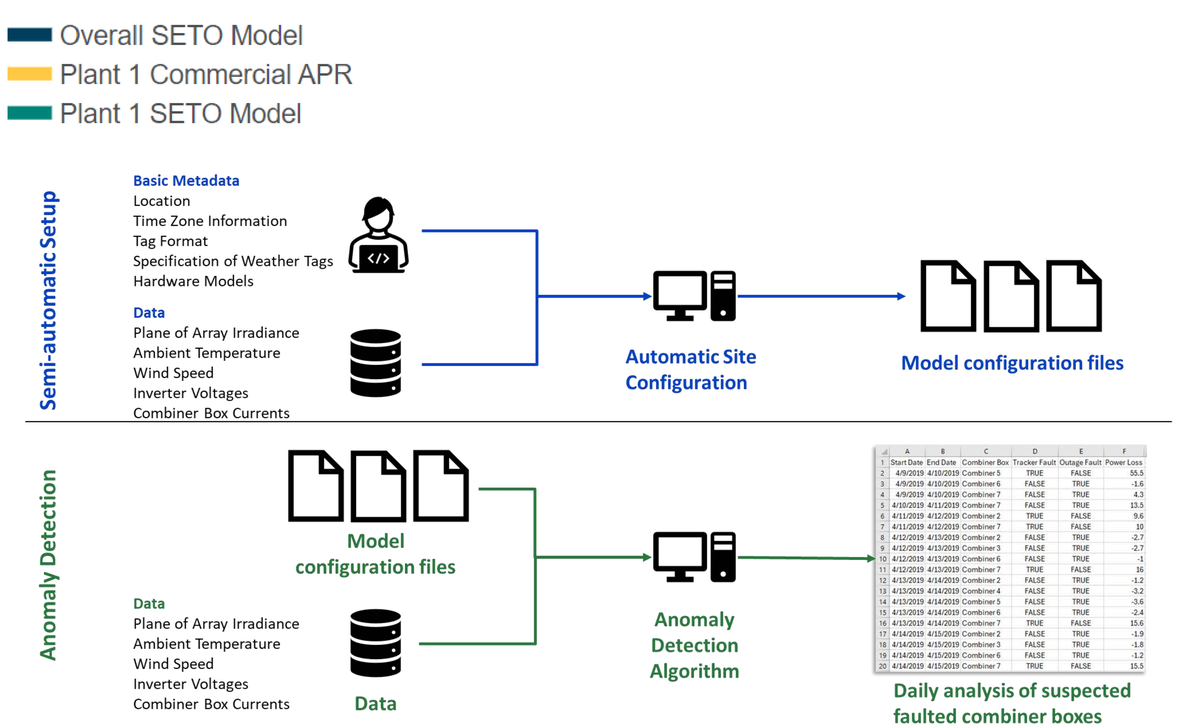
KEY MILESTONES

- Application of the anomaly detection algorithm to nine utility-scale solar plants, demonstrating adaptability and effectiveness in varied conditions.
- Validation process included comparing the algorithm's detections with aerial infrared scans, enhancing our understanding of its accuracy and reliability.

CONCLUSION

- Algorithm detects twice as many failures as “standard” commercial offerings used by utilities for monitoring and diagnostics
- Algorithm is tune-able with false positive rates as low as 7% (Much less than up to 50% with commercial tools)





