

An Updated Modeling Framework for Technology- and Market-Specific Shading Impacts on Annual Energy Yield

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PVPMC Workshop 2024, Salt Lake City

May 7th, 2024

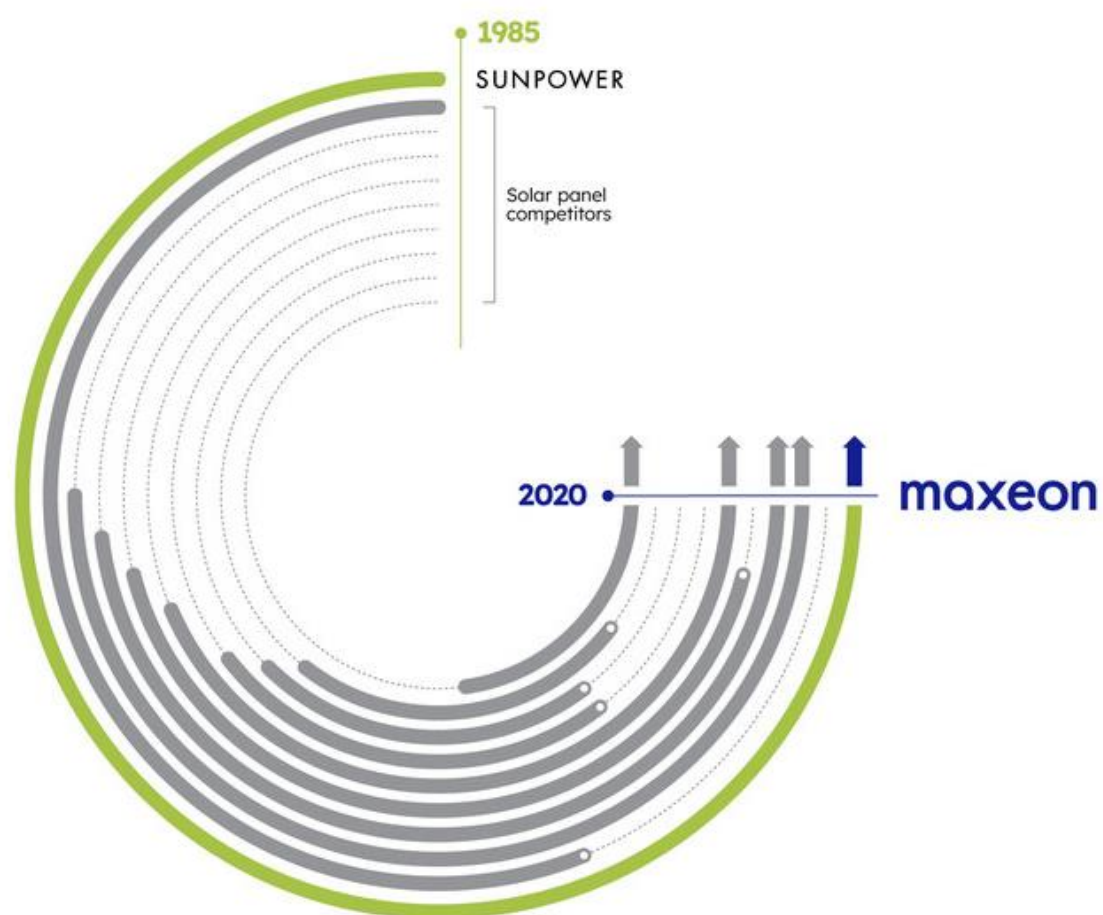
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POWERING POSITIVE CHANGE



maxeon

Founded in 2020 as a spin-off of SunPower Corporation, Maxeon leverages 39 years of global experience.



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MAXEON SOLAR TECHNOLOGIES AT A GLANCE

Headquarters	Singapore
2022 revenues	\$1 Billion+
Experience	+48 Million solar panels deployed
Global reach	+1,000,000 customers, 100+ Global Markets
Customer segments	Residential Commercial Power Plants
Customer-facing brands	SunPower Brand in most of the world Maxeon Brand in U.S. and Japan markets
2022 volume	~2,500 MW
Beyond the panel	AC Modules Battery Storage EV Charger Consumer Experience

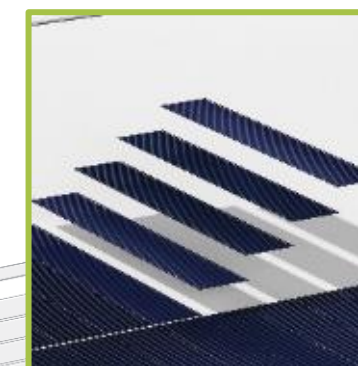
MAXEON IBC

Patented cell architecture with metal foundation



PERFORMANCE

Patented unique mono PERC & TOPCon shingled cell panel design



¹IBC: Interdigitated Back Contact ("IBC") technology.

²1.8 GW target capacity; majority of capacity operational as of January 1, 2023.

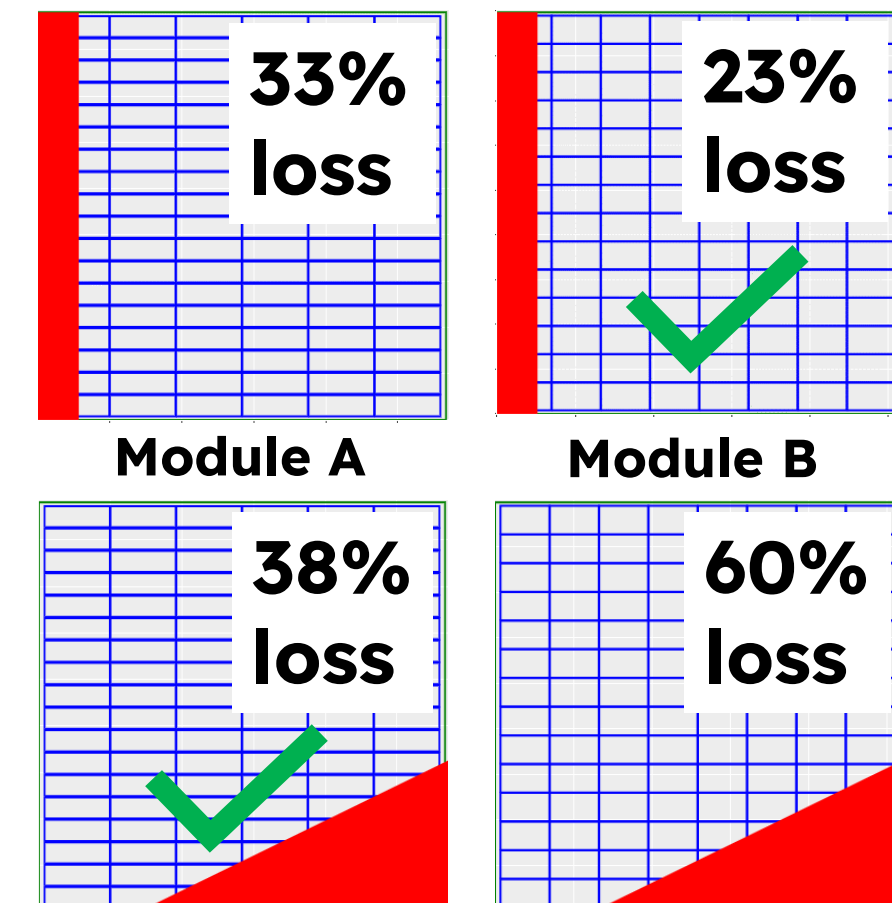
³JV: Huansheng Photovoltaic (Jiangsu) Co., Ltd. ("HSPV").

Introduction & Motivation

- Shading can have a substantial impact on the energy harvest of PV systems, especially in DG (RES and COM).
- **Technology-specific shading loss differences can sometimes exceed differences in effects like incidence angle modifier (IAM), low light, and module temperature coefficient.**
- However, quantifying the impact of technology-specific factors on energy yield is complex. Therefore, this often gets neglected or over-simplified.
- Many shade studies focus on specific shade scenarios, but usually stop short of incorporating data on the occurrence of different shade cases to properly generalize the results. **The goal of this study is to use observed shade scenarios in RES and COM (future: UPP) market segments to estimate realistic distributions of annual energy impact.**
- **Cell & module technology also greatly affects hotspot behavior and reliance on bypass diodes.**

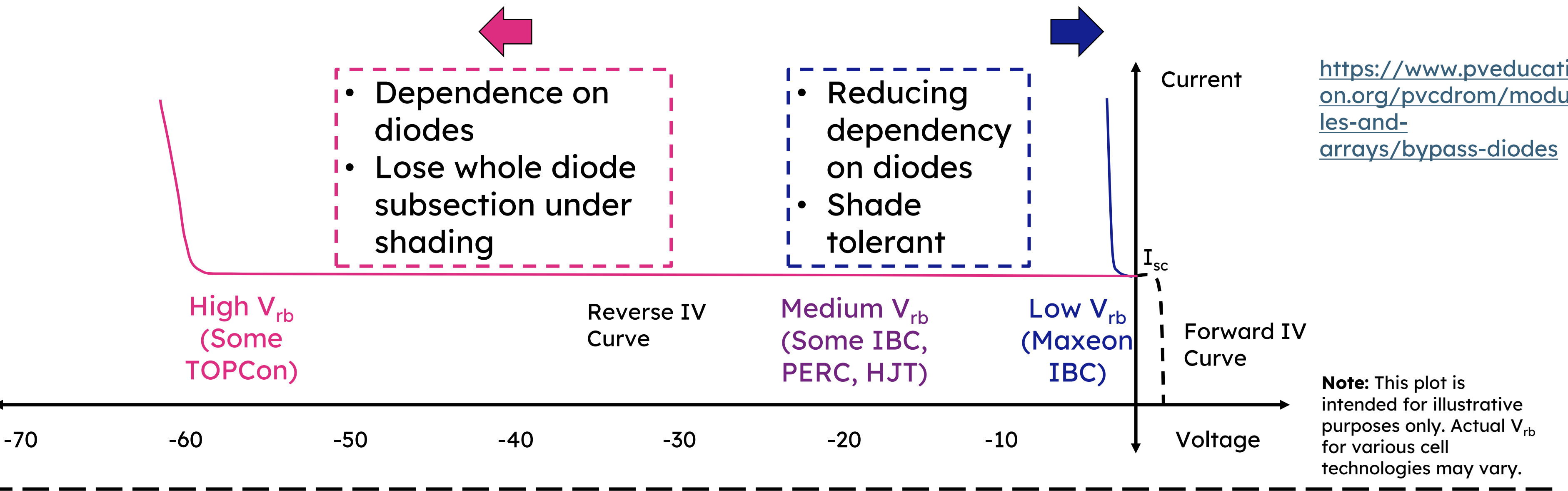


Two modules with different cell technology, wafer size, and circuit design: Which module has better performance while shaded?



Terminology/ Background

Reverse Breakdown Voltage (V_{rb})



Module Level Power Electronics (MLPE): Maximum power point tracking at the module level.

String Level Power Electronics (SLPE): Maximum power point tracking at the string or system level.

Key Results

- Technology-specific **shade loss differences** can be as high as 0.5-3% in DG market segments – an impact often as large or larger than **module temperature coefficient, low light, or IAM**.
- **Modules with low V_{rb}** have significantly **lower energy losses** and annual bypass diode activation frequencies.
- **Module Circuit design** has bigger impact in **heavily shaded systems** or large area shades.

Relative difference in annual energy yield [%] from Conventional PERC Module

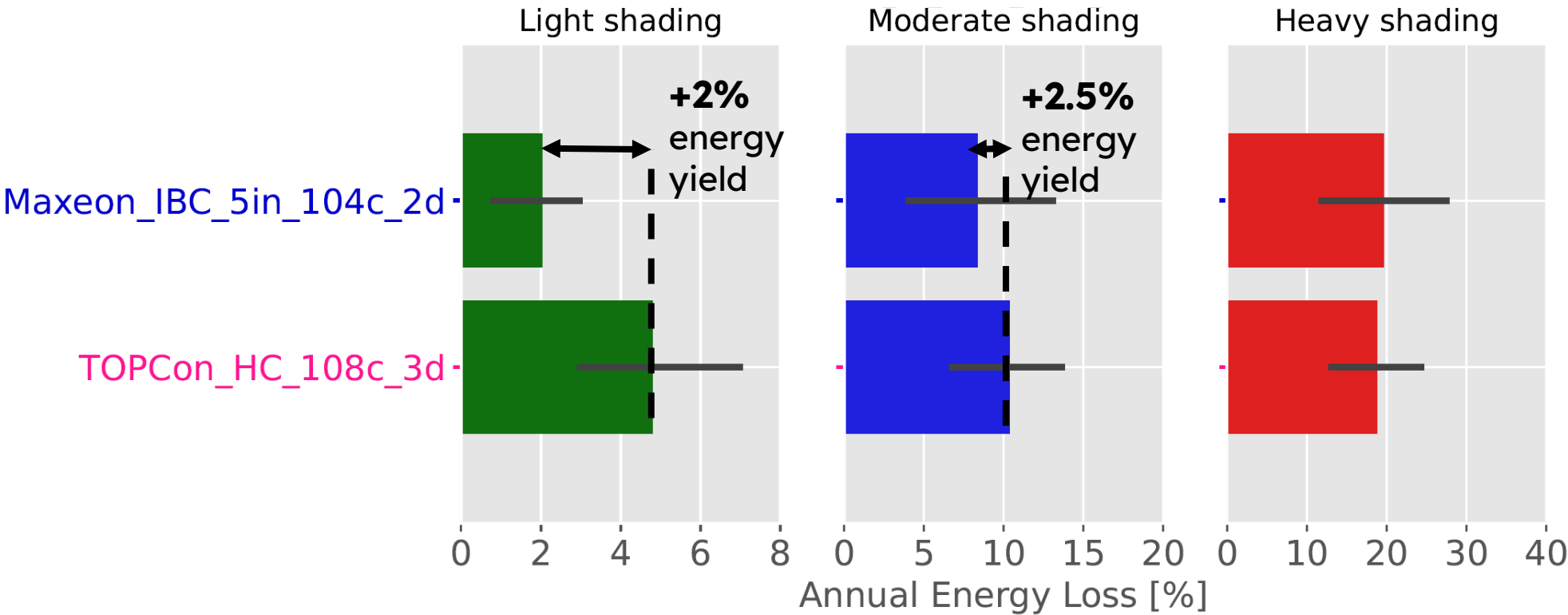
Yield and effects simulated using PVLib^{1, 2}

Module Technology	Other Effects			Representative DG Shade Effect		
	IAM	Low light effect	Temperature effect	Light shading	Moderate shading	Heavy shading
Maxeon_IBC	0.4%	-0.7%	2.3%	2.4%	2.4%	2.0%
Maxeon_TOPCon_shingled	1.5%	-0.1%	2.2%	-0.2%	0.7%	0.2%
TOPCon_HC	0.0%	0.0%	2.0%	-0.2%	0.2%	3.4%

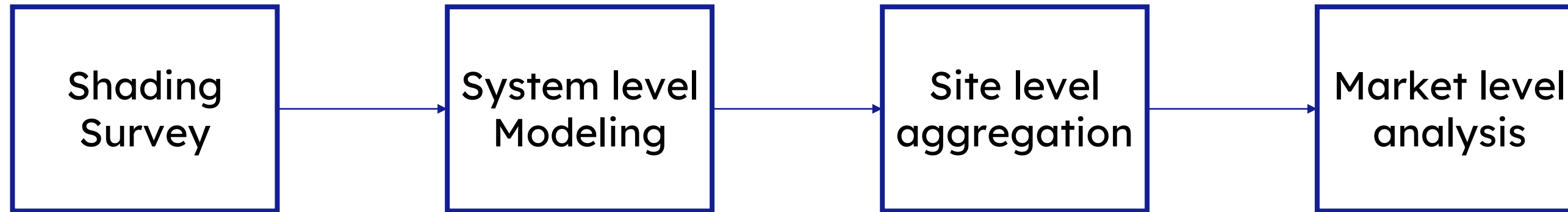
Notes:

- IAM provided by Manufacturers used in this study. Actual differences in IAM may be less significant.
- Yield and losses are the average values from modeling for 2 RES systems sizes, 2 system orientations, and 4 US locations.

