Quantifying Mismatch Losses in Small Arrays

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Brief Overview

- Mismatch Losses – Definition and Significance
- Research Goals
- Data Collection
- Module Parameter Variation
- Mismatch Losses -- Examples

Mismatch Losses – Definition and Significance

- $$Electrical\ Mismatch\ Loss = \frac{\sum P_{Mod,Max} - P_{Sys,Max}}{P_{Sys,Max}}$$

- Unshaded systems with uniform module orientation
- Includes manufacturer's performance tolerances and degradation-induced mismatch between modules
- Includes spatial variation of incident radiation and module temperature

Mismatch Loss = Recoverable Power

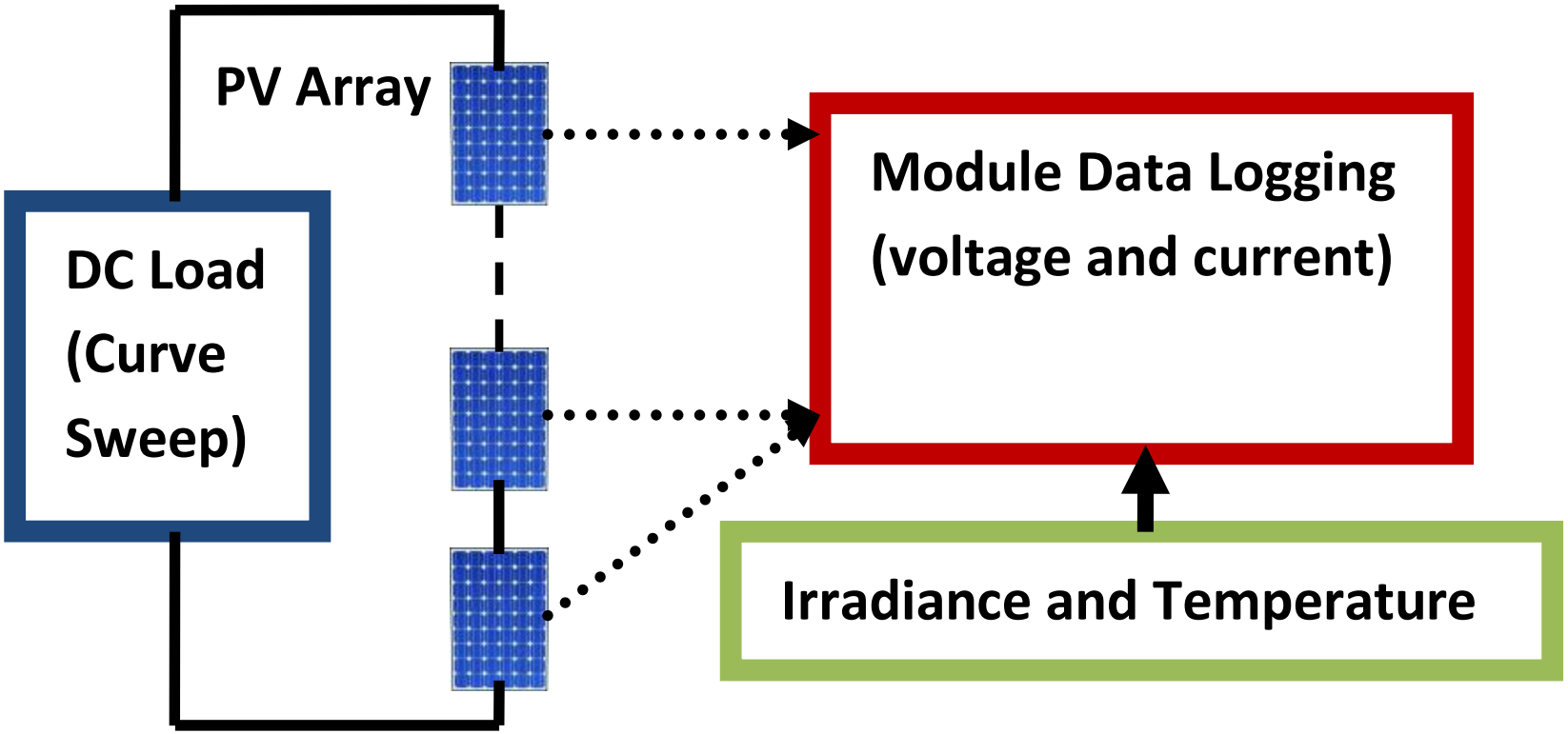
Research Goals

Quantify typical module-to-module performance variation and associated losses in installed PV arrays

- How accurate is standard 1-2% mismatch derate?
- How do losses vary with operating conditions?
- What is the impact of system age?
- Are losses PV technology dependent?

