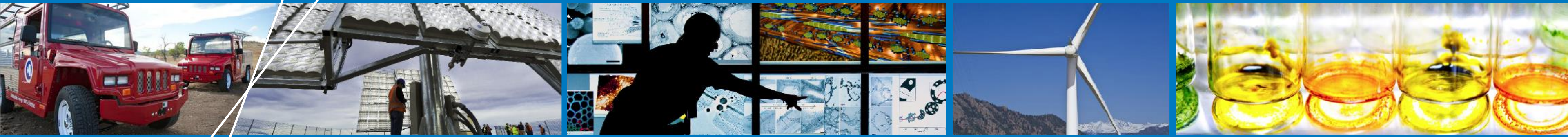
Performance Modeling and Testing of Distributed Electronics in PV Systems



APEC 2015, Charlotte NC

Chris Deline

3/18/15

Roadmap

- Overview of Distributed MPPT (DMPPT) in PV
- Performance benefits of DMPPT
- Shade modeling in SAM

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- Overview of Distributed MPPT (DMPPT) in PV
- Performance benefits of DMPPT
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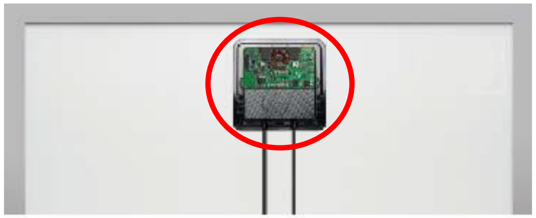
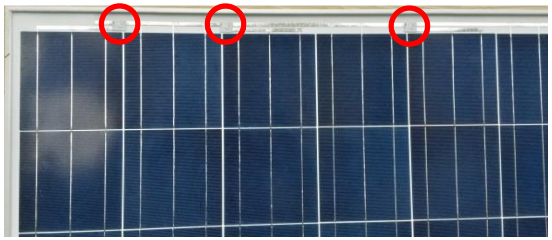
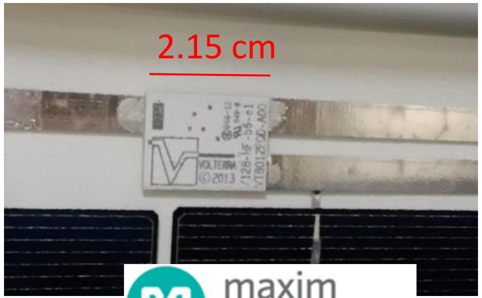
Examples of Distributed MPPT products