Start Date	End Date	Combiner Box	Tracker Fault	Outage Fault	Power Loss
4/9/2019	4/10/2019	Combiner 5	TRUE	FALSE	55.5
4/9/2019	4/10/2019	Combiner 6	FALSE	TRUE	-1.6
4/9/2019	4/10/2019	Combiner 7	FALSE	TRUE	4.3
4/10/2019	4/11/2019	Combiner 7	FALSE	TRUE	13.5
4/11/2019	4/12/2019	Combiner 2	TRUE	FALSE	9.6
4/11/2019	4/12/2019	Combiner 7	TRUE	FALSE	10
4/12/2019	4/13/2019	Combiner 2	FALSE	TRUE	-2.7
4/12/2019	4/13/2019	Combiner 3	FALSE	TRUE	-2.7
4/12/2019	4/13/2019	Combiner 6	FALSE	TRUE	-1
4/12/2019	4/13/2019	Combiner 7	TRUE	FALSE	16
4/13/2019	4/14/2019	Combiner 2	FALSE	TRUE	-1.2
4/13/2019	4/14/2019	Combiner 4	FALSE	TRUE	-3.2
4/13/2019	4/14/2019	Combiner 5	FALSE	TRUE	-3.6
4/13/2019	4/14/2019	Combiner 6	FALSE	TRUE	-2.4
4/13/2019	4/14/2019	Combiner 7	TRUE	FALSE	15.6
4/14/2019	4/15/2019	Combiner 2	FALSE	TRUE	-1.9
4/14/2019	4/15/2019	Combiner 3	FALSE	TRUE	-1.8
4/14/2019	4/15/2019	Combiner 6	FALSE	TRUE	-1.2
4/14/2019	4/15/2019	Combiner 7	TRUE	FALSE	15.5

PROJECT NAME: Smart, Hardened, Prefabricated PV Array for 50-Year Service Life

Last 5 digits of project number: **09828**
Principal Investigator (PI): **Dave Lutian**
Lead Organization: **SolarFlexes**
PI Email: **dave@solarflexes.com**

BACKGROUND and OVERVIEW

- Project costs, performance & service lives are limited by traditional construction-based approach to utility-scale PV arrays
- This project tests a single-axis tracking array designed around automated factory processes
- This enables lightweight structural BOS and factory-installed health monitoring system

METHODS

- Finite element analysis of racking structure to ASCE 7 wind loads and UL 2703 safety factors
- Laboratory testing of prefabricated PV arrays for transportation robustness to IEC 62759-1
- Laboratory testing of lightweight anchor structures per International Building Code 1808
- Ai/ML training using a prototype testbed at NREL Flatirons Wind Research Facility

KEY MILESTONES

- Complete transportation robustness testing per IEC 62759-1, damaging ≤1% of tested PV cells
- Achieve analytical 2:1 safety factor for structural BOS
- Meet 2:1 safety factor test conditions for lightweight anchors per International Building Code 1808
- Install & commission two 350 kW pilot projects at Mississippi Army National Guard facilities, including one facility historically exposed to extreme weather
- Demonstrate LCOE reduction ≥$0.005/kWh compared to industry benchmark costs using NREL SAM software

CONCLUSION

- Milestones aim to demonstrate that:
  - Smart, hardened, prefabricated PV arrays leveraging automated factory assembly, rapid installation and AI health monitoring can reduce LCOE by ≥$0.005/kWh
  - Prefabricated PV arrays can disproportionately benefit underserved/underrepresented communities by accelerating utility scale PV adoption and reducing training requirements for high-paying solar jobs
  - Single-axis trackers can be economically installed in areas with wind design speeds ≥150 mph

PHOTOVOLTAICS TRACK

Smart, hardened, prefabricated PV arrays can **improve LCOE,** system performance, and service life through **factory automation, rapid installation, lightweight racking, and AI/ML** health monitoring.

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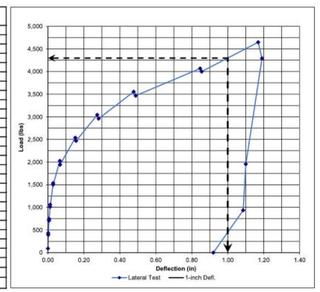




Transportation Robustness Testing & Prototype Installation (NREL Flatirons, UC-San Diego)

