Methods for Analysis of Outdoor Performance Data

NREL

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Outline

• Motivation: Impact of uncertainty in degradation rates ($R_d$)

• Methodologies
  1. IV data taken in discrete intervals
  2. Continuous data, PVUSA & Performance Ratio
  3. Additional methodologies for continuous data - Classical Decomposition, ARIMA

• Historical $R_d$ and what we can learn from it.
  1. Methodologies
  2. Number of measurements
  3. Climate
Motivation

For solar industry to keep growing we need to accurately understand & predict how different technologies behave/change with weather, climate and time.

Change of power output with time is degradation rate \((R_d)\)….uncertainty is very important too.

2 examples from NREL:
Different observation lengths, seasonality etc. \(\rightarrow\) Leads to different uncertainties

\[
R_d \text{ (Module 1)} = (0.8 \pm 0.2) \%/\text{year} \\
R_d \text{ (Module 2)} = (0.8 \pm 1.0) \%/\text{year}
\]

Same \(R_d\) but very different uncertainty
Manufacturer Warranty often twofold: 90% after 10 years, 80% after 25 years

Probability to default warranty:

- 1.0 %/year uncertainty = 46%
- 0.2 %/year uncertainty = 4%

Probability to invoke warranty:

- 1.0 %/year uncertainty = 57%
- 0.2 %/year uncertainty = 24%

Higher $R_d$ uncertainty significantly increases warranty risk
Degradation Rate ($R_d$) - Discrete Points

1. Translation to reference conditions (IEC60891)
2. Time series to determine degradation rate

$R_d = (0.33 \pm 0.07) \%$/year

Quarterly taken I-V curves for degradation

$$FF = \frac{P_{max}}{I_{sc} \cdot V_{oc}} = \frac{I_{max} \cdot V_{max}}{I_{sc} \cdot V_{oc}}$$
Degradation Rate - Discrete Points

Monocrystalline-Si

Degradation is due to decline in $I_{sc}$, ($V_{oc}$ & FF are stable) $\rightarrow$ clues to degradation mechanism

Problem: 1. Labor-intensive, has to be clear sky
2. Large arrays $\rightarrow$ portable I-V tracer may not be available
3. Typically historical data not available

I-V curves provide clues to underlying failure mechanism
The plant was originally constructed by the Atlantic Richfield oil company (ARCO) in 1983. Provided electricity, data & experience in the 1980s and 1990s. Plant was dismantled in the late 1990s.

**PVUSA Rating Methodology**

Improved PVUSA models include Sandia & BEW model**

1. Step: Translation to reference conditions (use a multiple regression approach)

\[ P = H \cdot (a_1 + a_2 \cdot H + a_3 \cdot T_{ambient} + a_4 \cdot ws) \]

\( H = \) Plane-of-array irradiance  
\( T_{ambient} = \) ambient temperature  
\( ws = \) wind speed  
\( a_1, a_2, a_3, a_4 = \) regression coefficients

Reference conditions:
PVUSA Test Conditions (PTC): \( E=1000\) W/m², \( T_{ambient}=20^\circ\)C, wind speed=1 m/s

Need basic weather station to collect \( T_{ambient} \) and wind speed on top of irradiance
Seasonality leads to required observation times of 3-5 years* \( \rightarrow \) long time in today’s market

Long time required for accurate \( R_d \)

Classical Decomposition

Signal = Trend + Seasonality + Irregular

Original Data

![Graph showing original data with DC Power (W) on the y-axis and Time (Months) on the x-axis. The data points form a downward trend over time.]
Classical Decomposition

\[ \text{Signal} = \text{Trend} + \text{Seasonality} + \text{Irregular} \]

**Original Data**

![Original Data Graph](image)

**Trend**

12-month centered-Moving Average

![Trend Graph](image)
Classical Decomposition

Signal = Trend + Seasonality + Irregular

Original Data

Seasonality
Average of each month for all years of observation

Trend
12-month centered-Moving Average
Classical Decomposition

Signal = Trend + Seasonality + Irregular

**Original Data**

**Seasonality**
Average of each month for all years of observation

**Trend**
12-month centered-Moving Average

**Irregular**

Determine $R_d$ from Trend graph for higher accuracy

ARIMA

AutoRegressive Integrated Moving Average (ARIMA)