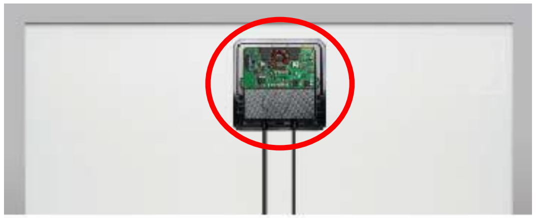
Frame - attached

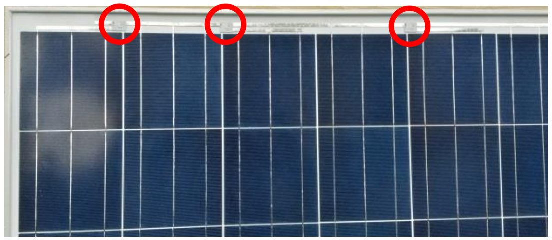
J-box embedded

Laminate embedded

Credit: Enphase Energy, Tigo Energy, Maxim Integrated

Examples of Distributed MPPT products





[e] enphase ENERGY

Tigo® energy

maxim integrated™

Frame - attached

J-box embedded

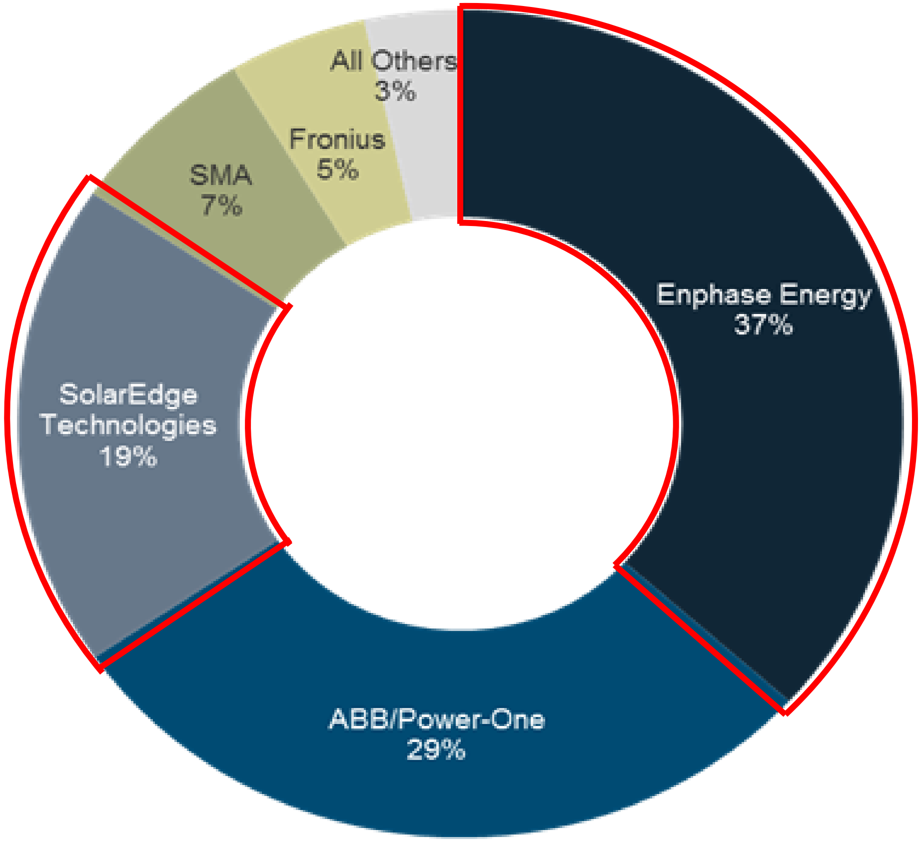
Laminate embedded

DMPPT = MLPE, microinverter, power optimizer…

Credit: Enphase Energy, Tigo Energy, Maxim Integrated

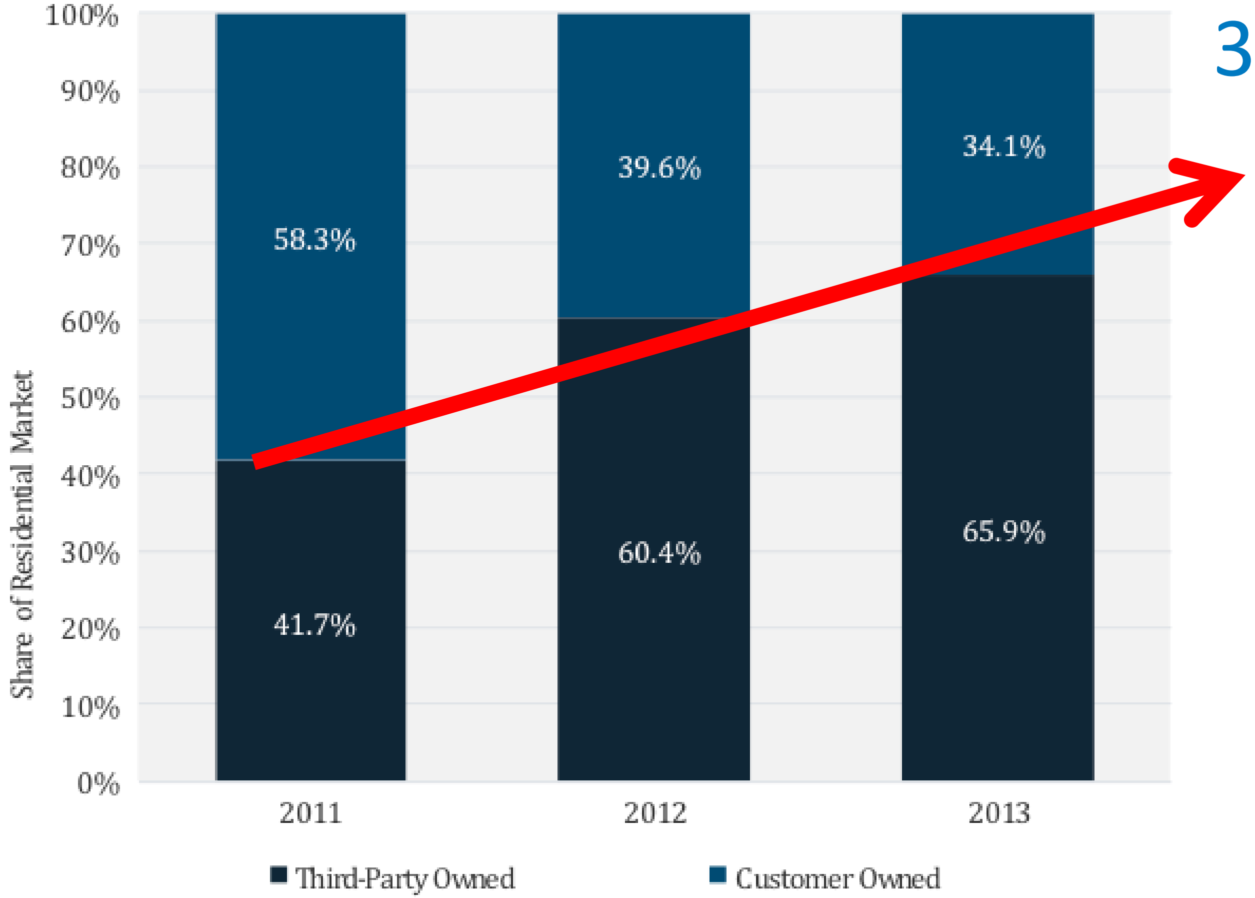
US residential market (1H 2014)