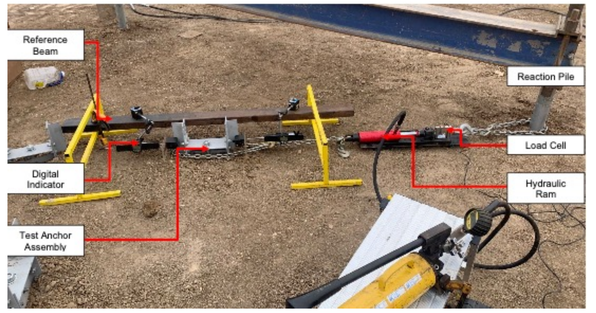
Measurements

Load (lbs)	Def (in)
91	0.000
432	0.002
391	0.002
744	0.006
709	0.006
1,058	0.012
1,011	0.012
1,534	0.029
1,502	0.029
2,027	0.067
1,942	0.068
2,539	0.153
2,468	0.157
3,043	0.274
2,960	0.282
3,553	0.477
3,466	0.488
4,068	0.847
3,999	0.855
4,647	1.170
4,291	1.191
1,955	1.101
935	1.086
0	0.920
0	0.911









Lightweight Anchor Testing (NREL Flatirons)

Additional project contributors: NREL, Mississippi Army National Guard, UC-San Diego, California Clean Energy Fund, CTL|Thompson, CPP Wind Engineering, DNV Americas

PROJECT NAME: PV Performance Modeling Collaborative (PVPMC)

Last 5 digits of project number: **38267**
Principal Investigator (PI): **Marios Theristis**
Lead Organization: **Sandia National Laboratories**
PI Email: **mtheris@sandia.gov**

PHOTOVOLTAICS TRACK

Developing and validating PV models in a global collaborative can improve market transparency and reduce perceived uncertainty and financial risks

BACKGROUND and OVERVIEW

- PV performance modeling is generally presumed to be relatively simple, but the accuracy and uncertainty depends on the analysis and modeling pipeline
- The market is consistently inundated with new modeling software and capabilities, highlighting the necessity for enhanced transparency and independent validations
- PVPMC increases the value of PV performance models by improving their functionality, demonstrating and quantifying validity, and engaging a wide range of stakeholders

METHODS

- Develop, improve, and publish PV models in peer-reviewed manuscripts
- Make PV modeling functions available to the public via pvlib-python
- Curate, document and publish open-access datasets
- Conduct model validation studies, and run blind modeling intercomparisons
- Engage with stakeholders via the PVPMC website, email list, workshop, pvlib-python, IEA Task 13

KEY MILESTONES

- 10 pvlib-python releases with > 20 new functions developed by this project
- 5 PVPMC workshops with record numbers of participation (> 230) and submissions (> 80)
- > 40 technical publications and presentations in journals and conferences
- 2 blind modeling comparisons engaging with 56 participants from 49 organizations and 17 countries
- 4 technical datasets were processed, documented, and published on Duramat Data Hub

CONCLUSION

- PVPMC generates open-source modeling functions that are available to the public via pvlib-python
- Model validation studies provide valuable information for PV developers and investors
- More accurate quantification of model uncertainty leads to lower financing risks
- Round robin model comparisons help improve the performance of available models and lead to more standardized and consistent results

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Take a picture to **view PVPMC's list of publications**

Model development

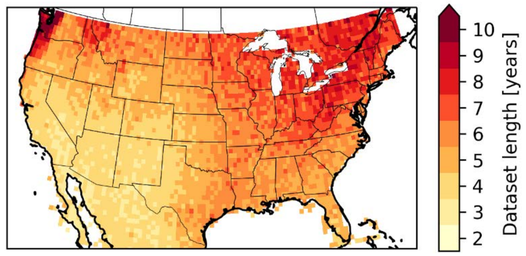


Fig. 1: Example of PVPMC's PV Atlas Task demonstrating performance loss rate (PLR) uncertainty due to climatic variability and dataset length. The map shows the minimum number of years of data to achieve uncertainties within ±0.05%/year. Attention is required when evaluating PV power plants in different climates, because the same assumptions do not apply everywhere.

