An Update from the cell cracking working group on DuraMAT's effort on Detecting, Assessing, and Mitigating Power Loss of Cracked Cells

Martin Springer (NREL), Jennifer Braid (SANDIA), Xin Chen (LBL), Tim Silverman (NREL), Sang M Han (OSAZDA), and Oliver Zhao (Stanford University)

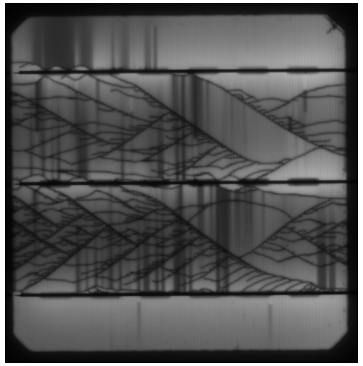
DuraMAT webinar 2021-07-12

Publication Number: NREL/PR-5K00-80495

DuraMAT Working Groups

Fall 2020 virtual DuraMAT workshop raised two important questions:

- *When does a cell crack become damage?*
- *How does the glass/glass module design affect module durability?*
  - →Watch out for the September 2021 webinar of the glass/glass working group!



Electroluminescence image of cracked cell[1]

Cell Cracks Working Group

- brings together subject matter experts from universities, national laboratories, and industry
- identifies research areas for short- and long-term research opportunities
- facilitate discussion through bi-monthly meeting series
- leverages the capabilities developed within the DuraMAT network

Interested in participating? - Reach out to:

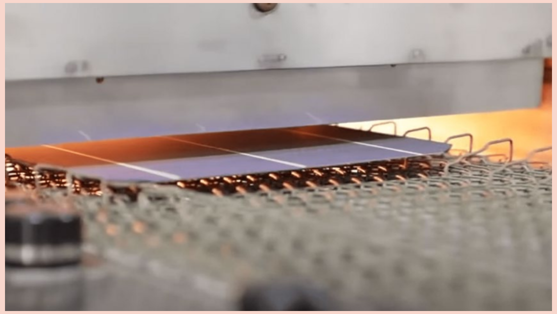
Martin Springer (martin.springer@nrel.gov), Jennifer Braid (jlbraid@sandia.gov), or Oliver Zhao (ozhao32@stanford.edu)

[1] A. Gabor, *Cracked Cell Solutions and Research Opportunities*, DuraMAT Working Group Meeting, 2021

Origin of cracks[1]

Manufacturing

Firing[3]



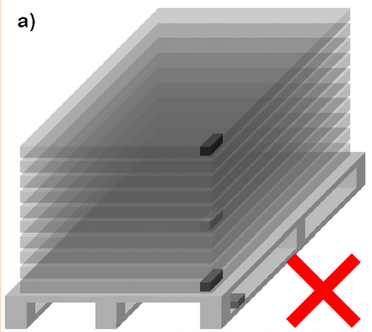
https://pv-manufacturing.org/teaching-resources/pv-factory-tutorials/pvfactory-8-cofiring

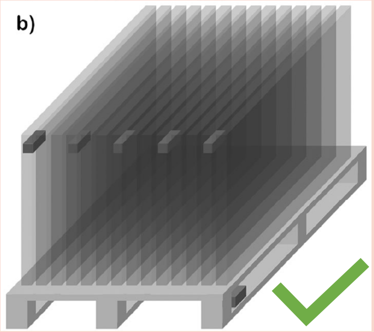
Soldering[4]

Henkel, 2018

Installation

Transportation[6]





Mounting

https://energieadvisor.org/how-to-install-solar-panels/

https://www.upsbatterycenter.com/blog/materials-needed-solar-panel-installation/

[1] L. Papargyri *et al, 2020*, doi: https://doi.org/10.1016/j.renene.2019.07.138.
[2] A. Kumar and S. N. Melkote, 2018, doi: 10.1016/j.promfg.2018.02.156.
[3] Kohn, et al. Proceedings of the 25th EUPVSEC Spain. 2010.
[4] A. Gabor *et al.*, 2006. https://www.steelandsilicon.com/pubs/Gabor_20060914.pdf
[5] M. Israil, et al. 2013. https://doi.org/10.1177/0142331212457583
[6] M. Köntges, et al. 2016, doi: 10.1002/pip.2768.

Origin of cracks[1]

Operational loading and environmental conditions

Thermal cycles

https://pv-magazine-usa.com/2021/01/14/cams-acquires-belectrics-u-s-solar-om-business/

Wind

https://www.pv-magazine-australia.com/2019/05/14/arctech-unveils-new-single-axis-tracker/

Snow

https://insidesources.com/green-where-the-sun-doesnt-shine/

Severe weather events

Hailstorm

https://gazette.com/thetribune/colorado-led-nation-in-hail-damage-in-2018-according-to-state-farm-report/article_bb838686-4a60-11e9-b80a-e7169733fc02.html

Hurricane

https://pv-magazine-usa.com/2018/08/24/a-how-to-solar-power-strong-enough-for-a-hurricane/

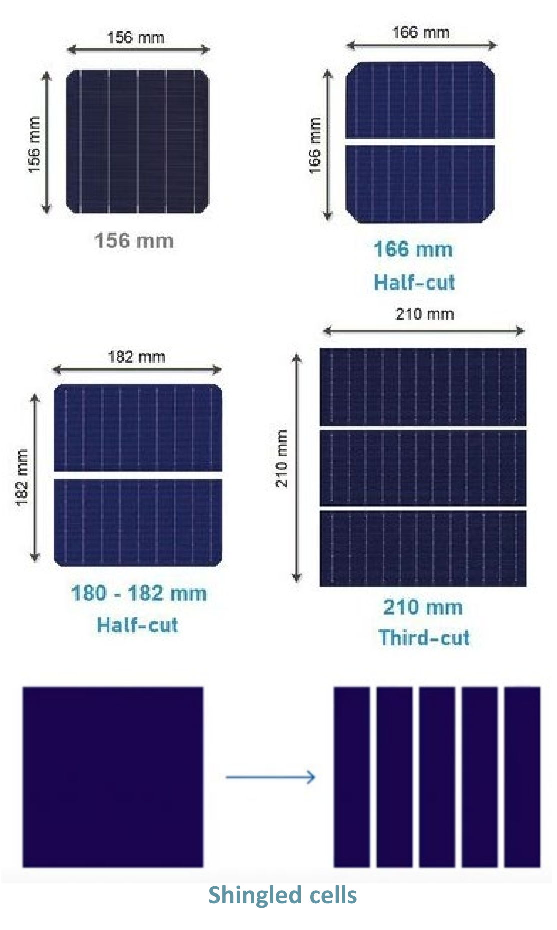
Tornado

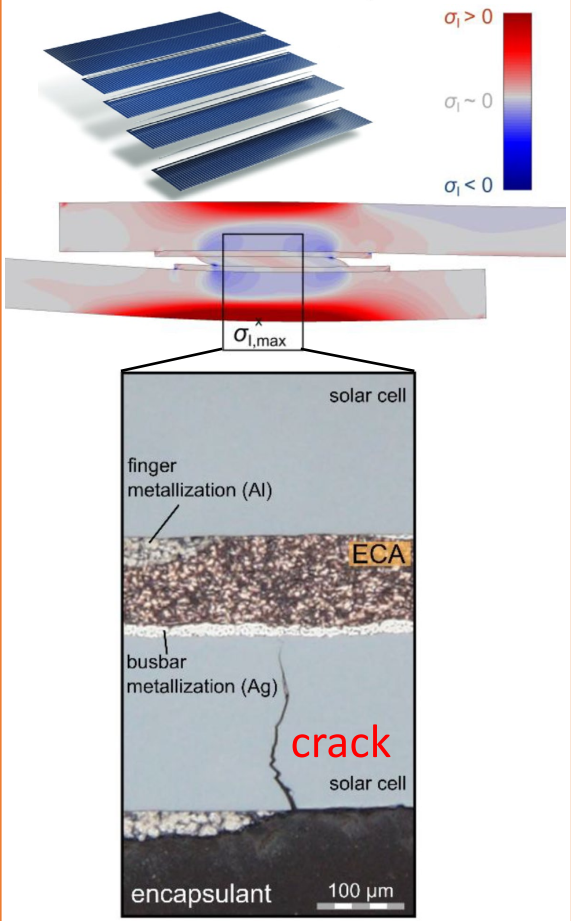
https://www.twincities.com/2016/09/08/storm-damages-national-guard-camps-new-solar-energy-project/

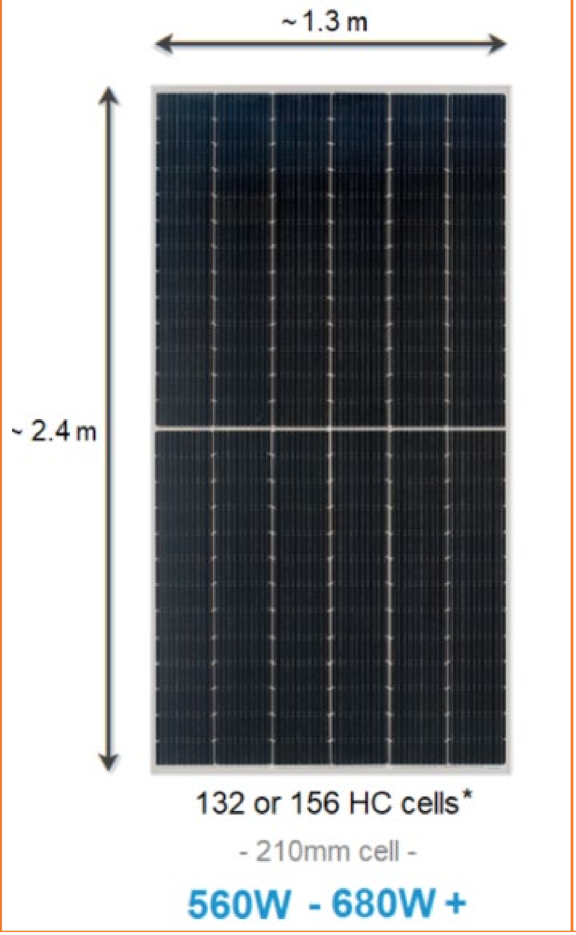
[1] L. Papargyri *et al.*, 2020, doi: https://doi.org/10.1016/j.renene.2019.07.138.

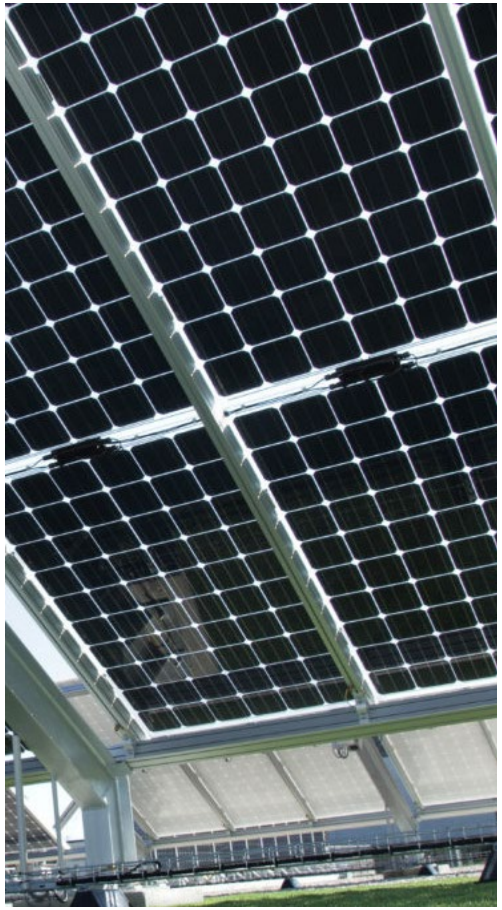
New challenges arising from new technologies (some examples)

Cut Cells[1]	Shingled interconnection[2]	Larger modules[1]	Glass/Glass modules[3]









[1] https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels
[2] N. Klasen, et al. 2021 SILICON PV, Hamelin
[3] https://www.pv-magazine.com/2020/06/11/french-bifacial-standards-measure-up/

Outline

- *Xin Chen (LBL):* Crack Detection Algorithm & Data Analytics
- *Jennifer Braid (SANDIA):* Measurement of Photovoltaic Cell Crack Characteristics in Modules Using Digital Image Correlation
- *Tim Silverman (NREL):* Characterization and weathering of existing cracks in commercial modules.
- *Sang Han (OSAZDA):* Low-Cost Advanced Metallization to Reduce Cell-Crack-Induced Degradation for Increased Module Reliability.
- *Oliver Zhao (Stanford University):* Concluding remarks

DuraMAT
Durable Module Materials Consortium

Crack Detection Algorithm & Data Analytics

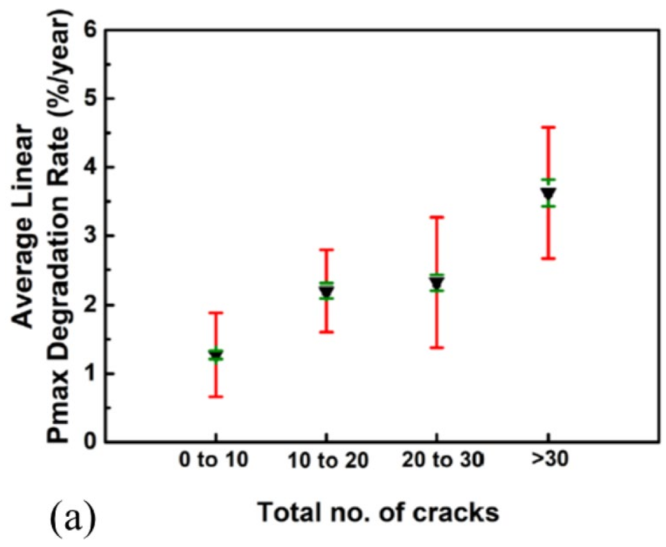
Xin Chen, Todd Karin, Anubhav Jain

July/12/2021

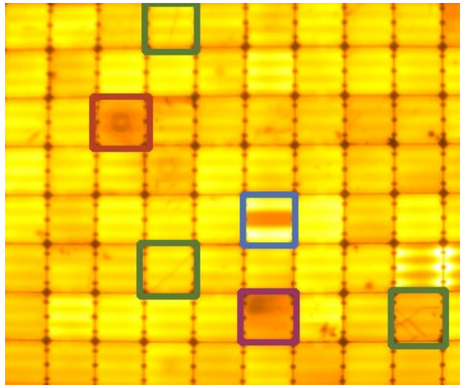
Background

- The power loss of solar modules is considered a threaten to the durability of the solar cells
- Cracks can propagate and lead to the electrical isolation and accelerate the degradation rate[1]
- Other defects induced by fire, humidity, etc. can also cause power loss

What causes the crack to propagate?
How do cracks influence degradation rate & power loss?
How to collect the features of the cracks from thousands or more solar modules?
How to quickly determine whether the module in field needs to be replaced due to defects?



Relation of degradation rate and crack number



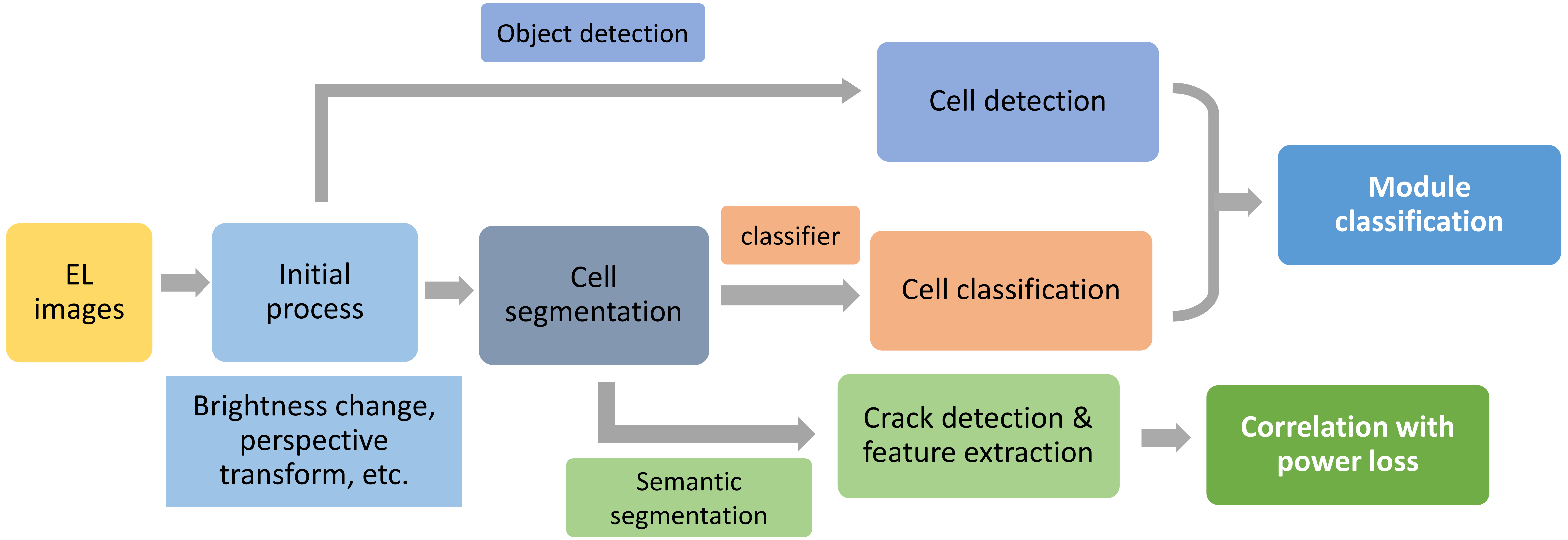
Electroluminescence image of solar module in field (defective cells are labelled with box)

Electroluminescence image of solar module in lab

[1]N. Shiradkar, "Key Results from All India Survey of PV Module Reliability: 2016," in *NREL PV Reliability Workshop*, Lakewood, CO, 2018.

General Process of automatic processing[1-3]

PV-vision be found at: https://github.com/hackingmaterials/pv-vision



[1] IEA-PVPS T13-10. (2018). *Review on Infrared (IR) and Electroluminescence (EL) Imaging for Photovoltaic Field Applications*.

[2] Anwar, S. A., & Abdullah, M. Z. (2014). Micro-crack detection of multicrystalline solar cells featuring an improved anisotropic diffusion filter and image segmentation technique. *Eurasip Journal on Image and Video Processing*, *2014*, 1–17. https://doi.org/10.1186/1687-5281-2014-15

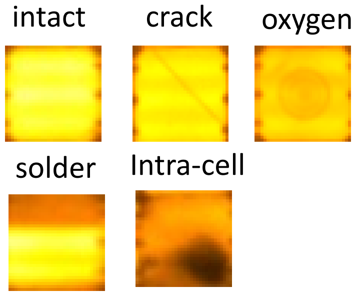
[3] Spataru, S., Hacke, P., & Sera, D. (2017). Automatic detection and evaluation of solar cell micro-cracks in electroluminescence images using matched filters. *2017 IEEE 44th Photovoltaic Specialist Conference, PVSC 2017*, 1–6. https://doi.org/10.1109/PVSC.2017.8366343

Image process with machine learning

classifier

Random Forest, LeNet, ResNet

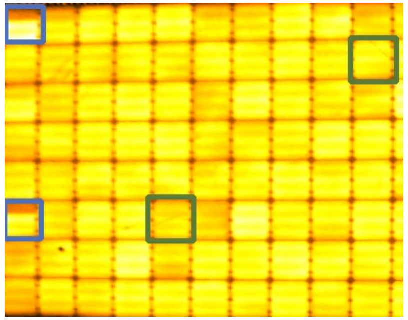
CAT



Object detection

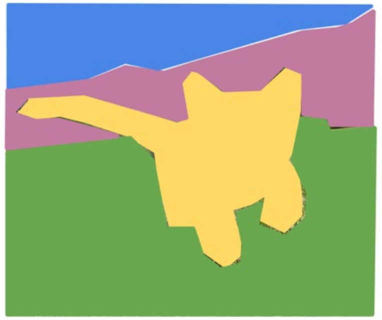
YOLO model

DOG, DOG, CAT

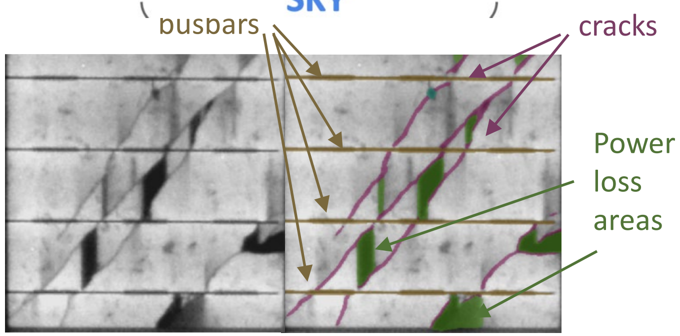


Semantic segmentation

Unet model



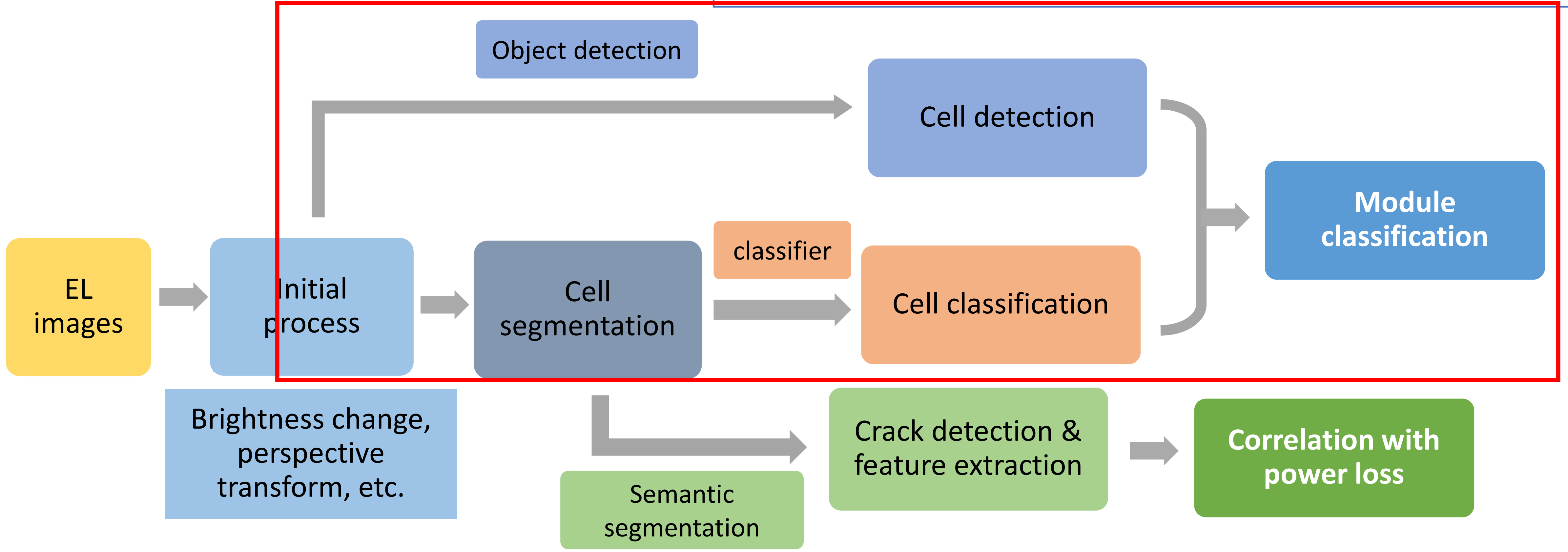
GRASS, CAT, TREE, SKY



Dog and cat images: https://web.eecs.umich.edu/~justincj/teaching/eecs498/FA2020/schedule.html