Residential Rooftop Mean Annual Energy Losses for SLPE systems



Analysis Methodology



112 RES & 35 COM
Rooftop sites from
Customer database
surveyed in Google
Earth for shading.

Past RES surveys
performed by NREL³,
⁴ are combined to
obtain realistic
irradiance loss
distributions.

Each site modeled physically and
electrically to obtain Annual Energy.

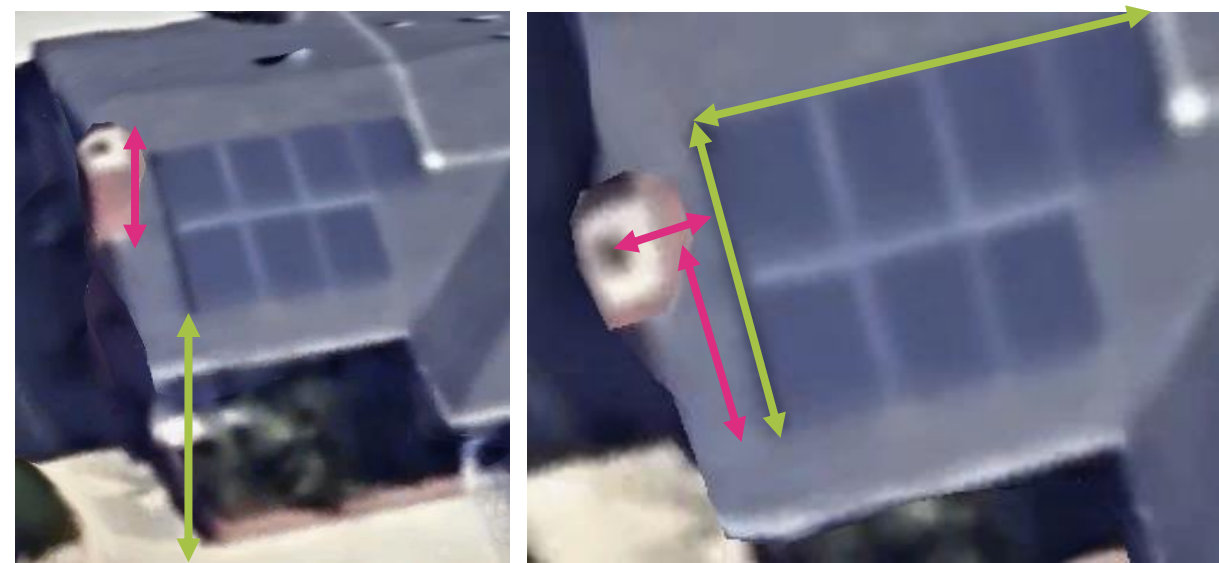
This analysis methodology
quantifies the impact of
technology-specific factors on
energy yield at the Market level.

Analysis of energy
loss performed for
all sites to get
insights into
Technology and
Market specific
shading impacts.

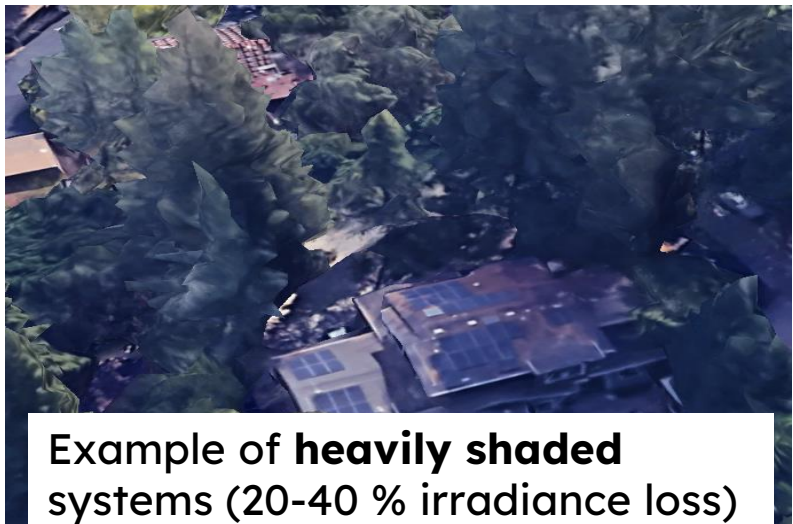
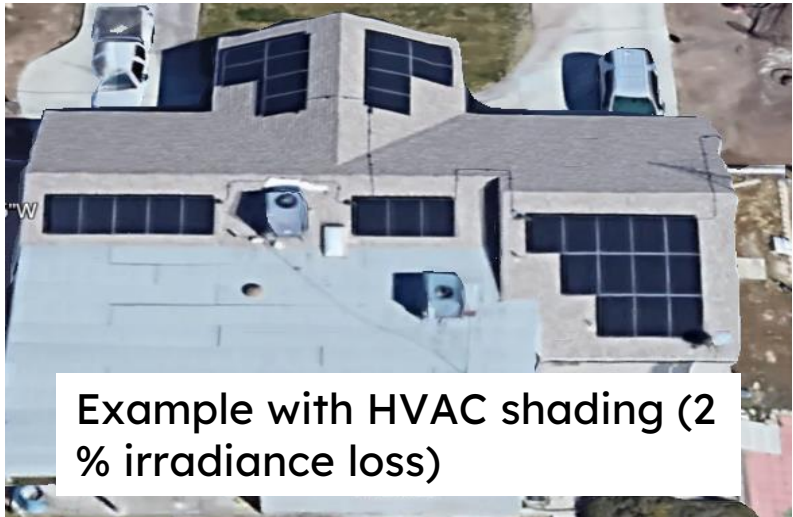
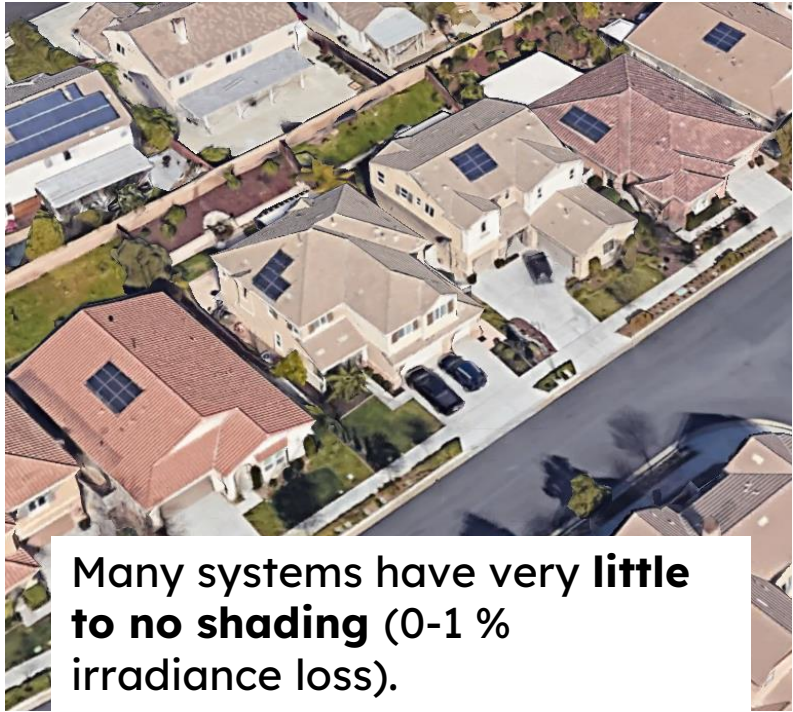
Residential Rooftop Survey: Customer Sites

Methodology:

- Each **site surveyed using Google Earth/Street View** for close shade objects.
- Each subsystem surveyed separately, and their azimuth angle is noted.
- **The location of each close shade object is obtained w. r. t. the system.**
- **Ray tracing used to obtain estimated annual irradiance loss.**



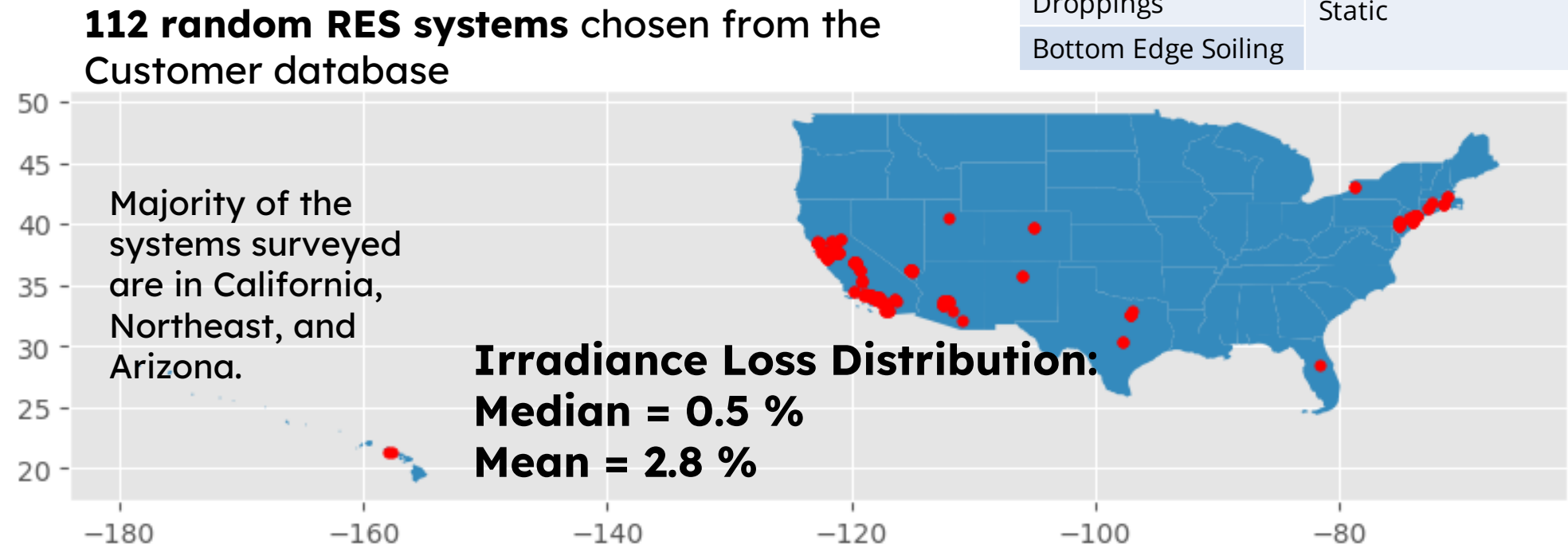
Shade Type	Modeling Method
Chimney	Simplified Ray Tracing
HVAC	
Vent Pipe	
Pole	
Tree	
Shed or Cabin	
Wall	
Wire	Static
Leaves & Bird Droppings	
Bottom Edge Soiling	



Less avoidable shading:
Leaves & Bird droppings, Edge soiling, and vent pipes

Less avoidable shading: +
Chimney, HVAC, etc.

More avoidable shading: +
Trees, Roofs, etc.



How does Customer survey compare to other surveys?

Key Points:

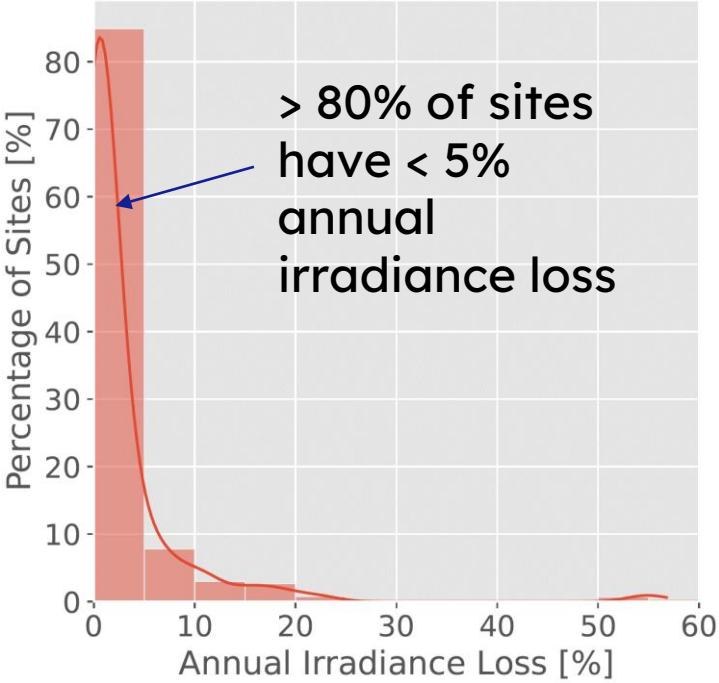
- Different surveys show different annual irradiance losses.
- These distributions were combined to obtain a more realistic irradiance loss distribution for further analysis.