Independent model validation

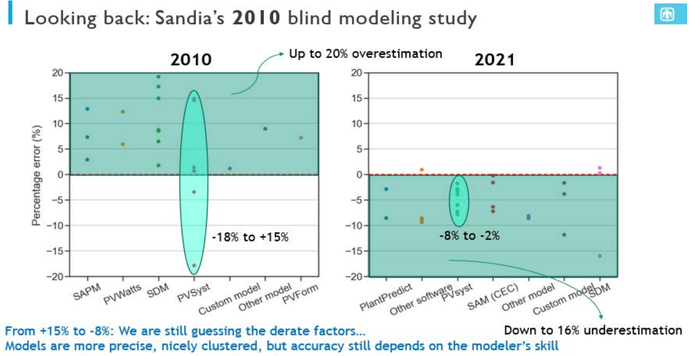


Fig. 3: Screenshot from our plenary presentation in WCPEC-8 showing a comparison of the 2021 blind PV performance modeling study vs. the first one in 2010. The results show that the modelers are still guessing the derates, whereas the models have improved significantly exhibiting higher precision.

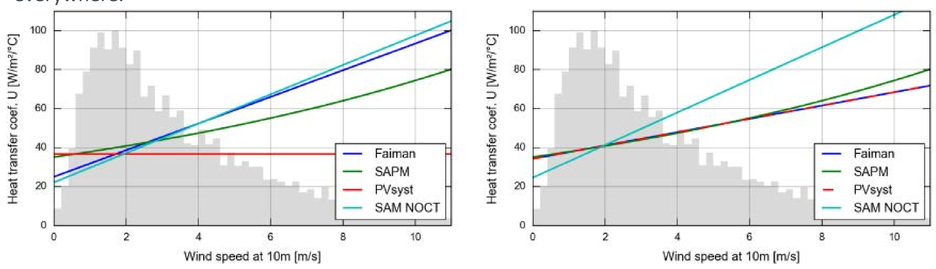


Fig. 2: Example of the parameter translation toolkit showing the heat transfer coefficients calculated by 4 models before translation (left) and after (right). The NOCT SAM model has only one degree of freedom and cannot fully match the others.

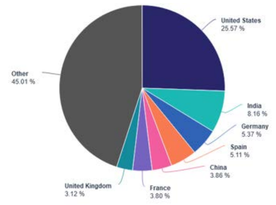


Fig. 6: The PVPMC website receives > 250k visits per year; email list exceeds 6k.

PVPerformance MODELING COLLABORATIVE

PVPMC represents the US in the IEA PVPS

Stakeholder engagement



Fig 4. pvlib-python tutorial participants at the 2023 PVPMC workshop.

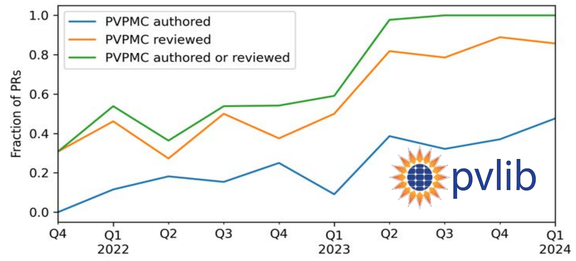


Fig. 5: PVPMC contributions (pull requests) to pvlib-python.

Some of PVPMC's blind modeling participants/stakeholders:

Additional project contributors: Joshua S. Stein, Clifford W. Hansen, Kevin Anderson, Lelia Deville

PROJECT NAME: PV Proving Grounds

Last 5 digits of project number: **38268**
Principal Investigator (PI): **Bruce King**
Lead Organization: Sandia National Labs
PI Email: **bhking@sandia.gov**

BACKGROUND and OVERVIEW

- The PV Proving Grounds Core Capability is a testbed for field validation of technologies with promise to address climate change and future energy needs.
- PVPG emphasizes validation under real-world operating conditions, usage scenarios and relevant time scales.
- PVPG supports a diverse set of stakeholders, including system developers, module manufacturers, financiers, system modelers and instrumentation specialists.