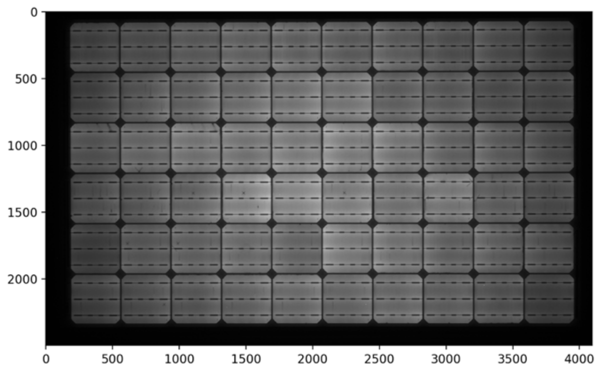
General Process of automatic processing[1-3]

PV-vision be found at: https://github.com/hackingmaterials/pv-vision



[1] IEA-PVPS T13-10. (2018). *Review on Infrared (IR) and Electroluminescence (EL) Imaging for Photovoltaic Field Applications*.
[2] Anwar, S. A., & Abdullah, M. Z. (2014). Micro-crack detection of multicrystalline solar cells featuring an improved anisotropic diffusion filter and image segmentation technique. *Eurasip Journal on Image and Video Processing*, *2014*, 1–17. https://doi.org/10.1186/1687-5281-2014-15
[3] Spataru, S., Hacke, P., & Sera, D. (2017). Automatic detection and evaluation of solar cell micro-cracks in electroluminescence images using matched filters. *2017 IEEE 44th Photovoltaic Specialist Conference, PVSC 2017*, 1–6. https://doi.org/10.1109/PVSC.2017.8366343

Cell segmentation tools



Raw image

Binary threshold

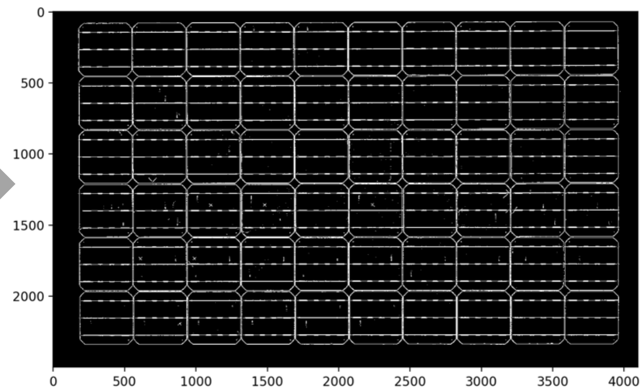
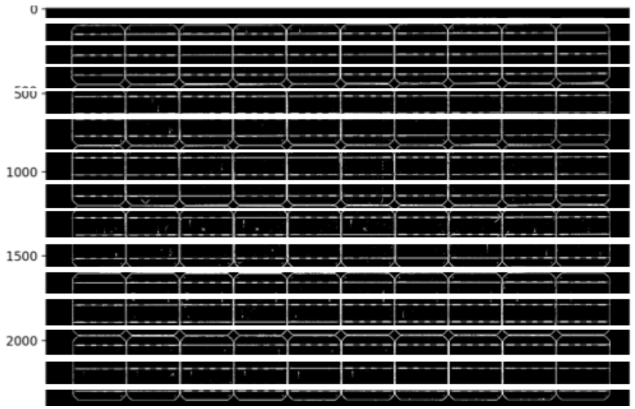
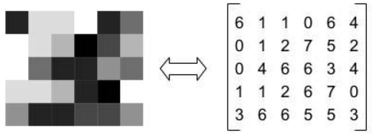


Image after binary threshold

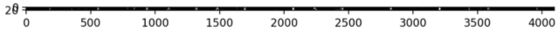
Split along x or y axis



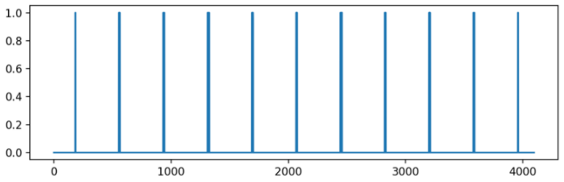
Schematic diagram of splits



Gray scale sum up along x or y axis

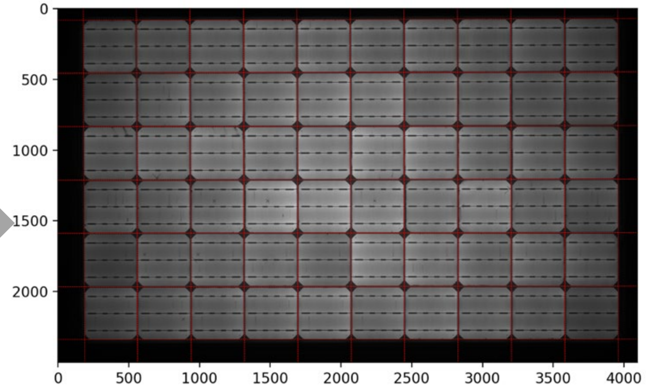


Detect edges in each split



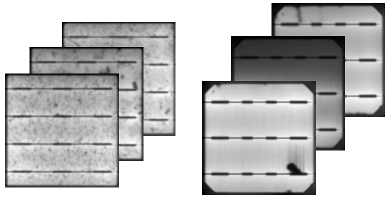
Detected internal edges from each split

Linear fit edges in each split

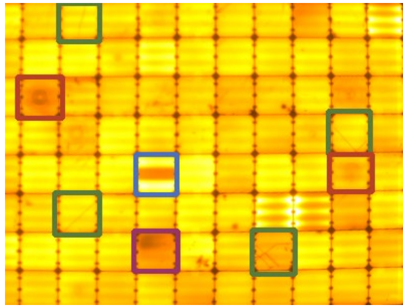


Detected internal edges from the whole module

Crop out



Module classification

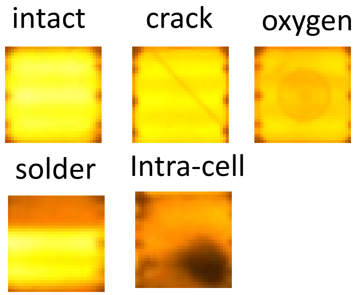


YOLO

Count defective cells detected in the module

Count cells classified in each category

classifiers



Classification criterion:
If no defective cell or ‘crack’ <= 1:
    Category 1
elif (‘crack’ >= 2 or ‘oxygen’ >= 1 or ‘intra > 0’) and ‘intra’ < 2:
    Category 2
elif ‘intra’ >= 2:
    Category 3

Module classification

Dataset and training

1063 images of solar modules sampled for training and 241 images sampled for testing

Category		Intact	Crack	Oxygen	Intra-cell	Solder
Image						
Training set	YOLO	133027(97.8%) unannotated	1663(1.2%)	853(0.63%)	360(0.26%)	170(0.12%)
	classifiers	2661 (46.9%)	1663(29.3%)	853(14.9%)	360(5.9%)	170(3.0%)
Testing set		29527(95.7%)	659(2.1%)	451(1.46%)	136(0.44%)	75(0.24%)

<u>Yolo model</u>

- The 1063 images split into training set and validation set with validation size as 20%
- The training set is augmented through vertical flip, horizontal flip, 180-degree rotation and random crop. The validation set and testing set are not augmented.
- Input: default $416 \times 416 \times 3$ RGB images

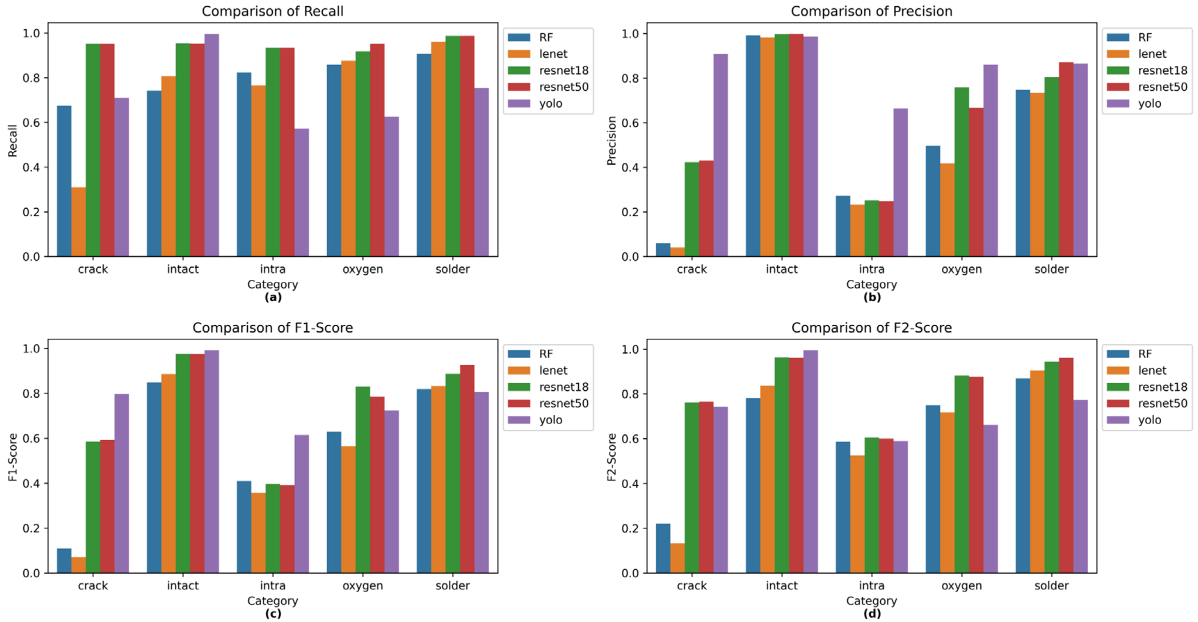
<u>Classifiers</u>

- The 1063 images of modules are segmented into images of solar cells where 97.8% are ‘intact’ solar cells. To make the training set more balanced, part of the ‘intact’ cells are discarded. The final training set contains 5707 images of segmented solar cells
- RF: 5-fold cross-validation is used to do hyperparameter tuning.
  - Input: $n \times 1024$ matrix constructed from flattened 32×32 gray scale image.
- CNN models: the training split into sub-training and validation set with the validation size as 20%.
  - Input: $32 \times 32 \times 3$ RGB images
- The training set is augmented through random vertical flip, horizontal flip and 180-degree rotation. The 241 images are segmented for testing. The ‘intact’ cells are not discarded to approach the real case.

Module classification

Testing

Metrics comparison

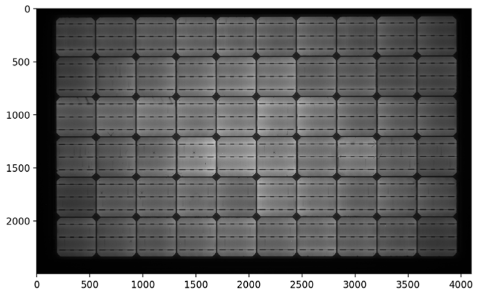


$$
\begin{aligned}
precision &= \frac{TP}{TP + FP} \\
recall &= \frac{TP}{TP + FN} \\
F1 &= \frac{2 \times precision \times recall}{precision + recall} \\
accuracy &= \frac{TP + TN}{TP + FN + TN + FP}
\end{aligned}
$$

Distribution of defects
(>15,000 modules)

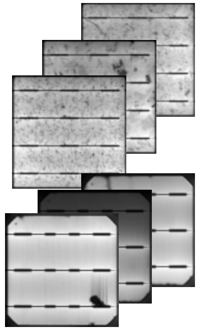
Defect type	Average % of defects/column	
	EDGE columns	CENTER columns
Crack	12.9%	5.3%
Oxygen	6.3%	
Solder	9.1%	5.8%
Intra	13.1%	5.3%

Crack feature extraction



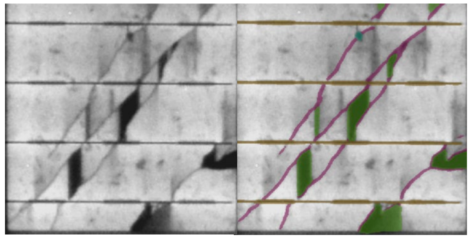
Solar module

crop



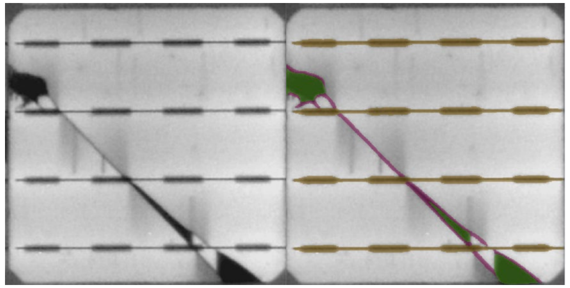
Cropped solar cells

UNet



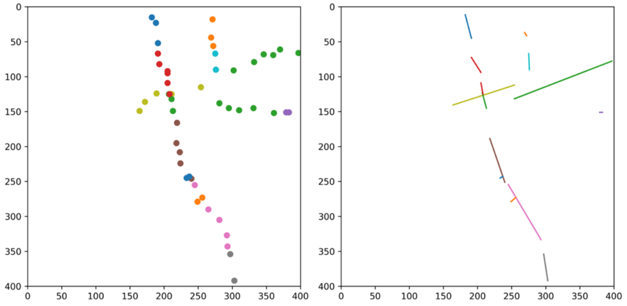
Masks predicted by UNet model. Left: original image. Right: masks are highlighted in different colors. Purple (crack), Green (power loss area), brown (busbar). F1 metric=0.862

- UNet model trained to segment the cracks with overall F1 metric of 0.89
- Tools developed to calculate crack features (length, orientation, etc.)



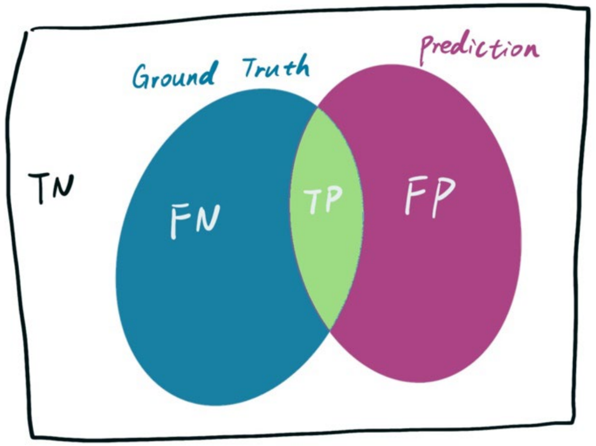
Left: original image. Right: predicted masks. F1 metric=0.882

vectorized



Left: crack vectors. Right: poly-fitted cracks.

Testing
Intersection over Union(**IoU)**



F1 score $$F_1 = \frac{2TP}{2TP + FN + FP}$$

Overall metric $$F_1 = \frac{\sum 2TP}{\sum 2TP + FN + FP}$$

Acknowledgement

Anubhav Jain

Todd Karin

Thank you!

Measurement of PV Cell Crack Characteristics in PV Modules using Digital Image Correlation

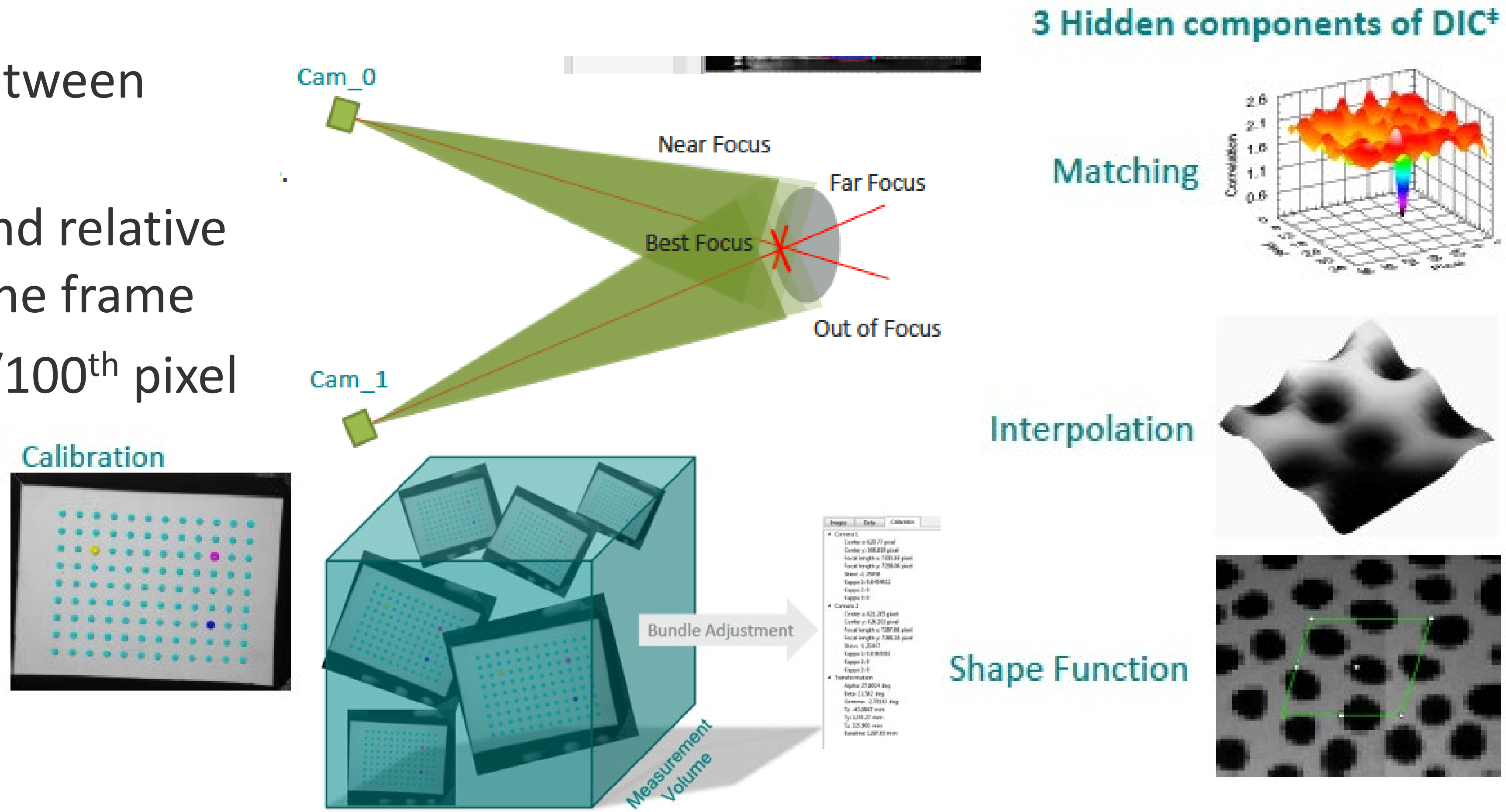
Jennifer L. Braid, Charles Robinson, Joshua S. Stein (Sandia National Laboratories)

Duncan Harwood (D2Solar)

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.

Methodology: Digital Image Correlation

- Matches patterns between consecutive images
- Detects rigid body and relative movements within the frame
- Interpolates up to 1/100th pixel resolution
- Stereo DIC detects in and out of plane displacements

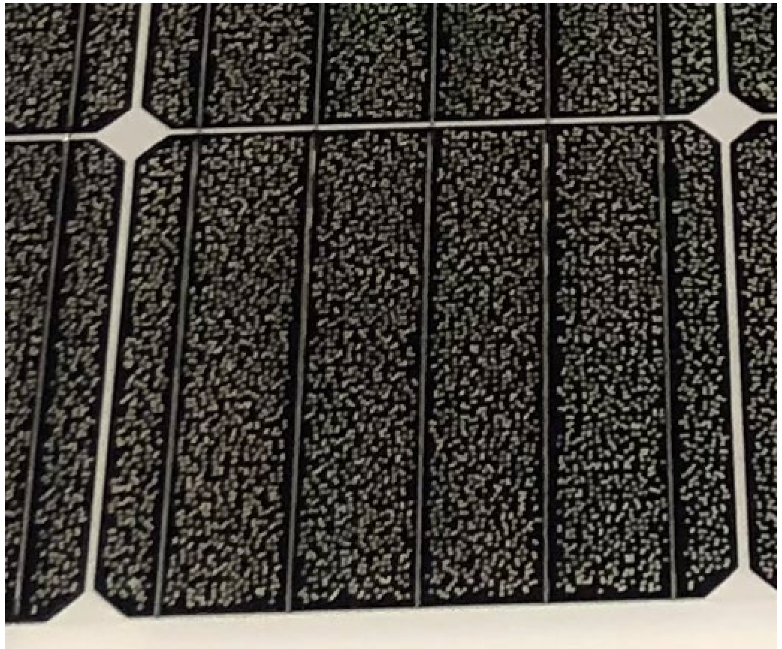


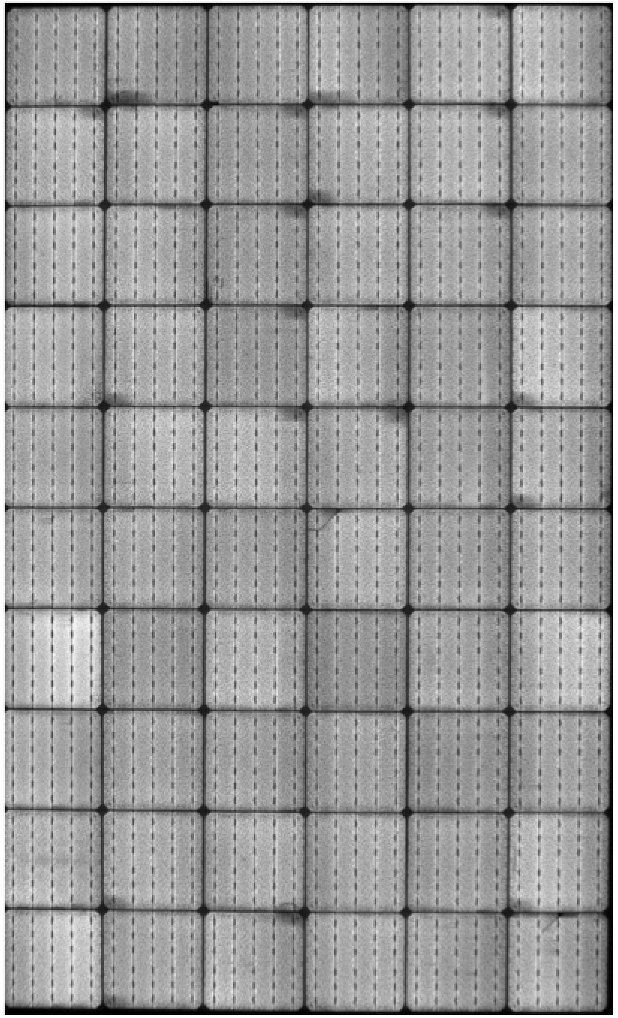
Steps of Stereo Digital Image Correlation

