Modeling of PV Module Power Degradation to Evaluate Performance Warranty Risks

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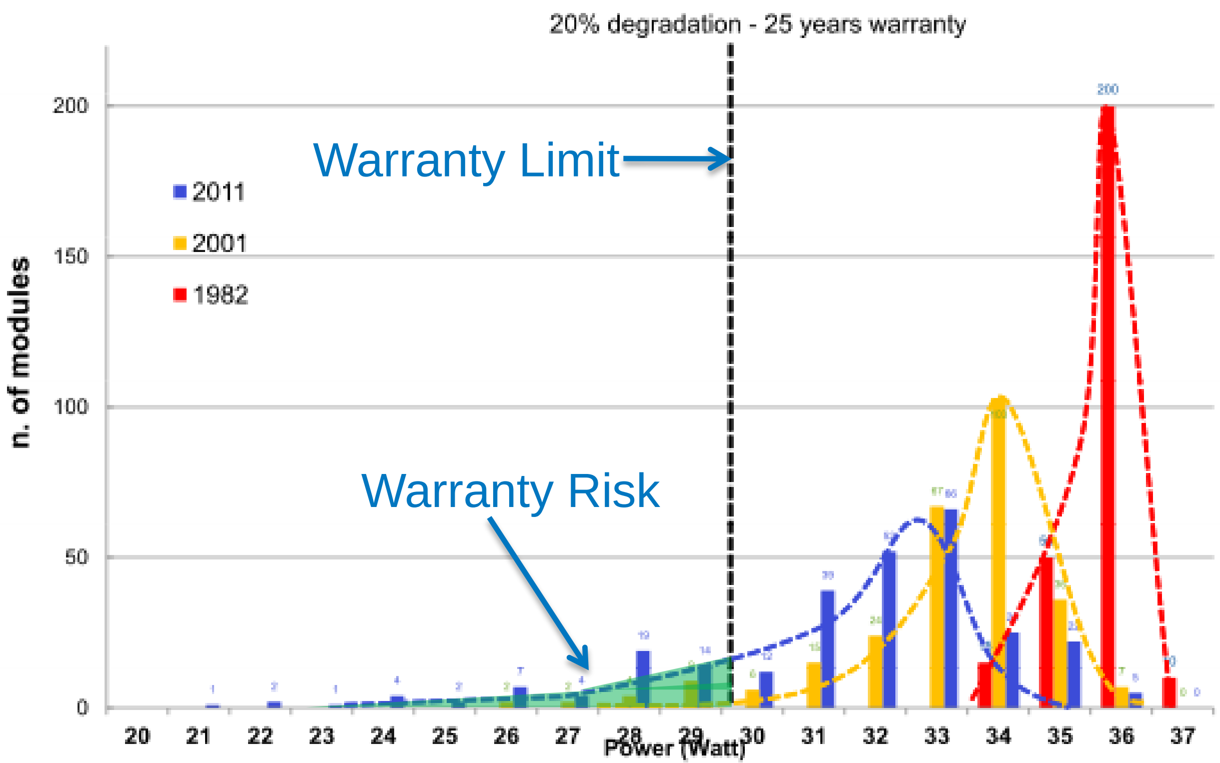
Motivation

- Module manufacturers provide performance warranties
- Goal: Quantify associated financial risk
- Illustration: Data from SUPSI – ISAAC PV system built 1982



T. Friesen, presented at 2nd SOPHIA Workshop PV-Module Reliability", May 3-4, 2012, Lugano.

Model for time evolution of module power distributions is needed!