- Consistent with “low” shading:
- Customer sites survey →
 - Tesla 2022⁵
 - Tigo 2015 / GTM Research⁶

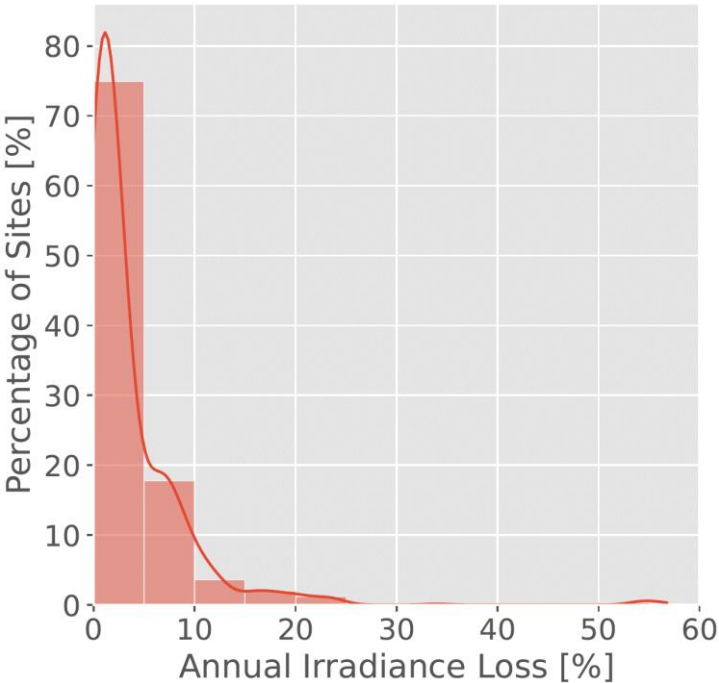
Median choice for modeling →

- Consistent with “high” shading:
- NREL MLPE 2014*⁴ →
 - Highest: NREL/PVEL 2012³

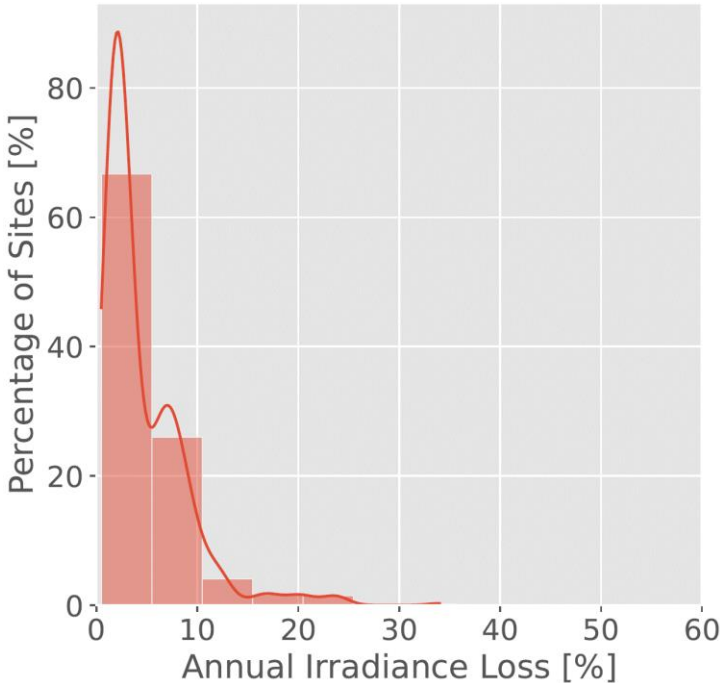
Low shade data set



Medium shade data set



High shade data set



Percentile of distribution	10%	20%	30%	40%	50%	60%	70%	80%	90%
Low irradiance loss data set (Customer survey)	0.07%	0.13%	0.22%	0.32%	0.53%	0.93%	1.77%	3.31%	7.46%

	Lightly shaded			Moderately shaded			Heavily shaded		
Medium (combined)	0.09%	0.28%	0.80%	1.40%	1.88%	2.49%	3.45%	6.32%	9.04%

High irradiance loss data set (NREL MLPE 2014 survey)	1.32%	1.67%	1.96%	2.36%	2.86%	3.62%	6.03%	7.40%	9.32%
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References:
[5] Tesla Solar Inverter Architecture White Paper.
[6] Whitepaper: Optimization with Impedance Matching and Predictive IV.

* NREL MLPE 2014 Irradiance Loss Calculation Methodology:
• Unshaded power assumed as output power of best performing module.
• Shading Index calculated as stated in the reference.
• Assuming Shading Index is equivalent to Annual energy loss, and all systems utilize conventional PERC series modules, the irradiance loss is calculated using interpolation from modeled results.

Modeling Framework

Overview

SunPower/
PVMismatch

An explicit Python PV system IV & PV curve trace calculator which can also calculate mismatch.

8 Contributors 44 Issues 9 Discussions 68 Stars 27 Forks



pvlib

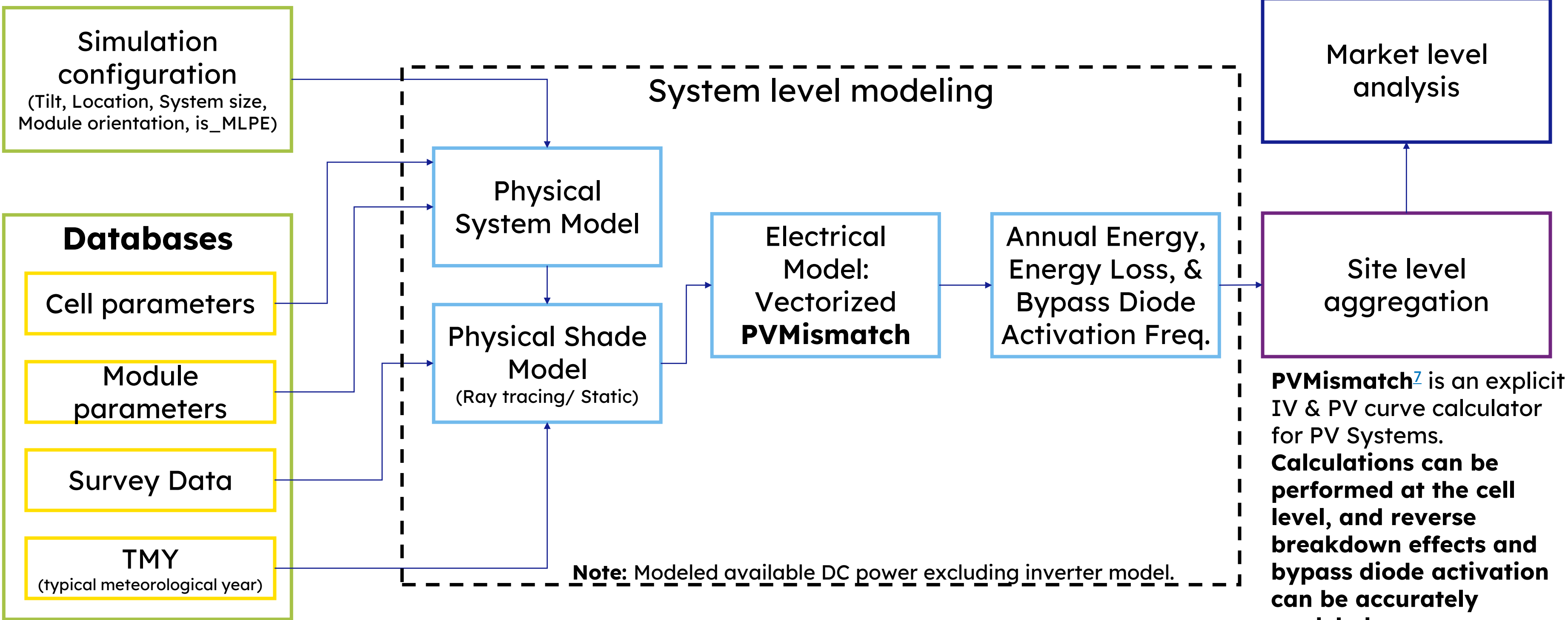
Shapely



pandas



NumPy



The modeling framework allows for automated large-scale computation of multiple sites & module technologies.

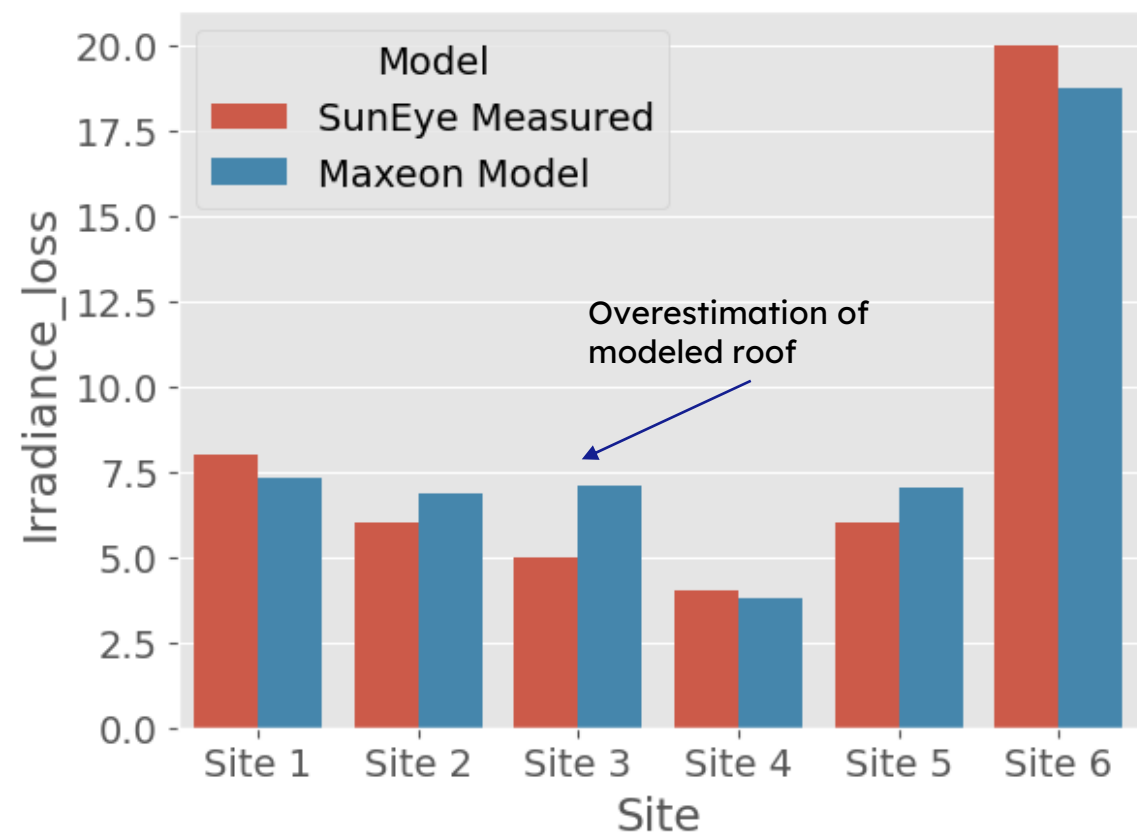
PVMismatch⁷ is an explicit IV & PV curve calculator for PV Systems. **Calculations can be performed at the cell level, and reverse breakdown effects and bypass diode activation can be accurately modeled.**

Documentation:
<https://sunpower.github.io/PVMismatch/>

Model Validation

System Level Irradiance Loss Validation

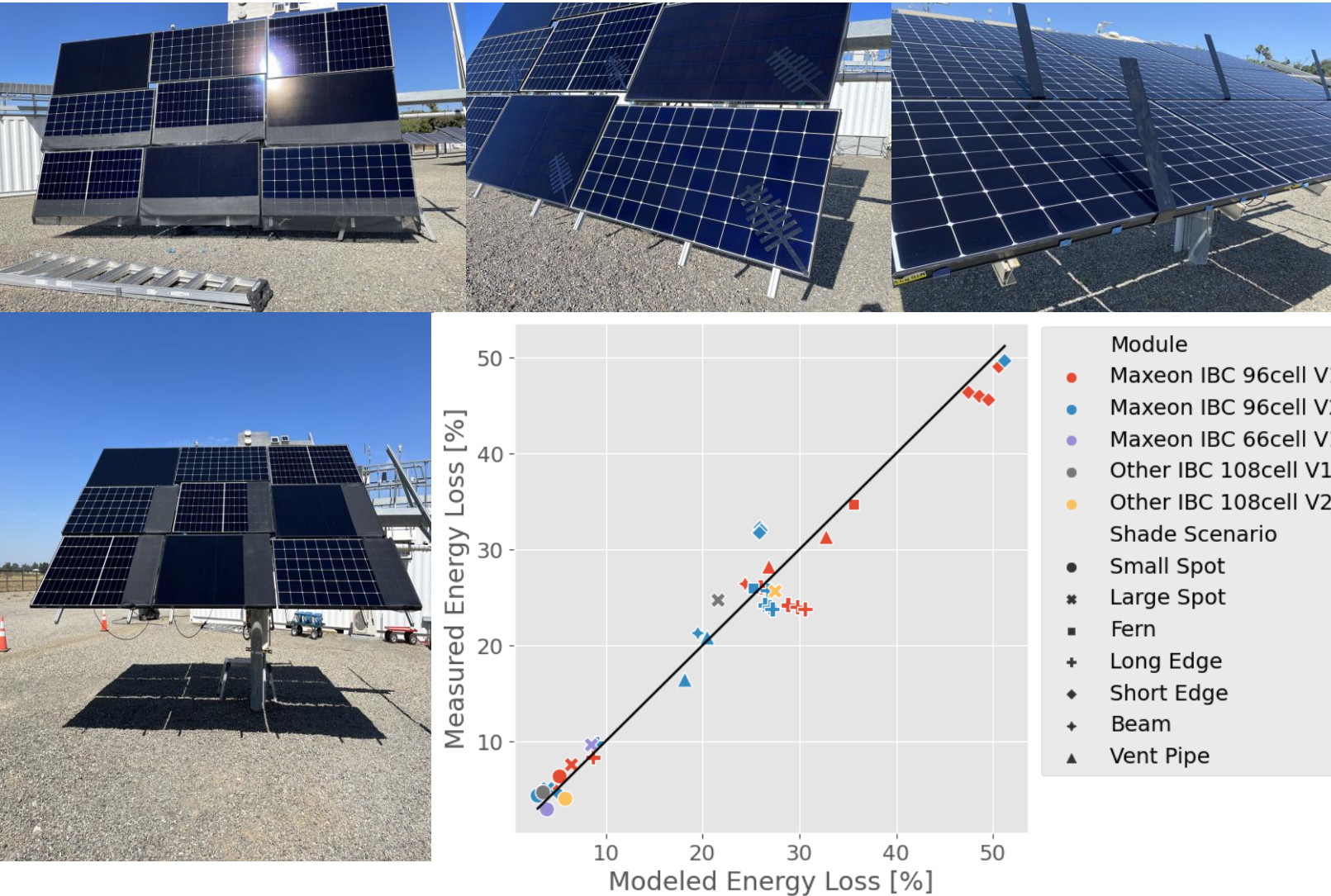
- NREL provided addresses and detailed **SunEye measurements for 6 sites** from the NREL 2012 study³.
- Each site surveyed using Google Earth / Street View.
- The modeled annual irradiance losses (**Maxeon Model**) were compared to the measured results (**SunEye Measured**).