Sample Requirements for DIC

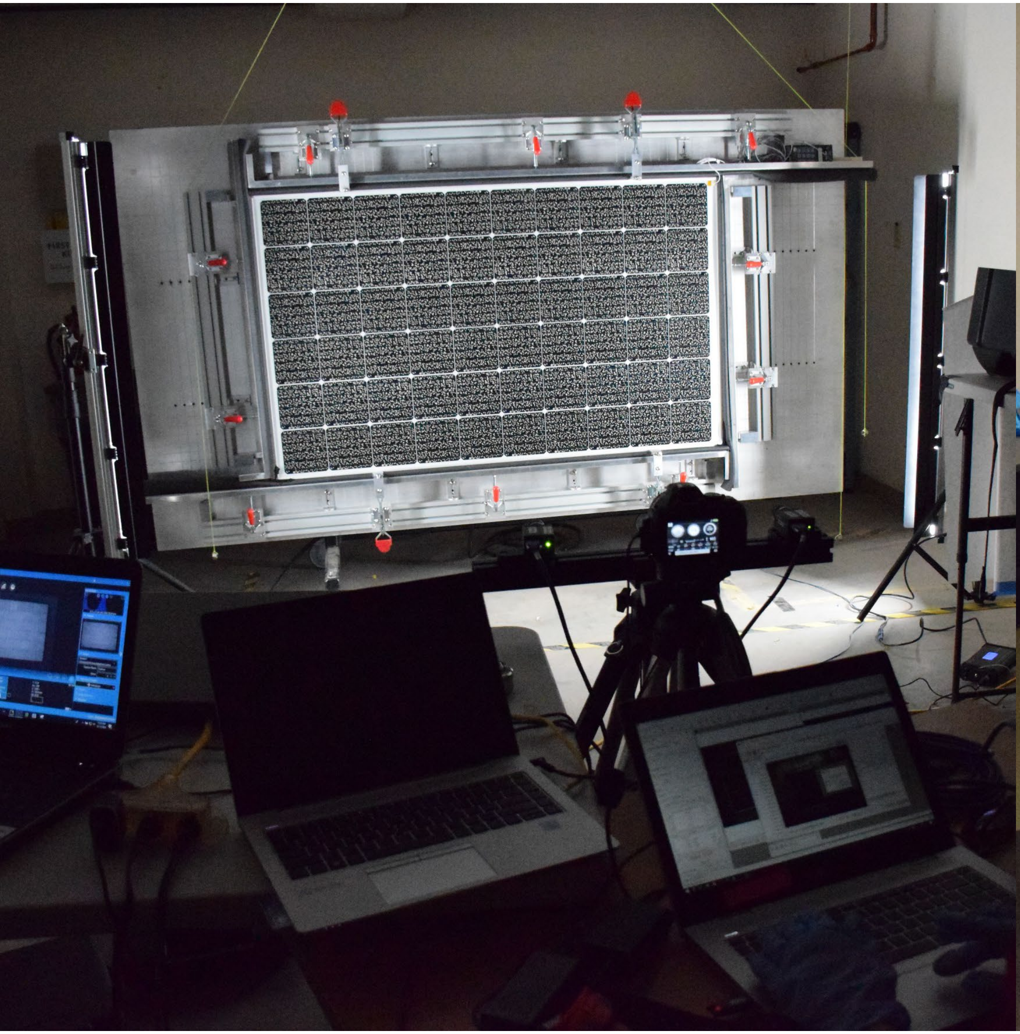
DIC requires high-contrast patterning

- Shown screen-printed on cells prior to lamination, for visible imaging
- Speckle pattern is visible in EL image, but does not impede detection of cracks and other features

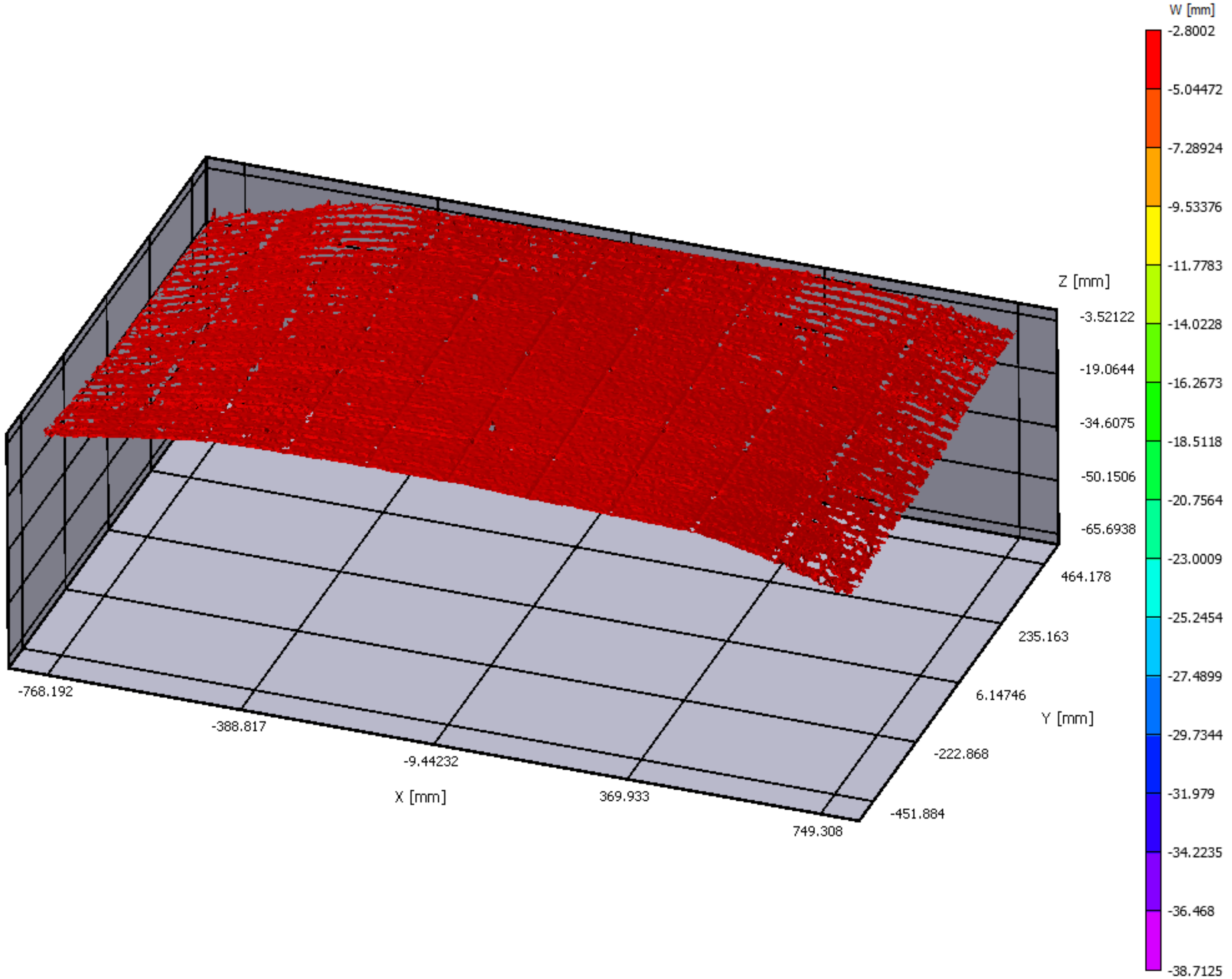




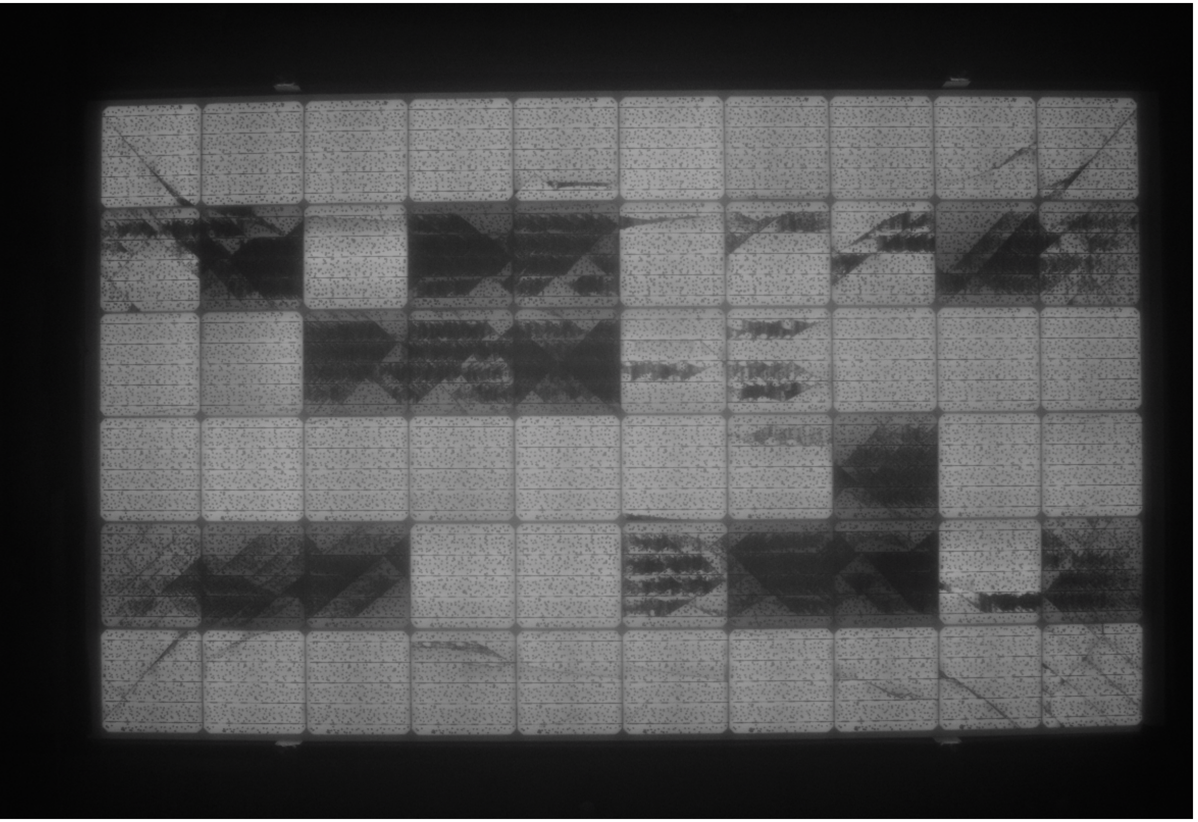
Experimental Setup



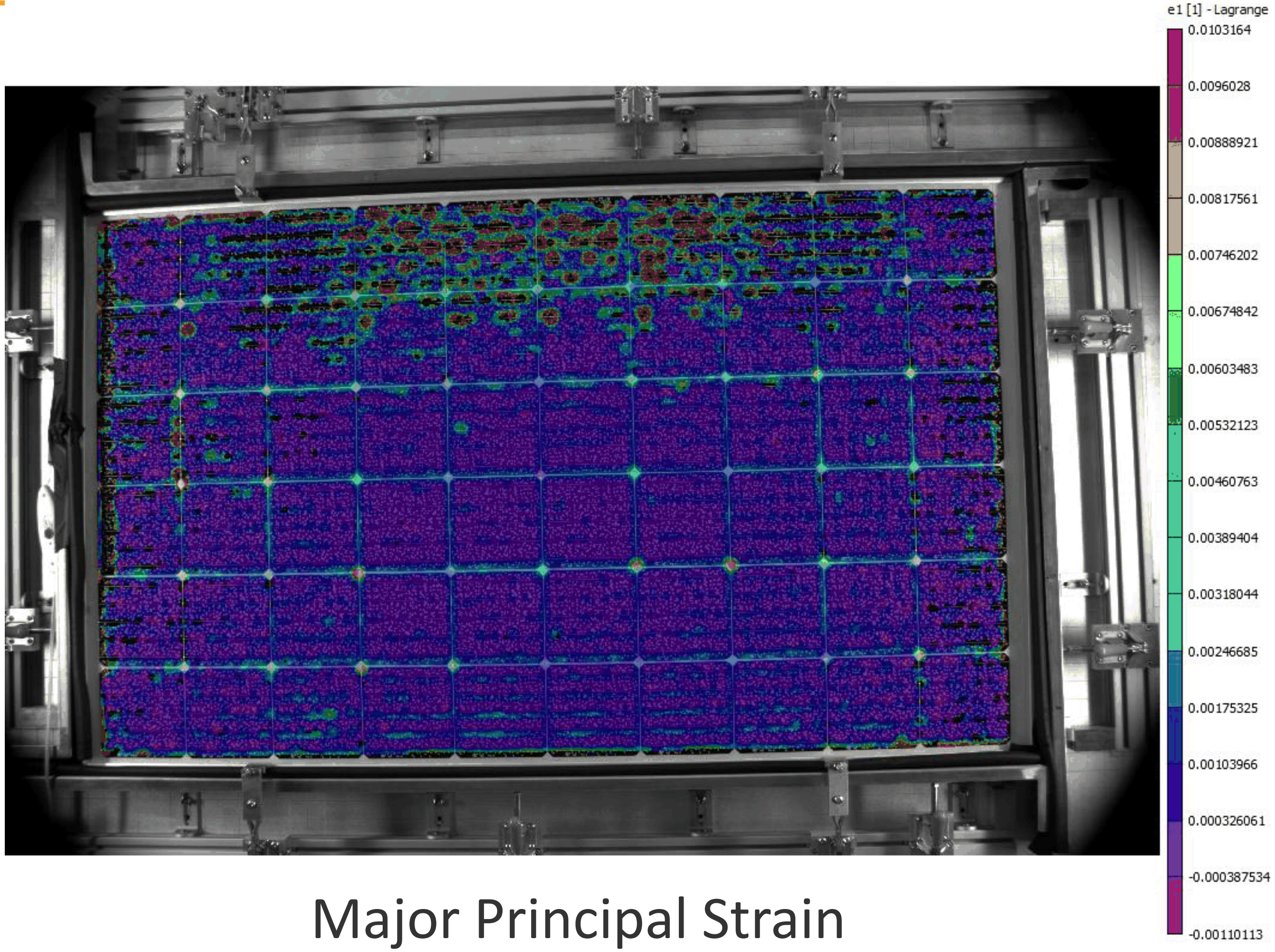
Full-field cell displacement 0 to -5100 Pa