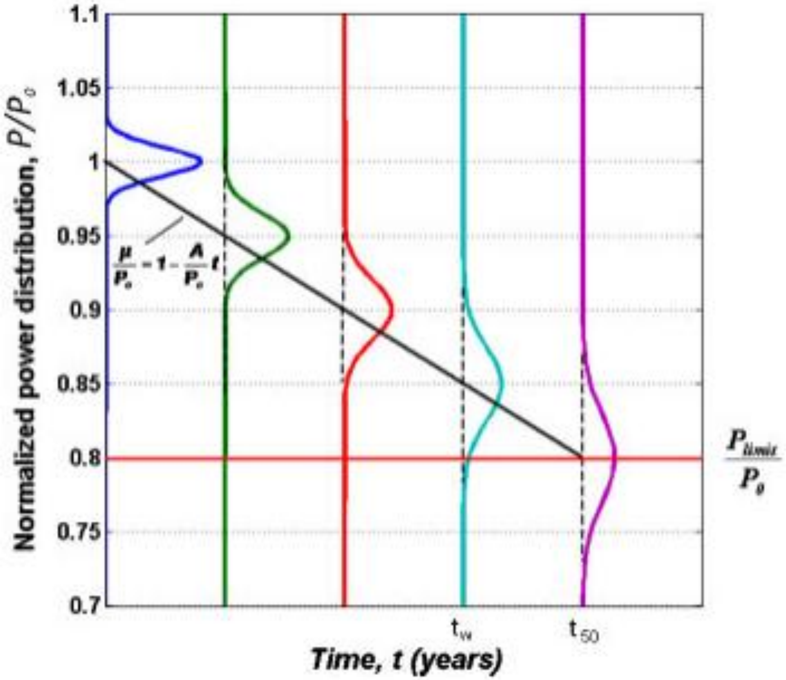
Outline

- Motivation
- Context
- Annual Degradation Rate: A Fresh Look
- Systematic Approaches:
  - ✓Monte Carlo
  - ✓Convolution
- Application
- Summary and Outlook

Context: **Vázquez and Rey-Stolle**

- Time evolution of a Gaussian distribution of module powers

$$p(P,t) = \frac{1}{\sqrt{2\pi}(\sigma_0 + Bt)} \exp\left\{ -\frac{1}{2}\left[\frac{P-(P_0 - At)}{\sigma_0 + Bt} \right]^2 \right\}$$

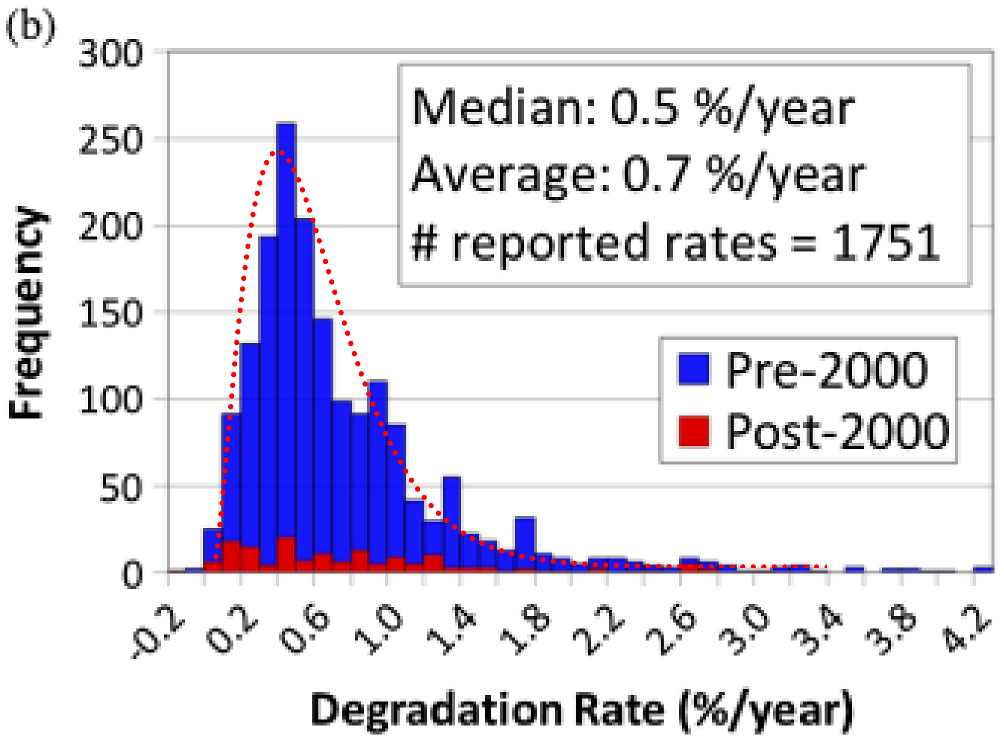


M. Vázquez and I. Rey-Stolle, Prog. Photovolt.: Res. Appl. 16 (2008) p. 419.

Extend to arbitrary, realistic module power distributions
Relate broadening to degradation rate distributions

Context: **Jordan and Kurtz**

- Encompassing compilation of published measured annual degradation rates r_D for PV modules
- Example result: Distribution $q(r_D)$ for crystalline Si modules



D.C. Jordan and S.R. Kurtz, Prog. Photovolt.: Res. Appl. (2011).