Data Collection: System Design

Simultaneous I-V curves at the module level

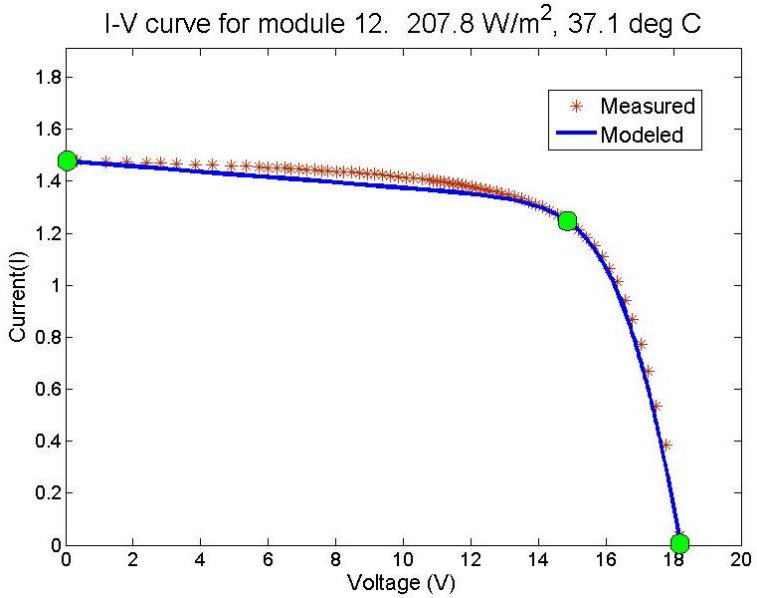


Data Collection: I-V Curve Sweeps

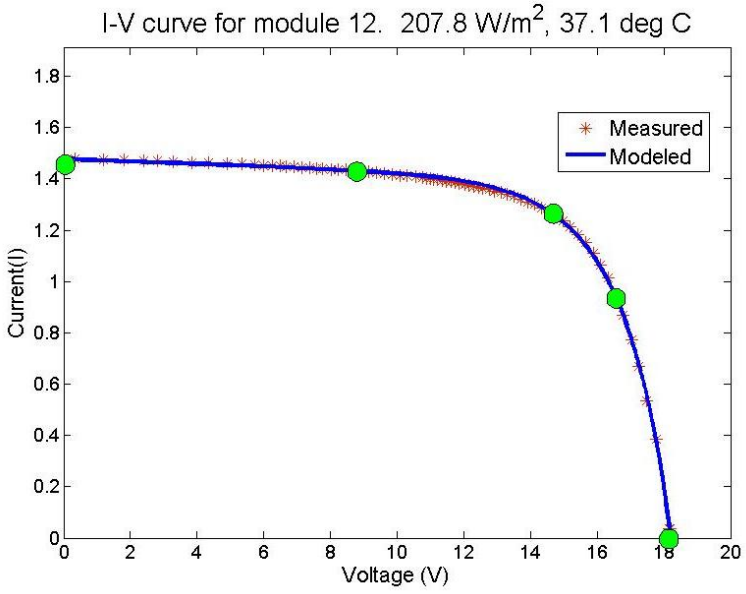
- High (~1000 W/m^2) and low (~250 W/m^2) light levels
- 1 minute I-V sweep
- Plane-of-array irradiance and back-of-module temperature averaged over curve sweep
- Multiple run data taken under similar conditions

Single Diode Model Fitting

No



Yes



Arrays

- Newer (< 5 years) and older (5-11 years) systems
- Residential sized (~1-5kW)
- Crystalline silicon, thin film (CdTe, CIS/CIGS, a-si), and hybrid technologies
- Located in Arizona, Colorado, and New Mexico