DMPPT market share: 56%



Source: GTM Research U.S. PV Leaderboard, Q2 2014

US residential market – 3rd party ownership



3rd-party-owned in 2014 : 68%

Source: GTM Research U.S. Residential Solar Financing 2014-2018

DMPPT pro/con

Pro:

- Flexibility of design
- Meets NEC 690.12
- Data monitoring
- Shade performance
- Warranty

Con:

- Cost
- Efficiency (maybe)
- More potential points of failure
- O&M concerns

NEC 690.12 (2014)

Code requires rooftop PV conductors greater than 10’ from the array to be de-energized in event of emergency

Compliance options:

Remote relays

Roof-mounted inverters

Microinverters and Power Optimizers

Credit: Midnite Solar, SMA, Tigo

NEC 690.12 (2014)

Code requires rooftop PV conductors greater than 10’ from the array to be de-energized in event of emergency

Compliance options:

Credit: SolarPro

Other emerging inverter trends:

- California Rule 21 (grid support capabilities for PV inverters)
- Storage capabilities for utilities without net metering, or with time-of-day pricing
- NEC 690.12 (2017): proposed module-level shutdown

Roadmap

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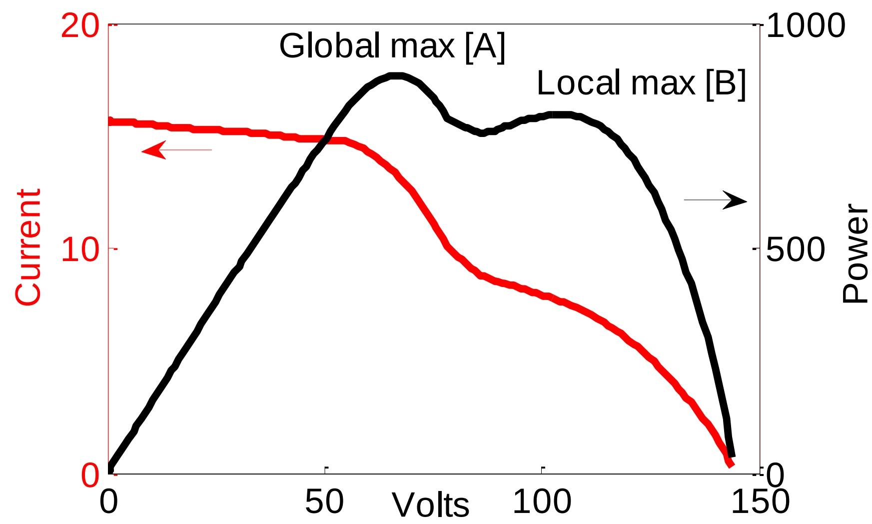
Recoverable vs. Non-recoverable loss in PV

Partial shading leads to power loss from reduced irradiance (non-recoverable) and panel mismatch (recoverable)

The better the peak-power tracking (MPPT) granularity, the higher the recoverable power

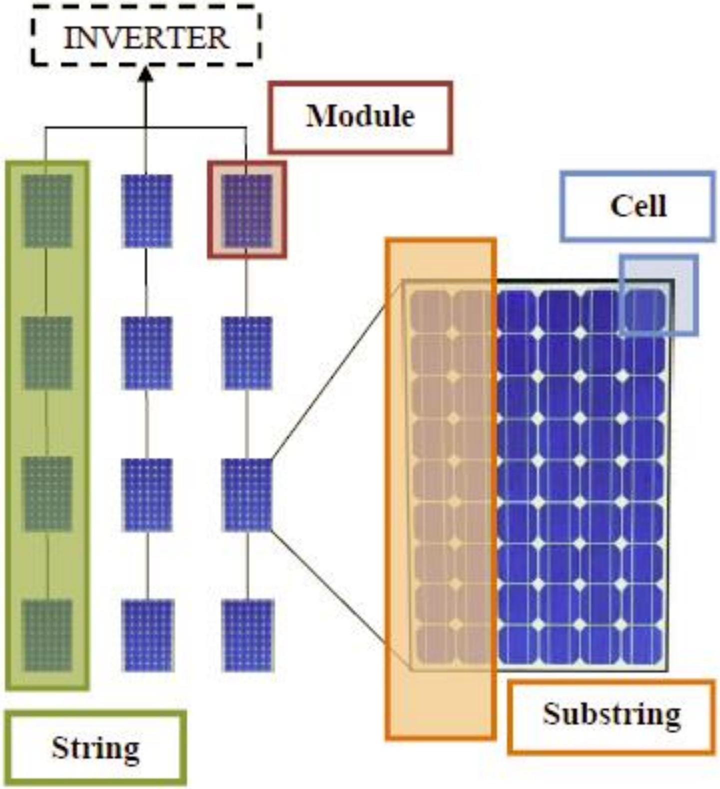


Mismatched panels in a series string. Either bypass diodes are turned on in the shaded panels (point [A]) or all panels operate at a low current (point [B])

