# Quantifying Photovoltaic Module-to-Module Mismatch Losses with Real-World Rooftop Systems

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## Novelty Points

* Development of a novel method to estimate mismatch losses based on the recorded MPPT of each module from real-world SolarEdge systems
* Comprehensive benchmark of module-to-module mismatch losses across 22 diverse rooftop systems spanning multiple countries and climate zones
* Advanced filtering methodology to separate bypass diode activation from normal mismatch conditions
* Monte Carlo validation framework quantifying methodology error (±1.2%)

## Introduction

### Commercial PV Overview

* PV is essential for combating climate change, with exponential growth in deployment
* Recent rapid growth in rooftop PV installations globally
* Rooftop PV systems typically suffer more from mismatch losses compared to utility-scale installations due to:
  + Complex roof geometries
  + Partial shading from nearby objects
  + Non-uniform orientations
  + Installation constraints

### Mismatch Loss Introduction

* **Definition:** Mismatch loss in a PV system series connection is the difference between the sum of individual module maximum power points and the actual combined string power output
* **Sources of mismatch losses in rooftop PV:**
  + Manufacturing inconsistencies and parameter variations
  + Light-induced degradation (LID) and aging effects
  + Module aging at different rates
  + Soiling and temperature differences across the array
  + Site-specific conditions: partial shading, varying module orientations
  + Potential-induced degradation (PID) and damaged module diodes
  + Bypass diode activation events
* **Literature Review:**
  + Historically, studies on mismatch losses have presented conflicting conclusions
  + Some research indicates mismatch losses significantly reduce system output [refs]
  + Other studies argue that these losses have minimal impact on overall performance [refs]
  + A gap exists in comprehensive real-world field studies across diverse conditions

### SolarEdge Technology Introduction

* To mitigate mismatch losses, SolarEdge Technologies has developed DC-DC converters known as optimisers
* **Key features:**
  + Allow modules to operate independently at their maximum power points (MPP)
  + Provide real-time MPP data on each module’s operating conditions
  + Enable module-level monitoring and fault detection
  + Continuous 5-minute interval telemetry data collection
* **Research Opportunity:**
  + The extensive data available from SolarEdge optimisers presents an unprecedented opportunity to assess real-world PV mismatch losses
  + Large-scale deployment enables statistical analysis across diverse geographic and climatic conditions

### Study Objectives

* **Primary aim:** Quantify mismatch losses accurately based on MPP data recorded by SolarEdge systems across diverse real-world conditions
* **Secondary objectives:**
  + Validate single-diode model reconstruction methodology
  + Categorise mismatch patterns by installation characteristics
  + Analyse seasonal and geographic variations
  + Develop filtering methods for bypass diode detection

## Methodology

### Overview of Proposed Method

* The proposed method consists of four sequential steps:
  + 1. Reconstruct the I-V curve of each module based on the measured MPPT using the single-diode model.
  + 2. Calculate the combined I-V curve if the modules were connected in series
  + 3. Find the MPPT of the combined series I-V curve
  + 4. Compare the energy produced by a series connection vs. the sum of individual module energies to calculate mismatch loss

### I-V Curve Reconstruction

#### Single-Diode Model Foundation

The single-diode equation is given by:

**Where:**

* = module output current
* = photogenerated current
* = dark saturation current
* = diode ideality factor
* = number of cells in the module
* = thermal voltage =
* = Boltzmann constant
* = cell temperature in Kelvin
* = electron charge
* = module output voltage
* = module series resistance
* = module shunt resistance

#### Parameter Extraction

* Based on the single-diode equation and assuming measured voltage and current represent the maximum power point, the dark saturation current can be derived as:
* The photogenerated current is calculated by rearranging equation (1):

#### Implementation Process

For each measurement timestamp:

* extracted from PV module datasheet (.PAN files)
* calculated based on the measured module temperature
* recorded by the SolarEdge optimiser
* and calculated using equations (2) and (3)
* Full I-V curve constructed using pvlib.pvsystem.v\_from\_i function
* An example of a reconstructed IV curve from the measured MPP is shown in Figure 1 (a) and (b)

### Series Connection I-V Simulation

* **Methodology:** Simulated I-V curve constructed assuming all modules are connected in series
* **Bypass diode modelling:** Each module is assumed to have at least one bypass diode with a negligible voltage drop
* **Mathematical approach:** Series connection I-V curve calculated as the voltage sum for each current value
* **Current limiting:** When combined current pushes modules into reverse voltage, bypass diodes activate
* An example of series connection IV curve from the individual module IV is shown in Figures 1 (b) and (c)

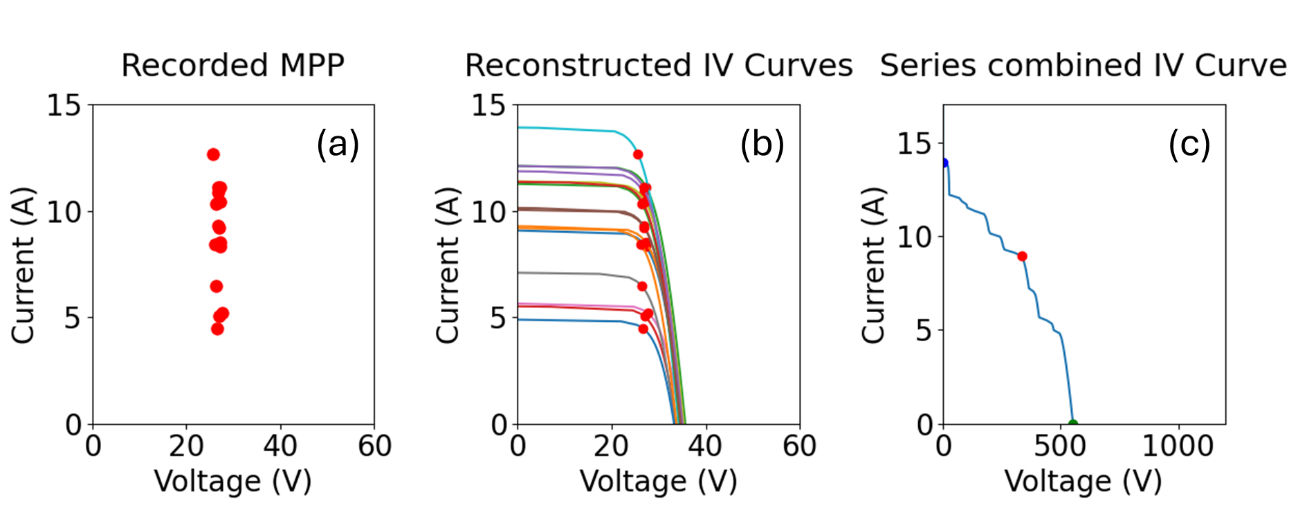
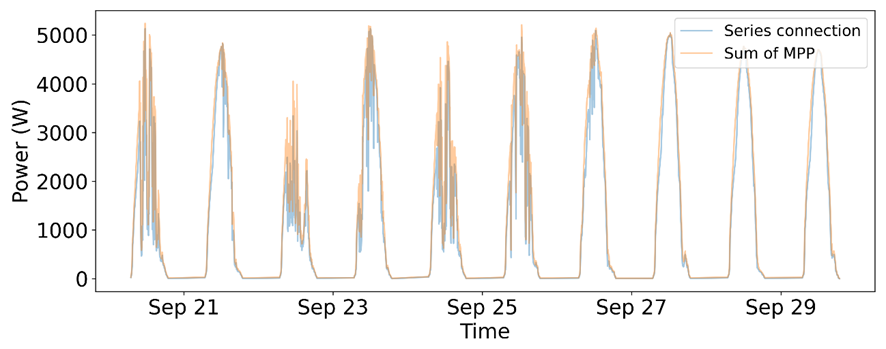