Maxeon modeled annual irradiance losses generally agree well with measured losses with a maximum absolute difference of ~2%.

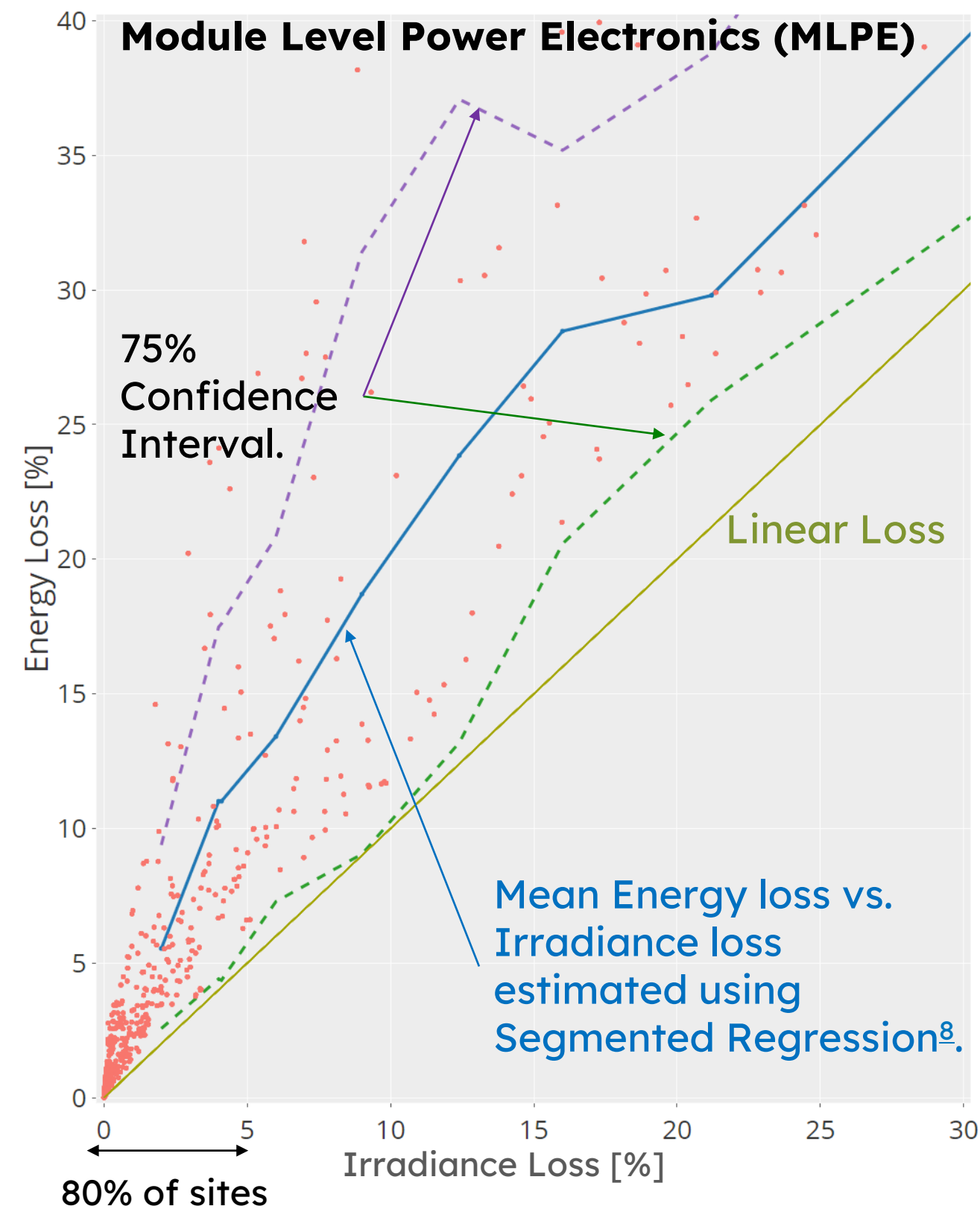
PVMismatch Validation

- Previous published validation of PVMismatch⁹.
- Multiple modules (Maxeon and competitor IBC variants) were tested at the Maxeon facility in Davis, CA.
- Standardized shade scenarios include Spot, short and long edge, vent pipe, and fern shading for module characterization.
- PVMismatch results usually agree well with experiment.

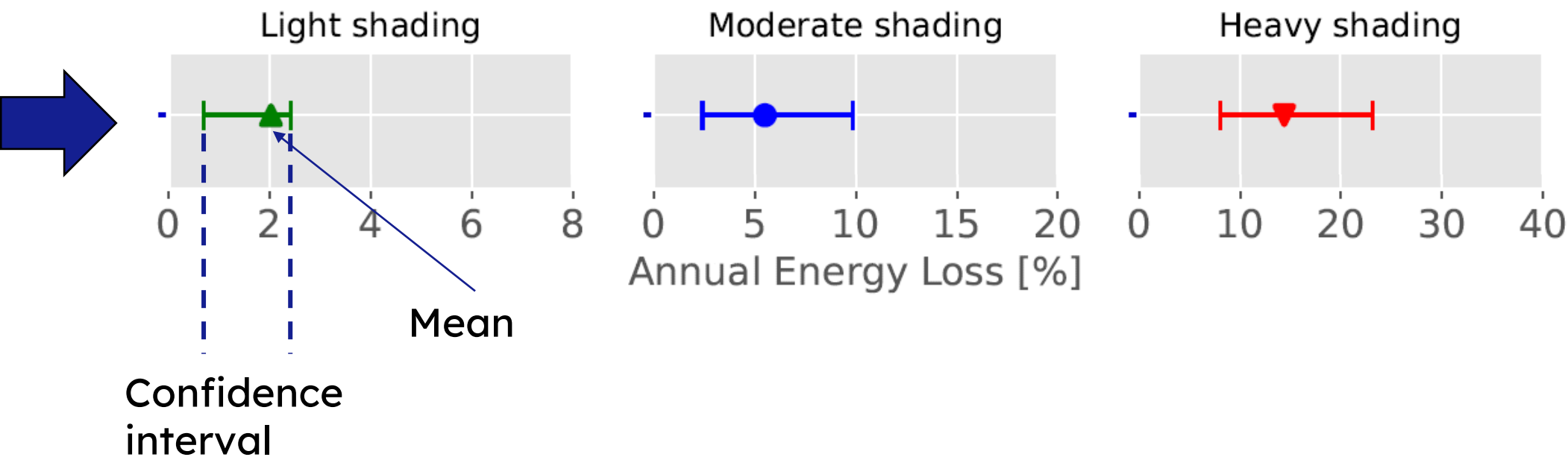


Market Level Analysis: Irradiance loss vs. Energy loss

Example: Maxeon IBC module



- Large variance in energy loss at each irradiance loss level.
- Variance is captured by a mean and confidence interval



Residential Rooftop (RES) Modeling Results

Comparing various Module Technologies

Irradiance

Loss Levels
(Percentiles of
distribution)

20%

50%

80%

▲

●

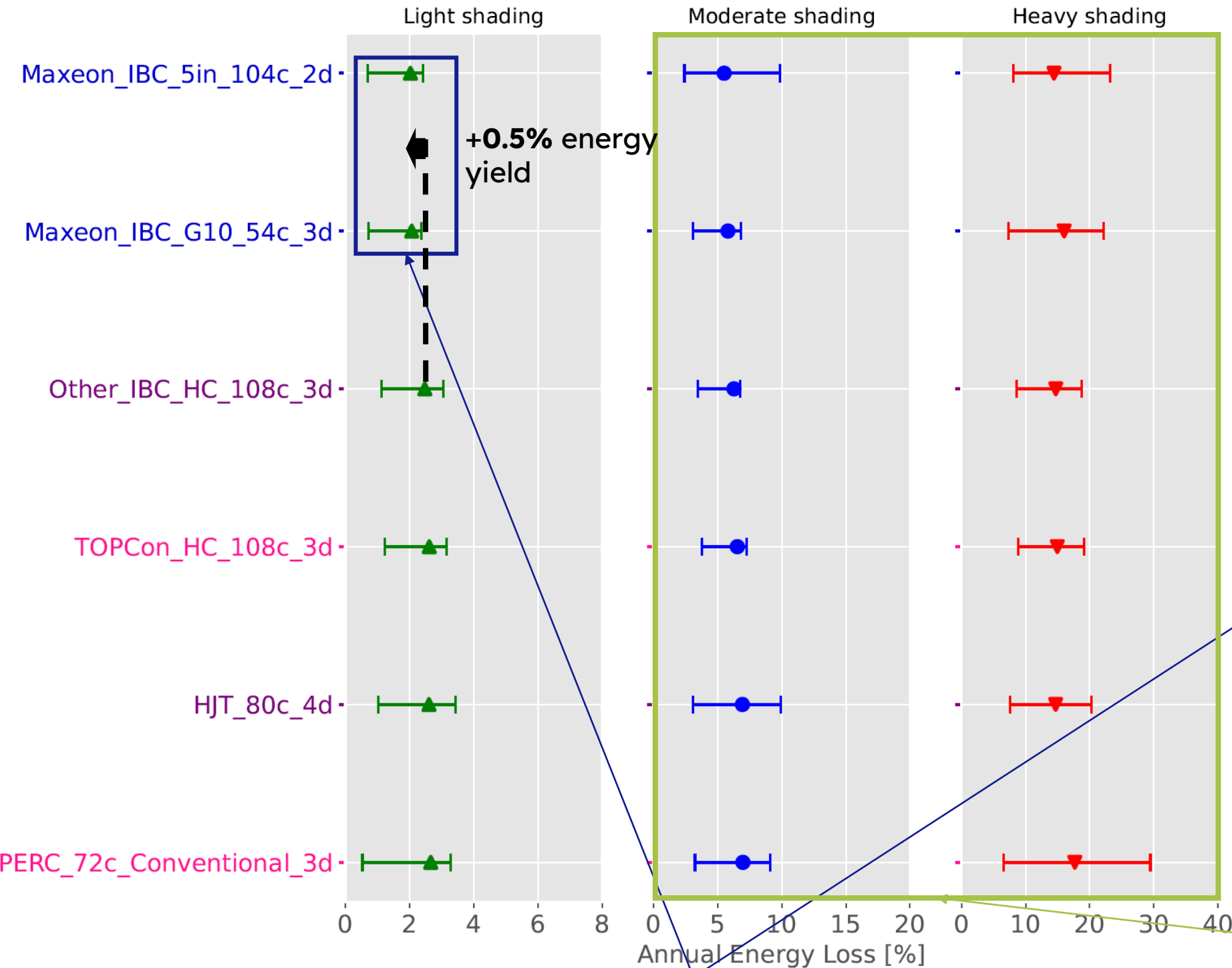
▼

Light [0.28%]