C. Deline, B. Marion, J. Granata, S. Gonzalez. *A Performance and Economic Analysis of Distributed Power Electronics in Photovoltaic Systems*. NREL Report No. TP-5200-50003. Golden, CO: National Renewable Energy Laboratory, December 2010

Overview of Distributed MPPT

Finer peak-power tracking granularity leads to reduced mismatch



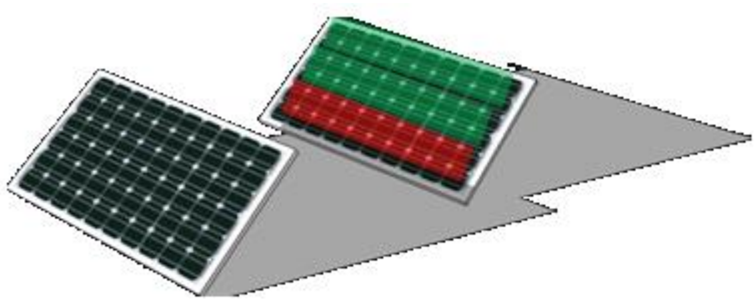
Annual performance improvement under heavy shade

+2%	+8%	+9%	+12%
String	Module	Submodule	Cell

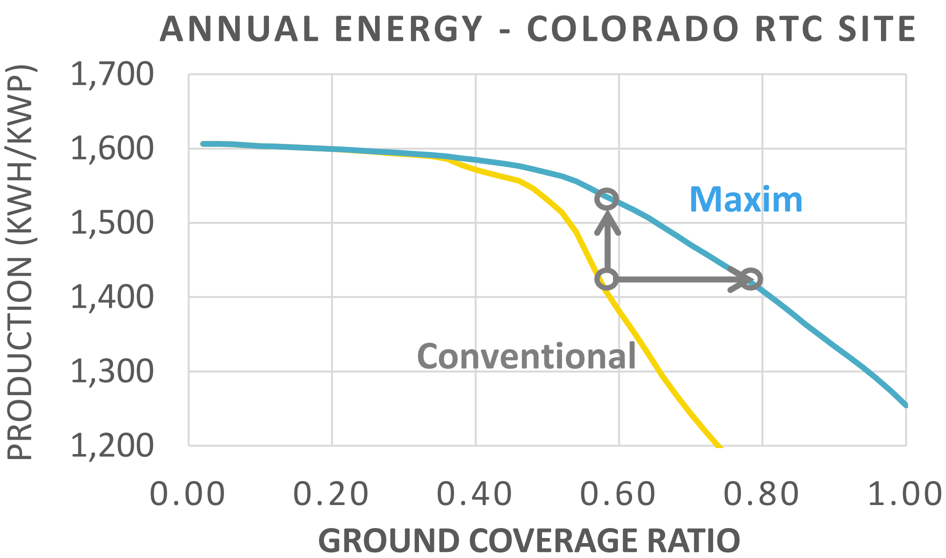
MPPT Granularity →

S.M. MacAlpine, M.J.Brandemuehl, R.W.Erickson, "Potential for power recovery: simulated use of distributed power converters at various levels in partially shaded photovoltaic arrays," in Proc. PVSEC 2011.

Sub-module power conversion



*Mismatch occurs **within** the module



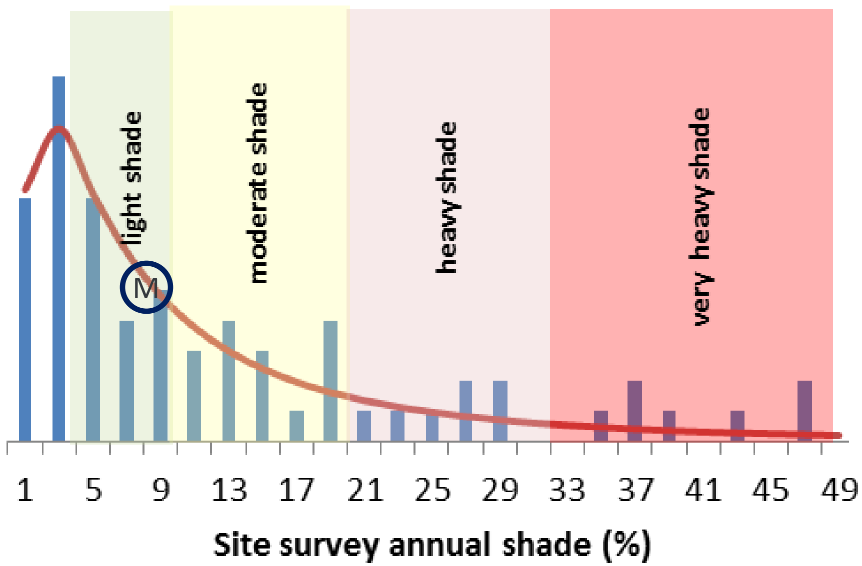
Sub-module DC-DC converters:

- Enable 10-20% tighter row pitch, -or-
- 1-3% more energy / panel at the same row pitch

C. Deline et al., "Evaluation of Maxim Module-Integrated Electronics at the DOE Regional Test Centers", 40th IEEE Photovoltaic Specialists Conference, Denver, CO, 2014

Shading Survey gives real-life conditions

Survey of >60 residential installations provides distribution of **shade extent**



Imaging tool shows shade obstructions for residential rooftops

Deline, C., Meydbray, J., Donovan, M. (2012) NREL Report No. TP-5200-54876

Assessment of typical shade conditions

Shade Recovery Factor (SRF) measures the fraction of shade loss recovered by DMPPT

$$SRF = \frac{\sum P_{DMPPT} - \sum P_{Normal}}{\sum P_{unshaded} - \sum P_{Normal}} = \frac{Recovered\ Power}{Lost\ Power}$$

Hanson A, Deline C, MacAlpine S, Stauth J, Sullivan C, "Partial-Shading Assessment of Photovoltaic Installations via Module-Level Monitoring", IEEE Journal of Photovoltaics, **4** 1618-1624, 2014

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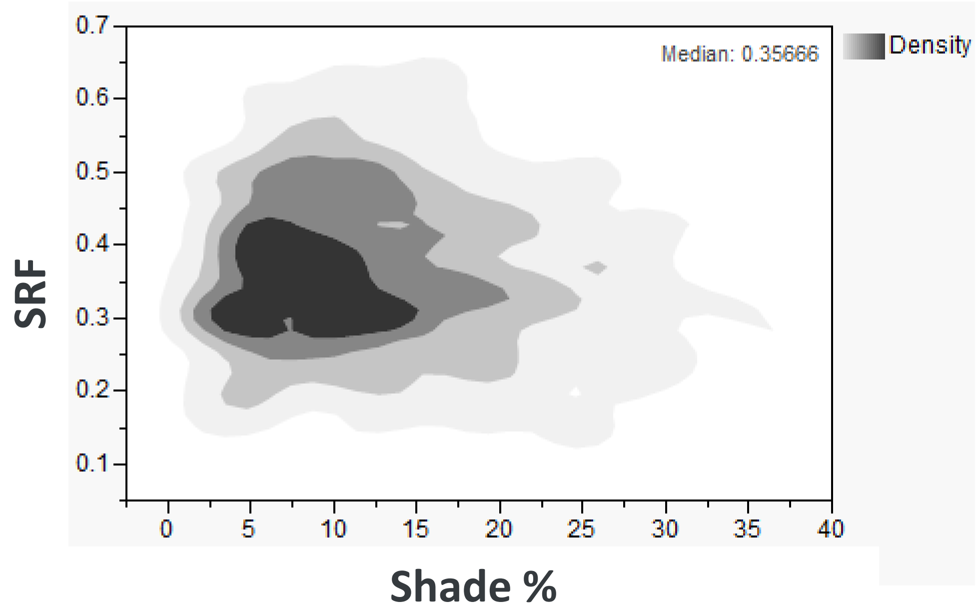
Survey of > 300 systems with power optimizers