METHODS

- Field research is focused on three key areas: System Long-Term performance, the Regional Test Centers (RTC), and Emerging Technologies.
- Core field laboratories are located at the Photovoltaic Systems Research Laboratory (PSEL) at Sandia and the Outdoor Test Facility (OTF) at NREL
- Research and validation across diverse climate zones is enabled by an independent network of sites in Florida, Louisiana, Michigan and Nevada.

KEY MILESTONES

- Conduct long-term observation of fielded PV systems, selected for technical diversity, to assess non-linear degradation and identify emerging failure modes.
- Conduct collaborative field research in partnership with US industry to validate new technologies and accelerate product development.
- Conduct independent assessments of emerging PV technologies, including novel PV modules, monitoring systems and balance of systems components.

CONCLUSION

- Publicly available PV field performance data and high-accuracy degradation calculations are provided to increase consumer confidence in commercial products
- Industry partners gain access to National Lab expertise in evaluation of novel technologies through the Regional Test Centers
- Emerging measurement capabilities and techniques are assessed in response to industry needs

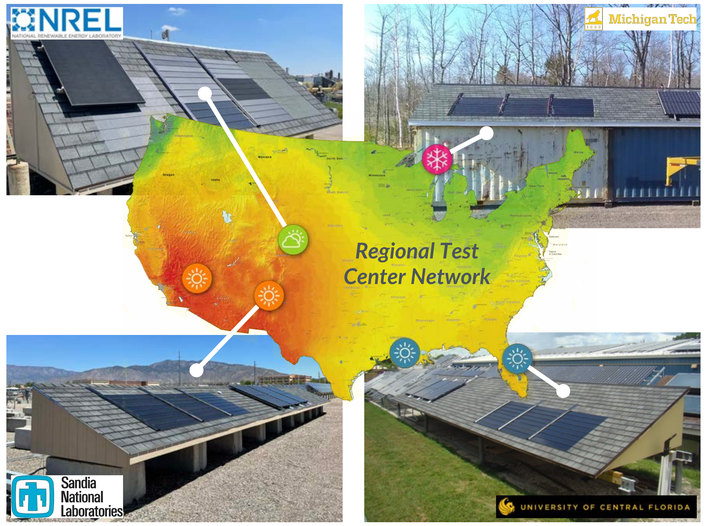
PHOTOVOLTAICS TRACK

PV Proving Grounds combines **outdoor field demonstrations** with precision laboratory measurements **to validate PV design** and durability

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Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2024-03085C

For more information



Building Integrated Roof System Demonstration

- Long-term study: established 2020, expected to run through at least 2025
- Ongoing product validation of shingle operation and viability of different packaging and cell types
- 9 distinct shingle variants/4 conventional module types
- Four climates
- Supports thermal modeling

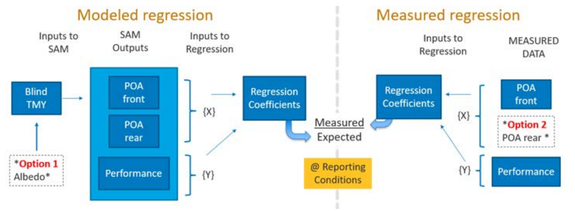
Bifacial research supports instrumentation and standards

- Addresses gaps in industry knowledge regarding proper monitoring of bifacial field performance
- Variability is significantly reduced through the inclusion of measured rear irradiance
- In particular, a calibrated bifacial reference module can provide the best accuracy



System Long Term Evaluation

- Provide long-term operational field exposure of PV systems focused on commercial relevance and new technology.
- Established 2016, sustainability plan created to ensure incorporation of new technologies through at least 2036
- Recent installations focus on bifacial, TOPCon, HJT, large format modules
- Major outputs: published degradation rates, open source data sets, open source modelling parameters