Module heated via reverse bias and loaded to -5100 Pa

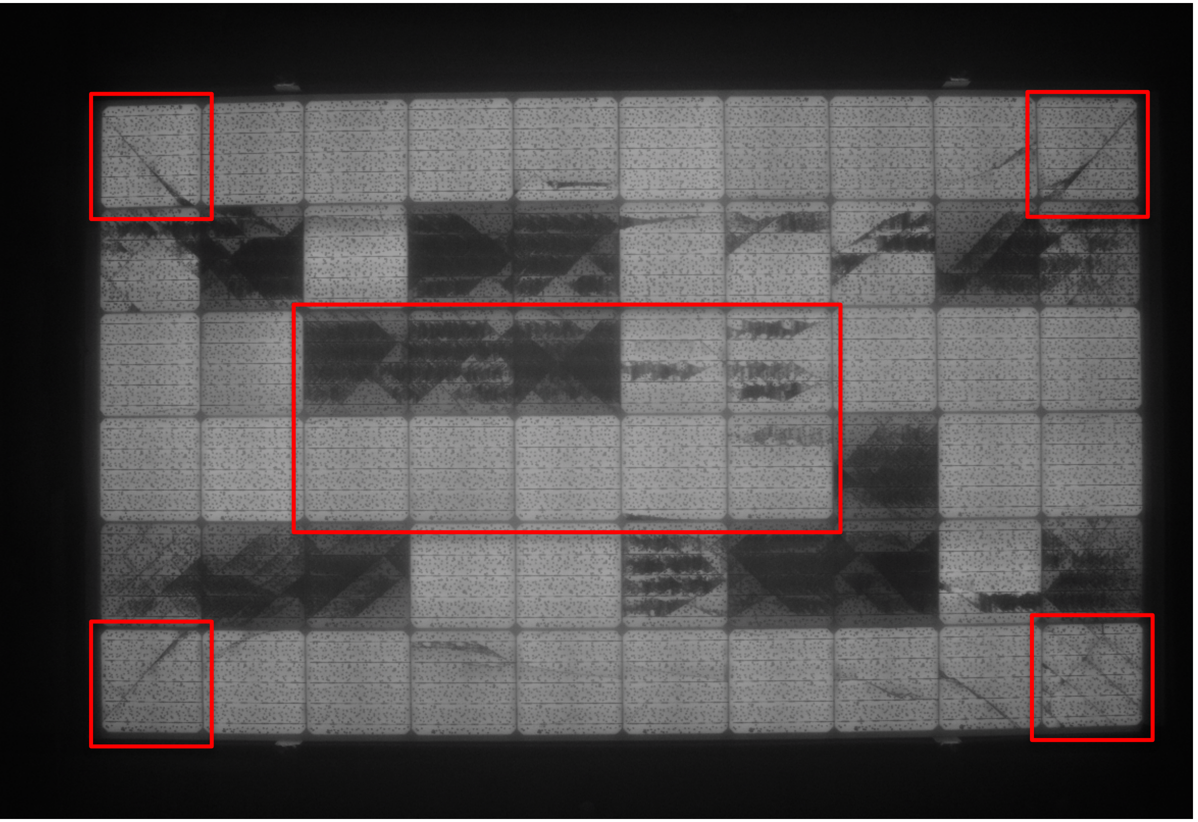


Electroluminescence

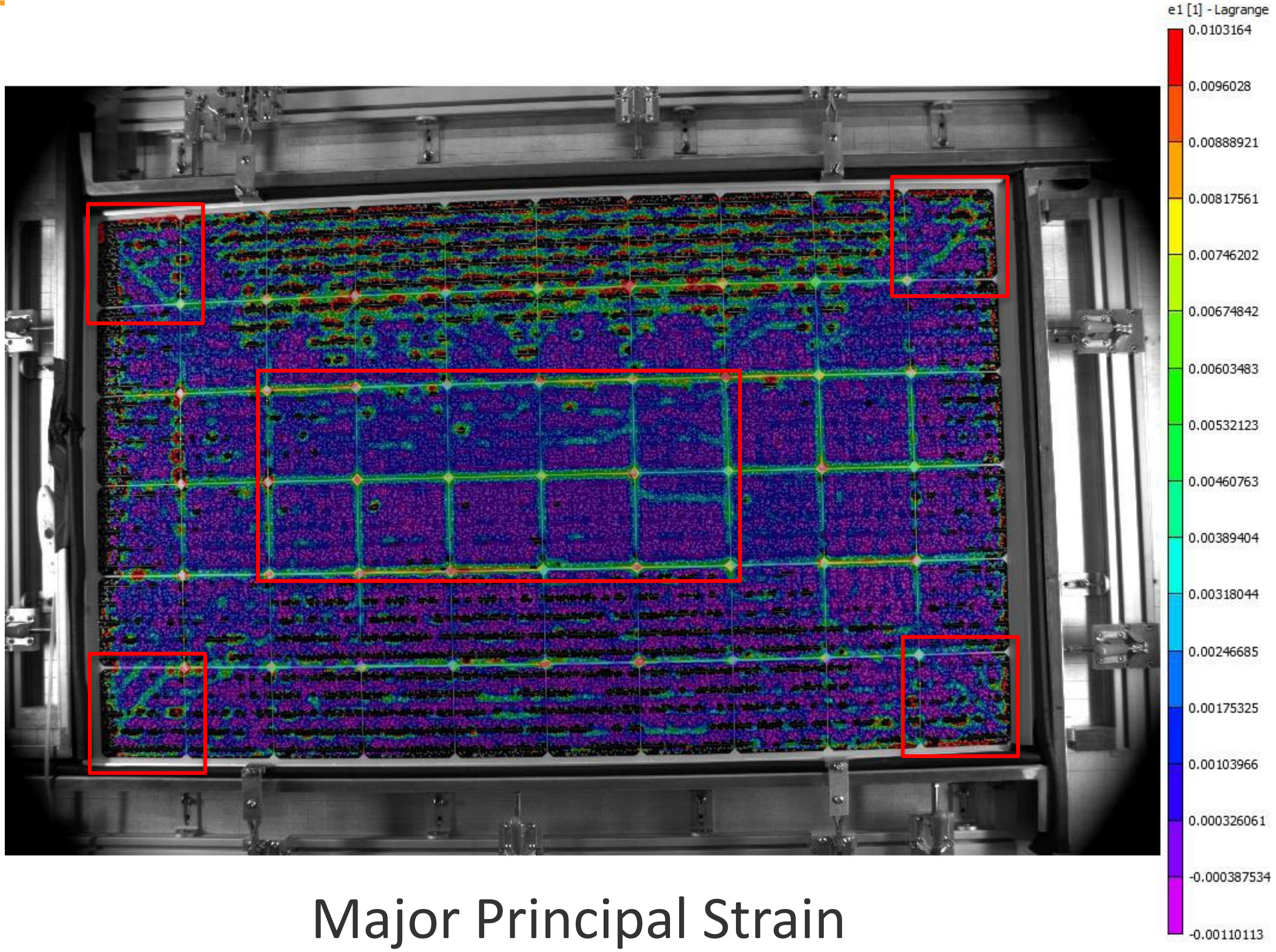


Major Principal Strain

Module at 40°C, -5100 Pa

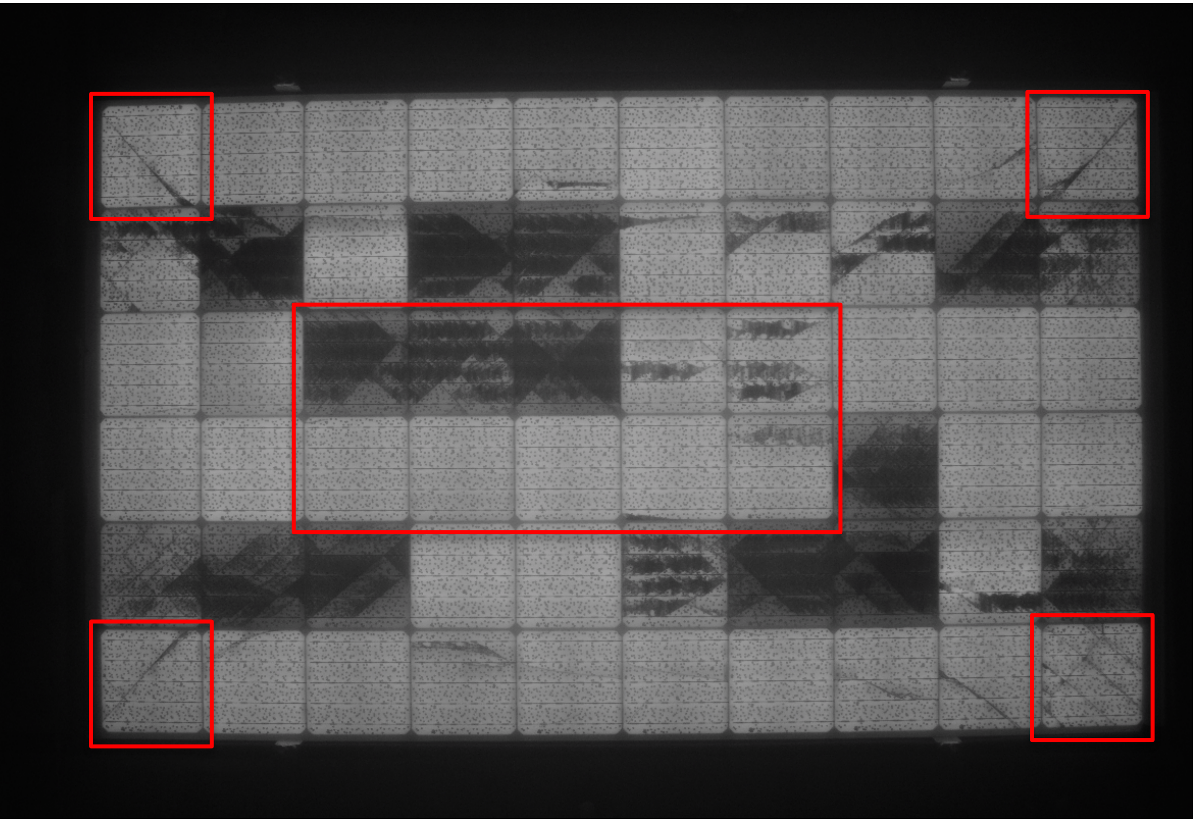


Electroluminescence

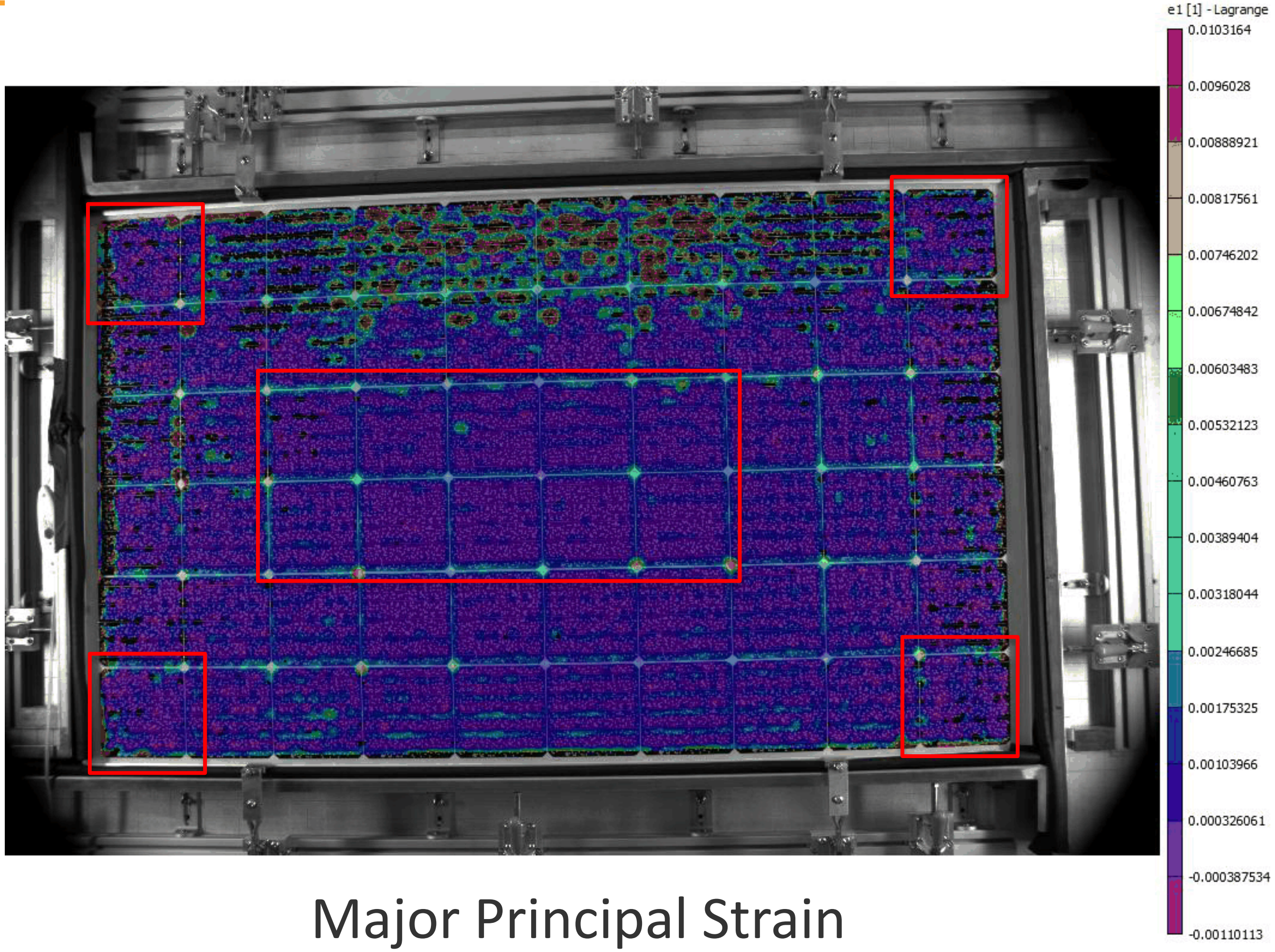


Major Principal Strain

Cell fragment separation via principal strain



Electroluminescence



Major Principal Strain

Conclusions

- Cell-level displacement and strain were successfully measured using the DIC technique on encapsulated patterned cells
- Major principal strain reveals cell and fragment separation of 10s of microns in full field images of a heated, mechanically loaded module
- DIC on cells shows some distortion of the speckle pattern through glass, but allows measurement of cell cracks for evenly displaced areas.
- Future work: using DIC to relate the evolution of physical crack properties to electrical properties as measured by EL and IV.

DuraMAT
Durable Module Materials Consortium

Characterization and weathering of existing cracks in commercial modules

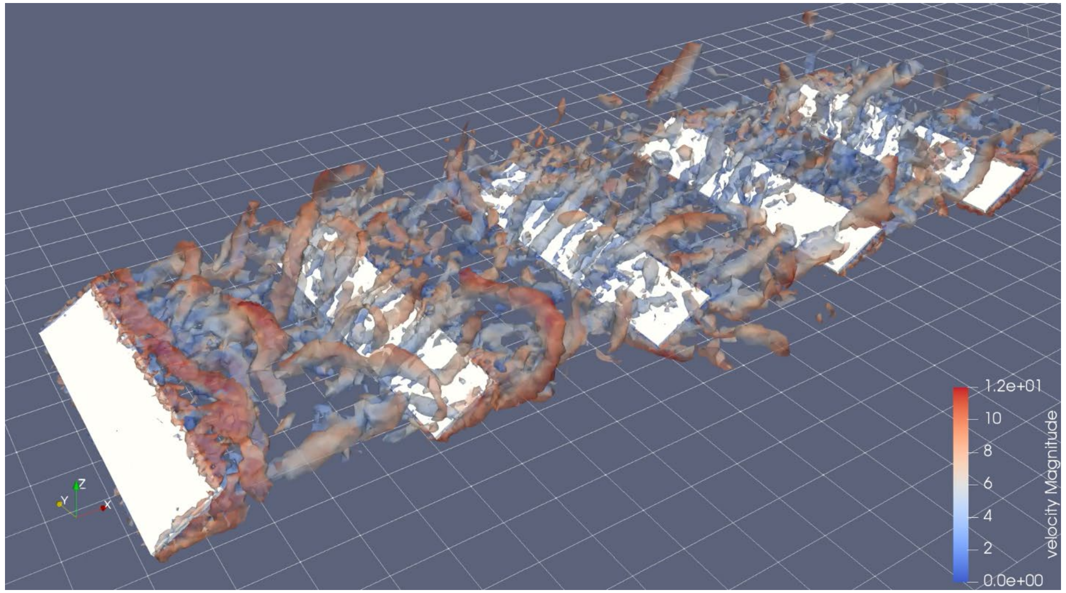
Timothy J Silverman, Michael Deceglie, Ethan Young, Nick Bosco, Michael Owen-Bellini, Daniel Fregosi, Bijaya Paudyal, Will Hobbs, Michael Bolen, Cara Libby

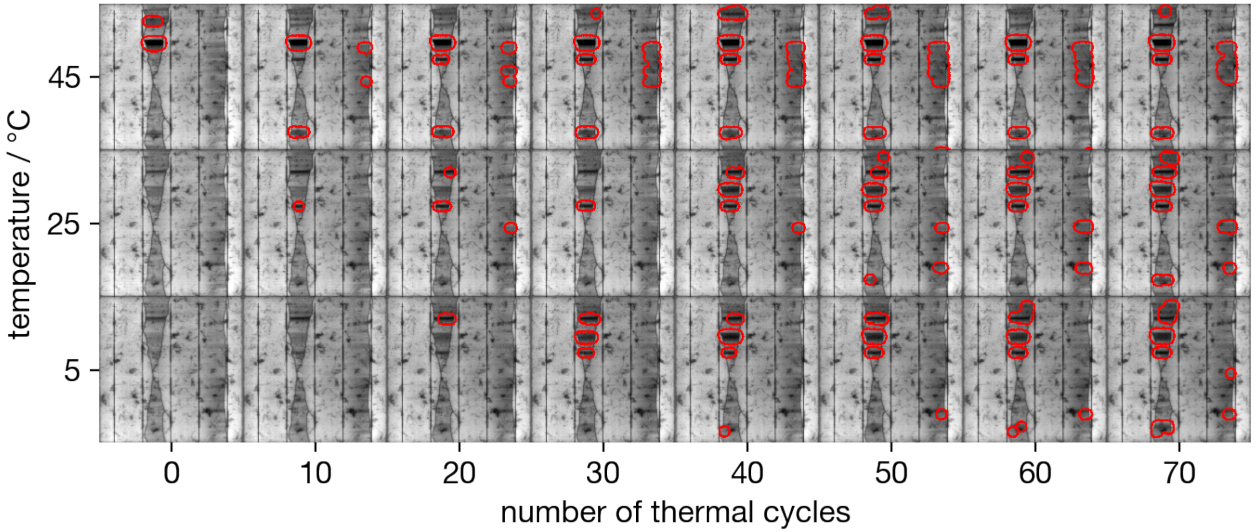
DuraMAT webinar 2021-07-12

Energy Materials Network
U.S. Department of Energy
NREL
Sandia National Laboratories
BERKELEY LAB
SLAC NATIONAL ACCELERATOR LABORATORY

Headlines to remember

- Benign cell cracks may develop into harmful ones
- We're developing the first accelerated mechanical load tests designed for field relevance
- Standard mechanical load tests go well beyond most wind-driven loads
- The transition from benign to harmful crack is messy

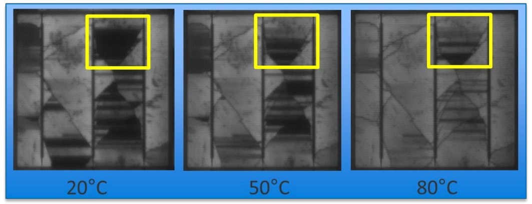




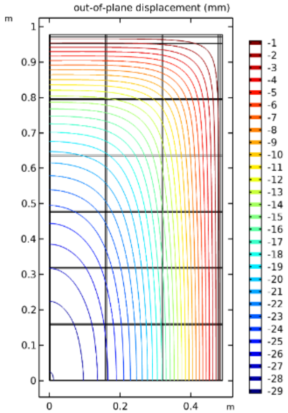
Project approach

- Measure crack degradation in the field
- Reproduce it in physical testing and simulations
- Correlate crack features with degradation (or probability of developing safety issues)
- Identify relevant accelerated test protocols

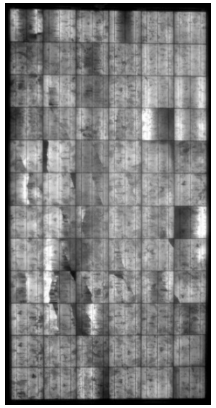

Field testing at large-scale PV plants and NREL outdoor test array



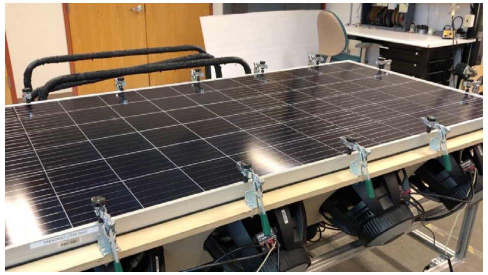
Temperature-dependent electroluminescence imaging



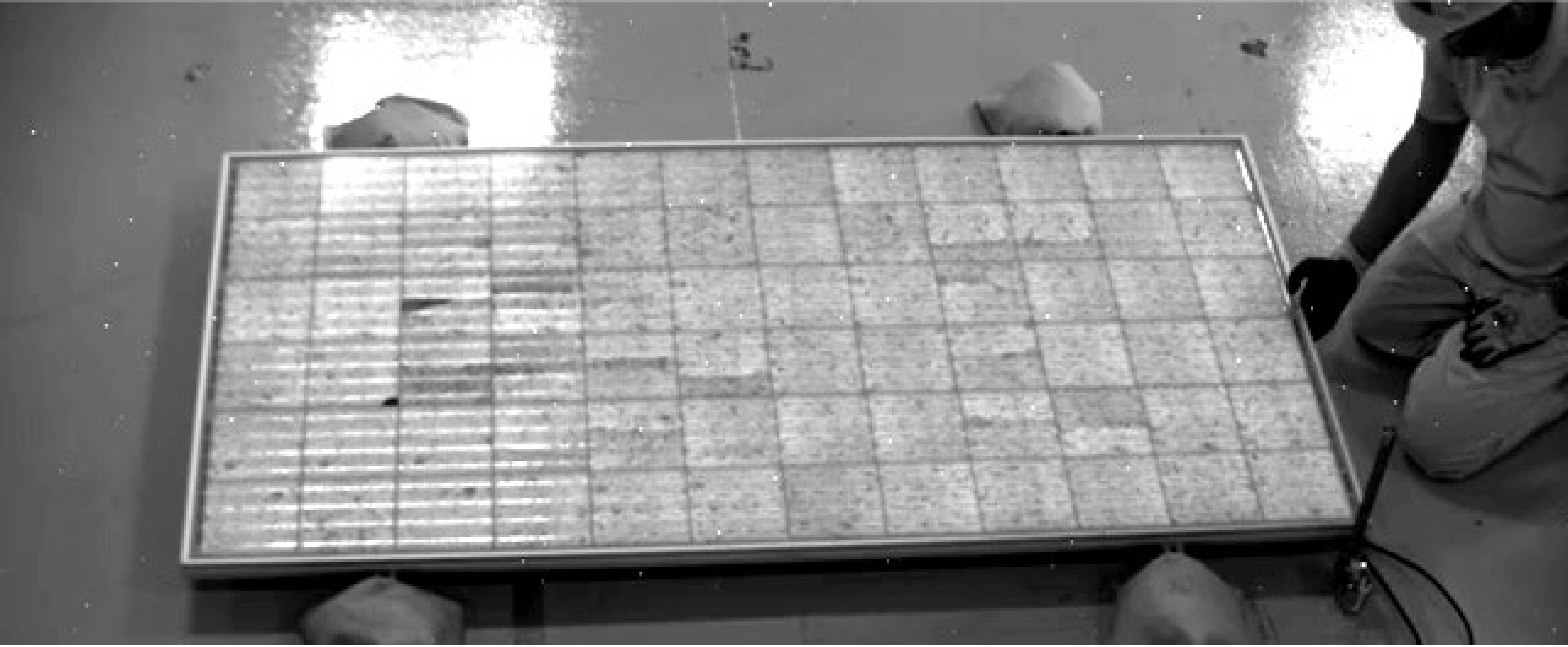
Predictive simulation



Crack detection algorithm and data analytics



Accelerated aging

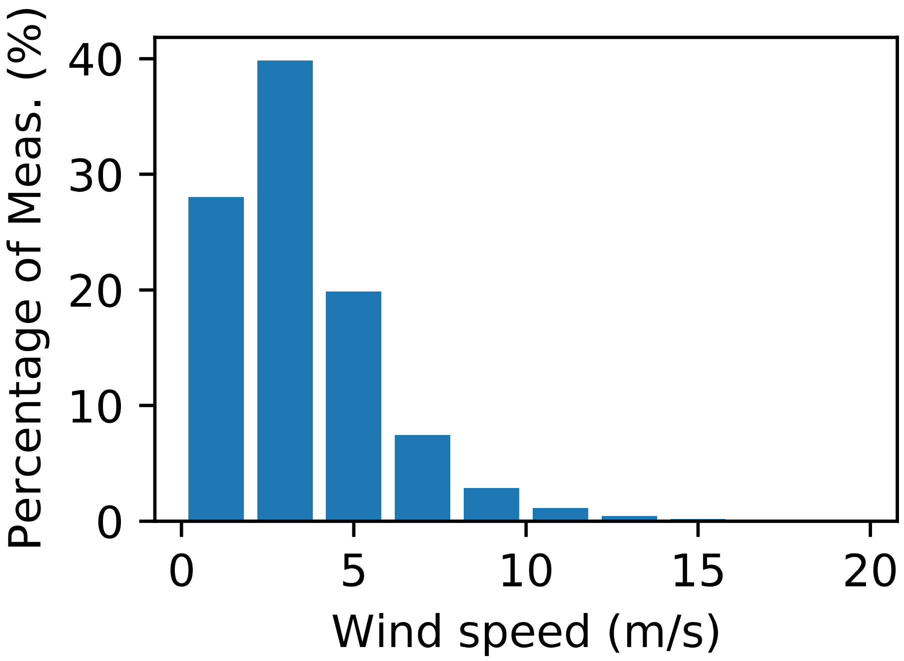


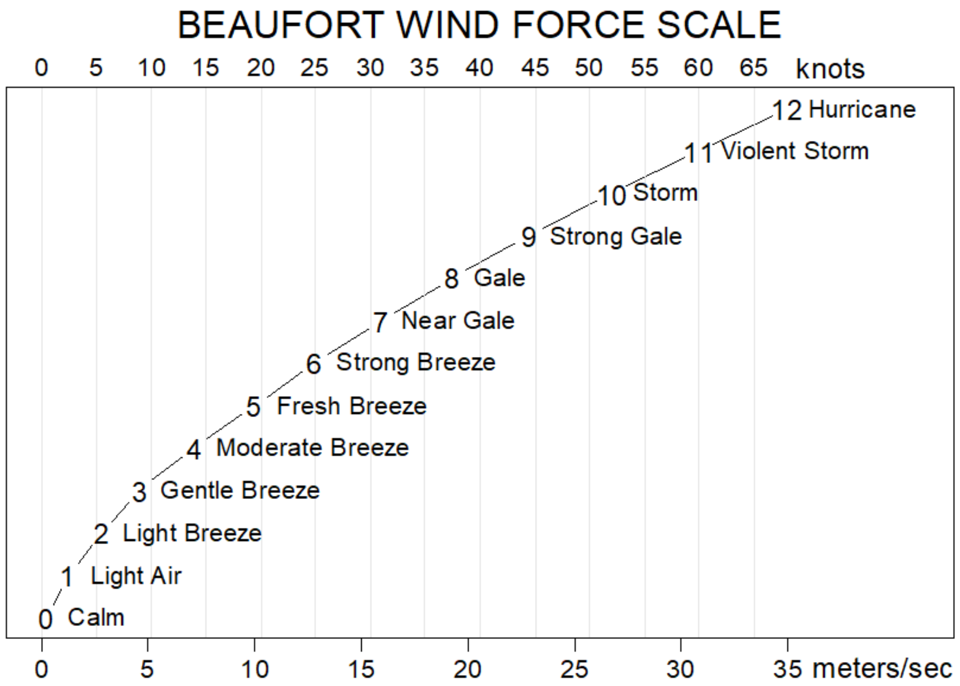
We tested commercial 72-cell mc-Si modules

Dropped onto a rack to break ~1/3 of cells

Pressure cycles should be informed by observed weather

Distribution of windspeeds observed at NREL

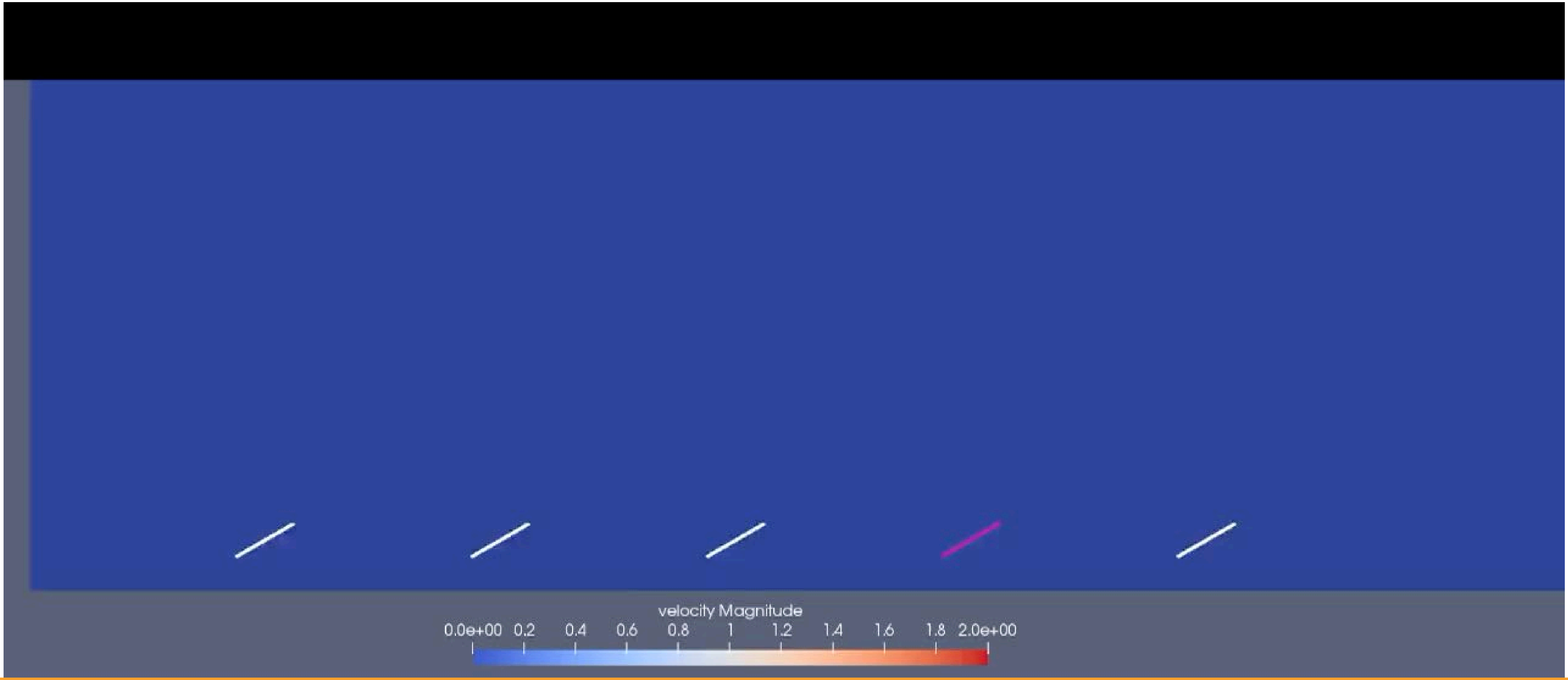




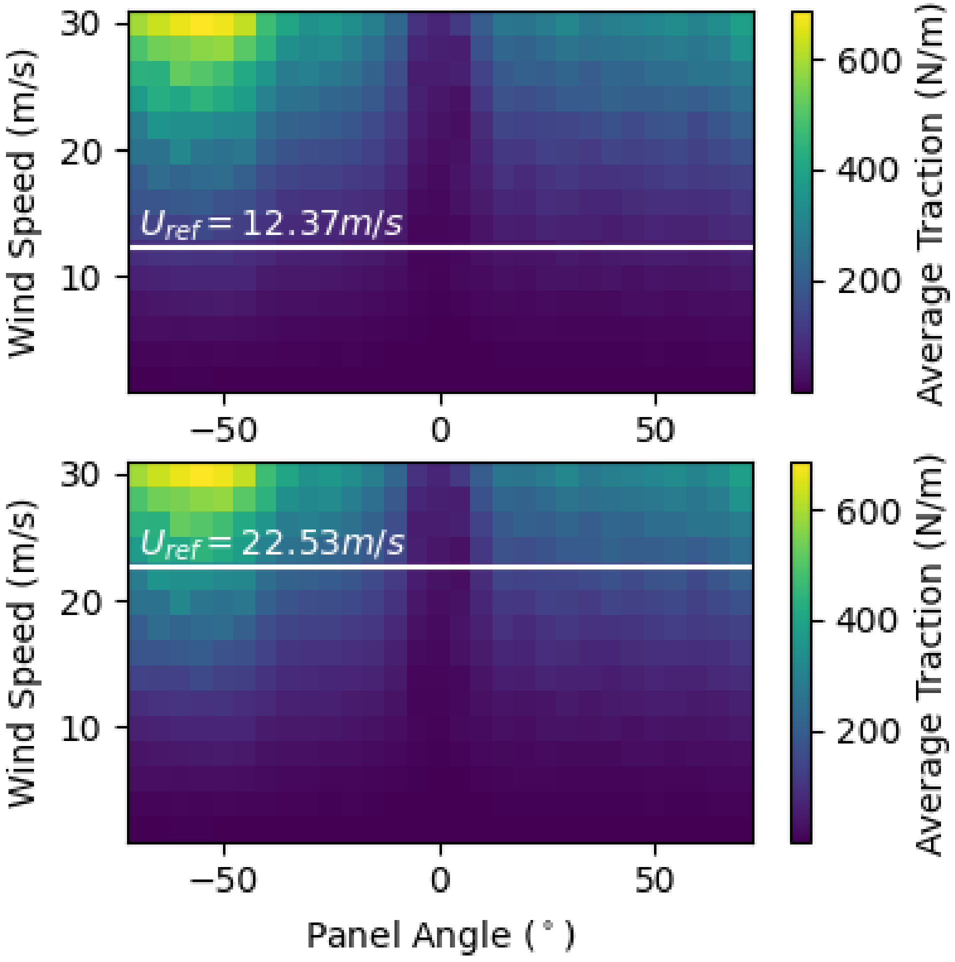
https://en.wikipedia.org/wiki/Beaufort_scale

Wind Pressure Modeling

Unsteady Simulation Results: $\theta = 30°$ and $U_{ref} = 1m/s$



Replicating the windiest week and windiest hour of the year



Windiest week:
Beaufort scale: 6
Strong breeze
Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.