Model trend & seasonality component w/ Linear Combination of weighted differences & averages

\[ P_t - P_{t-12} - \phi \cdot P_{t-1} + \phi \cdot P_{t-13} = \delta + \varepsilon_t - \theta \cdot \varepsilon_{t-12} \]

\( P = \text{Power} \)
\( c, \delta, \phi, \theta = \text{constant} \)
\( \varepsilon = \text{noise} \)

1. Built several Models \( \rightarrow \) minimize noise component
2. Chose parsimonious model w/ aid of several selection criteria

2 free software packages, US Census Bureau, Bank of Spain: plug & play, sensitive to outliers!

Many statistical software packages include time series analysis (JMP, Minitab, R etc)
Developed script to make model selection less sensitive to outliers.

Use ARIMA to model data, then decompose

Outliers

Compare sensitivity of 3 methods to outliers

Procedure:
1. Dataset from NREL
2. Introduce outliers sequentially
3. Calculate $R_d$ & study effect on all 3 methodologies

ARIMA most robust against outliers
Data Shifts

Compare sensitivity of 3 methods to data shifts
Example: inverter change

Procedure:
1. Dataset from NREL
2. Introduce a data shift deliberately
3. Multiply shifted section with a scaling factor
4. Calculate $R_d$ & study effect on all 3 methodologies

Correct data shifts by minimizing residual sum of squares
Data Shift Results

Results from induced shift

Real Shift – Blind test

Data shift correction procedure is successful for all 3 approaches.

Data shift cause: Erratic ambient Temp sensor.
Misleading degradation rate if \( R_d \) calculated after shift.

Residual minimization technique works on real shifts
PVUSA – Weekly Intervals

Multi-crystalline module

**Monthly Intervals**

**Weekly Intervals**
PVUSA – Weekly Intervals

Multi-crystalline module

Monthly Intervals

Weekly Intervals

Weekly intervals → converges in less time
Performance Ratio

**PVUSA**

**Monthly PR**

**Daily PR**

Multi-crystalline Si system

\[
Y_f = \frac{E}{P_0} \\
E = \text{Net Energy output} \\
P_0 = \text{Nameplate DC rating}
\]

\[
Y_r = \frac{H}{G} \\
H = \text{In-plane Irradiance} \\
G = \text{Reference Irradiation}
\]

\[
PR = \frac{Y_f^*}{Y_r}
\]

Can apply same modeling approaches to minimize seasonality

Data Filtering

Example on how variable $R_d$ may be depending on irradiance filtering (may not be representative)

Filtering interval too tight or broad $\Rightarrow$ $R_d$ may be substantially different and uncertainty goes up

A. Kimber paper showed uncertainty may be reduced by using only sunny days

Data filtering has important impact on determined $R_d$

Discrete vs. Continuous Data

**IEC 60891**

- IEC60891-Method1
- IEC60891-Method2
- IEC60891-Method3

$R_d$(IEC-M1) = (0.33 ± 0.07) %/year

$R_d$(IEC-M2) = (0.34 ± 0.06) %/year

$R_d$(IEC-M3) = (0.30 ± 0.07) %/year

**PVUSA**

- St.Least Squares
- Class.Decomp.
- ARIMA

$R_d$(PVUSA SLS) = (0.47 ± 0.12) %/year

$R_d$(PVUSA CD) = (0.34 ± 0.04) %/year

$R_d$(PVUSA AR) = (0.33 ± 0.08) %/year

Quarterly taken IV + IEC translation less uncertainty than PVUSA

PVUSA + Modeling uncertainty is comparable to IEC method
## Methodologies - Summary