Modelled Rear Irradiance
- Albedo and GHI
- Albedo, GHI and DHI

Measured Rear Irradiance
- Rear-facing reference cell
- Bifacial reference module







Field work supports international standards

- IEC 61853: Photovoltaic module performance testing and energy rating
- IEC 61724: Photovoltaic system performance

Additional project contributors: Bill Sekulic, Chris Deline (NREL)/Laurie Burnham, Marios Theristis, Jennifer Braid (Sandia)

PROJECT NAME: Accelerated Selection of Optimal Perovskite Alloys for Solar PV Using a Combined Quantum and Machine Learning Hierarchical Approach

Last 5 digits of project number: **09515**
Principal Investigator (PI): **Alex Zunger**
Lead Organization: **University of Colorado Boulder**
PI Email: **Alex.Zunger@colorado.edu**

PHOTOVOLTAICS TRACK

Two-pronged Approach: (1) Large supercell **QM-DFT for *disordered ternary alloys*** and (2) **ML driven by DFT** for ***ordered compounds*** has initial successes in identifying potential **new, PV stable** HP compounds

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BACKGROUND and OVERVIEW

- This research addresses an ongoing shortcoming in the current photovoltaics (PV) research on halide perovskites (HPs) that has been based largely on intuitive, trial-and-error searches of a miniscule fraction of the possible space of HP alloys, thus running the risk of missing **opportunities of better HP candidates**.
- The method develops and applies a **hierarchical 2-prong approach in a computational design framework** to efficiently & reliably screen millions of hypothetical HPs for optoelectronic applications that will leverage and accelerate ongoing closely coupled with *interative* experimental materials development & validation efforts.

METHODS

- Overall, a **two-pronged theoretical predictive strategy** that involves a search and for novel, digital composition ordered HP compounds and alloys that have PV approporiate band gaps and stability culminating in experimental validation.
- Two-pronged **theory** approach: (1) **Machine Learning (ML)** based on high-quality QM (DFT) set of building blocks to predict digital compositions meeting band gap & stability criteria; (2) **DFT calculations** of sreened *triple-halide dis-ordered alloys of single-perovskites, including producing area maps* of predicted PV band gap & stability ranges.
- **Experimental validation** by iterative handoffs to NREL experimental group and industry partners.

KEY MILESTONES

- Formation of and periodic feedback from Industry Working Group (7 members) [Completed]
- Discrepancies between DFT and experiment for known compounds; initial predictions with experimental process initiated [Theory completed, Experiment 50% complete]
- Errors of ML stabilities and band gaps are within < 0.2 eV compared with DFT [Completed]
- Dissemination: Journal publications/technical conference presentations. [Completed]
- Major meeting with Industry Working Group for feedback on progress and 2nd Budget Period activities [To be completed by June 2024]
- Report: Best-of-class predicted materials with target band gaps & stability and validation by experiment [Underway]
- Workshop to stimulate further interactions with greater perovskite community [Plan: March-June 2025]

CONCLUSION

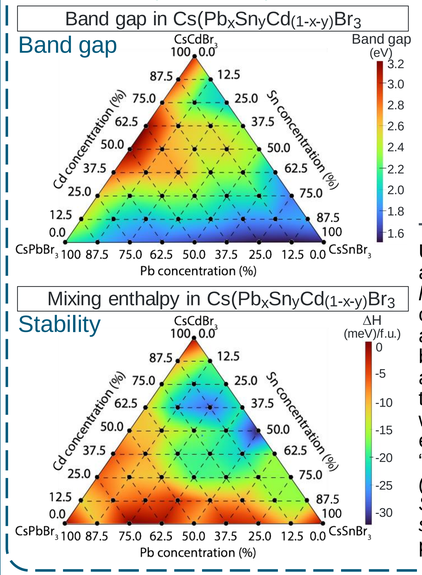
- At end of this 1st Period, a series of new ML and DFT HPs have been predicted with the initial phase underway for experimental validation for best-of-class new materials.
- **Impacts:** ***First***, the collaboration and guidance of our industry working group is key to provide rapid transfer & more wide-ranging oversight on the relevance of the work. ***Second:*** this project & closely coordinated theory-guidance/experimental validation approach is designed to provide a world-class resource for competitive advantages over international competitors.