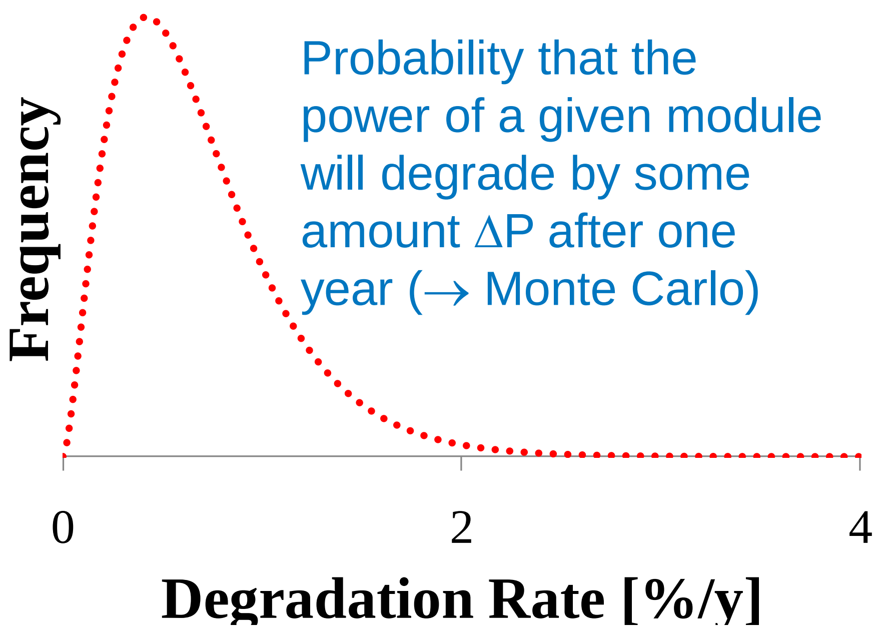
Reasonably good fit with gamma distribution

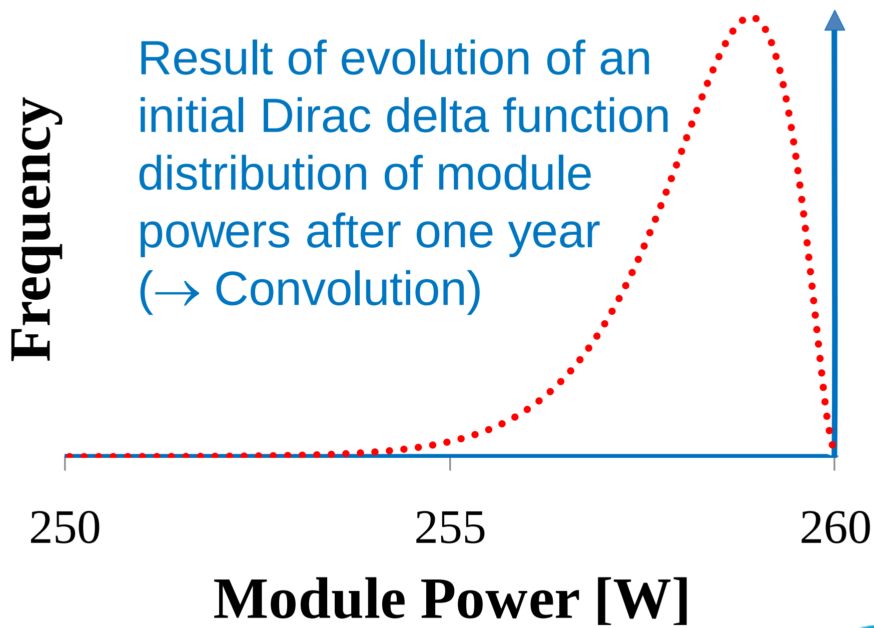
Annual Degradation Rate: A Fresh Look

- Determined from power P measured at time t and t+Δt

$$r_D = \frac{[P(t) - P(t + \Delta t)]}{\Delta t} \quad \text{(with } \Delta t \text{ in years)}$$