Test: 3 million cycles of 100 Pa (RMS)

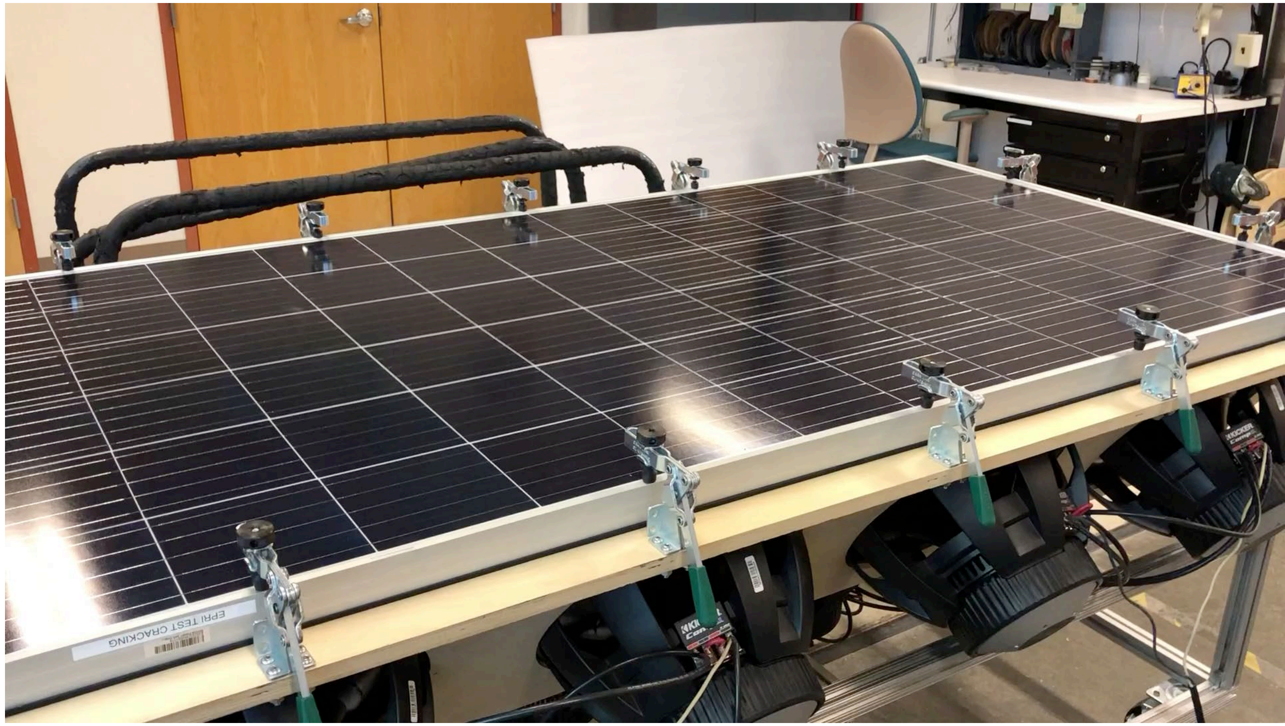
Windiest hour:
Beaufort scale: 9
Strong/severe gale
Slight structural damage (chimney pots and slates removed).

Test: 36000 cycles of 350 Pa (RMS)

Lower pressure amplitude and higher cycle count than standard tests

Applying the proposed tests

- Replicate years of the roughest parts of field service
  - Apply thousands or millions of moderate-pressure cycles
  - Stay below the module’s resonant frequency
  - Field-relevant tests now, field-equivalent tests next
- Measure the progress of failure with intermediate characterization
  - Temperature-dependent EL imaging
- Compare to field degradation of identical modules



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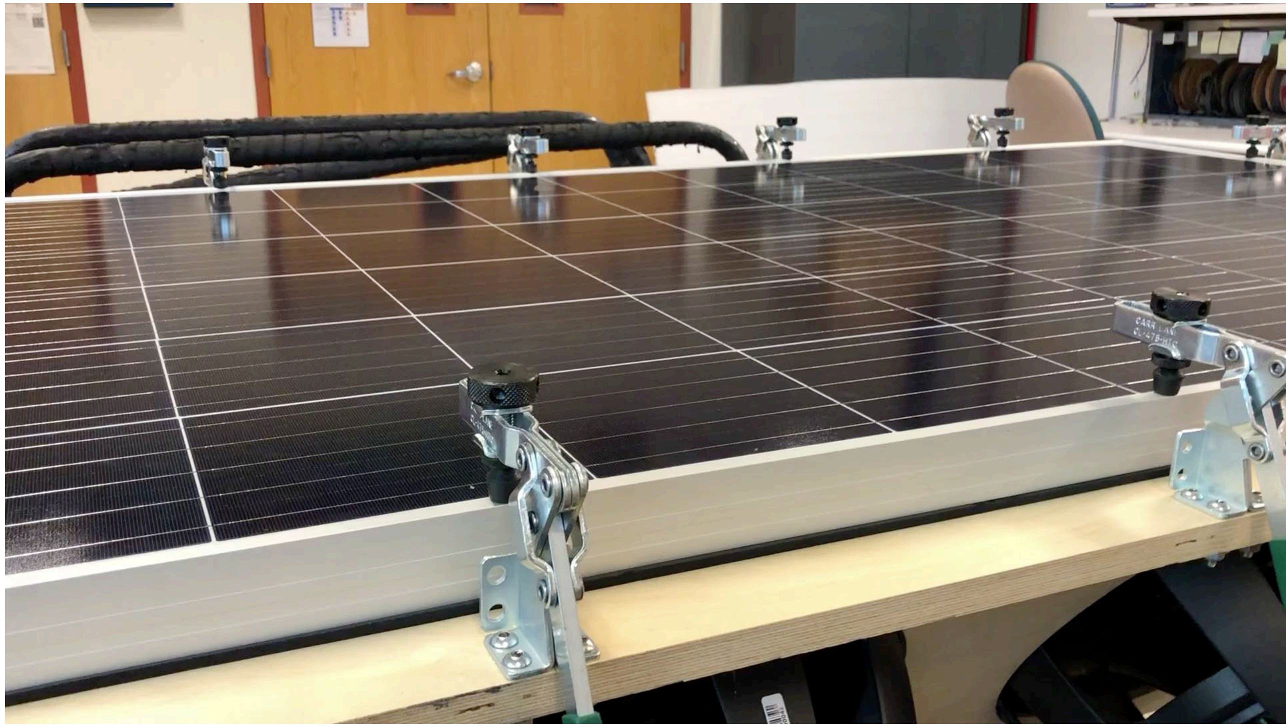
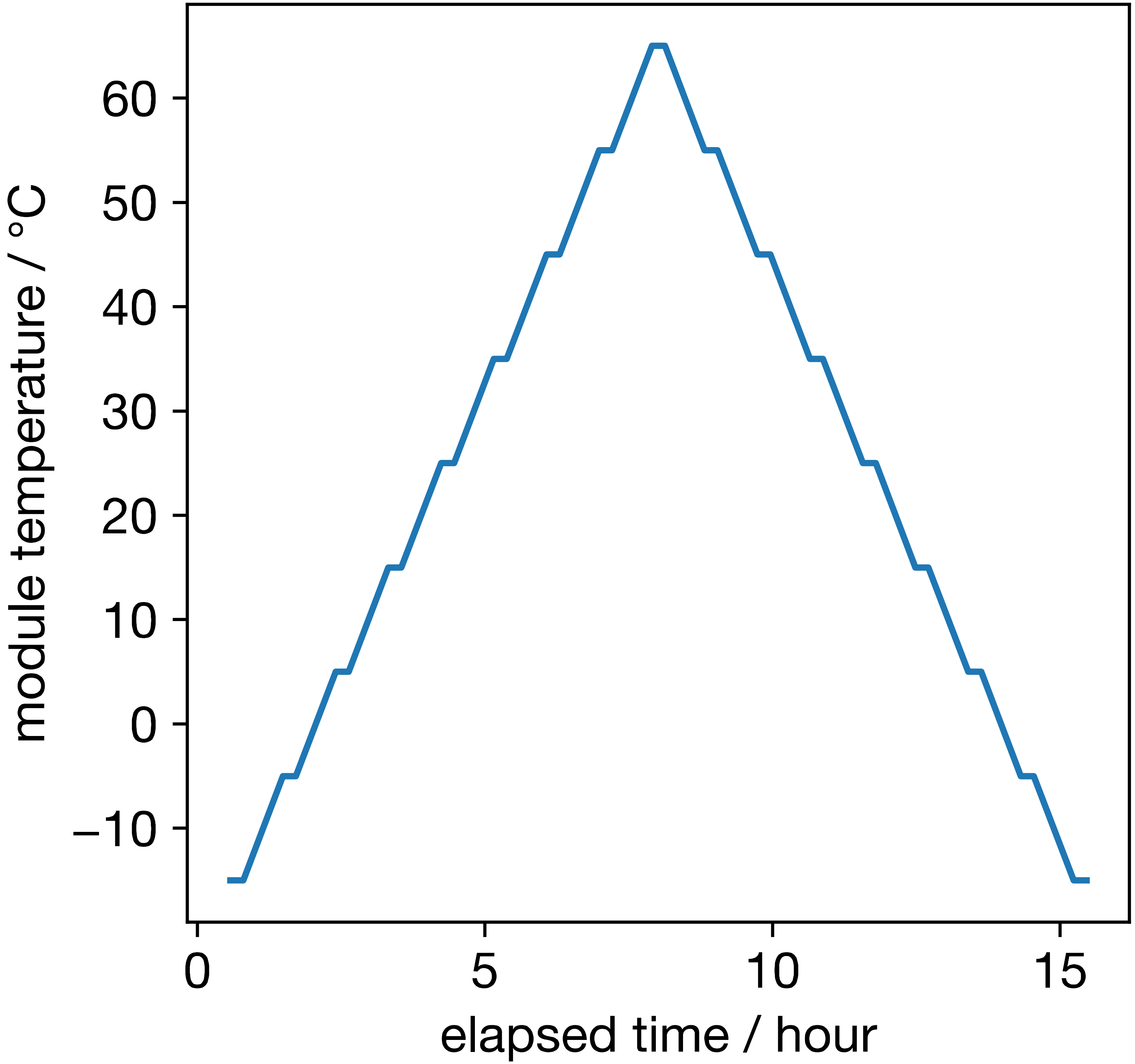


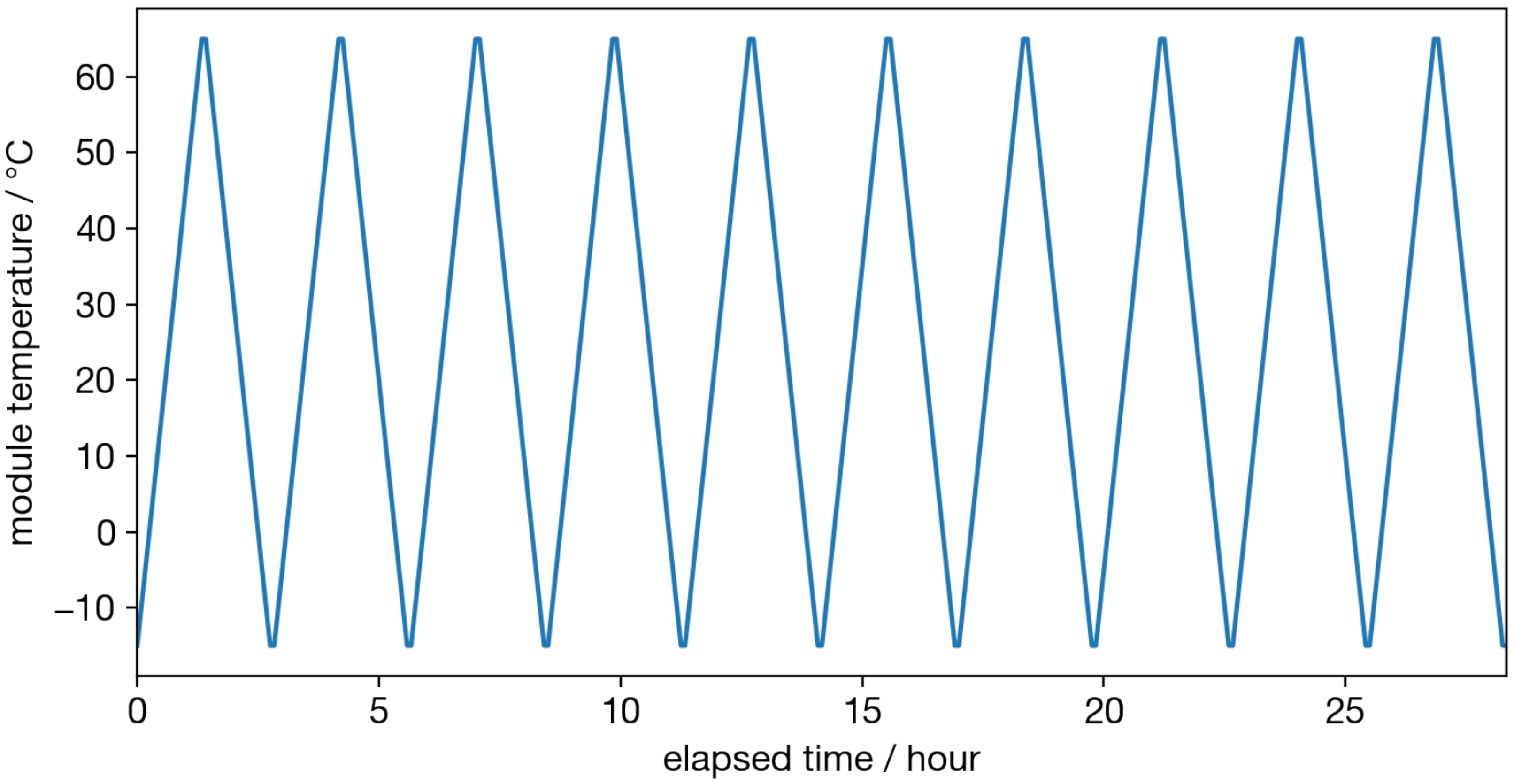
We collect EL images on full-size modules while varying temperature

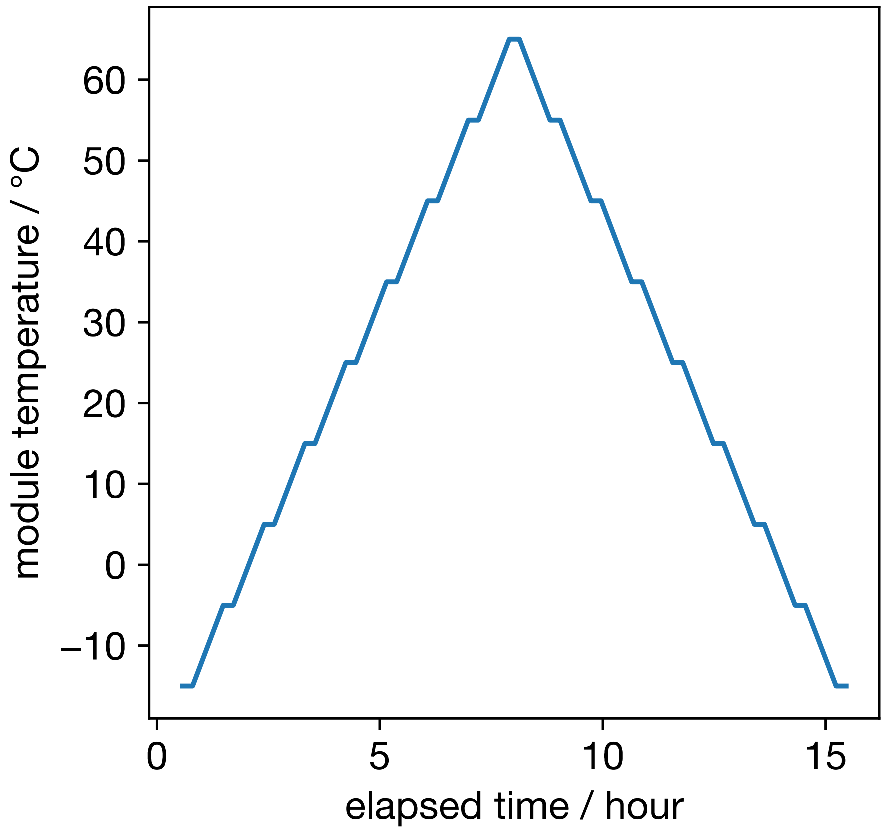


We collect EL images at a ‘staircase’ of temperatures

–15 °C to +65 °C in 10 °C steps

30-minute dwell at each temperature





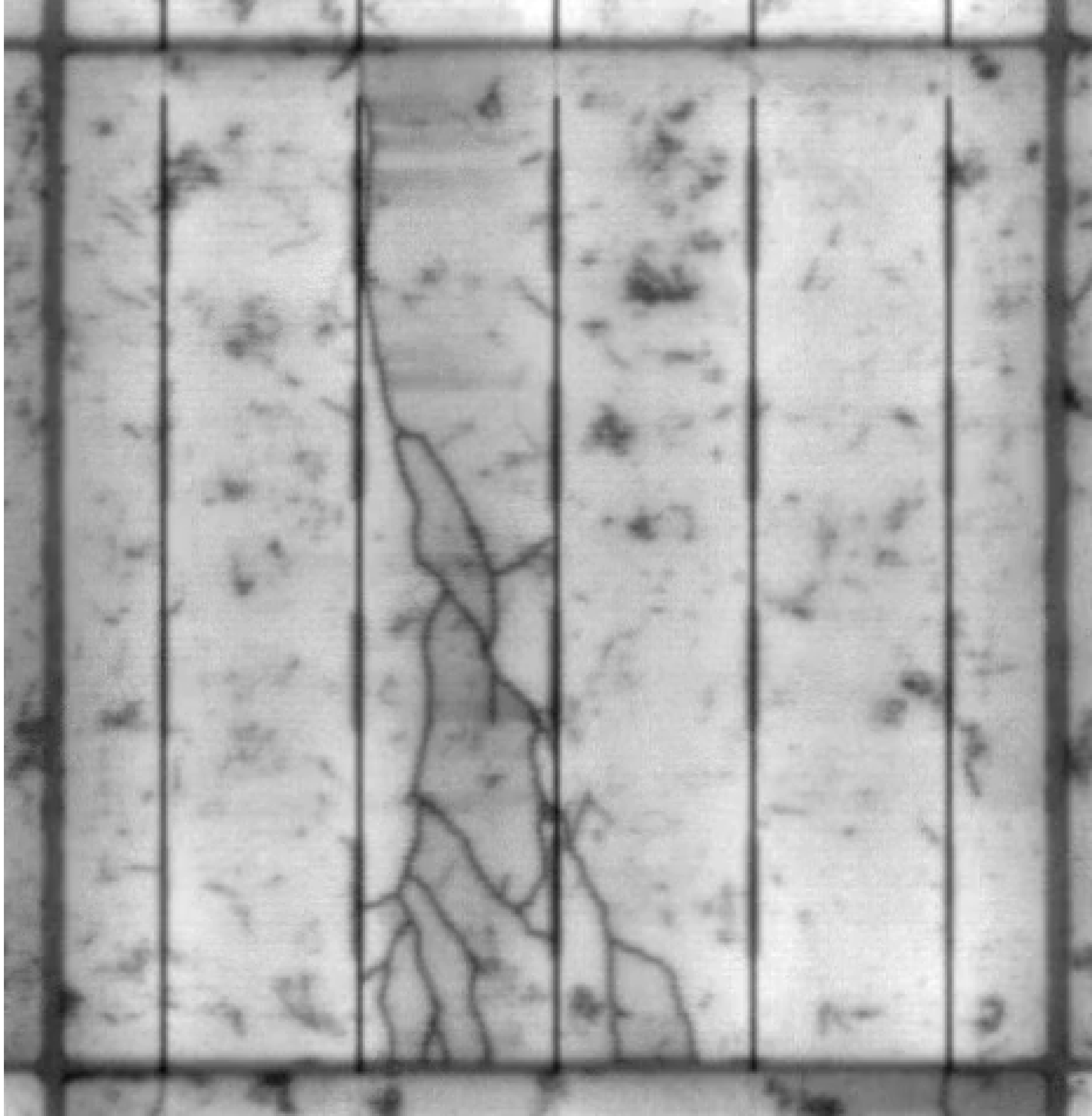
In some tests, we interleave the imaging staircase with thermal cycles