Figure : (a) The recorded MPP for each module, (b) The reconstructed IV curve for each module, (c) The reconstructed IV curve if they were connected in series

### Power Comparison and Mismatch Calculation

* MPP of the series connection I-V curve identified through power curve optimisation
* Comparison performed between:
  + Sum of individual module MPP powers (SolarEdge case)
  + Combined series string MPP power (traditional string inverter case)
* **Mismatch loss calculation:**
* An example of the power comparison of one test site for 10 days is shown in Figure 2
* Please see Appendix D for the comparison of all sites and all seasons



*Figure 2: Power comparison between the case of each maximum power and the power if they were connected in series.*

### Bypass Diode Filtering

* **Challenge:** Internal bypass diode activation creates artificial mismatch signals
* **Detection methodology:**
  + Voc outlier analysis using IQR methods
  + Isc outlier detection for fault identification
  + Classification system:
    - Type 1: 1/3 Voc loss (1 diode activated)
    - Type 2: 2/3 Voc loss (2 diodes activated)
    - Type -1: High Voc + Low Isc (variable activation)
* **Data filtering:** Timestamps with diode activation excluded from mismatch analysis

## Test Site Selection and Aggregation

### Site Characteristics

* **Total sites:** 22 selected installations with diverse orientations and technologies
* **Geographic distribution:**
  + Australia: Queensland, Victoria, South Australia, New South Wales
  + North America: Texas, Arizona, Nevada, California, Ohio, Iowa
  + Europe: Netherlands, Germany, France
* **System specifications:** Detailed in the comprehensive site database (Table 1)

### Data Collection Protocol

* **Temporal sampling:** 10 days selected per season (March, June, September, December 2024)
* **Measurement frequency:** 5-minute intervals for all parameters
* **Recorded parameters:**
  + Module temperature and ambient temperature
  + Module MPP current and voltage
  + Power output per optimiser
  + Inverter-level data

### Site Classification System

* Based on visual analysis using satellite and street view imagery, sites are classified into two categories based on module orientation:

#### **Category 1: Single Orientation (16 sites)**

* All modules face the same direction
* Uniform tilt and azimuth angles across the installation
* Mismatch sources: manufacturing tolerances, temperature gradients, soiling variations, and potential partial shading effects
* Common in standard residential and commercial installations

#### **Category 2: Multiple Orientation (6 sites)**

* Modules face different directions due to complex roof geometry
* Mixed tilt and/or azimuth angles across the installation
* Additional mismatch sources: varying irradiance conditions due to orientation differences
* Typically found in installations with architectural constraints or complex roof designs

## Results

### Overall Statistical Analysis

* **Comprehensive dataset:** 22 sites × 4 seasons × 10 days = 880 site-season combinations
* **Mean mismatch loss:** 14.4 ± 5.0% (after bypass diode filtering)
* **Range:** 5.3% (Site 4034376, single orientation) to 22.0% (multiple orientation)
* **Distribution characteristics:** Site-specific variation attributed to local installation conditions and orientation complexity

### Orientation-Based Results

#### Case 1: Single Orientation Sites (16 sites)

* **Representative examples:** Site 4034376 (7.5% loss), Site 4002138 (9.2% loss)
* **Average mismatch loss:** 12.6 ± 4.6%
* **Range:** 5.3% to 21.5%
* **Installation characteristics:** Uniform orientation provides consistent irradiance conditions, but is still subject to environmental factors

#### Case 2: Multiple Orientation Sites (6 sites)

* **Representative examples:** Site 3455043 (19.0% loss), Site 4111492 (22.0% loss)
* **Average mismatch loss:** 19.1 ± 2.2%
* **Range:** 17.0% to 22.0%
* **Impact quantification:** ~6.5% additional mismatch compared to single orientation sites
* **Installation reality:** Common when architectural constraints require multiple orientations