Arrays

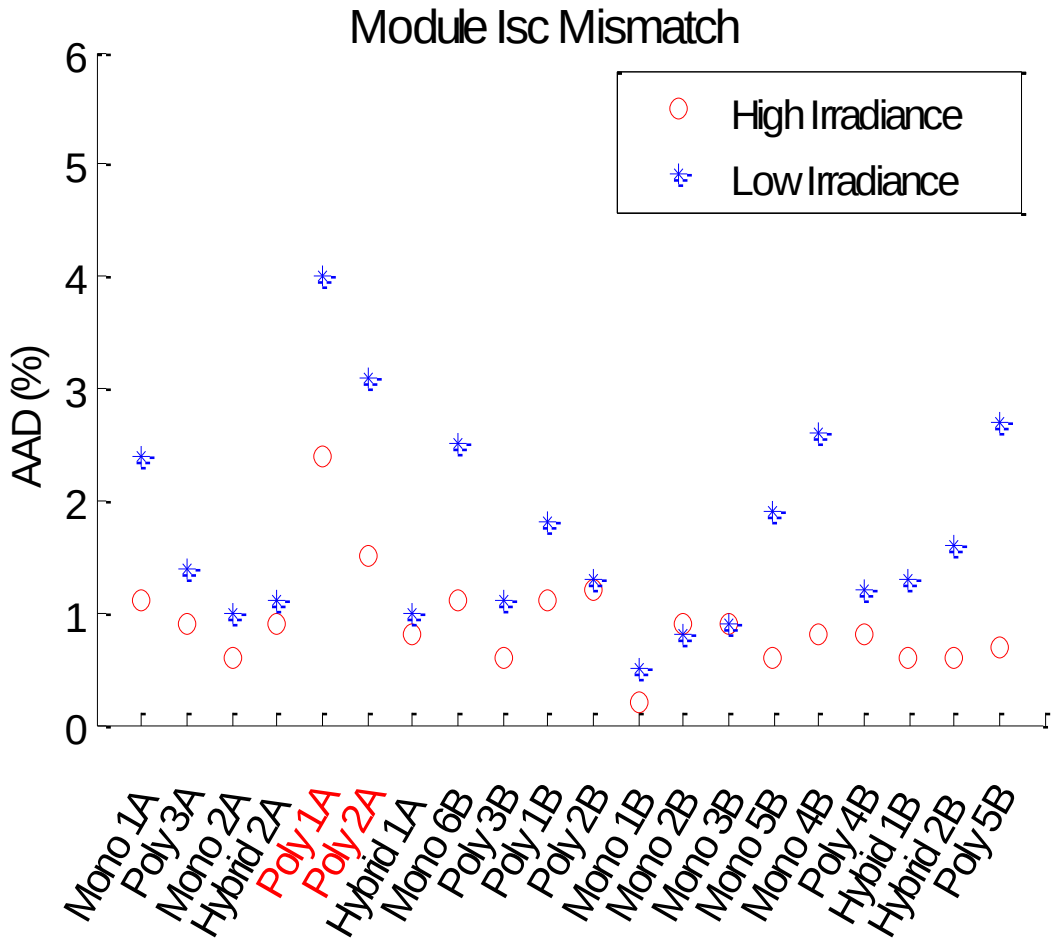
Newer Systems		Older Systems			
Array	# Modules	Array	# Modules	Array	# Modules
Mono 1A	24	Mono 1B	21	Hybrid 1B	8
Mono 2A	9	Mono 2B	21	Hybrid 2B	8
Poly 1A	30	Mono 3B	27	Thin 1B	14
Poly 2A	15	Mono 4B	20	Thin 2B	32
Poly 3A	11	Mono 5B	9	Thin 3B	27
Hybrid 1A	12	Mono 6B	18		
Hybrid 2A	15	Poly 1B	21		
Thin 1A	20	Poly 2B	21		
Thin 2A	24	Poly 3B	18		
Thin 3A	24	Poly 4B	10		
Thin 4A	24	Poly 5B	32		

Module Parameter Variation

- Examine distributions of I_{sc}, V_{oc}, I_{mp}, V_{mp}, P_{mp} for each array
- Measurement uncertainty ~1% or less for voltage and current, ~2% or less for power
- Focus on:
  - I_{sc} – Variations in absorbed radiation across array
  - I_{mp} – Main contributor to mismatch in series strings
  - P_{mp} – Reflects both current and voltage variations