Estimated 36% shade recovery on average,
7% average shading loss



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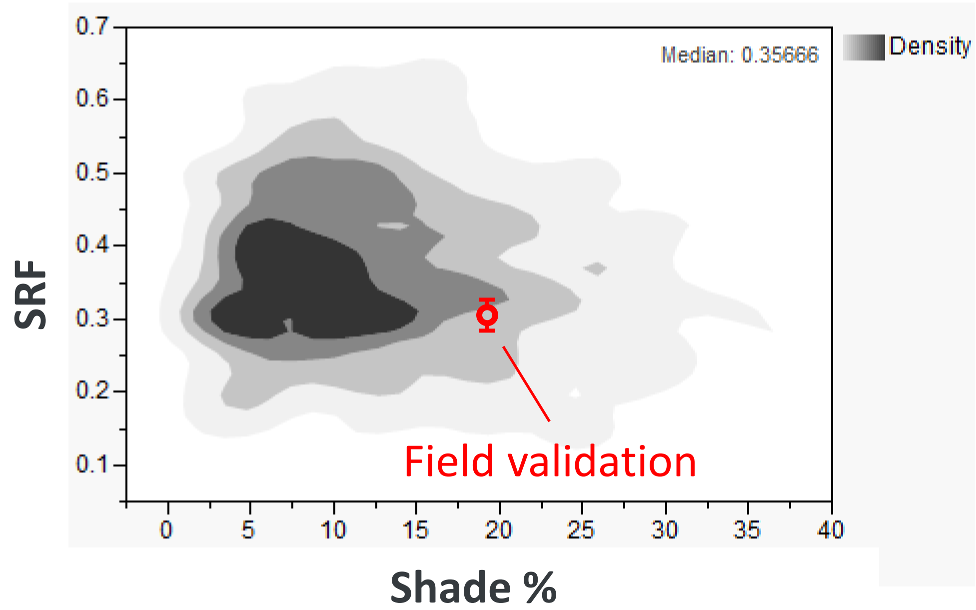
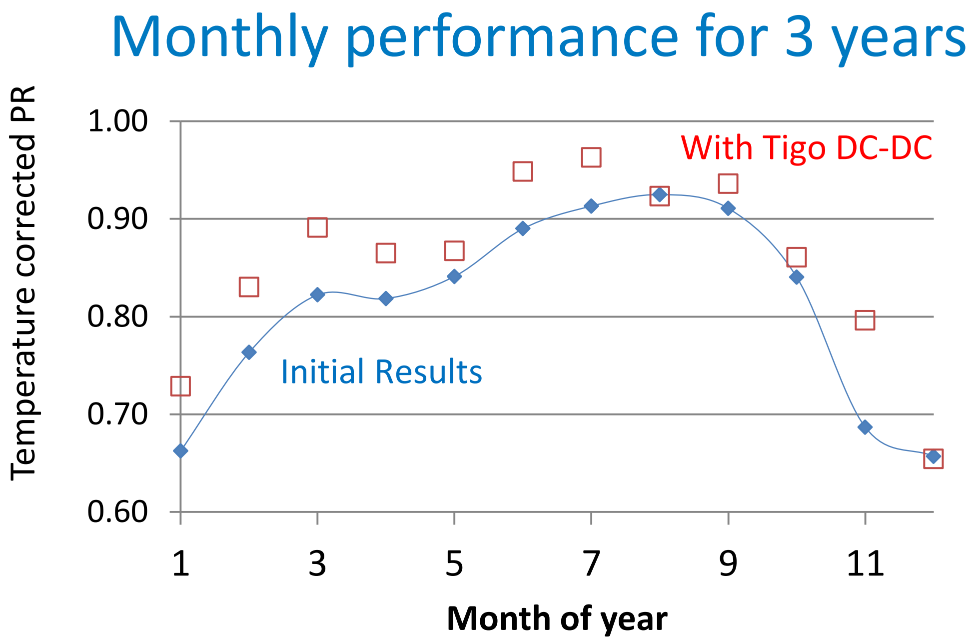


Hanson A, Deline C, MacAlpine S, Stauth J, Sullivan C, “Partial-Shading Assessment of Photovoltaic Installations via Module-Level Monitoring”, IEEE Journal of Photovoltaics, **4** 1618-1624, 2014

Validation: before and after Power Optimizers



*5.8% more energy with module-level MPPT. 30% shade recovery

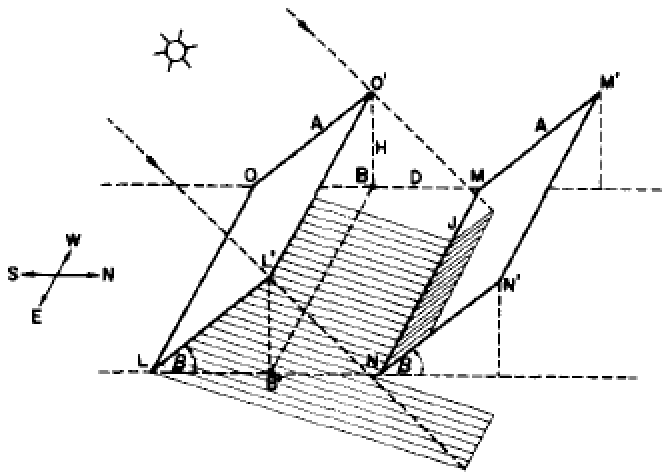
Hanson A, Deline C, MacAlpine S, Stauth J, Sullivan C, "Partial-Shading Assessment of Photovoltaic Installations via Module-Level Monitoring", IEEE Journal of Photovoltaics, **4** 1618-1624, 2014

Roadmap

- Overview of Distributed MPPT (DMPPT) in PV
- Performance benefits of DMPPT
- Shade modeling in System Advisor Model