### Seasonal Analysis

* **Winter pattern:** Generally, higher mismatch losses are observed
* **Physical explanation:** Lower solar altitude increases shadowing effects and reduces overall irradiance uniformity
* **Summer stability:** More consistent performance with reduced mismatch variation
* **Seasonal variation:** 2-4% difference between winter and summer averages

## Error Estimation Using Monte Carlo Simulation (MCS)

### Motivation for Validation

* **Model accuracy assessment:** Single-diode model approximation needs quantitative validation
* **Parameter dependencies:** Temperature and irradiance effects on model parameters:
  + Ideality factor variations
  + Series resistance temperature coefficient
  + Shunt resistance irradiance dependency

### Monte Carlo Methodology

#### Two-Diode Reference Model

* **Truth generation:** Use a comprehensive two-diode model with temperature/irradiance dependencies
* **Parameter distributions:** Based on literature review and manufacturer data
* **System simulation:**
  + Generate 10,000 dummy modules with realistic parameter distributions
  + Create 1000 dummy systems (10 modules each)
  + Apply temperature and irradiance variations

#### Validation Process

* **Branch 1: True Results Generation**
  + Calculate actual series connection I-V curves using the two-diode model
  + Account for temperature/irradiance parameter dependencies
  + Determine true series MPP power - Calculate true mismatch loss
* **Branch 2: Reconstructed Results**
  + Extract only MPP data (simulating SolarEdge measurements)
  + Apply proposed single-diode reconstruction methodology
  + Calculate reconstructed mismatch loss
  + Compare with true values

### Monte Carlo Results

* **Error quantification:** Mean error of 1.2% absolute (methodology underestimates true mismatch)
* **Error distribution:** Systematic bias toward underestimation
* **Uncertainty bounds:** ±1.2% confidence interval for mismatch loss estimates
* **Model validation:** Confirms single-diode approach is sufficiently accurate for field studies

#### Error Analysis Results

* **Statistical Metrics:**
  + Mean absolute error: 1.2%
  + Standard deviation: 0.8%
  + 95% confidence interval: ±1.6%
  + Systematic bias: Slight underestimation
* **Validation Conclusions:**
  + Single-diode approach sufficient for field study accuracy requirements
  + Temperature dependencies have minimal impact on overall results
  + Irradiance effects on shunt resistance are properly captured in the model

## Discussion

### Comparison with Previous Studies

#### NREL Distributed Power Electronics Research

* **MacAlpine et al. (2009) - University of Colorado/NREL Study:**
  + **Focus:** Building-integrated PV systems with complex roof geometries using module-integrated DC-DC converters (MICs)
  + **Key findings:** Annual power output gains of over 10% for systems with differing panel orientations when using MICs
  + **Methodology:** Comprehensive simulation model validated with experimental data, accounting for cell-level irradiance and temperature variations
  + **Mismatch sources:** Primarily, orientation differences and the nearby tree shading in series string configurations
* **Deline (2011) - NREL Technology Seminar Findings:** **Comprehensive mismatch loss estimates:**
  + Residential roof shade (single string): 5-15% system loss
  + Residential rooftop shade (multiple strings): 5-20% system loss
  + Orientation mismatch (East-West, single string): 5-20% system loss
  + Commercial inter-row shading: 1-5% system loss
  + Manufacturing parameter distribution: 0.2-1% system loss
  + Soiling (California/Southwest): 1.5-6.2% system loss