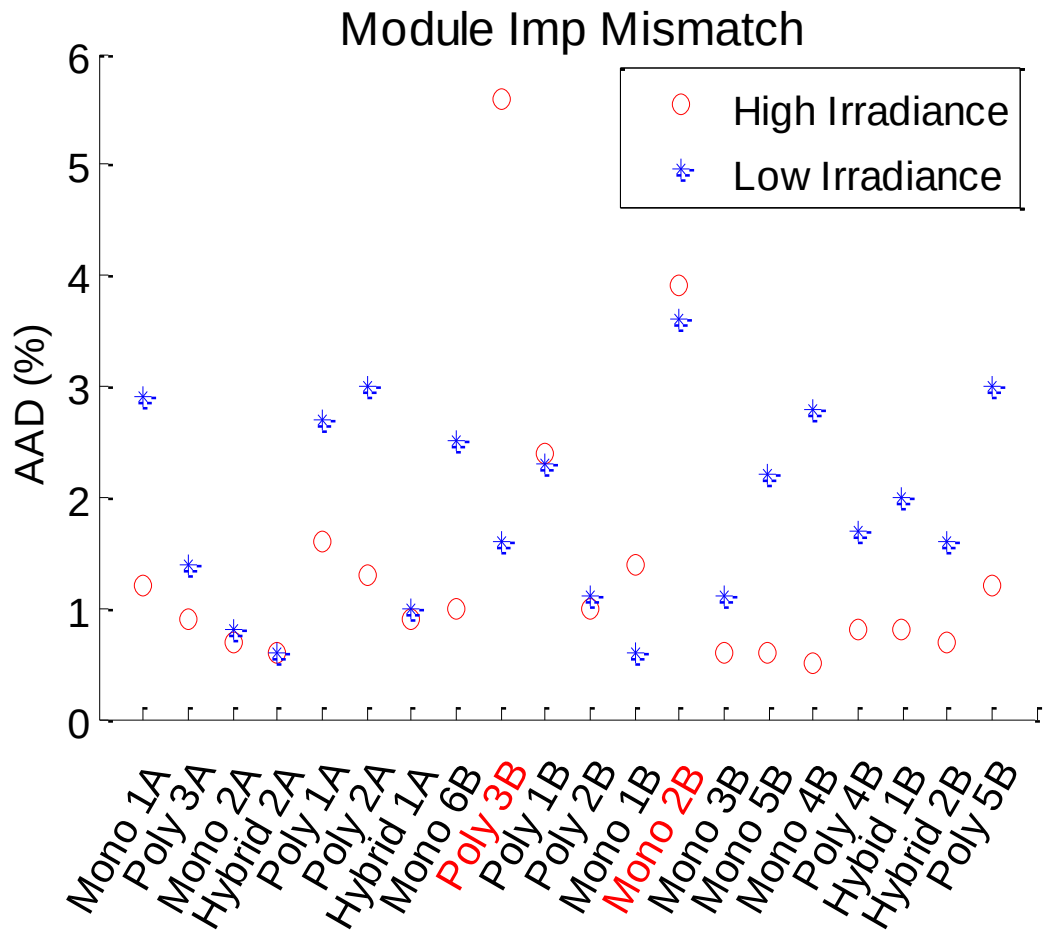
All coefficients of variation reported as average absolute deviation (AAD) from the mean

Module Parameter Variation - I_{SC}



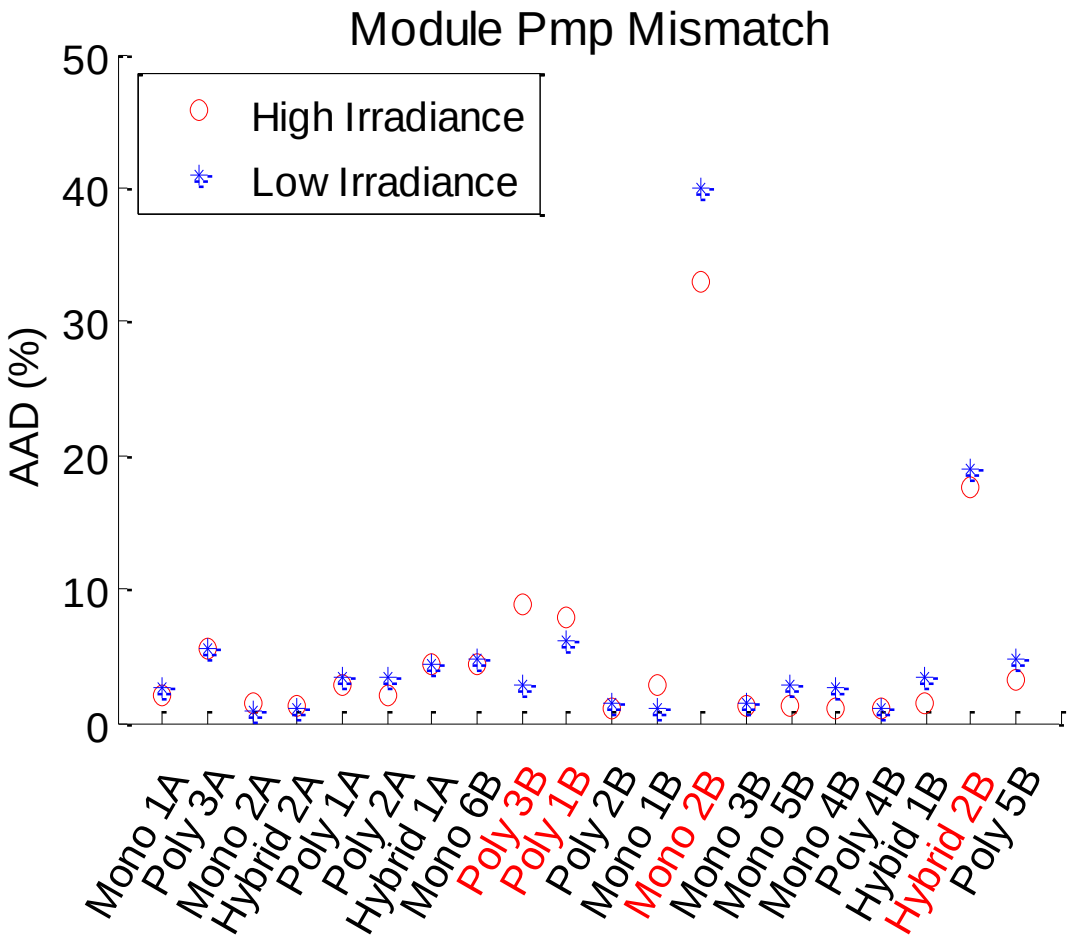
- I_{SC} mismatch generally low (2% or less)
- More mismatch at low irradiance
- Arrays with most mismatch are newer

