Introduction

Historical component failures
  20 years ago – Modules ; Today - Inverters

Historical degradation rates ($R_d$)
  Most modules degrade at 0.5%/year & are improving

Connection Degradation rate uncertainty & risk
  Higher uncertainty leading to higher risk
Growth of PV Industry

Reliability required to sustain exponential growth of industry

Sources:
- International: PV News, April 2009
- USA: http://www.eia.doe.gov/emeu/international/contents.html

Photo credit: Steve Wilcox, NREL PIX 15548

Alamosa Plant in Colorado
Reliability & Durability

- **Reliability**: Ability to perform designed task without failure \(\rightarrow\) discrete, disruptive events

- **Durability**: Ability to perform task without significant deterioration \(\rightarrow\) continuous, gradual decline

![Graph showing degradation fit and inverter replacement]

- Inverter Efficiency (%)
- DC Power (W)

<table>
<thead>
<tr>
<th>Date</th>
<th>DC Power</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec-02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr-04</td>
<td></td>
<td></td>
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<tr>
<td>Sep-05</td>
<td></td>
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<td>Jan-07</td>
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<td>Jun-08</td>
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</tbody>
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\(R_d=(-0.14\pm0.16)\%/\text{year}\)

Extreme example of inverter failure

**Both important for cost of electricity**
PV for Utility Scale Application (PVUSA)

The plant was originally constructed by the Atlantic Richfield oil company (ARCO) in 1983. Provided electricity, research opportunity, data & experience through the 1980s and 1990s. Plant was dismantled in the late 1990s.

Location: Carrisa Plains
Size: 5.2 MW
Data: 1988

Panels showed the highest maintenance

“CARRISA PLAINS PV POWER PLANT PERFORMANCE”, Wenger et al., PG&E, PVSC 1990.

Inverters seem to dominate O&M cost now.

Module stability has improved over the last 20 years → the next component requiring improvement is the inverter.

![Pie chart showing the percentage of system failures]

<table>
<thead>
<tr>
<th>Category</th>
<th>No. Events (%)</th>
<th>Cost (%)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter</td>
<td>37</td>
<td>59</td>
<td>25% from 1 lightning storm</td>
</tr>
<tr>
<td>DAS</td>
<td>7</td>
<td>14</td>
<td>90% from 1 lightning storm</td>
</tr>
<tr>
<td>AC Disconnect</td>
<td>21</td>
<td>12</td>
<td>50% due to dirt accumulation</td>
</tr>
<tr>
<td>Module/J Box</td>
<td>12</td>
<td>3</td>
<td>60% due to failed blocking diode</td>
</tr>
<tr>
<td>PV Array</td>
<td>15</td>
<td>6</td>
<td>45% from 1 lightning storm</td>
</tr>
<tr>
<td>System</td>
<td>8</td>
<td>6</td>
<td>All utility meter</td>
</tr>
</tbody>
</table>

Unscheduled maintenance costs for PV system operation

**Inverters seem to dominate O&M cost now**
Maximum Warranties - Inverters

Inverters suffer from early failures in the field due to temperature-related issues, mismatch between PV voltage and inverter window.

Qualification and performance standards for inverters and BOS are not well-defined.

Inverters are improving but still have wide distribution.

Source: Photon International, April 2010
Module maximum warranties typically greater than inverters

PV modules show smaller distribution
Degradation Rate ($R_d$)- Discrete Points

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

Quarterly taken I-V curves for degradation
Degradation Rate - Discrete Points

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

\[ FF = \frac{P_{\text{max}}}{I_{sc} \cdot V_{oc}} = \frac{I_{\text{max}} \cdot V_{\text{max}}}{I_{sc} \cdot V_{oc}} \]

Quarterly taken I-V curves for degradation
Degradation Rate - Discrete Points

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

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

I-V curves provide clues to underlying failure mechanism
Degradation Rate - Continuous Data

1. Translation to reference conditions (use a multiple regression approach)
2. Time series to determine degradation rate

PVUSA – multiple regression

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

Seasonality leads to required observation times of 3-5 years \(\rightarrow\) long time in today's market

Long time required for accurate \(R_d\)
Most modules degrade by ca. 0.5 %/year
Performance Energy Rating Testbed = PERT

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

Appears that CdTe, CIGS & poly-Si improved
Historical degradation rates are analyzed in a similar way.

Similar tendency found as with the PERT modules.

While the Si technologies remain stable, thin-films seem to have improved.

c-Si and Poly-Si show an uptick in $R_d$ → could be from new manufactures pushing into market*


Appears that CdTe, CIGS & poly-Si improved
Degradation Rate Uncertainty

Traditionally: need 3-5 years to determine $R_d^*$.  

Modeling: (i) Classical Decomposition  
(ii) ARIMA**

Accurate Determination of $R_d$ takes time  

Modeling can shorten required time

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Consequences of $R_d$ Uncertainty

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

$R_d$ (Module 1) = (0.8 ±0.2) %/year
$R_d$ (Module 2) = (0.8 ±1.0) %/year

Same $R_d$ but very different uncertainty
R\textsubscript{D} Uncertainty Impact on Warranty

Manufacturer Warranty often twofold: 90% after 10 years, 80% after 25 years

Probability to invoke warranty:

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

Higher R\textsubscript{D} uncertainty significantly increases warranty risk
Thank You!