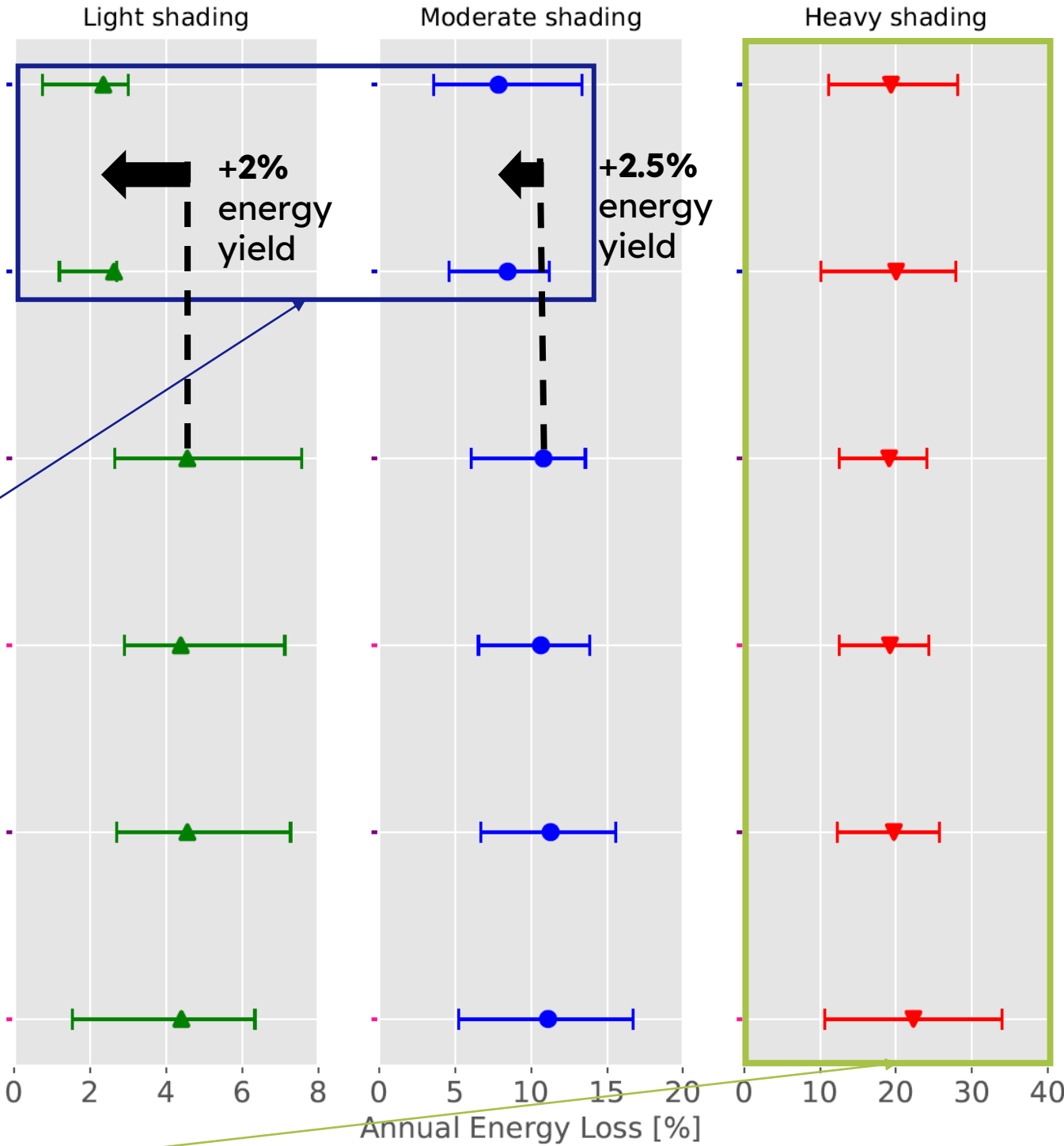
Moderate [1.88%]

Heavy [6.32%]

Module Level Power Electronics (MLPE)



String Level Power Electronics (SLPE)



Light & Moderate shading:
Modules with low Reverse Breakdown Voltage (V_{rb}) have lower energy losses.

Heavy shading:

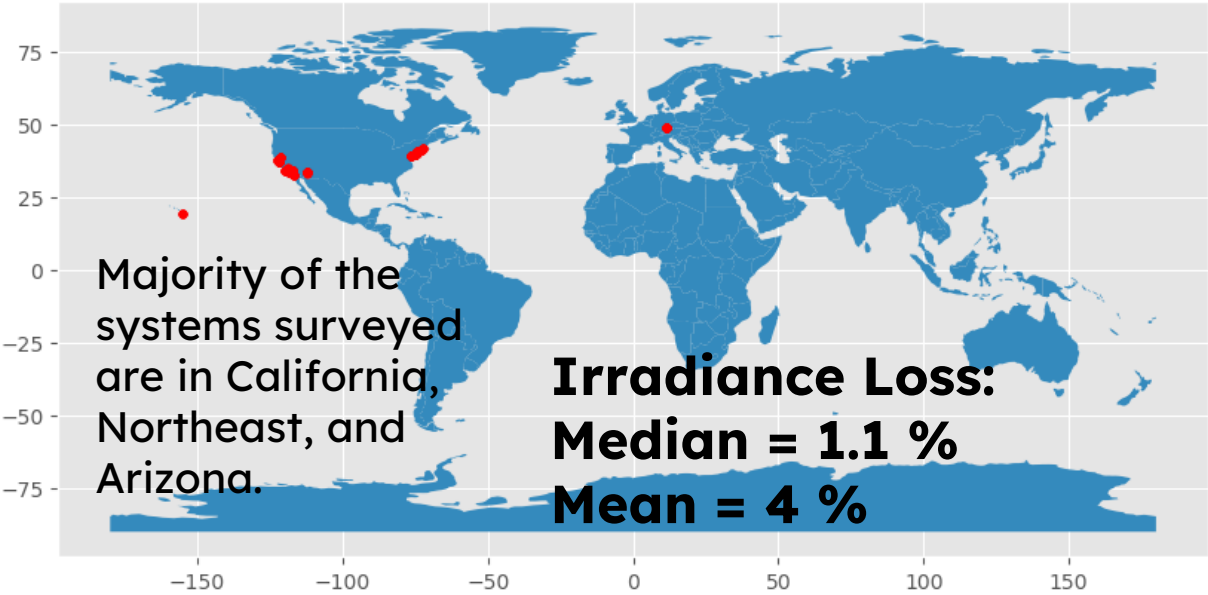
- Large variance at higher irradiance losses.
- Most module technologies have similar energy losses.
- **Utilization of MLPE provides biggest benefit.**



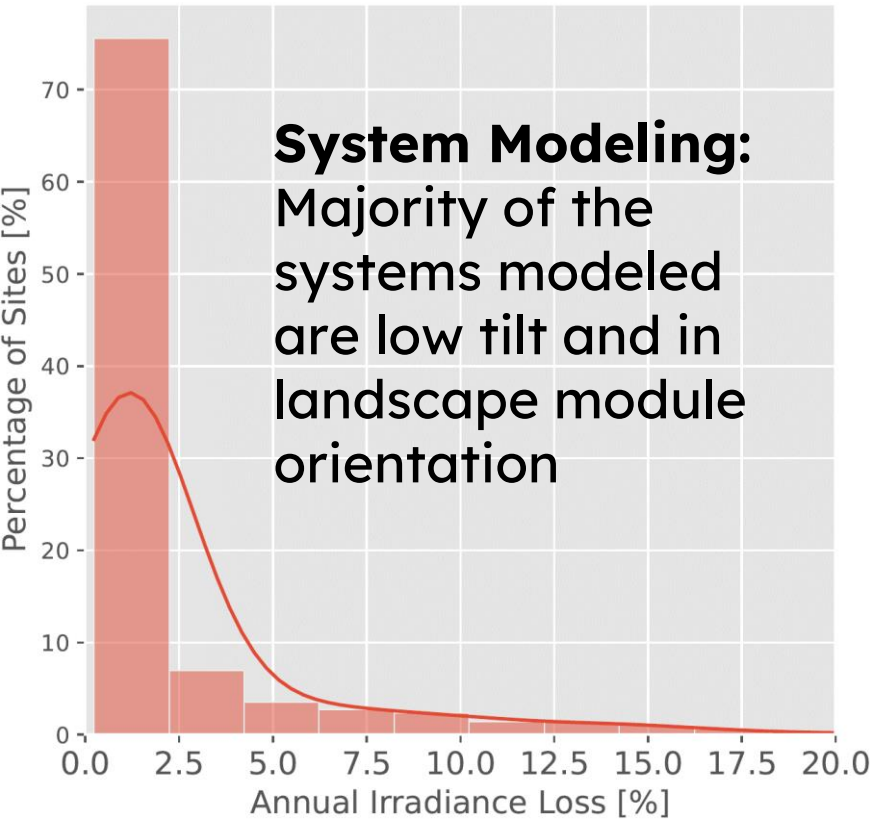
Commercial Rooftop Market Segment

Preliminary Results

35 random COM systems chosen from the Customer database



Customer sites shade data set



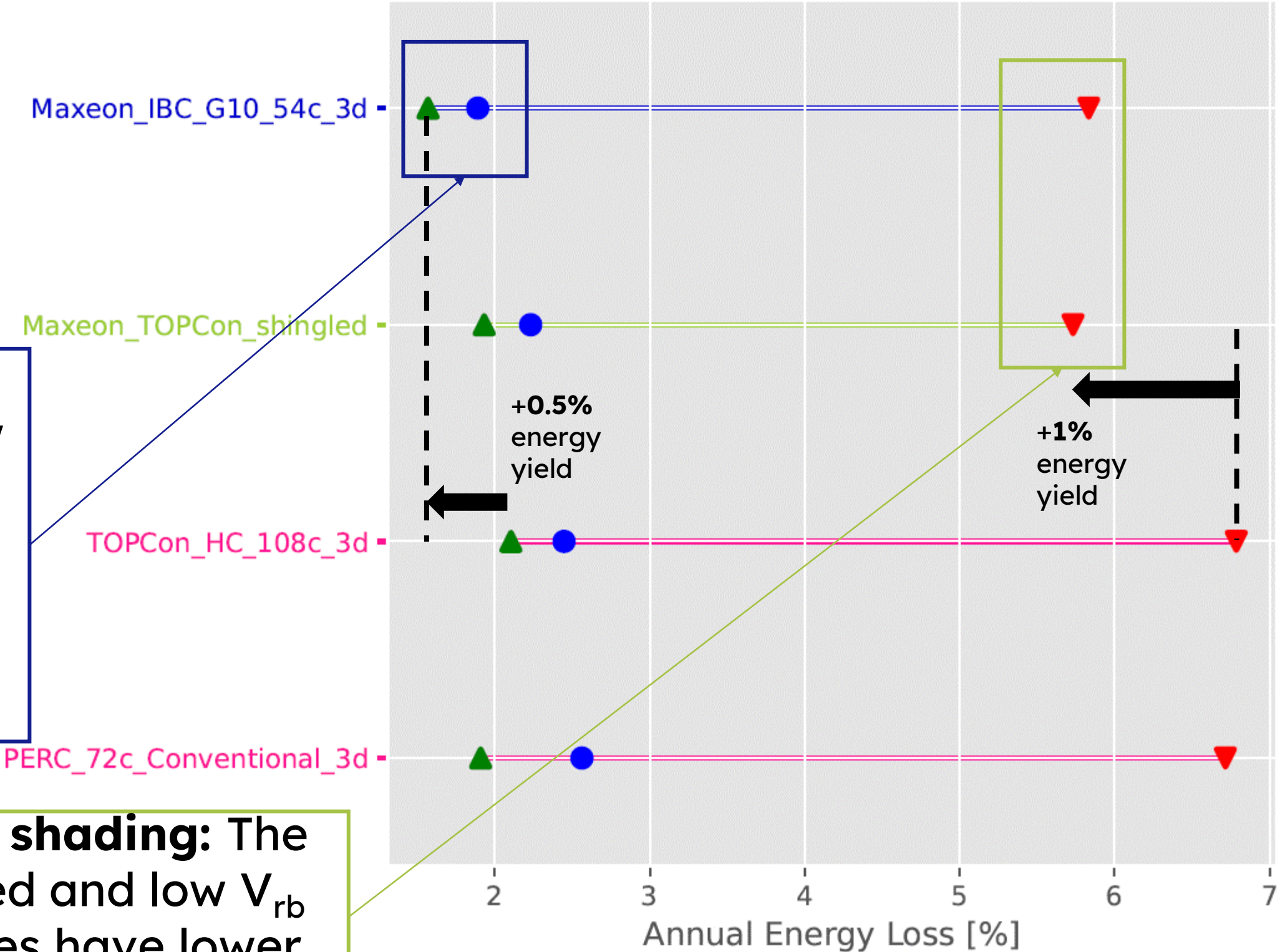
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Light shading:
Modules with low Reverse Breakdown Voltage (V_{rb}) have lower energy losses.

Heavy shading: The shingled and low V_{rb} modules have lower energy losses.

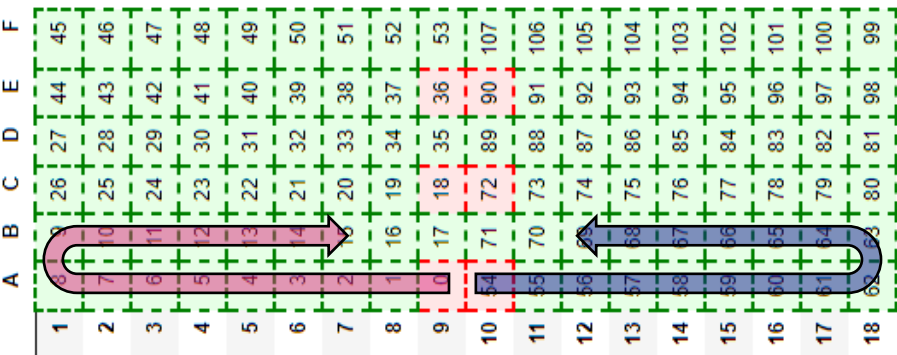
Irradiance	20%	▲ Light [0.52%]
Loss Levels	50%	● Moderate [1.12%]
(Percentiles of distribution)	80%	▼ Heavy [2.17%]

Mean energy losses for String level power electronics systems (SLPE)