Module Parameter Variation - I_{mp}



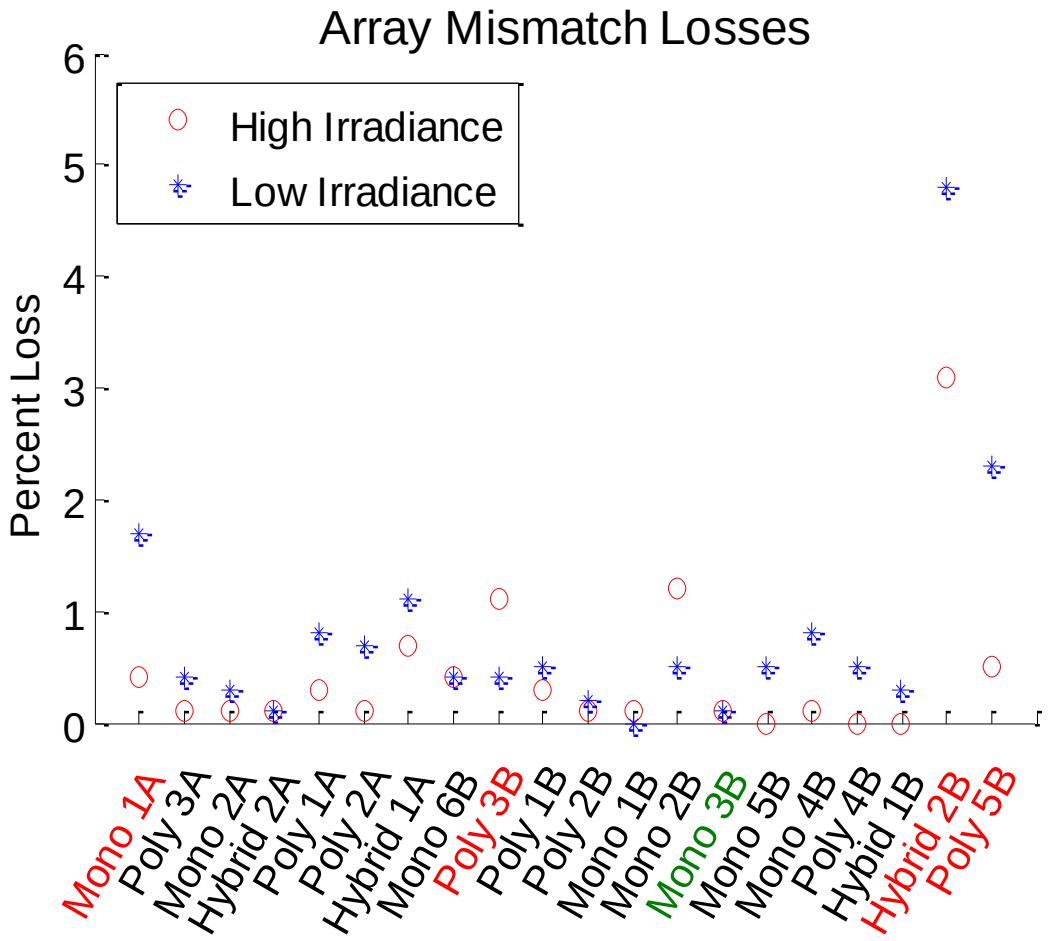
- I_{mp} mismatch not directly tied to I_{sc} mismatch
- No direct correlation between mismatch and array age