- Repeating this for module population yields distribution $q(r_D)$
- Two interpretations of $q(r_D)$:





Systematic Approaches: **Introduction**

- Monte Carlo simulation (evolution from year n to year n+1 by sampling module power & degradation rate distributions):

$$p^{s}_{n+1}(P) = p^{s}_{n}(P) - \tilde{q}^{s}(\Delta P)$$

- Convolution approach [used, e.g., to solve heat or diffusion equation, kernel is "fundamental solution" for $\delta(P-P_0)$]:

$$p_{n+1}(P) = \int_{-\infty}^{+\infty} p_n(P')\,\underbrace{\tilde{q}\left[-(P-P')\right]}_{\text{Kernel}}\,dP'$$

Kernel

- Main new aspects:
  - ✓Applicable to arbitrary initial module power distributions
  - ✓Explicitly consider distributions of degradation rates $q(r_D)$

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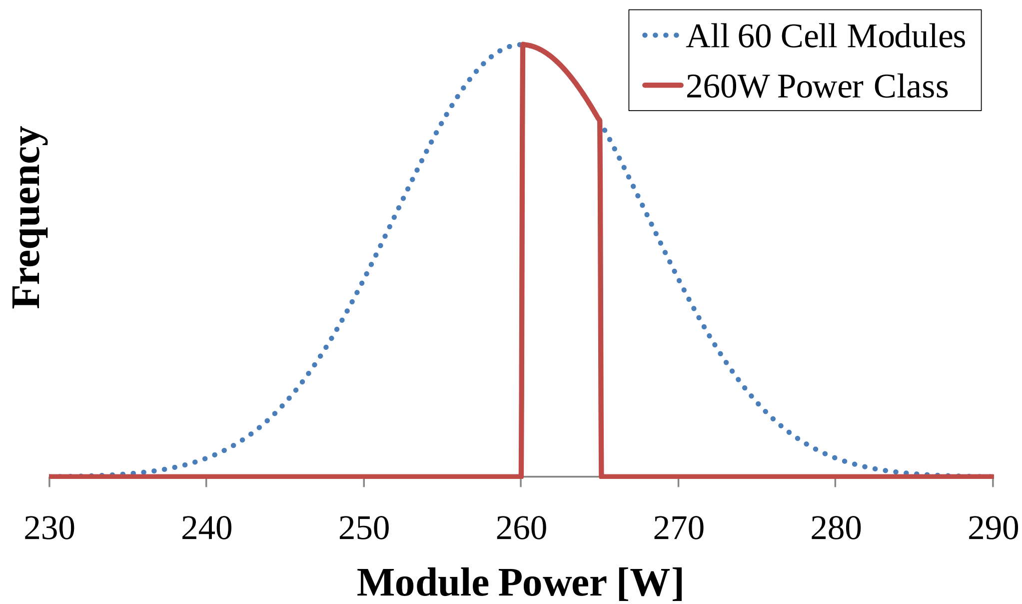
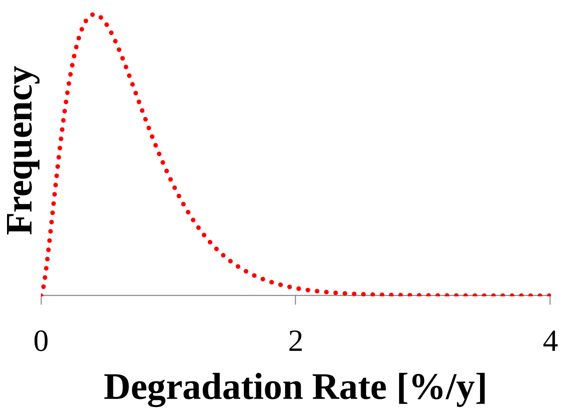
Systematic Approaches: **Choice of Parameters**