Two-pronged theory predictive strategy

Quantum mechanics: DFT Calculations

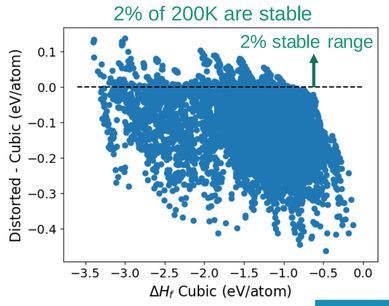
Direct calculations of the properties of complex, disordered, multi-component, non-digital HP alloys, avoiding approximations to the electronic structure during the ML steps.

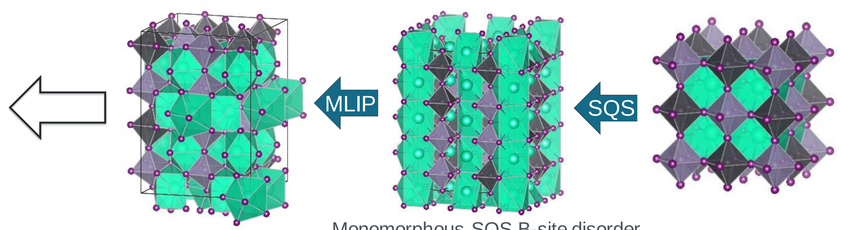
One material system example:



The novelty focus: Use N-component alloys where *at least two* of the components are already known to be growable (such as Sn and Pb for the B-sublattice), while exploring the effect of a single "ternary addition *Z" (such as Z=Ge, Cd, Sr, etc. on the B sublattice)* on the properties.

Machine Learning driven by DFT building blocks





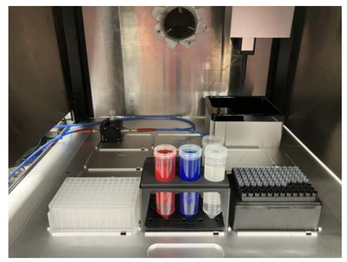
Of the "stable 2%", select: <2.0 eV and $\Delta H_d^{ML,PBE}$ < 0.3 eV/atom

Compound	E_g^{HSE06} (eV)	$E_g^{ML,HSE06}$(eV)
$KCsAgInBr_6$	1.278	1.549
$Rb_2AgInBr_6$	1.271	1.381
$Rb_2CuRhCl_6$	1.457	1.519
$RbCsCuSbBr_6$	1.328	1.559
$KRbCuSbBr_6$	1.301	1.595
$K_2CuRhCl_6$	1.446	1.586
$KCsCuRhCl_6$	1.473	1.459
$KRbCuRhCl_6$	1.450	1.457

Approach: Use high-quality DFT set of building blocks, then produce in ML many more digital compositions compounds to be tested for the potential pitfalls noted above: **Novelty**: ML and more rapid identifications

Exploratory synthesis & testing of predicted HP compounds and multi-component alloys (NREL: *just underway*)

Interative Handoffs Theory - Experiment



- Modified pipettor robot for algorithm-driven experimentation
- Demonstrated closed-loop exploration of absorption spectral and PL properties

Additional contributors: CU-Boulder (Charles Musgrave, L.L Kazmerski), Univ. of South Carolina (Christopher Sutton), NREL (Joe Berry)
Industry Working Group: First Solar, Cubic PV, Tandem PV, Energy Materials Corporation, Swift Solar, Blue Dot Photonics, Caelux