Module Parameter Variation - P_{mp}



- Some arrays see significantly more mismatch in power than in current due to module voltage mismatch

Array Mismatch Losses

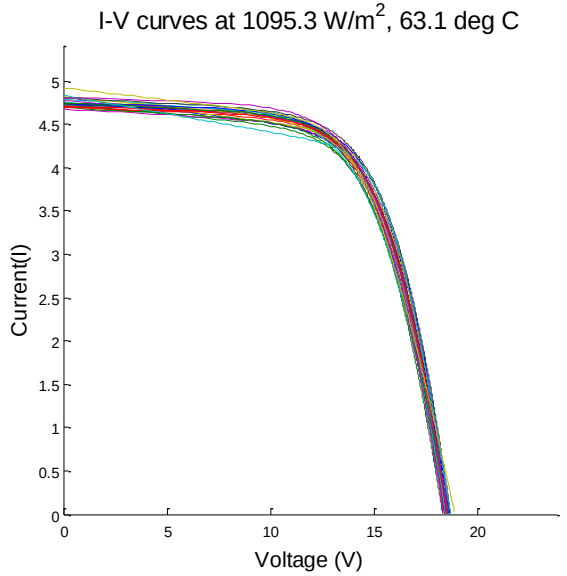


- Losses mostly < 1%
- Highest and lowest losses in older arrays
- Slightly greater losses under low irradiance conditions

Mismatch Loss – Mono 3B (1 string)

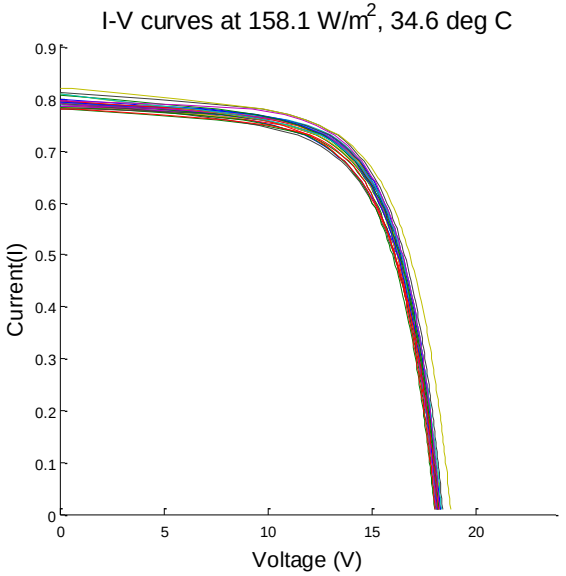
High Irradiance

Loss = 0.1%



Low Irradiance

Loss = 0.1%

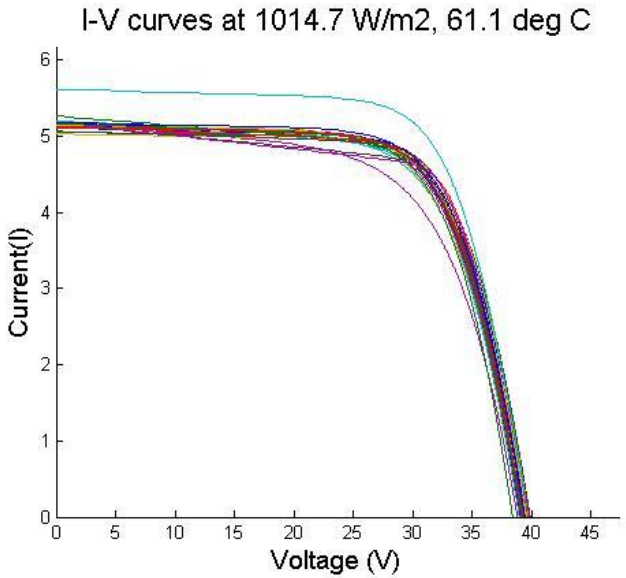


Well matched curves – very little loss

Mismatch Loss – Mono 1A (3 strings)