- Realistic initial module power distribution:
  - ✓Truncated Gaussian
  - ✓Representing one power class for given module construction

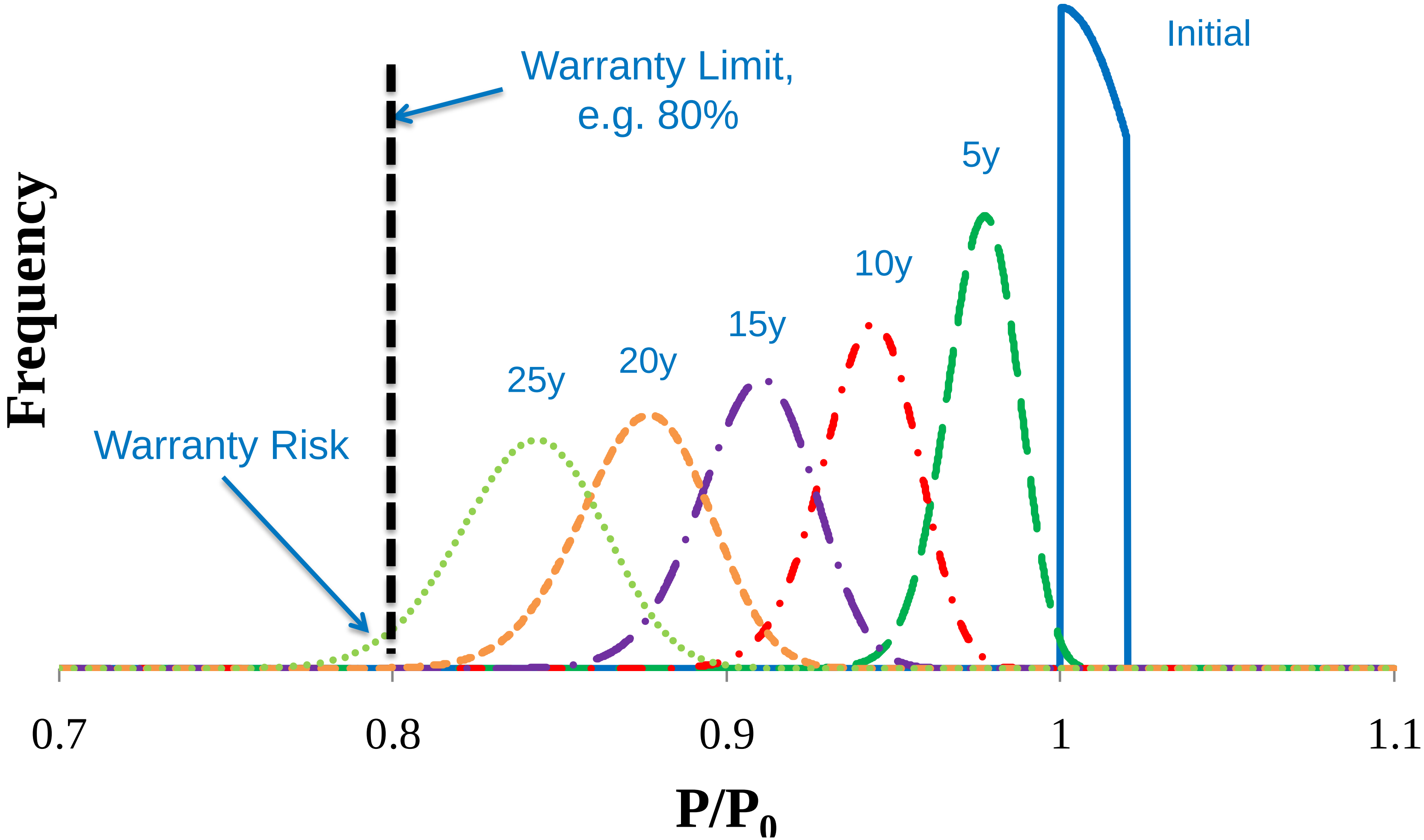


- Degradation rate distribution:
  - ✓Gamma distribution fit to data for mono c-Si by Jordan & Kurtz
  - ✓Maximum at 0.42%, median of 0.59%