Inter-row shading in System Advisor Model

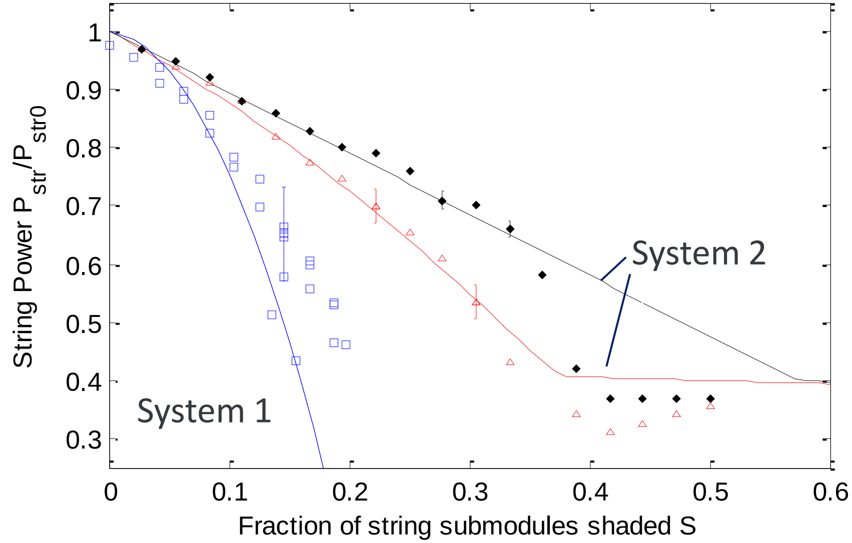
How much power is actually lost from inter-row shading?
Can you improve kWh/m^2 or \$/kWh by closer row spacing?



https://sam.nrel.gov/

C. Deline et al., "**A simplified model of uniform shading in large photovoltaic arrays,**" Solar Energy **96**, pp 274–282, 2013. Image credit: Thakkar 2010, Applebaum 1979

Experimental validation of SAM model

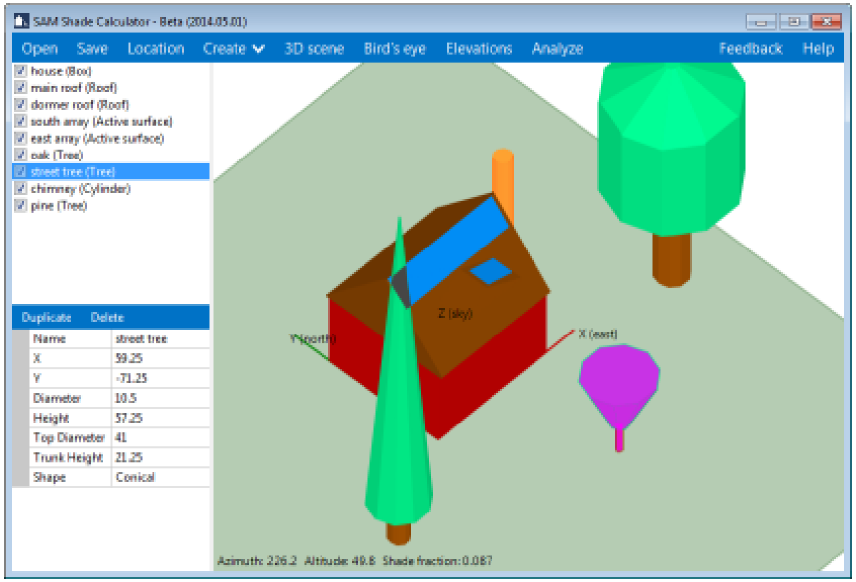


https://sam.nrel.gov/

C. Deline et al., "**A simplified model of uniform shading in large photovoltaic arrays,**" Solar Energy **96**, pp 274–282, 2013.

New: 3D scene shading in SAM

- Relevant for residential rooftop simulations
- Now: linear shade model (low accuracy)
- In progress: new shade database (correct shade loss predictions)
- Future work: distributed (module-level) MPPT performance



SAM 2014 shading tool snapshot

https://sam.nrel.gov/

S. MacAlpine, C. Deline, "Simplified Method for Modeling the Impact of Arbitrary Partial Shading Conditions on PV Array Performance", 31st IEEE PVSC, 2015 (not yet published)

Questions?

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chris.deline@nrel.gov

Ph: (303) 384-6359

Acknowledgments

This work was supported by the U.S. Department of Energy under Contract No. DOE-AC36-08GO28308 with the National Renewable Energy Laboratory

NREL
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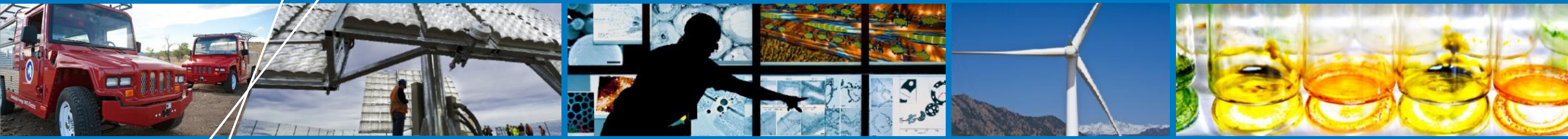