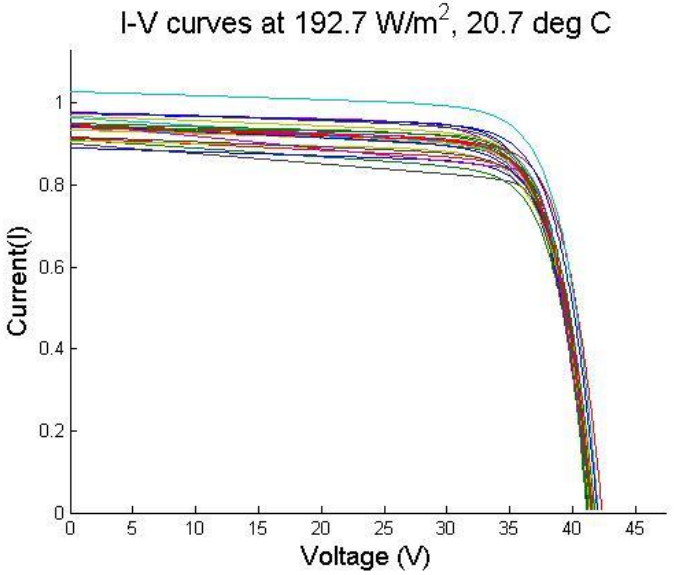
High Irradiance

Loss = 0.4%



Low Irradiance

Loss = 1.7%



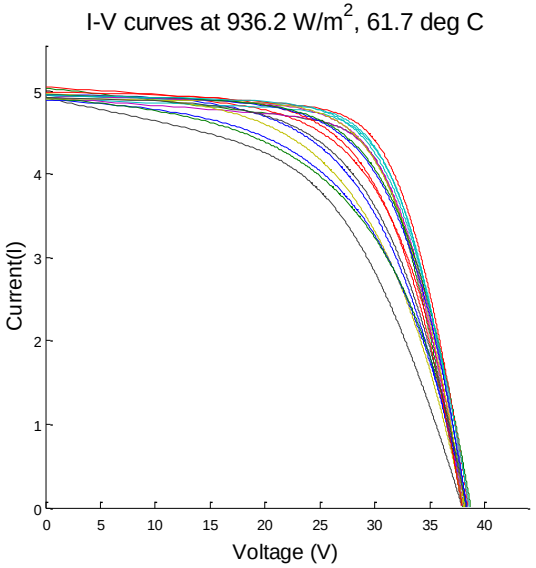
High: single current outliers cause little loss

Low: wide current variation around Imp causes greater loss

Mismatch Loss – Poly 3B (2 strings)

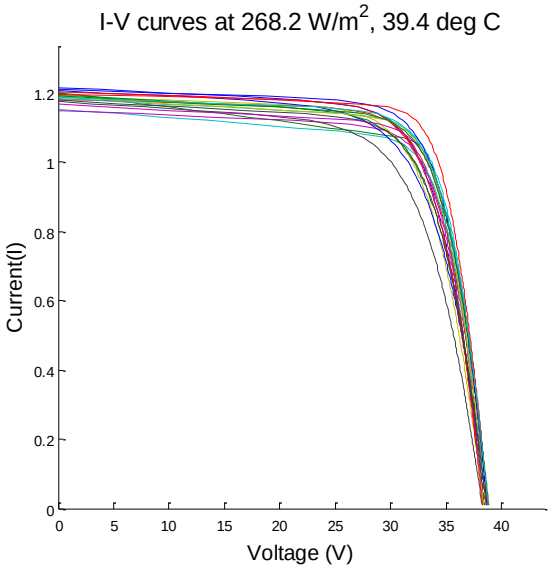
High Irradiance

Loss = 1.1%



Low Irradiance

Loss = 0.4%



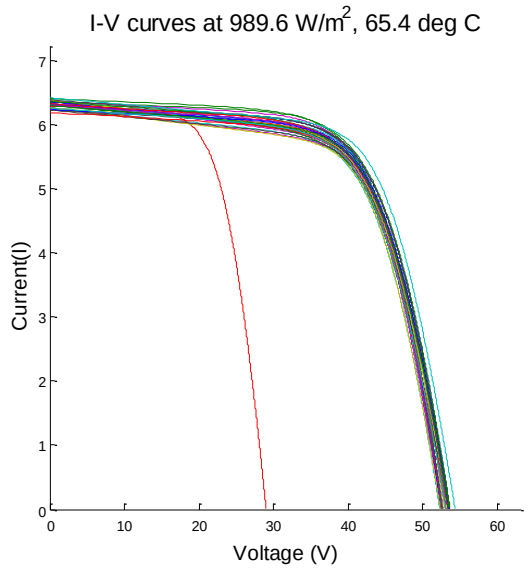
High: significant shunting/fill factor mismatch losses