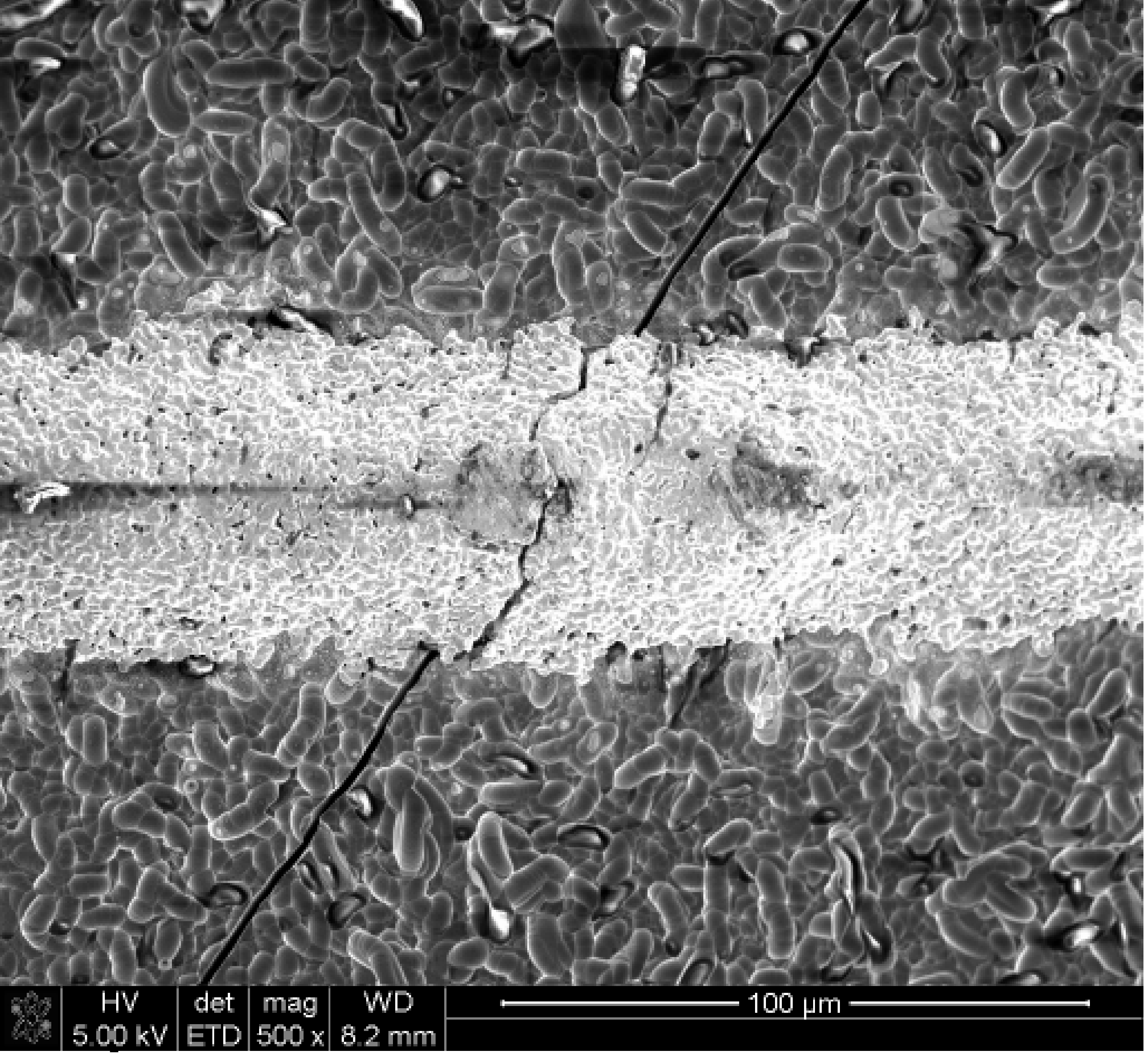
–15 °C to +65 °C at 1 °C/minute with 5-minute dwells

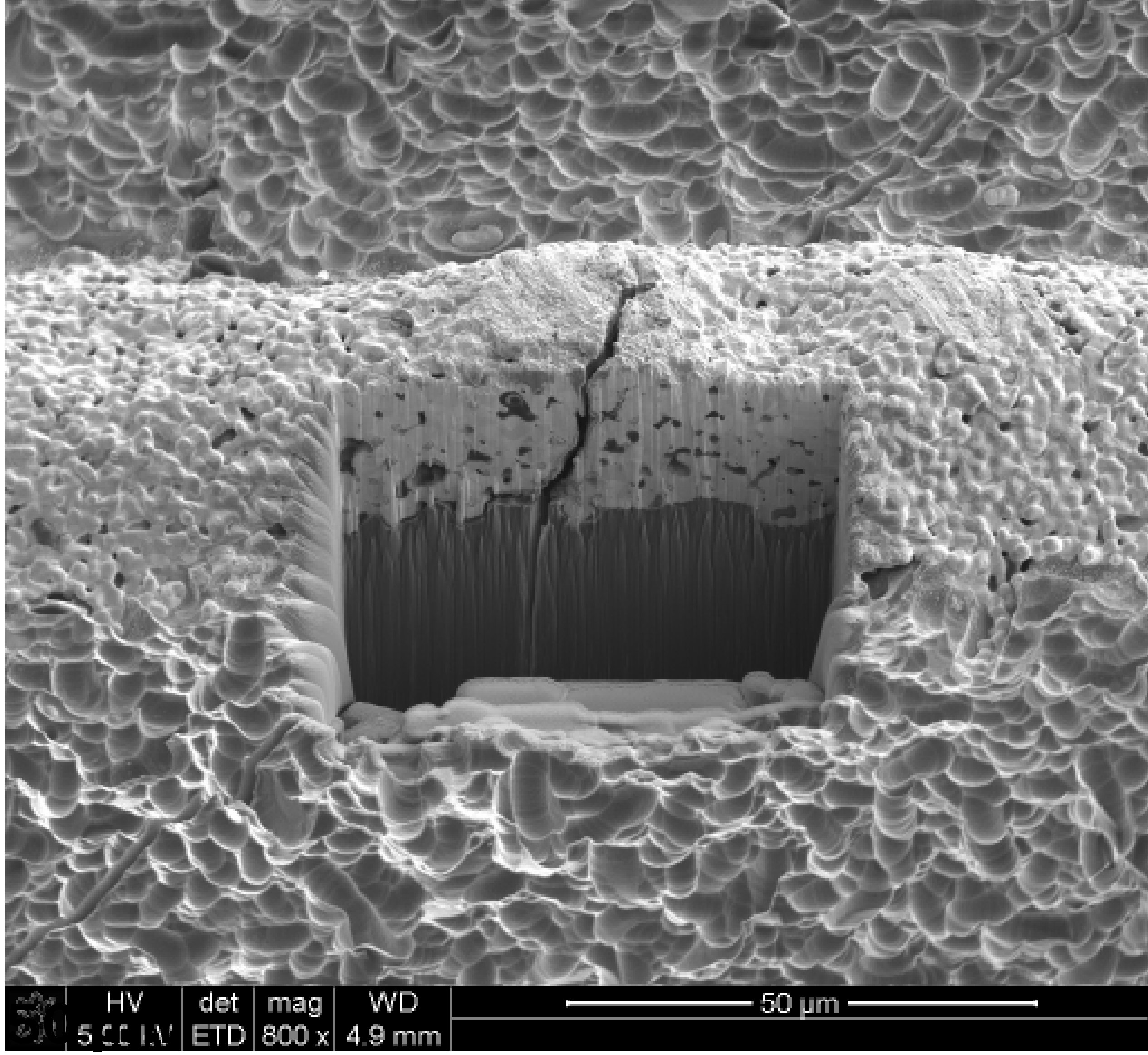
Results

Cracked cell EL depends on temperature

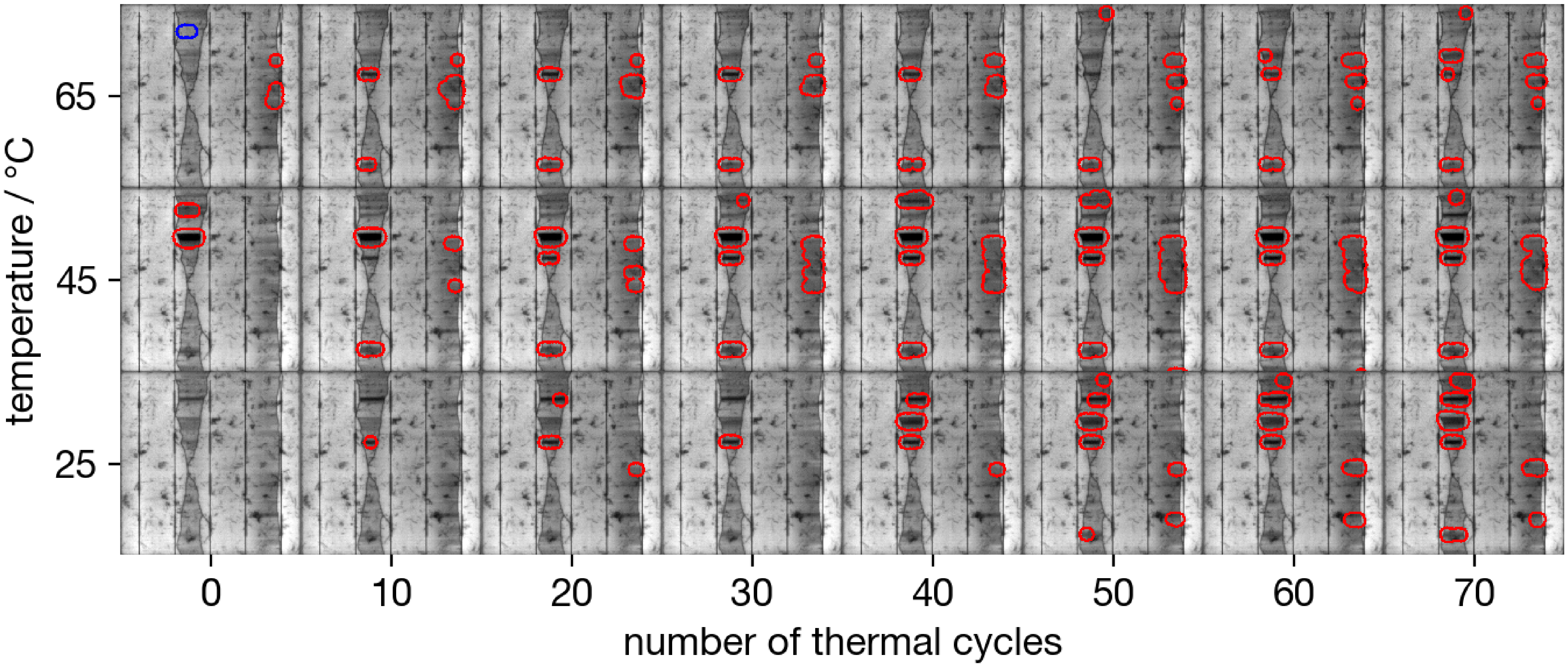
Deliberate, unweathered cracks
Single thermal cycle
–15 °C to 65 °C
Electroluminescence at nameplate I_{sc}





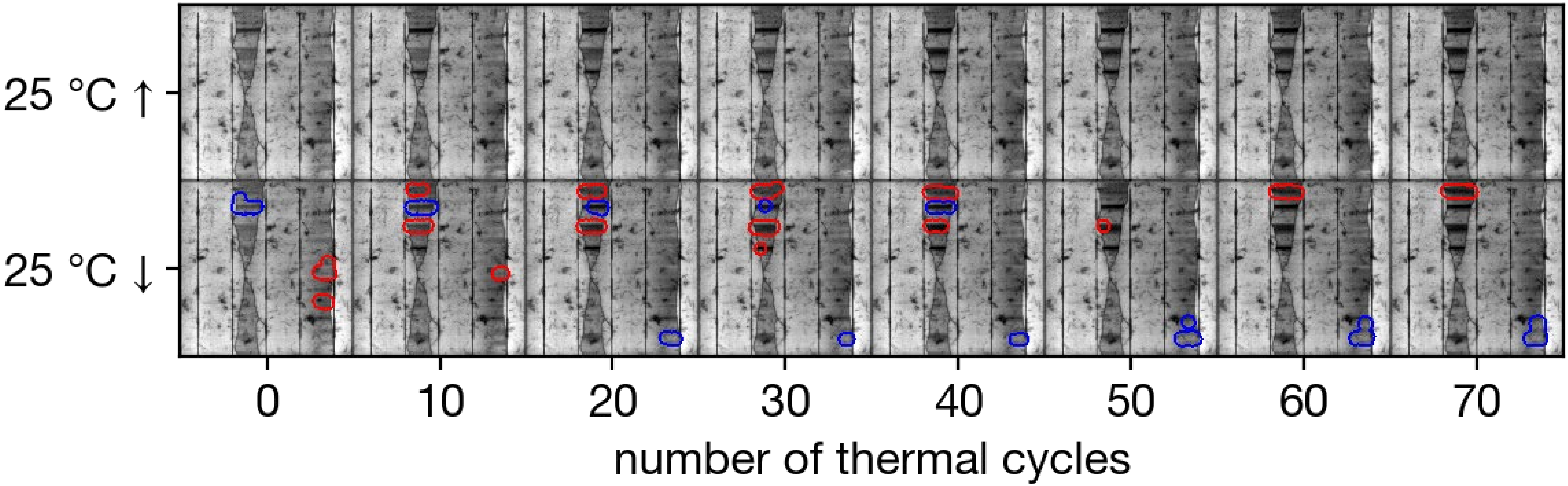


Broken metallization creates rough contact



Contact is not always worse at higher temperature!

Each image is compared to the initial 25 °C image



Recent thermal history affects images taken at the same temperature

‘Downstairs’ images are compared to the corresponding ‘upstairs’ image

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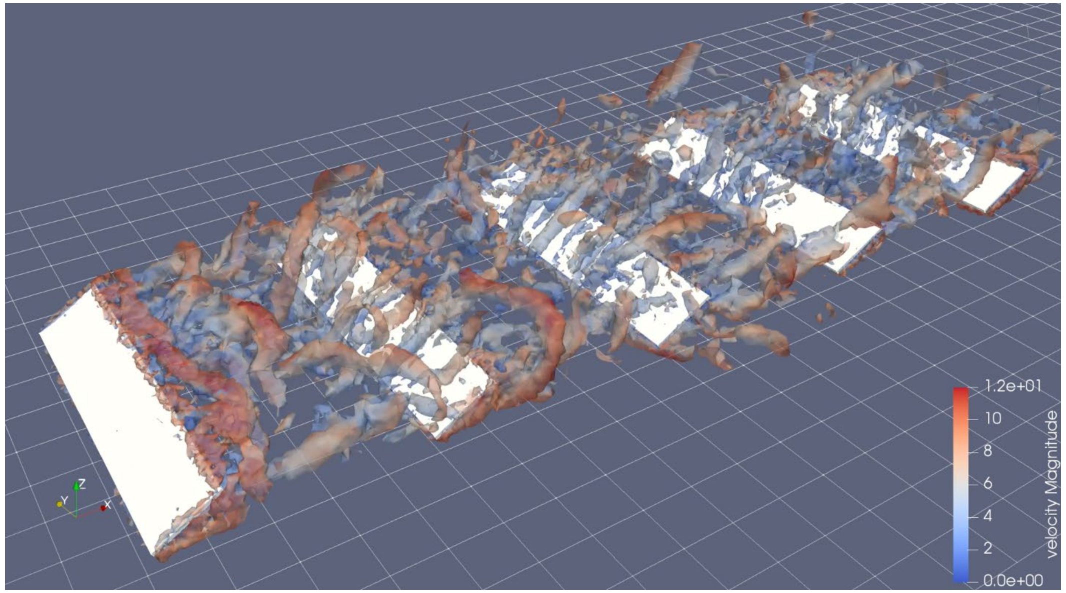
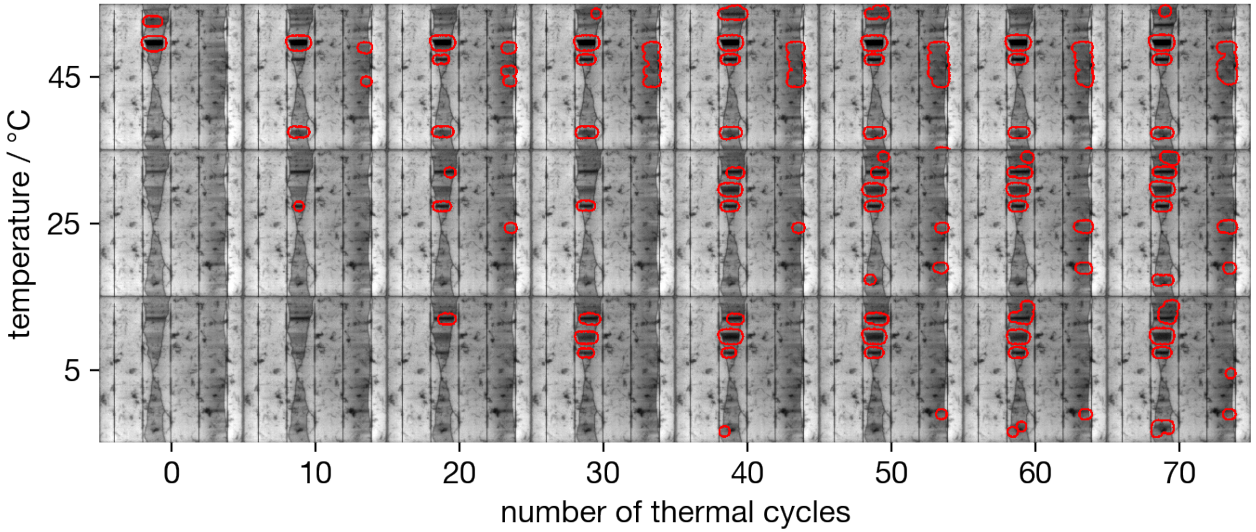




Acknowledgements

NREL: Timothy Silverman, Xin He, Ethan Young, Elizabeth Bernhardt, Peter Hacke, Byron McDanold

LBNL: Todd Karin, Anubhav Jain, Xin Chen

Southern Company: Will Hobbs

EPRI: Michael Bolen, Daniel Fregosi, Bijaya Paudyal, Cara Libby

This poster was developed based upon funding from the Alliance for Sustainable Energy, LLC, Managing and Operating Contractor for the National Renewable Energy Laboratory for the U.S. Department of Energy.

Thank you

www.duramat.org

DuraMAT Webinar

July 12, 2021

osazda ENERGY

Mitigating Power Loss of Cracked Cells

Andre Chavez[1,2,*], Brian Rummel[1,2], Nicolas Dowdy[1,2], Sang M Han[1,2], Nick Bosco[3], Brian Rounsaville[4], and Ajeet Rohatgi[4]

[*]Corresponding Author
[1]University of New Mexico, Albuquerque, NM, USA
[2]Osazda Energy, Albuquerque, NM, USA
[3]National Renewable Energy Laboratory, Golden, CO, USA
[4]Georgia Institute of Technology, Atlanta, GA, USA

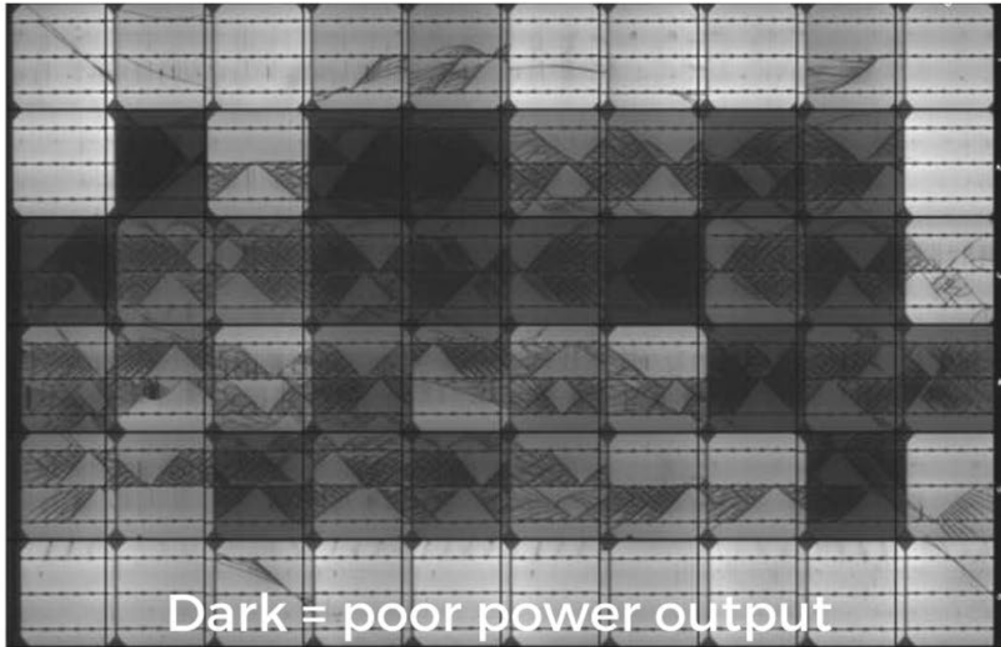
Acknowledgements:
Department of Energy DuraMAT (RGI-8-82224), DOE SETO (DE-EE0009013), DOE CINT (2019AU0023), and NMSBA

THE PROBLEM/OPPORTUNITY

SOLAR CELL CRACKING DECREASES POWER OUTPUT & COSTS
$100s OF MILLIONS IN LOSSES ANNUALLY

Solar Farm

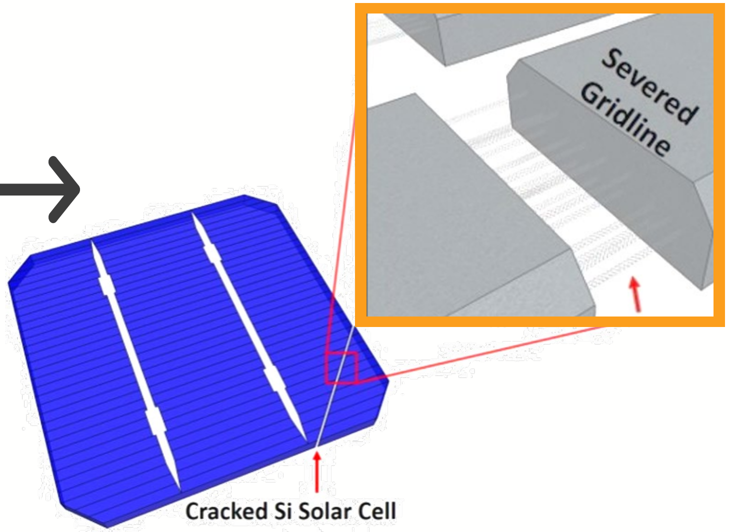
Cracked Solar Cells



THE SOLUTION

https://www.pv-tech.org/product-review-duponts-solamet-pv19b-metallization-paste-uses-proprietary-t/