Backup slides

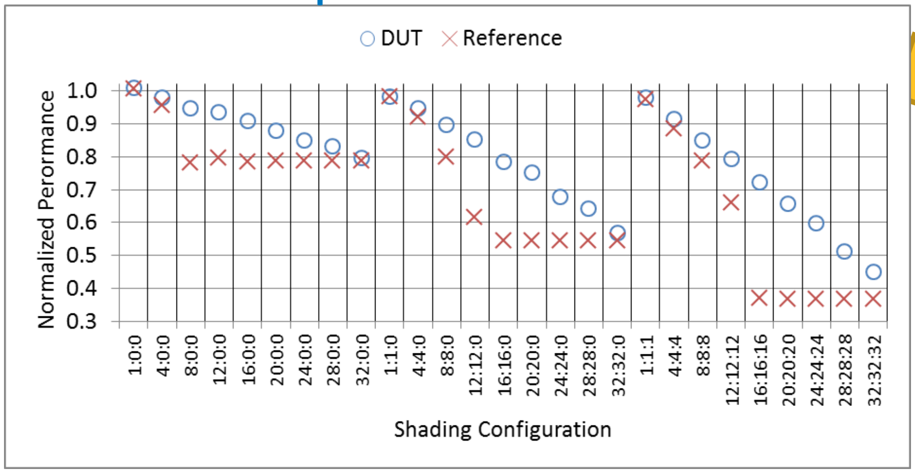
Side by Side Shading study

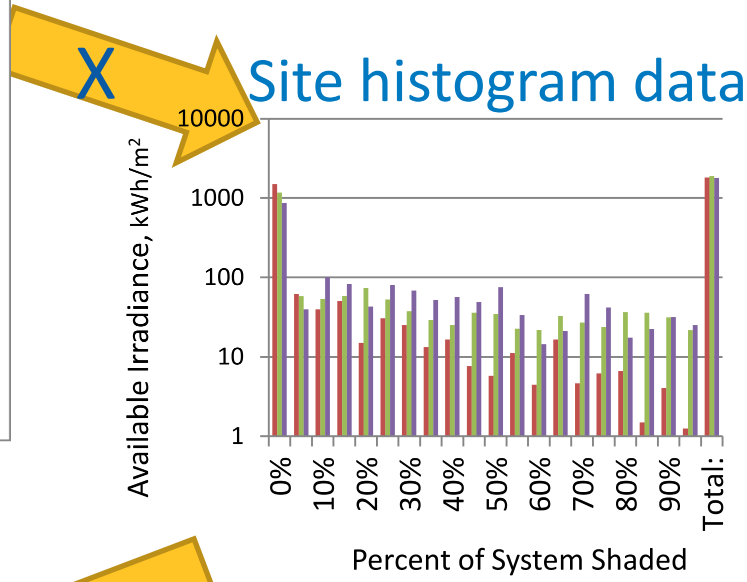
- **Side by side** comparison, 2 **identical** arrays
  - one with **string inverter**, one with **microinverters** (or DC converters)
- **Synthesized shading** using 60% opaque fabric
- Results are weighted based on **real residential shading scenarios** (annual)

Deline, C., Meydbray, J., Donovan, M., & Forrest, J. (2014). Photovoltaic shading testbed for module-level power electronics: 2014 Update. http://www.nrel.gov/docs/fy14osti/62471.pdf

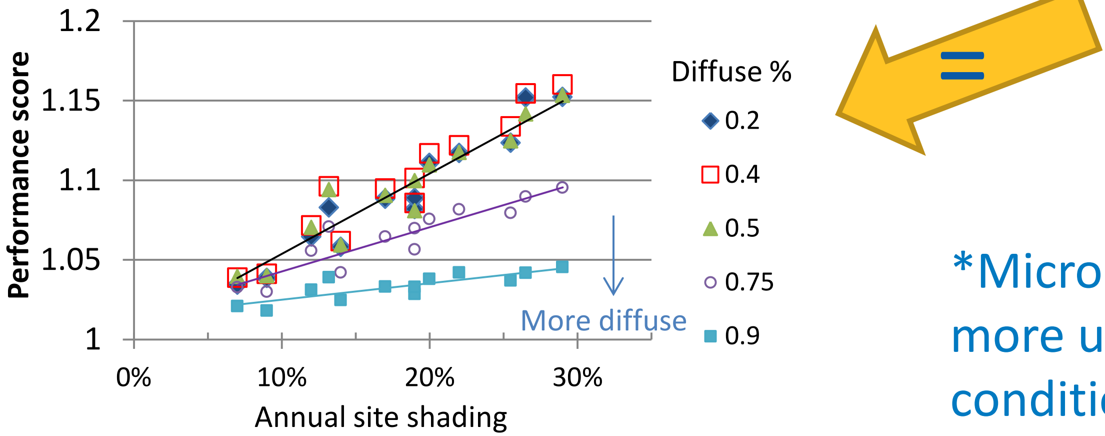
Side by Side Shading study - analysis

Raw performance data





Microinverter shade benefit



*Microinverters produced 10-12% more under heavily shaded conditions

Deline, C., Meydbray, J., Donovan, M., & Forrest, J. (2014). Photovoltaic shading testbed for module-level power electronics: 2014 Update. http://www.nrel.gov/docs/fy14osti/62471.pdf