Low: some current and voltage mismatch, but low mismatch loss

Mismatch Loss – Poly 5B (4 strings)

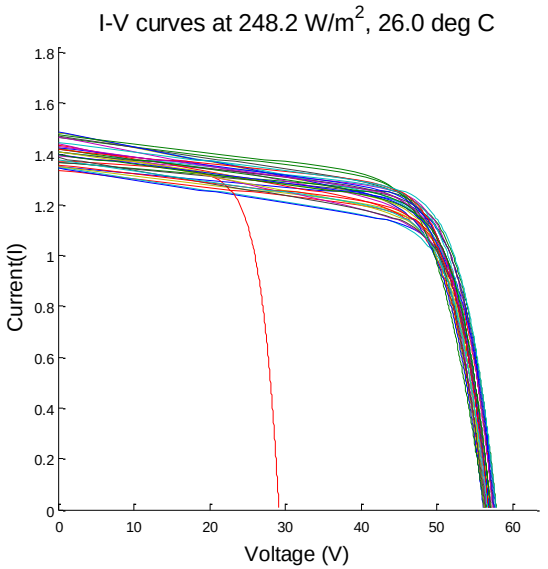
High Irradiance

Loss = 0.5%



Low Irradiance

Loss = 2.3%



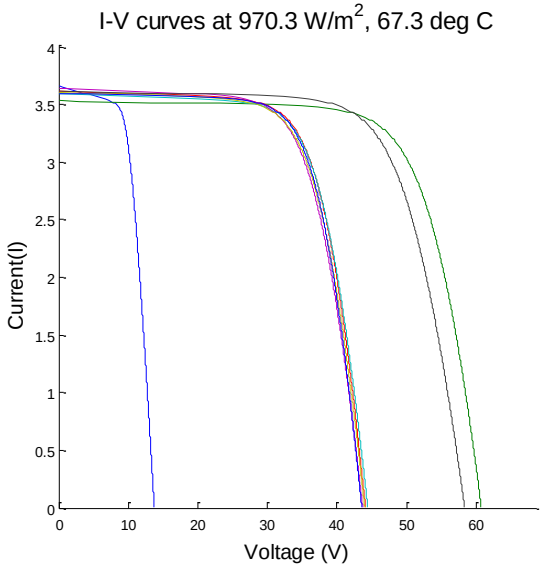
High: single voltage outlier causes little loss

Low: voltage outlier + wider I_{mp}/V_{mp} distributions increase losses

Mismatch Loss – Hybrid 2B (2 strings)

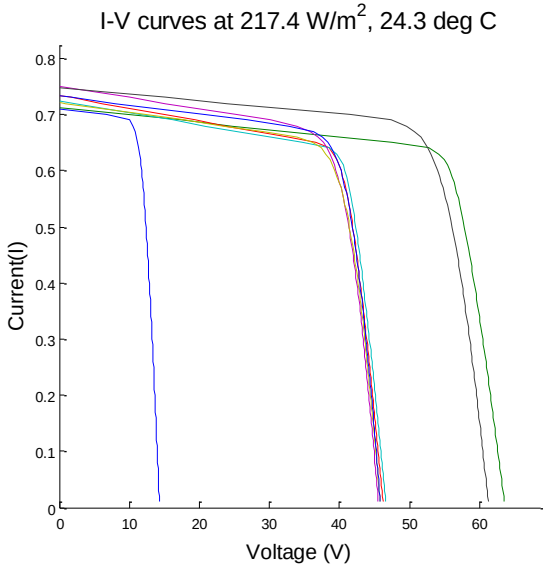
High Irradiance

Loss = 3.1% (21%)



Low Irradiance

Loss = 4.8% (5.6%)



Short, parallel strings + voltage mismatch = significant losses

Percent loss increases (blue) if considering central inverter voltage limits

Summary

- Standard 1-2% mismatch derate is reasonable (may overestimate) for 21st century PV arrays located in Southwest U.S. climate
- Mismatch losses tend to be higher under low irradiance conditions
- Mismatch losses depend more on an individual array's modules and configuration than on age or technology

Ongoing Work

- Annual simulation of mismatch losses
- Mismatch loss analysis for thin film arrays
- Investigation of higher degrees of mismatch and associated losses
- Extrapolation of results to larger arrays

Credits

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