#### Comparison with Current Study

* **Current study findings:**
  + 14.4 ± 5.0% mean mismatch loss in real-world field installations (22 sites)
  + Single orientation: 12.6 ± 4.6% (16 sites)
  + Multiple orientation: 19.1 ± 2.2% (6 sites)
* **Key differences in methodology:**
  + **NREL approach:** Controlled experiments with validated simulation models to simulate the electric loss from the optical measurement
  + **Current study approach:** Real-world field electrical data from SolarEdge optimiser measurements across 22 diverse installations
  + **Current study focus:** Quantification of baseline mismatch losses in existing installations with module-level power electronics
* **Validation of mismatch loss estimation:**
  + Despite different data sources and methodologies
  + Both studies arrive at similar results: the mismatch loss on the rooftop system is ~15%

### Implications for System Designers

* **Orientation planning:** Single orientation installations show lower mismatch losses (12.6%) compared to multiple orientation designs (19.1%)
* **Installation strategy:** Architectural constraints requiring multiple orientations add ~6.5% mismatch penalty
* **Technology selection:** Quantified benefits of module-level power electronics, especially for complex installations

## Conclusion

* **Overall mismatch quantification:** Real-world rooftop systems exhibit 14.4 ± 5.0% average mismatch loss
* **Orientation-based category impacts:**
  + Single orientation installations: 12.6 ± 4.6% (16 sites)
  + Multiple orientation installations: 19.1 ± 2.2% (6 sites)
* **Orientation impact:** Multiple orientations add ~6.5% additional mismatch compared to a single orientation
* **Seasonal patterns:** Winter conditions show elevated mismatch losses due to lower solar altitude
* **Methodology validation:** Monte Carlo simulation confirms ±1.2% accuracy of proposed approach
* **Novel methodology:** First comprehensive field study using optimiser-derived data for mismatch quantification
* **Geographic diversity:** Multi-continental study spanning diverse climate zones
* **Practical relevance:** Direct applicability to rooftop PV system design and modelling

## Appendices

### Appendix A: Derivation of Dark Saturation Current

#### Known Parameters

* **From SolarEdge measurements:** - Maximum power point voltage: - Maximum power point current:
* **From PV module datasheet:** - Module ideality factor: - Module cell number: - Module series resistance: - Module shunt resistance:

#### Mathematical Derivation

* **Objective:** Derive an expression for the dark saturation current from the single-diode equation
  + At maximum power point:
  + Since :
  + This yields: … (4)
  + Taking the derivative of equation (1) with respect to voltage:
* Solving for :
* Substituting into equation (4) and solving for yields equation (2).

### Appendix B: Bypass Diode Filtering Algorithm

#### Statistical Outlier Detection

* **Voc Outlier Classification:** - High outliers: - 1-diode activation: - 2-diode activation:
* **Isc Outlier Detection:** - High outliers: - Low outliers:

#### Activation Classification Algorithm

For each timestamp and optimiser:  
 if (Voc\_outlier == -1) AND (Isc\_outlier == 0):  
 diode\_activation = 1 # Type 1: 1 diode  
 elif (Voc\_outlier == -2) AND (Isc\_outlier == 0):  
 diode\_activation = 2 # Type 2: 2 diodes  
 elif (Voc\_outlier == 1) AND (Isc\_outlier == -1):  
 diode\_activation = -1 # Type -1: Variable  
 else:  
 diode\_activation = 0 # Normal operation

### Appendix C: Temperature and Irradiance Dependencies

#### Series Resistance (Rs)

* **Temperature dependency:** 0.356%/K (based on PERC module studies) [refs]
* **Physical basis:** Silver grid fingers and copper interconnects resistance increase with temperature
* **Irradiance dependency:** Minimal impact under normal operating conditions

#### Shunt Resistance (Rsh)

* **Temperature dependency:** Negligible effect on overall performance
* **Irradiance dependency:** Decreases with irradiance following the PVsyst exponential model
* **Implementation:** Dynamic adjustment based on measured irradiance levels

#### Ideality Factor (n)

* **Temperature dependency:** Minimal variation (0.006%/K for PERC modules)
* **Irradiance dependency:** Varies between 1.4-1.5 for 0.4-1.0 sun conditions
* **Model treatment:** Constant value approach validated within error bounds