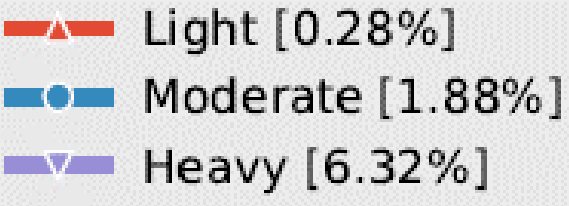


RES: Reverse Breakdown Voltage (V_{rb}) Effects

Module: 108 M10 Half cut cells, 3 bypass diode

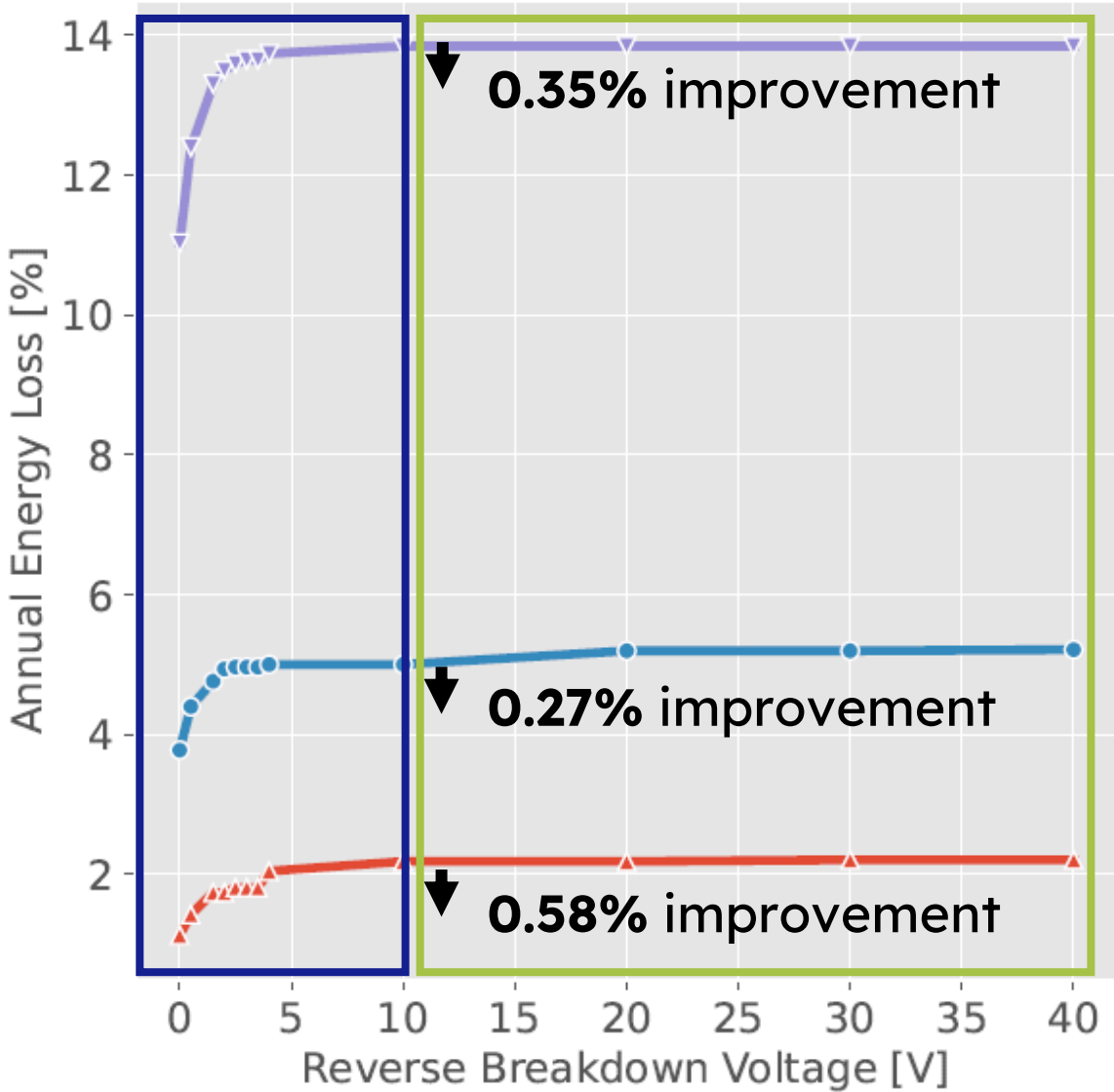


**Irradiance
Loss Levels**



V_{rb} can have a substantial effect on shade loss but is not captured as a variable in most performance modeling tools.

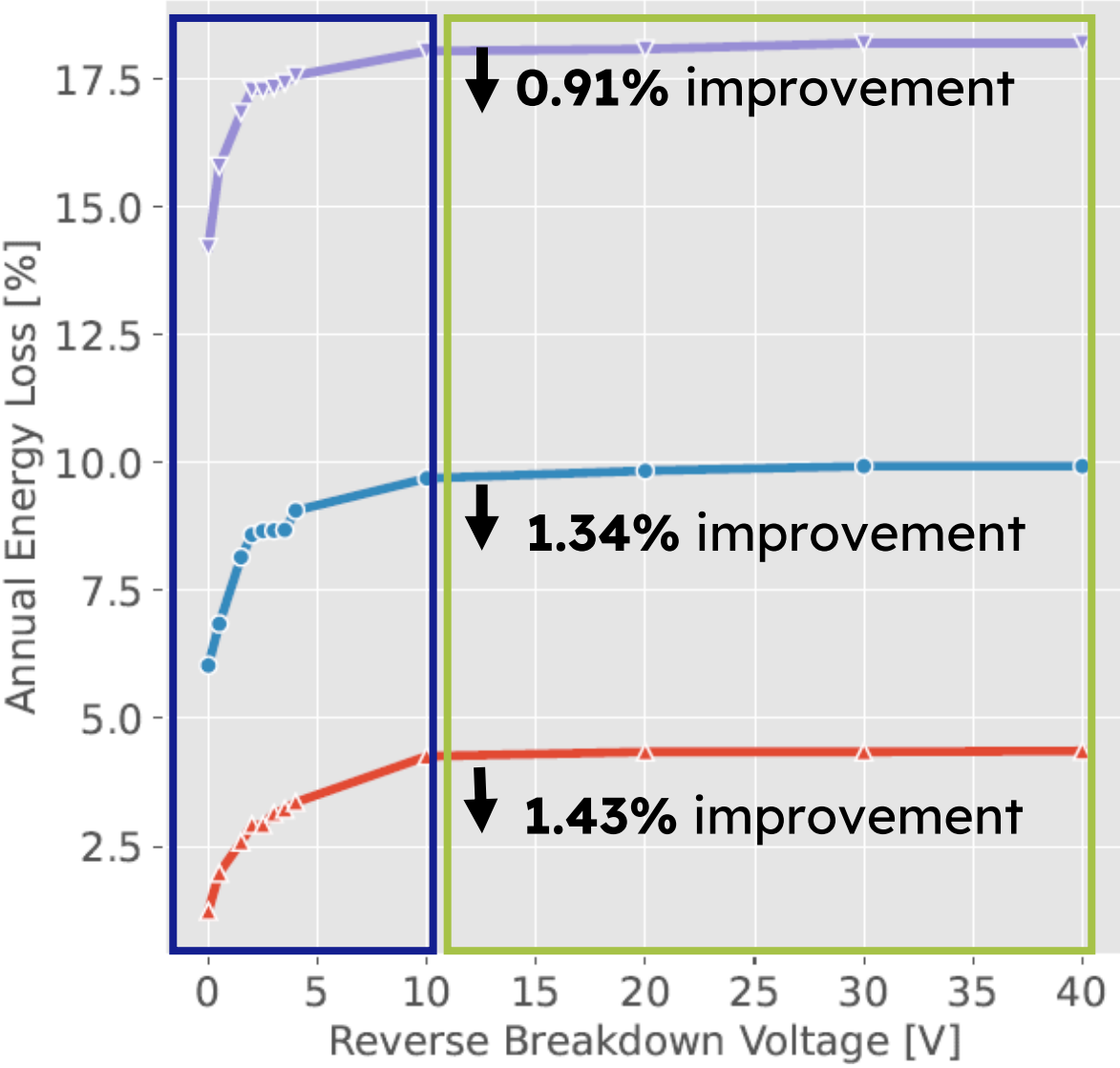
Module Level Power Electronics



Greater improvements in shade performance at lower V_{rb} .
Reduction in energy loss from 30 → 2V V_{rb} :
MLPE: 0.3 – 0.6 %
SLPE: 0.9 – 1.4 %

Negligible energy loss difference > 10 V.

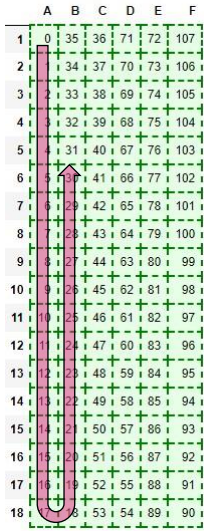
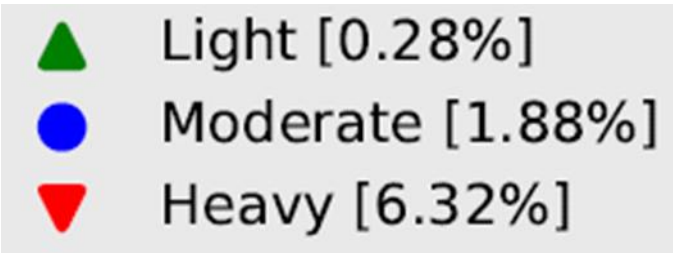
String Level Power Electronics



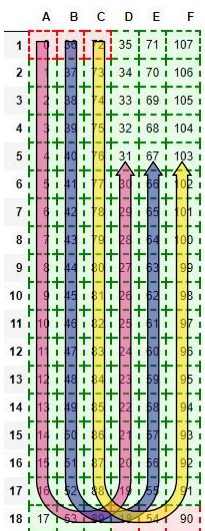
RES: What is the effect of circuit design for a given cell technology and cell size?

Hypothetical Modules: 108 M10 Half cut cells

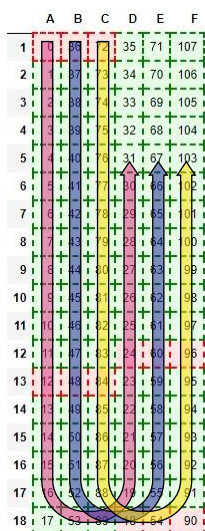
Irradiance Loss Levels



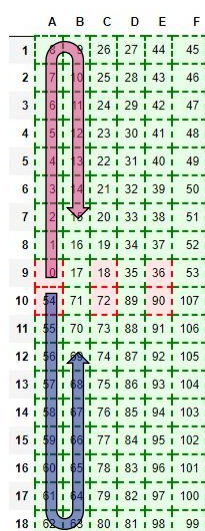
Series 2d & 3d
(2 & 3 bypass diodes)



Par1 2d
(3 parallel substrings & 2 bypass diodes)

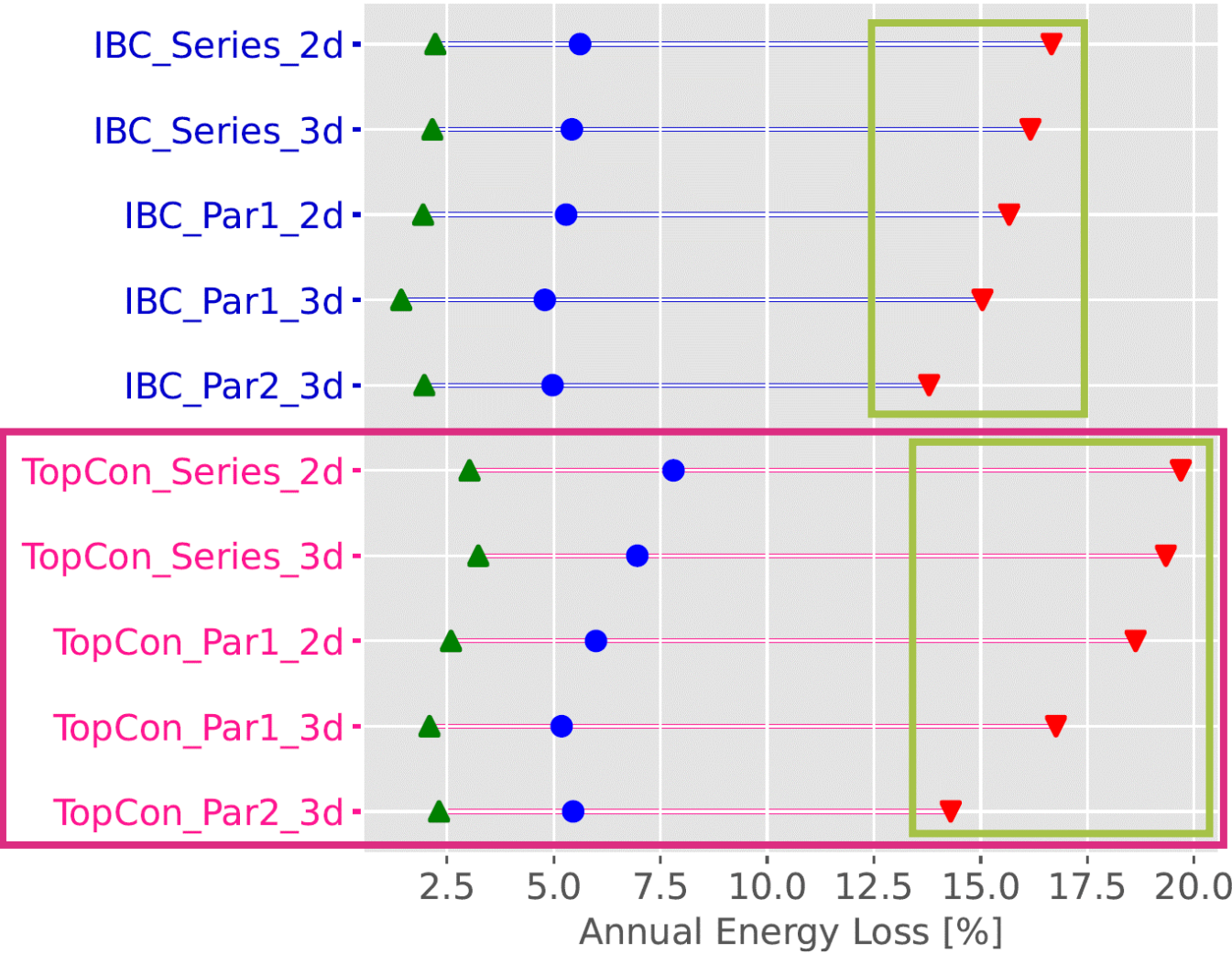


Par1 3d
(3 parallel substrings & 3 bypass diodes)