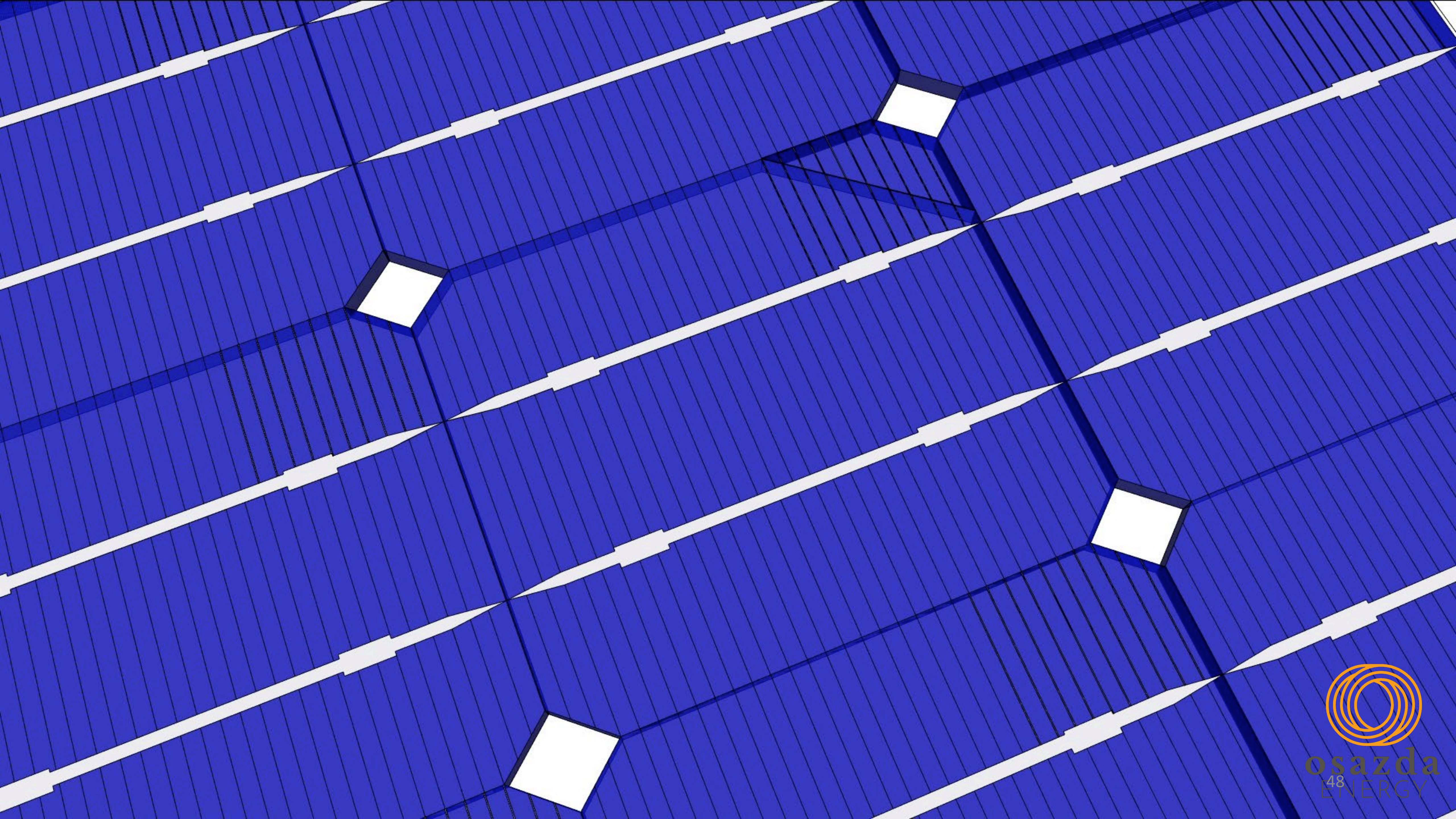
MetZilla additive + silver paste



makes fragile gridlines tough & elastic

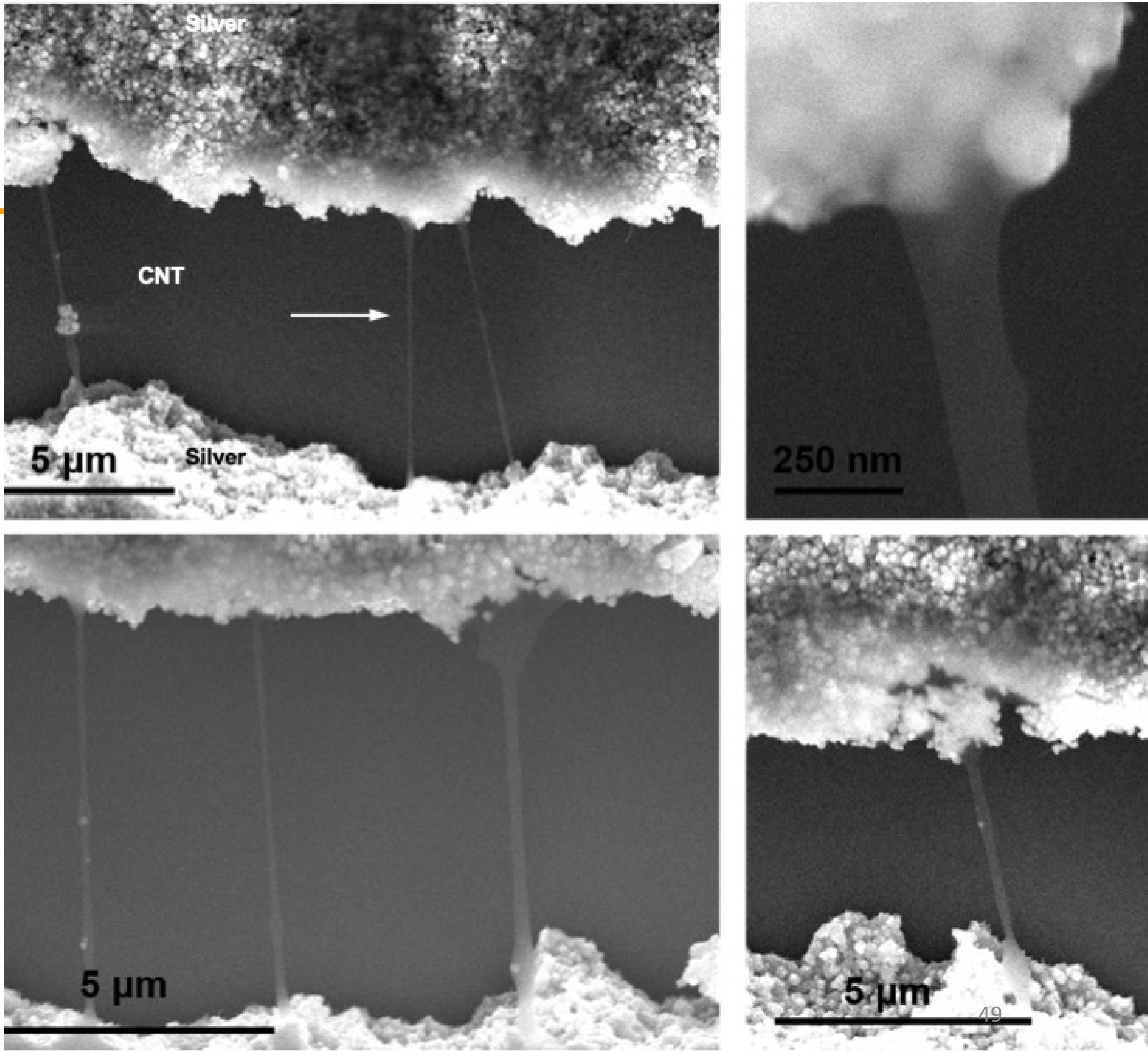
minimizing losses from cracking

OSAZDA ENERGY PROVIDES AN ADDITIVE FOR PASTES TO IMPROVE SOLAR PANEL DURABILITY



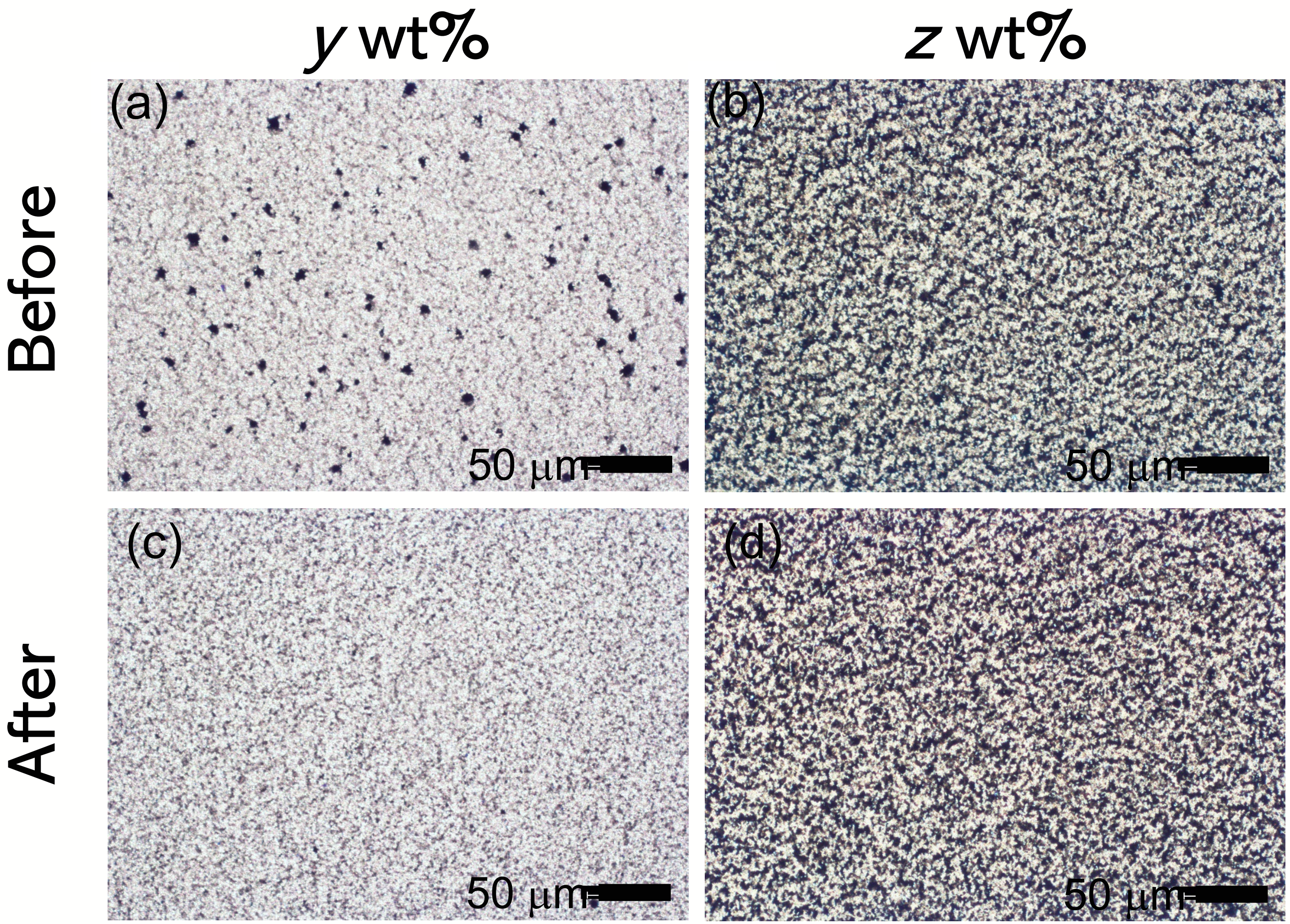
osazda
ENERGY

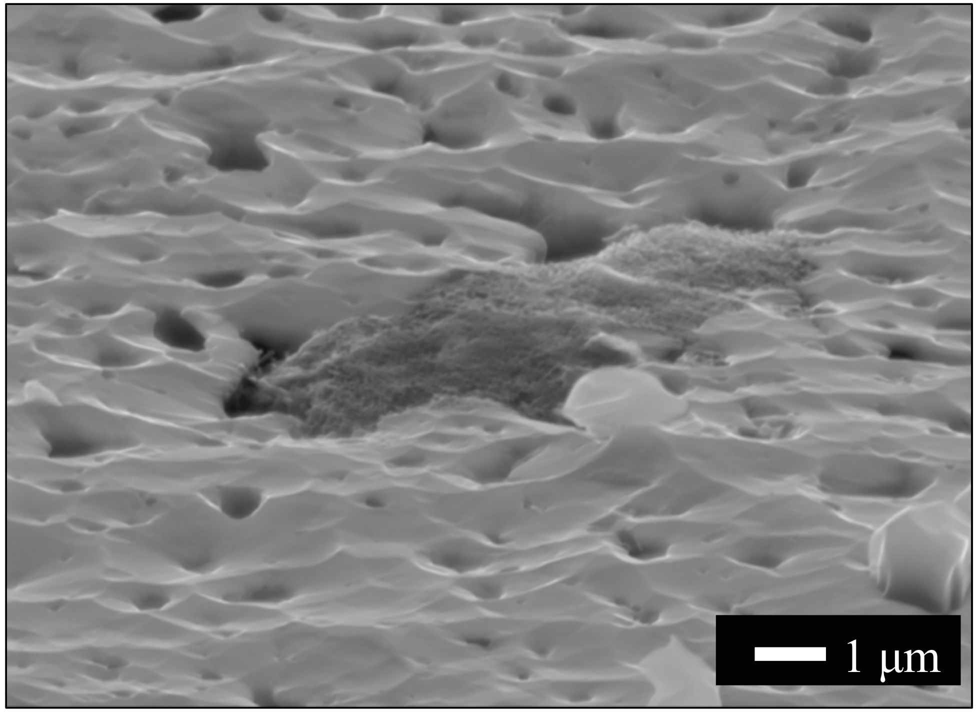
We bridge the cracks and make electrical connections.