<table>
<thead>
<tr>
<th></th>
<th>Time series</th>
<th>Data Type /# Data Pts.</th>
<th>Data Aqc.</th>
<th>Reference condition</th>
<th>Uncertainty</th>
<th>Outliers/Dt.shifts sensitivity</th>
<th>Implementation</th>
<th>Comments</th>
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<tr>
<td><strong>PVUSA</strong></td>
<td>SLS</td>
<td>continuous</td>
<td>DC, H, T, ws</td>
<td>PTC</td>
<td>ok?</td>
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<td>easy</td>
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<td>good</td>
<td>medium</td>
<td>high</td>
<td>easy</td>
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<td>“”</td>
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<td>“”</td>
<td>best</td>
<td>low</td>
<td>difficult</td>
<td>difficult</td>
<td>Software &amp; training required</td>
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<td>SLS</td>
<td>continuous</td>
<td>AC, H</td>
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<td>difficult for larger arrays</td>
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<td>easy</td>
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**SLS**: Standard Least Squares, **CD**: Classical Decomposition  
**H**: in-plane irradiance, **T**: temperature, **ws**: wind speed

**Contin. Data: Class. Decomp. may be good compromise**

**Discrete: Better take more than 2 measurements**
Performance Energy Rating
Testbed = PERT

More than 40 Modules,
> 10 manufacturers,
Monitoring time: 2 yrs-16 yrs

Appears that CdTe, CIGS & multi-Si improved

Pre: Installed before year 2000
Post: Installed after year 2000

Photo credit: Warren Gretz, NREL PIX 03877.

Degradation Rates – Literature Survey

Number of $R_d$ from literature: 1364 ca. 100 publications (see end)

Partitioned by date of installation: Pre- & Post-2000
Red diamonds: mean & 95% confidence interval

Crystalline Si technologies appear to be the same

Thin-film technologies saw significant drop in $R_d$ in last 10 years
Shell Solar E80-C modules deployed at NREL. Photo credit: Harin Ullal, NREL PIX 14725

Results from this array appears to support findings from literature
Development of Methodologies

Percentage of Indoor IV has increased manifold → better tools

Percentage PR has increased → more installations, easy to collect AC data, don’t necessarily need an entire weather station

Percentage PVUSA decreased significantly → pronounced seasonality & sensitivity to outliers

PVUSA methodology use has significantly declined
**R_d literature – Number of measurements**

40% take only 1 or 2 measurements

1 Measurement: baseline no longer available or were never taken → have to compare to nameplate rating

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**Procedure:**
1. Take quarterly I-V data set
2. Randomly pick 2 data points & calculate R_d → repeat many times
3. Randomly pick 3 data points & calculate R_d → repeat many times
4. R_d will depend on # of data points & time span → can create 2D map

**More than 40% of all R_d literature take only 1 or 2 measurements**
Effect of number of data points and years on $R_d$

"True $R_d"=-0.33 \%/year$ (dark blue)

The curve is very steep for small data points and short time span

Even between 2-3 years can come close to “true $R_d$" simply by taken a few more data points

Would like to see more data points taken
Degradation Rates around the World

Size of circle: number of modules/systems tested

No reported degradation rates in many climate zones
Degradation Rates around the USA

Similar picture as from around the world → some climate zones have not been investigated

No reported degradation rates in some climate zones
Rainflow Calculations

Steppe Climate has high damage due to thermal cycling

*Quantifying the Thermal Fatigue of CPV Modules_Bosco__NREL_International Conference on Concentrating Photovoltaics_2010
Analysis of all $R_d$ by climate

**Steppe Climate** shows significantly higher $R_d$ before 2000.

No significant difference.

Steppe Climate shows significantly higher $R_d$ before 2000.
Analysis of $R_d$ by climate – c-Si

Pre 2000

Post 2000

Analysis of Variance

Similar but not as distinct trend for c-Si

Use of automated equipment, low stress ribbon effect visible…?

Steppe Climate shows significantly higher $R_d$ before 2000
PV Data Acquisition

Use data from government-funded and other projects

Performance data accessible on web page

Eliminate blank spots on the map
Conclusion

- Uncertainty can result in significant warranty risk
- Time series Modeling with continuous data (PVUSA, PR ..) can significantly reduce uncertainty
- Cont. Data: Class. Decomp. May be a good compromise between quality of results & ease of implementation.
- Discrete data: better practice to take more than 2 measurements.
- Analysis from literature and our own systems indicate that degradation rates have improved for installations after 2000.
- Have no data from many of the world’s climate zones
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- Have no data from many of the world’s climate zones

Need more data!
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**Notation:** Title_Author_Institute/Country_Journal/Conference_Year