Par2 3d
Split module design

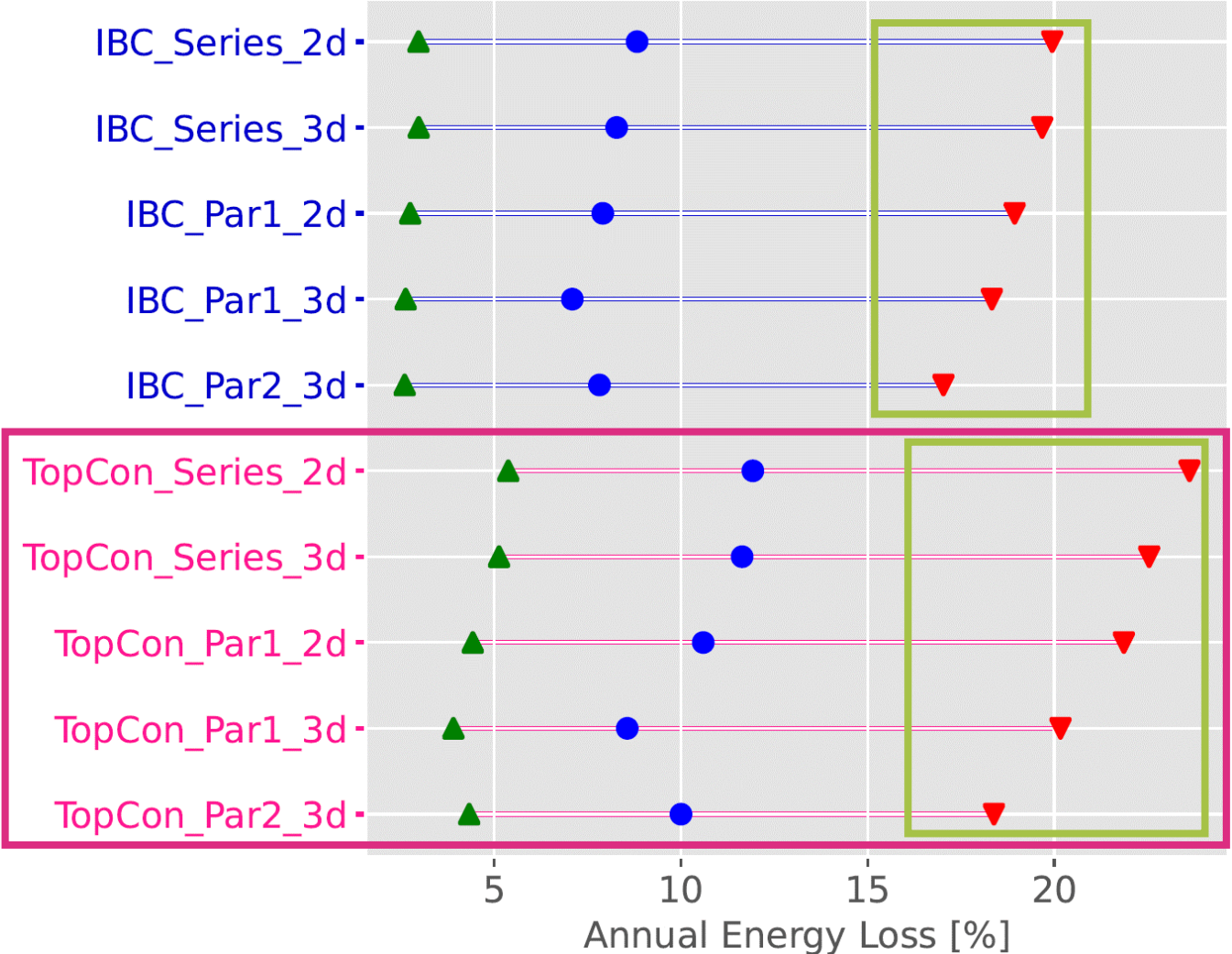
Module Level Power Electronics



Circuit design has a bigger effect on heavily shaded systems (with large area shades).

Circuit design effects are stronger for cells with high V_{rb} .

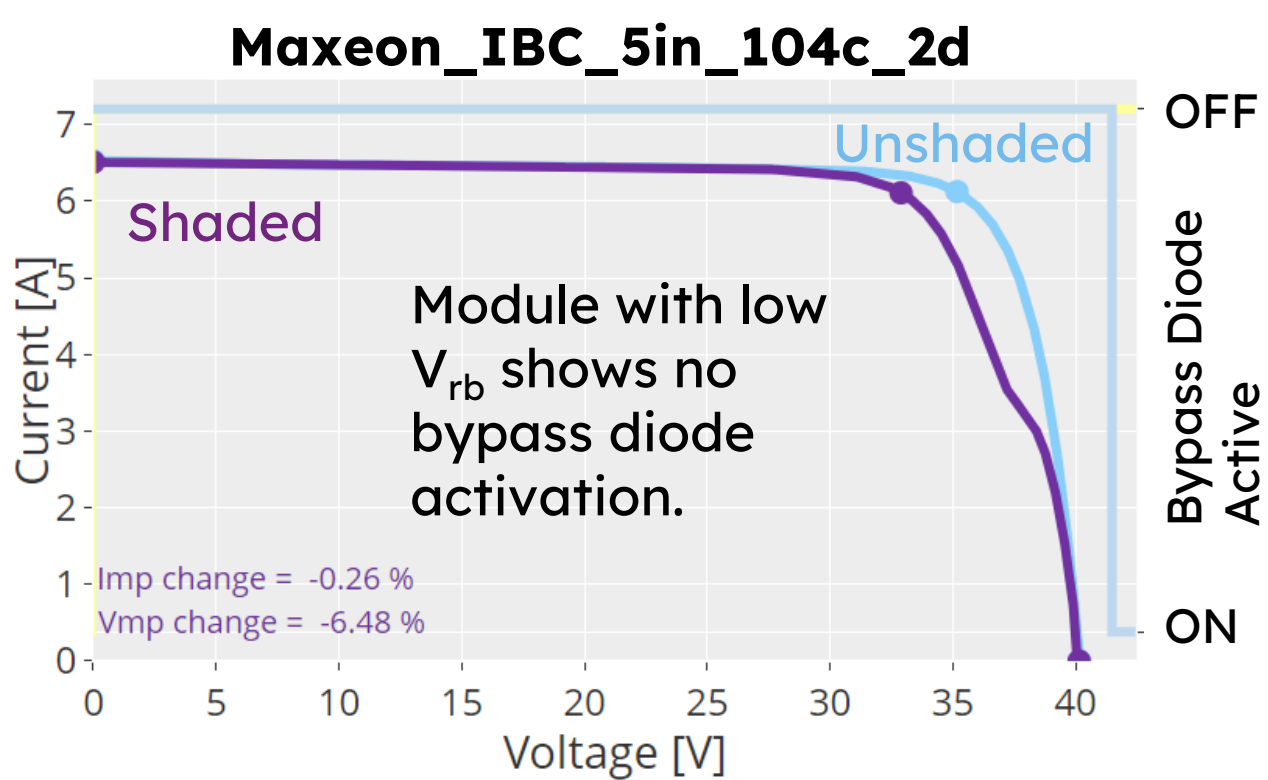
String Level Power Electronics



Notes:

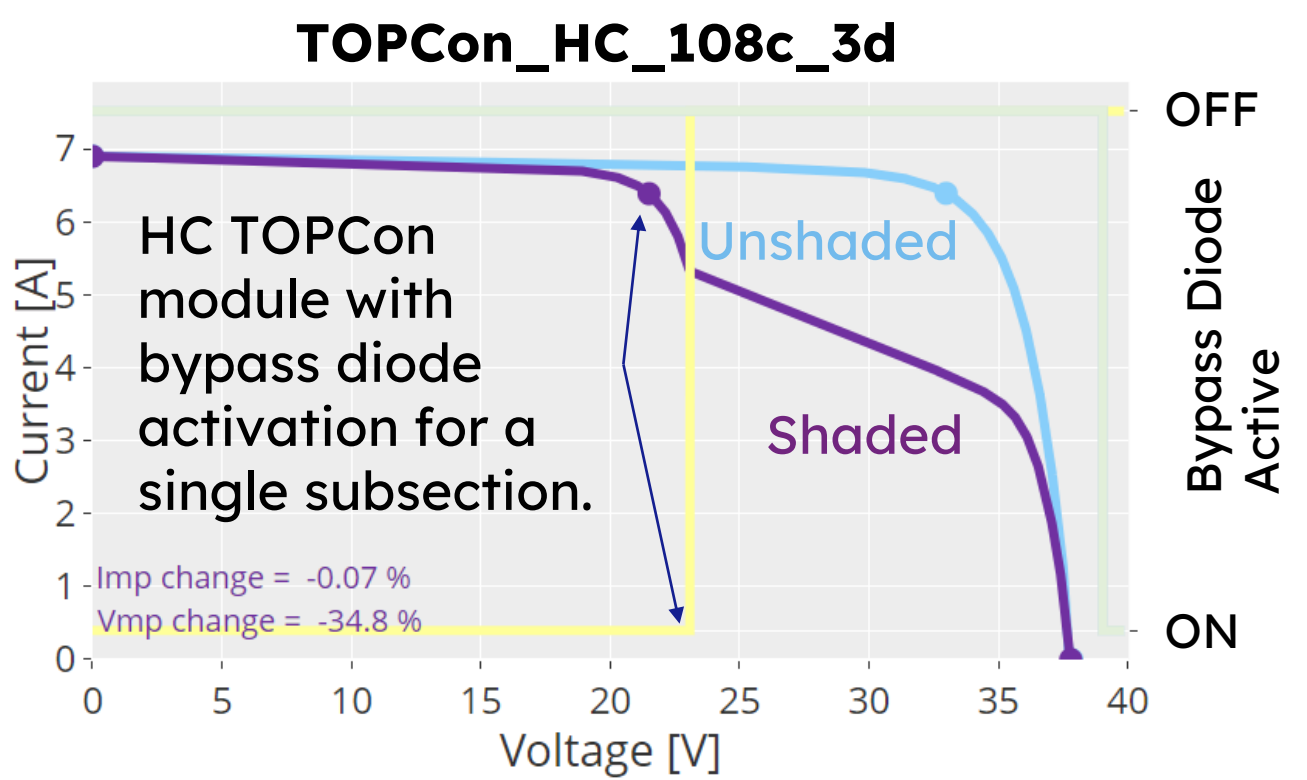
- Inverter voltage requirements ignored for this study.
- IBC modules modeled with low V_{rb} .
- This study ignores module temperature of hot spots (Reduced diodes leading to increased hotspot risk).

RES: Bypass Diode Activation



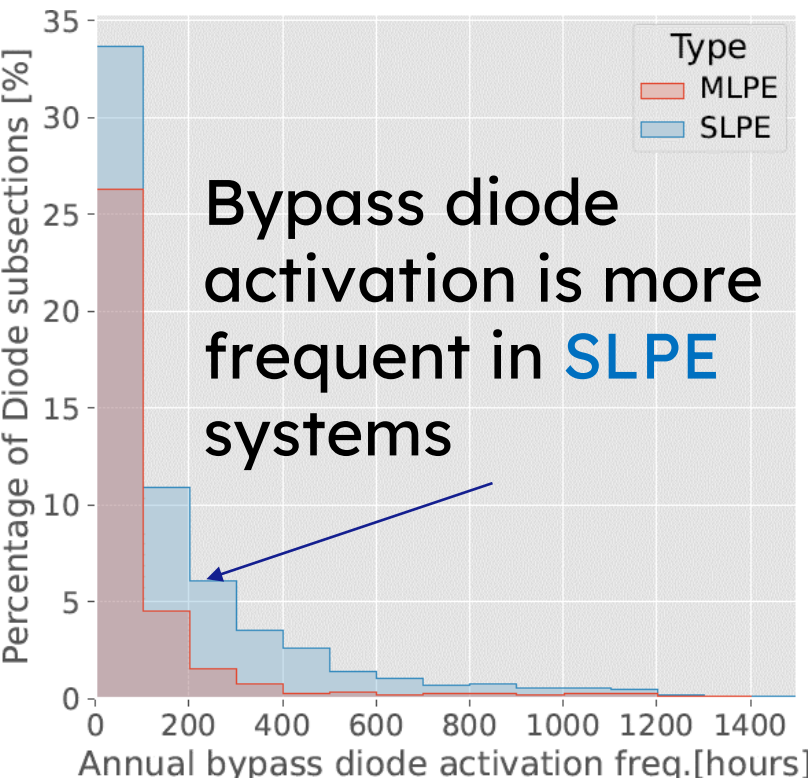
Shading a single cell in a module

With modification in the PVMismatch code, the bypass diode activation can be exposed for each subsection



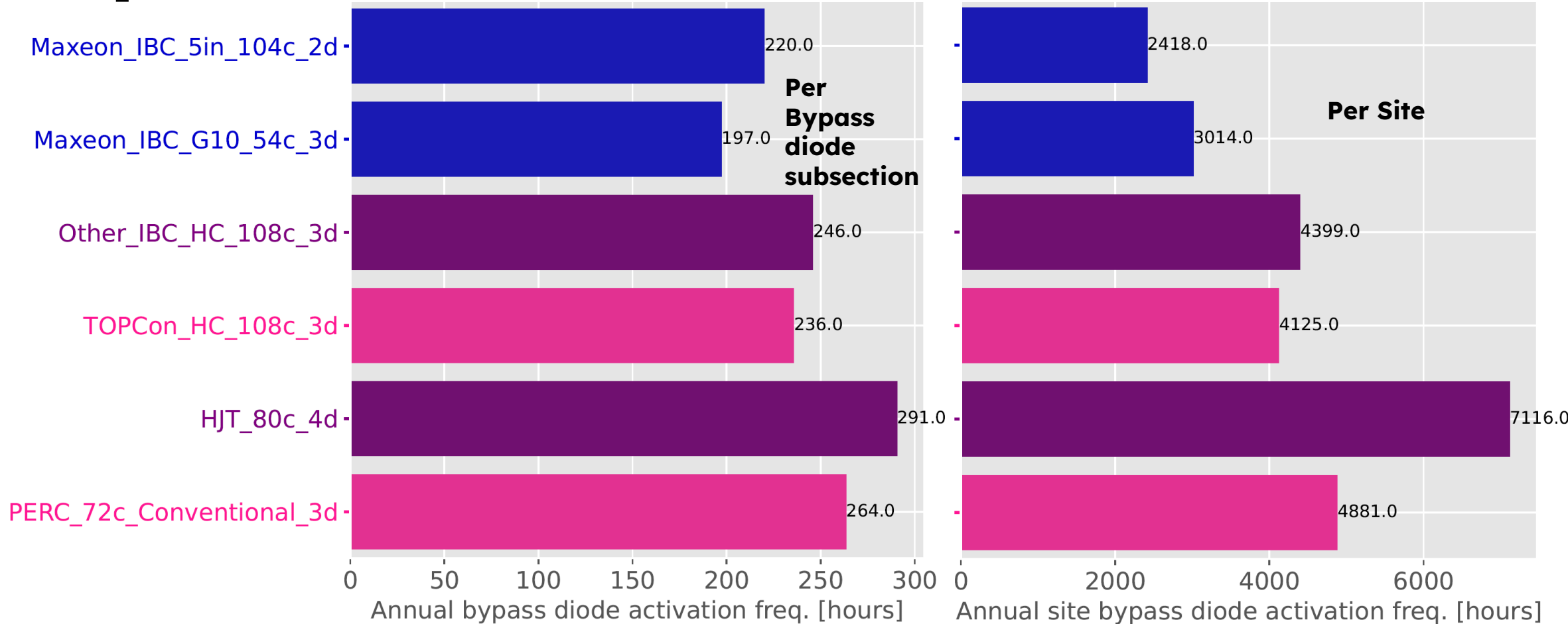
Annual bypass diode activation frequency [hours]

Example distributions for Maxeon IBC Module



Modules with low V_{rb} are less likely to activate bypass diodes under shading conditions and enables using fewer bypass diodes.