CNT AGGLOMERATION & MIXING

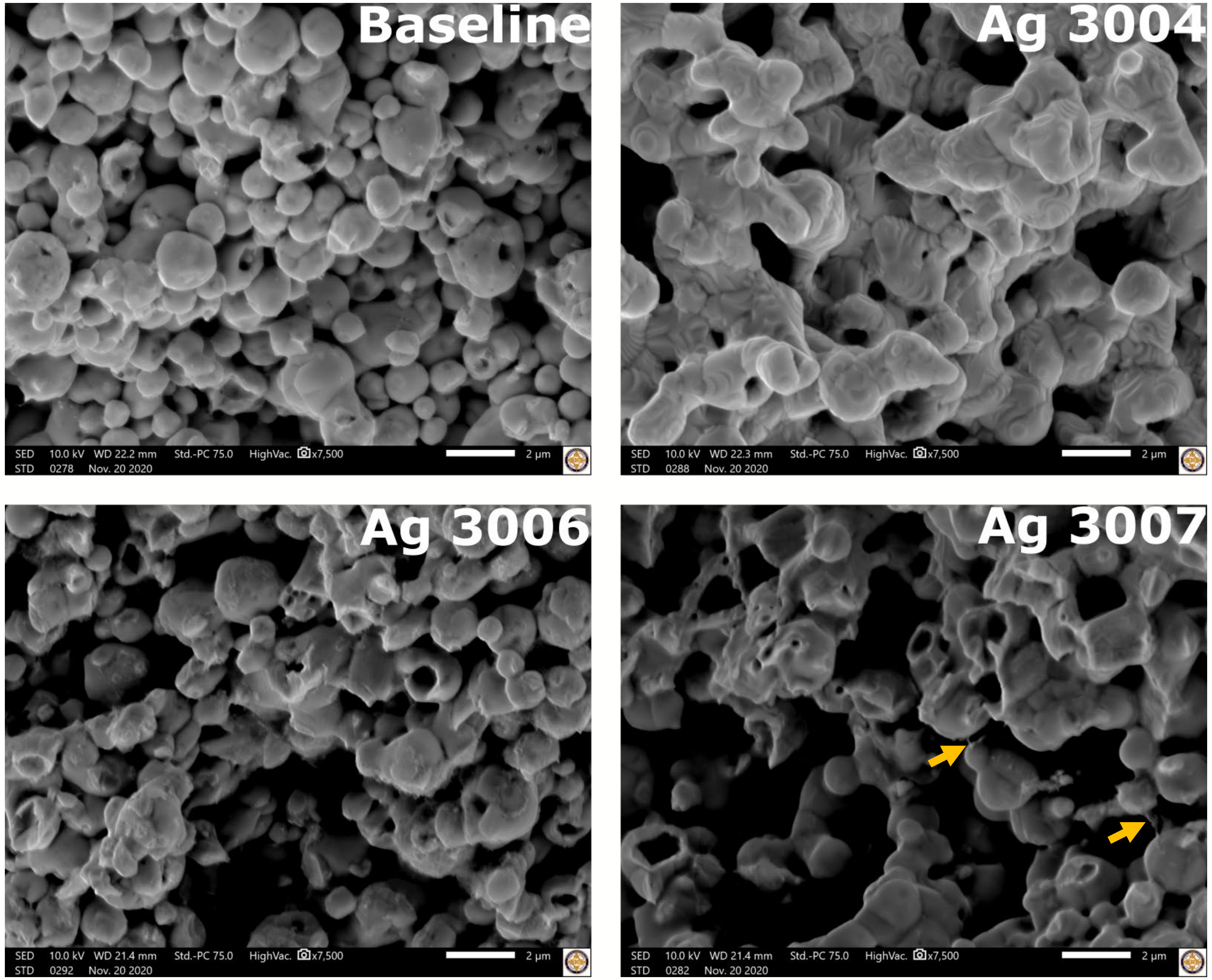
osazda ENERGY





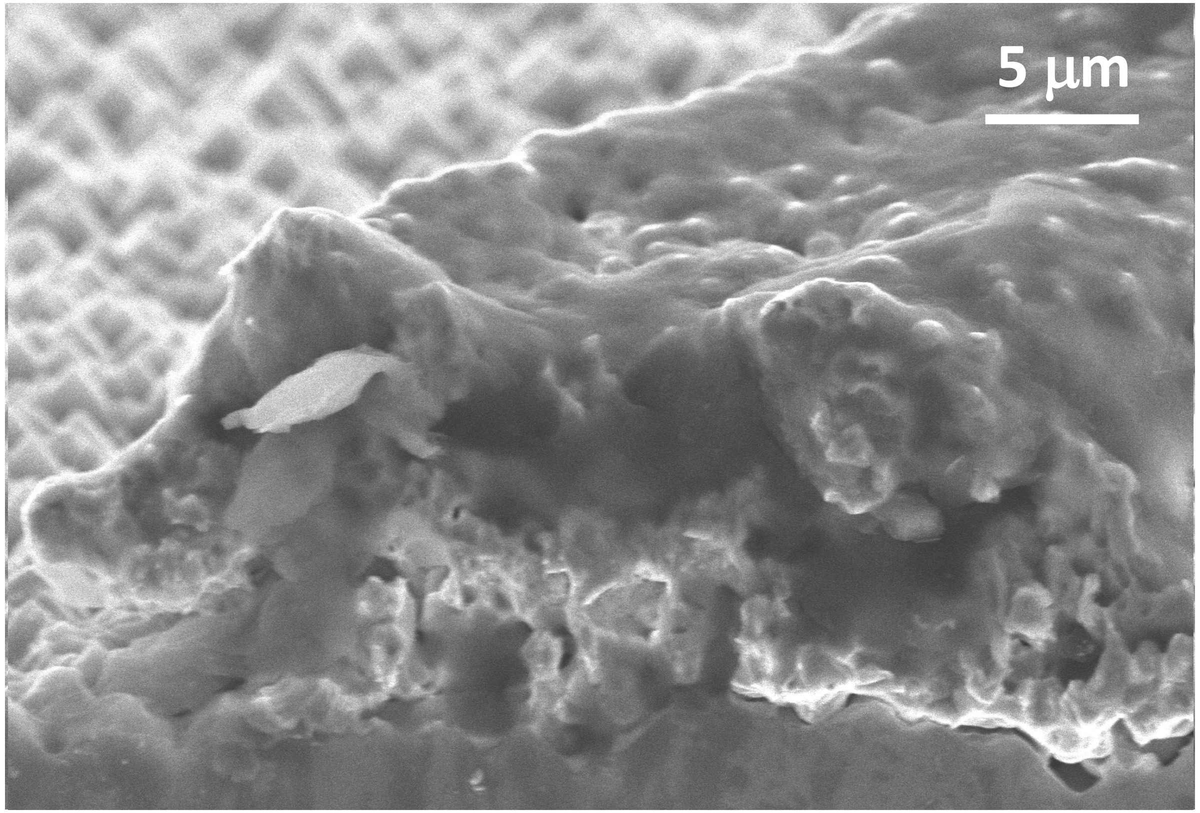
IMPACT OF CARBON NANOTUBES ON SILVER PARTICLE SINTERING

osazda ENERGY

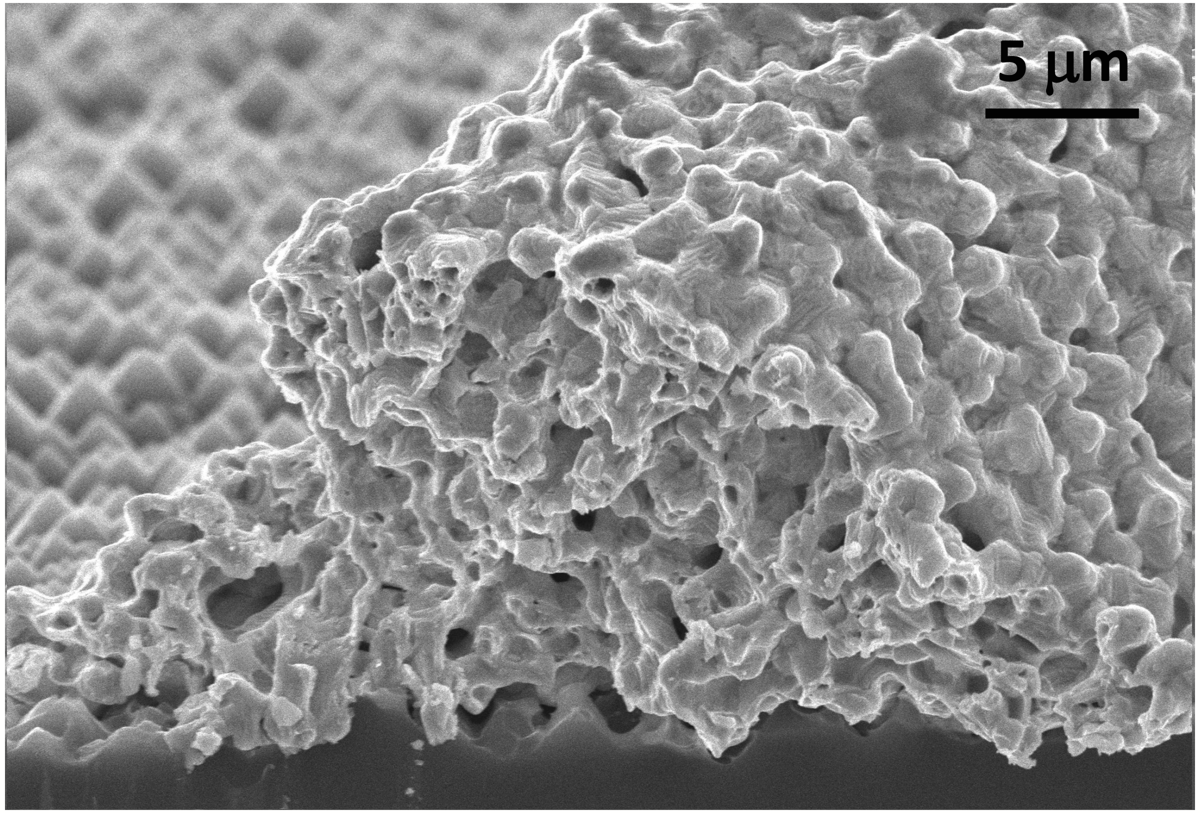


IMPACT OF CARBON NANOTUBES ON SILVER PARTICLE SINTERING

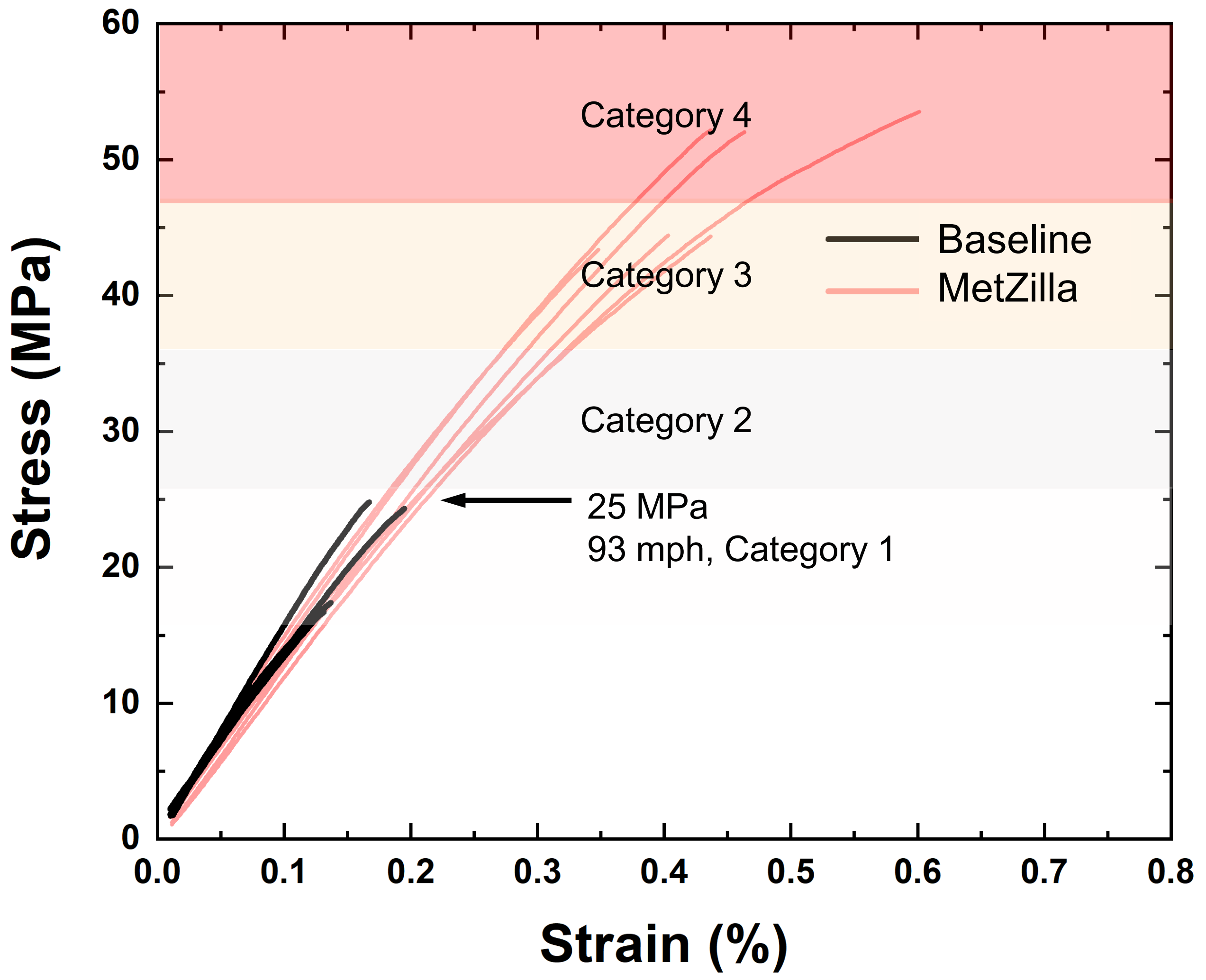
Commercial



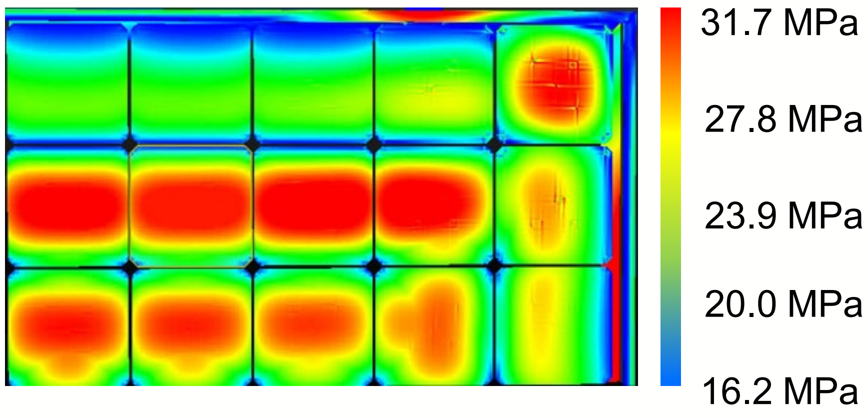
Composite



MODULE-LEVEL OBSERVATIONS TO MATERIALS PROPERTIES



Full Module Maximum Principal Stress

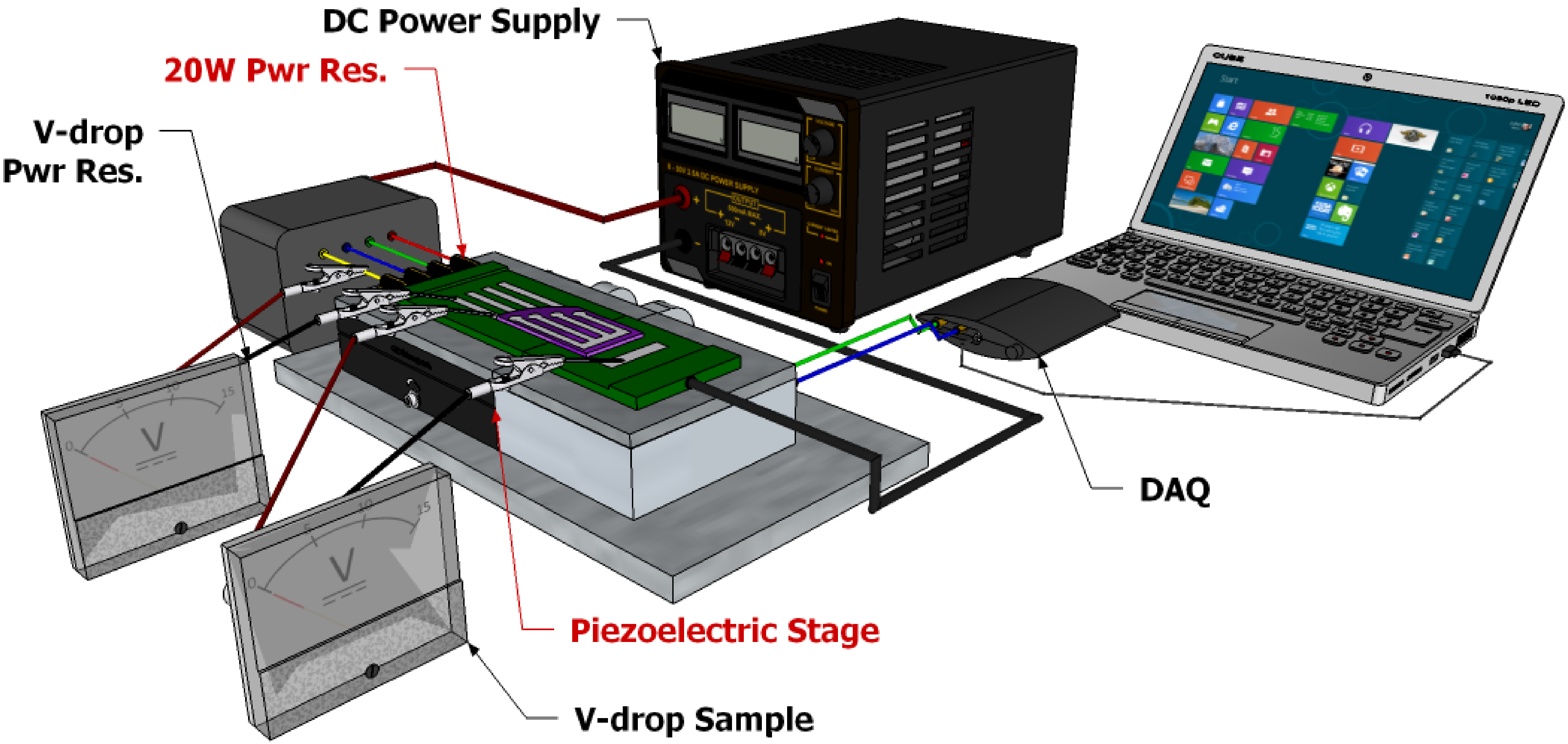


Courtesy of James Hartley at Sandia National Laboratories.

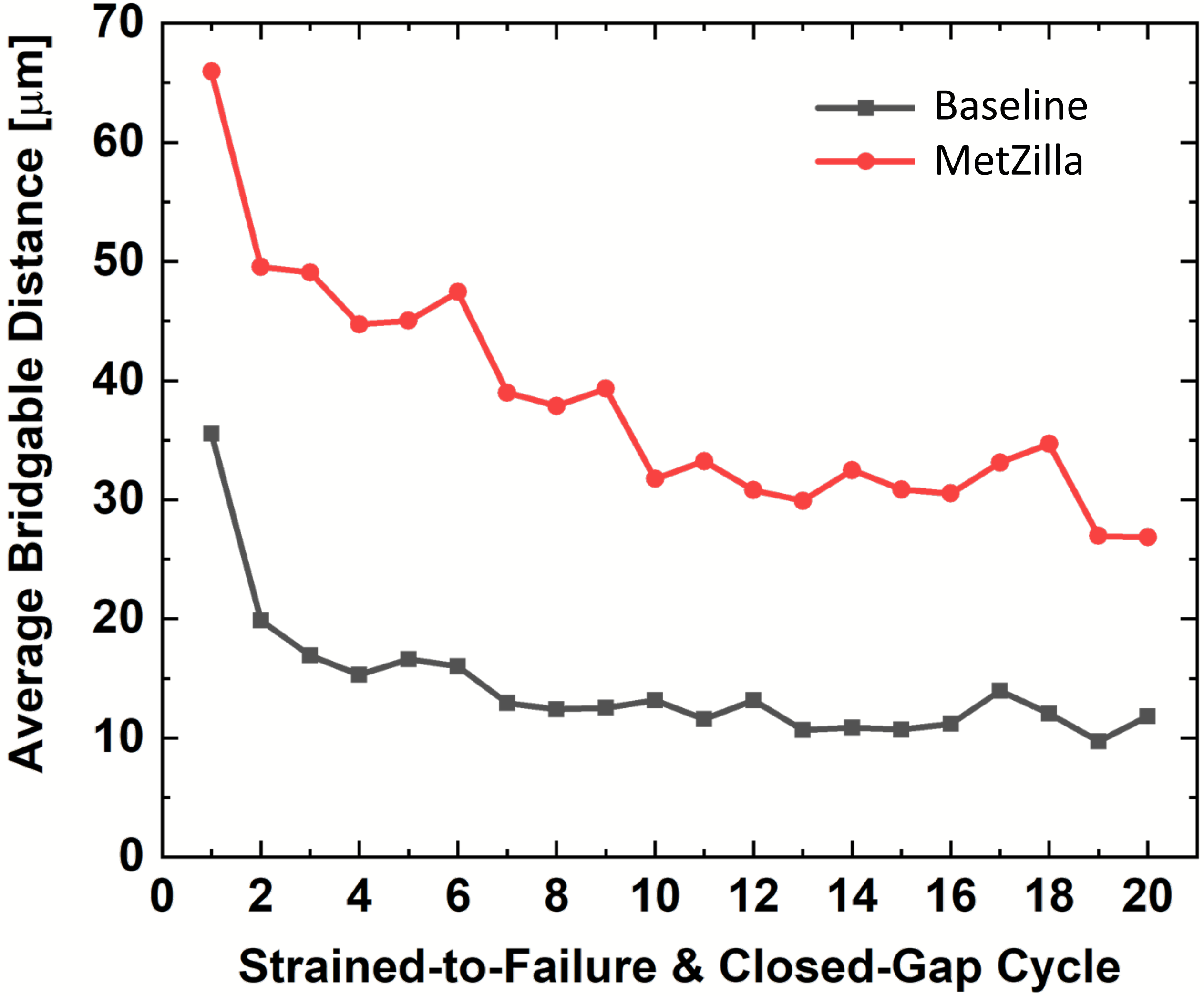
With MMC incorporation:

- 9.6-33% decrease in elastic modulus
- 153-574% increase in strain energy density

RACK (Resistance Across Cleaves & CracKs) Measurements

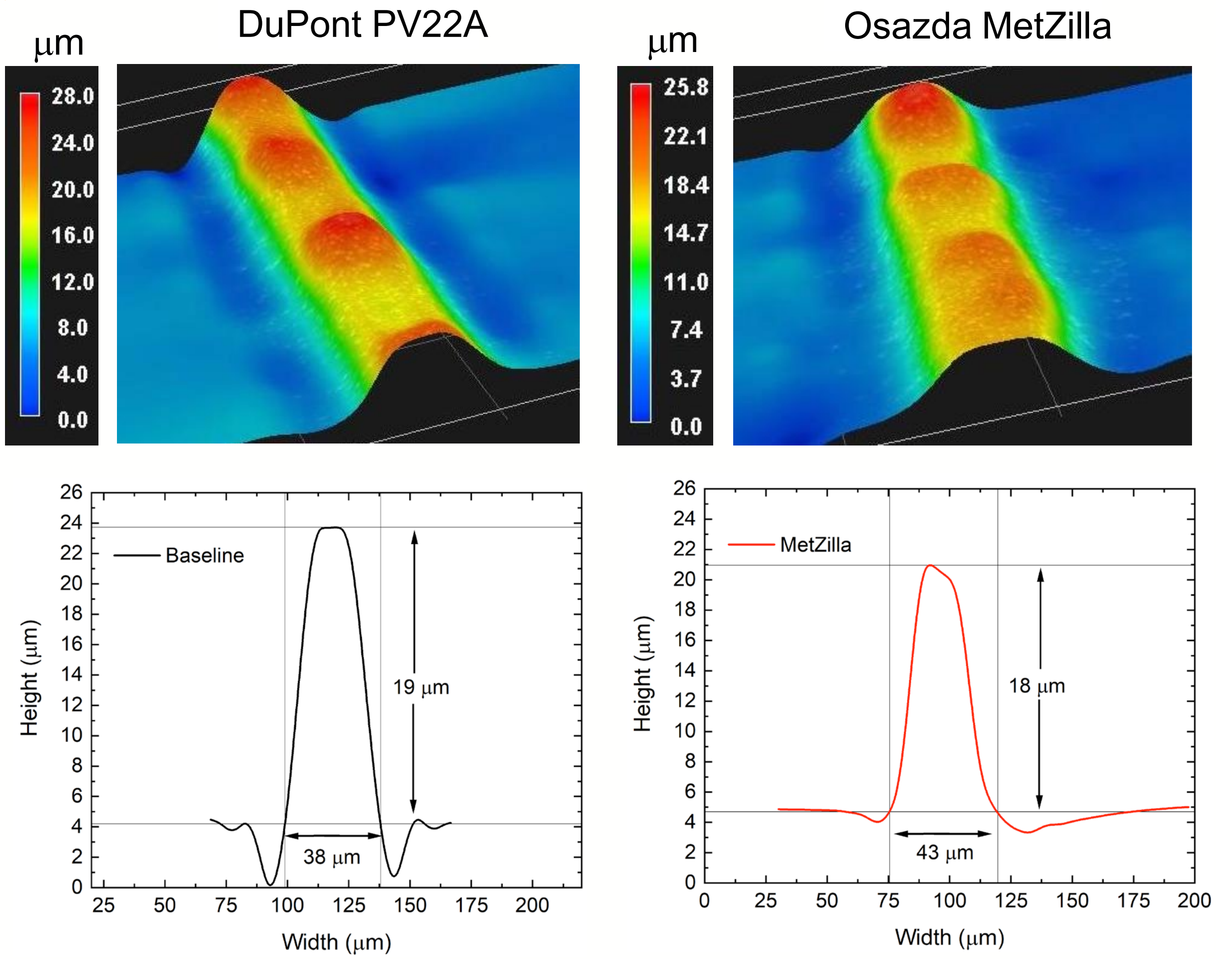


RACK TEST - ELECTRICAL GAP-BRIDGING AND SELF-HEALING



- **>65 µm** maximum bridgeable gap with optimum CNT loading
- "Self-healing" to bridge ~35 µm gaps repeatably

SCREEN-PRINT QUALITY

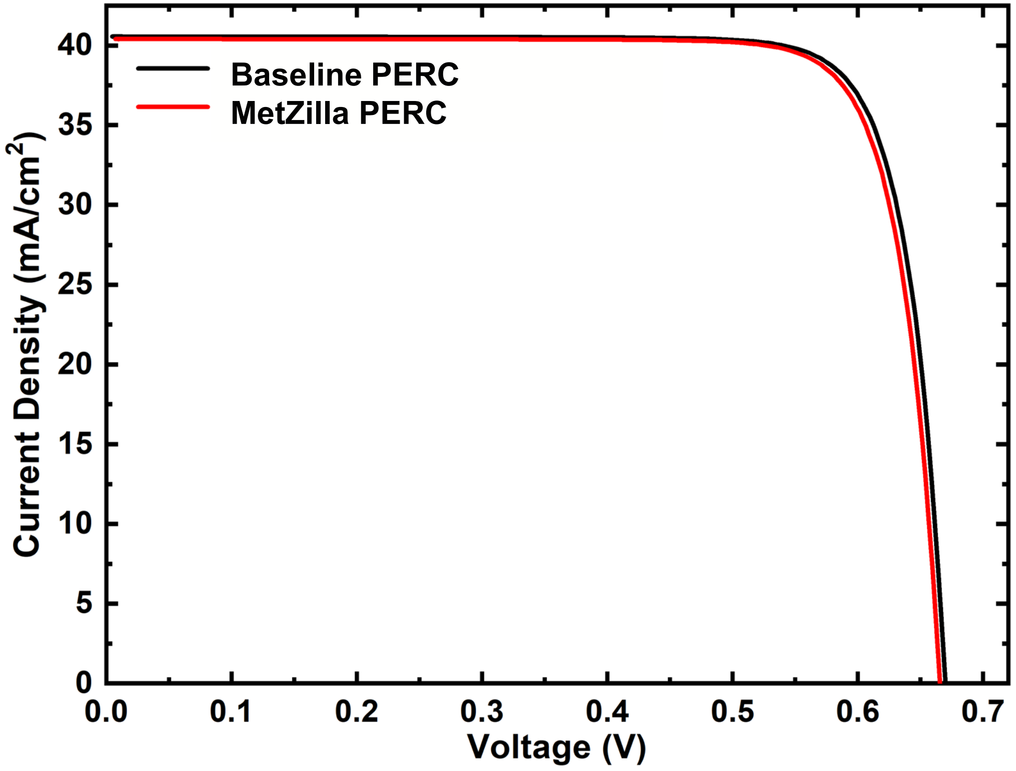


osazda ENERGY

	DuPont PV22A	Osazda MetZilla
Lay down Weight Wet	112 mg	108 mg
Lay Down Weight as Dried	90 mg	86 mg
Bus 2 Bus Resistance (Ω)	0.078	0.083
Contact resistance (mΩ-cm^2)	18	12
Line Height (µm)	19	18
Line Width (µm)	38	43

- Comparable screen print quality
- Slightly less laydown weight for MetZilla

CELL PERFORMANCE



AVERAGE OF 25 CELLS (GIT)

	Area (cm^2)	J_{sc} (mA/cm^2)	V_{oc} (V)	η (%)	FF (%)	R_{shunt} (Ω.cm^2)	R_{series} (Ω.cm^2)
Baseline	244	40.5 (±0.07)	0.67 (±0.004)	21.3 (±0.3)	78.6 (±0.6)	2.2×10^4 ($\pm 9.7 \times 10^3$)	0.72 (±0.08)
MetZilla	244	40.3 (±0.09)	0.67 (±0.002)	21.3 (±0.2)	78.9 (±0.6)	7.5×10^4 ($\pm 1.1 \times 10^5$)	0.67 (±0.12)

CONCLUSIONS

- Carbon nanotube addition enhances silver particle sintering.
- Increased fracture toughness by greater than ×6.7.
- Electrical gap-bridging up to ~65 μm and self-healing settling at ~25 μm.
- Cell performance from MetZilla-enhanced paste comparable to PV22A.
- No difference is expected under well controlled industrial process.
- Three-point-bending tests and mini-module stress testing underway.
- IEC 63209 testing on full-sized modules to begin Fall 2021.

Summary

Xin Chen - Crack Detection Algorithm & Data Analytics

- Machine learning automates damage mechanism identification and extraction of crack features.

Jennifer Braid - Measurement of PV Cell Cracks in PV Modules using DIC

- Digital Image Correlation enables cell level displacement measurements and allows for principal strain calculations highlighting cell fragment separation (cracks) on fully encapsulated, patterned modules.

Timothy Silverman - Characterization and weathering of cracks in modules

- EL images of cracked cells are snapshots of the current performance under current loading and temperature conditions → temperature-dependent!

Sang Han - Mitigating Power Loss of Cracked Cells

- The development of advanced materials such as CNT enriched metallization shows promising results in mitigating performance degradation of cracked cells.

Thank you for joining us today!

If you are interested in participating in the cell cracks working group, please reach out to:

Martin Springer (NREL): martin.springer@nrel.gov
Jennifer Braid (SANDIA): jlbraid@sandia.gov
Oliver Zhao(Stanford University): ozhao32@stanford.edu

Webinar Announcement

August 2021 – "Updates to the LCOE Calculator Tool in the DuraMAT Data Hub and LCOE Analysis of Latest PV Fleets Results" presented by Brittany Smith, NREL

Q & A Session

Please put your questions into the chat.