Mean annual bypass diode activation frequency [hours] for SLPE

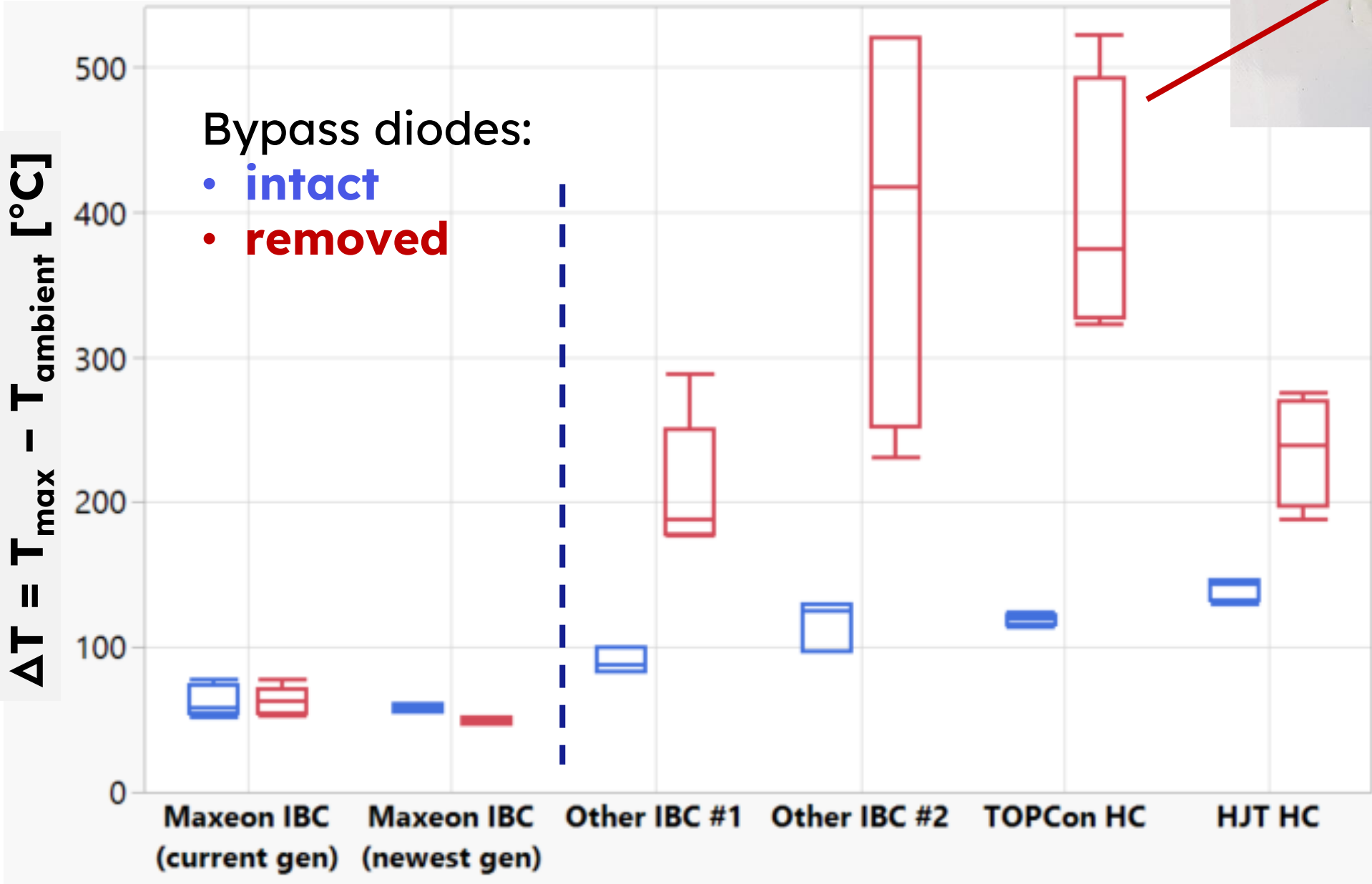


maxeon

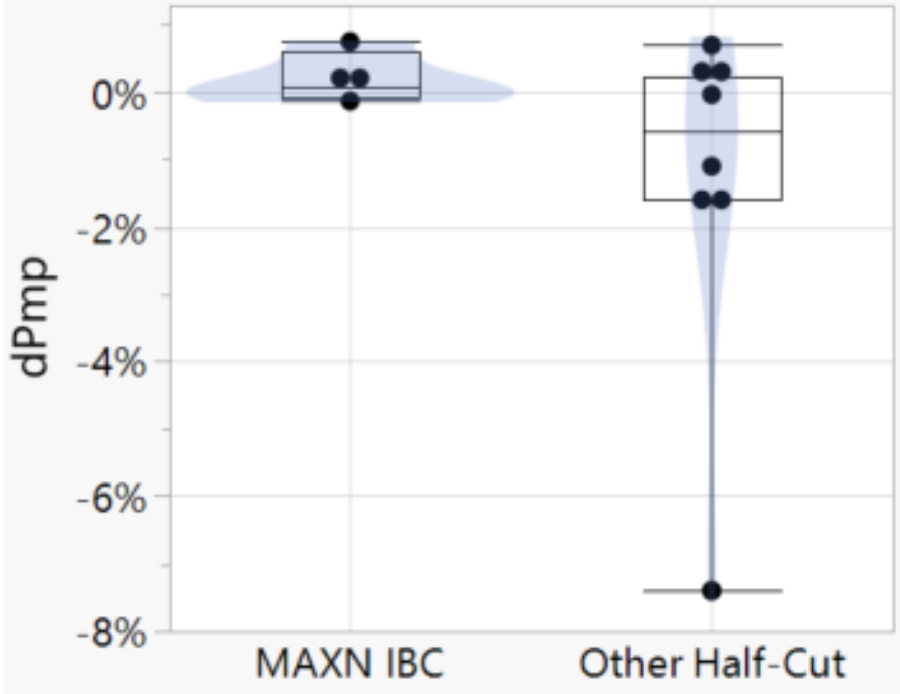
Shading → Hotspot Risk

Cell technology & module design can have a major effect on hotspot behavior, affecting both performance and reliability.

Field hotspot test with 50% of one cell shaded:
Huge difference due to cell tech & V_{RB}

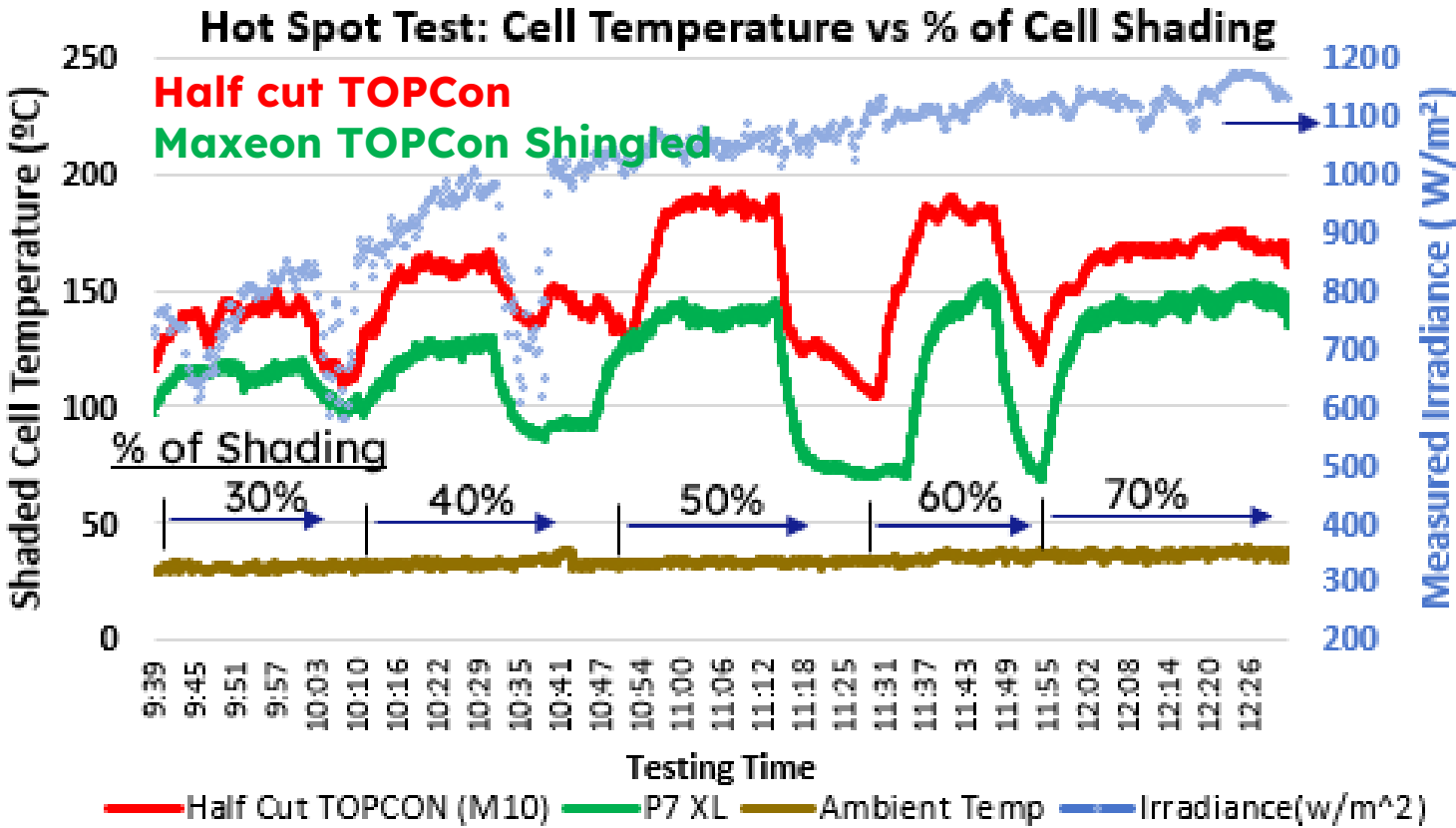


Significant permanent degradation with simulated diode failure -- ΔP_{mp} after only 20 minutes test:



Cell size and circuit design can also mitigate hotspot temperatures:

Shingled module with 3 parallel circuits and 1/3rd cut cells → 20-40°C cooler than **half-cut**



Key Highlights & Future Work

Key Highlights (that many performance modeling tools and studies don't capture):

- Technology-specific shading loss differences can sometimes exceed differences in effects like IAM, low light, and module temperature coefficient.
- **Modules with low V_{rb} have significantly lower energy losses, annual bypass diode activation frequencies, and hotspot temperatures.**
- **Shingled modules have lower energy losses and hotspot temperatures.**

Planned activities:

- Utility Power Plants (UPP):
 - Row-to-row shading might be the most common scenario.
 - Include fixed tilt and tracker (with and without backtracking) systems.
- System-level validation of the modeling framework.

Collaboration opportunities:

- 3D-modeling to improve our physical modeling.
- MLPE and shading data sets (especially COM & UPP market segments).
- Leaves & Bird droppings, and edge soiling data sets for accurately modeling their occurrence in the field.

Acknowledgments & References

Acknowledgements:

The authors would like to thank

- Chris Deline from NREL for sharing previous shade survey data.
- Zak Stelly-Riggs and the field-testing team from Maxeon Solar Technologies for supporting model validation and hotspot testing.

References:

1. *pvlib python: 2023 project update*, K. Anderson, C. Hansen, W. Holmgren, A. Jensen, M. Mikofski, A. Driesse, Journal of Open Source Software, 8(92), 5994, (2023).
2. *pvlib iotools — Open-source Python functions for seamless access to solar irradiance data*, A. Jensen, K. Anderson, W. Holmgren, M. Mikofski, C. Hansen, L. Boeman, R. Loonen, Solar Energy, 266, 112092, (2023)
3. *Partial Shade Evaluation of Distributed Power Electronics for Photovoltaic Systems*, C. Deline, 2012 IEEE Photovoltaic Specialists Conference, June 3–8, 2012.
4. *Partial-Shading Assessment of Photovoltaic Installations via Module-Level Monitoring*, C. Deline, S. MacAlpine, A. Hanson, J. Stauth, C. Sullivan, 40th Photovoltaic Specialist Conference (PVSC), June 8–13, 2014.
5. *Tesla Solar Inverter Architecture White Paper*, 2022.
6. *Whitepaper: Optimization with Impedance Matching and Predictive IV*, Tigo.
7. *Accurate Modeling of Partially Shaded PV Arrays*, B. Meyers, M. Mikofski, 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), Washington, DC, USA, 2017, pp. 3354-3359, doi: 10.1109/PVSC.2017.8521559.
8. *Regression Analysis: Segmented Regression*, Wikipedia.
9. *A fast parameterized model for predicting PV system performance under partial shade conditions*, B. Meyers, M. Mikofski, M. Anderson, 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, USA, 2016, pp. 3173-3178, doi: 10.1109/PVSC.2016.7750251

Thank you!