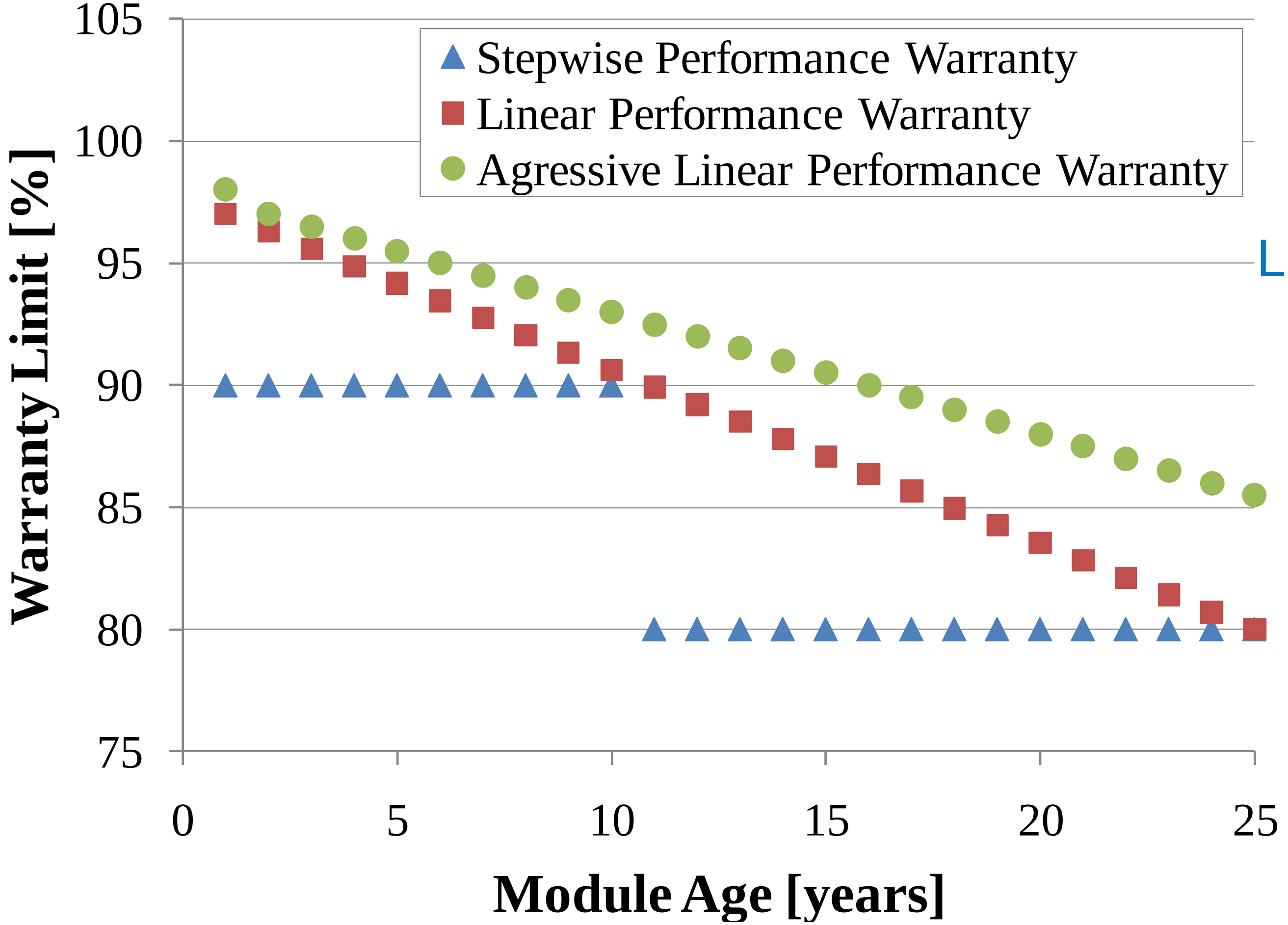
Systematic Approaches: **Central Result**

- Time evolution:



Application: **Performance Warranties**

- Three different examples:

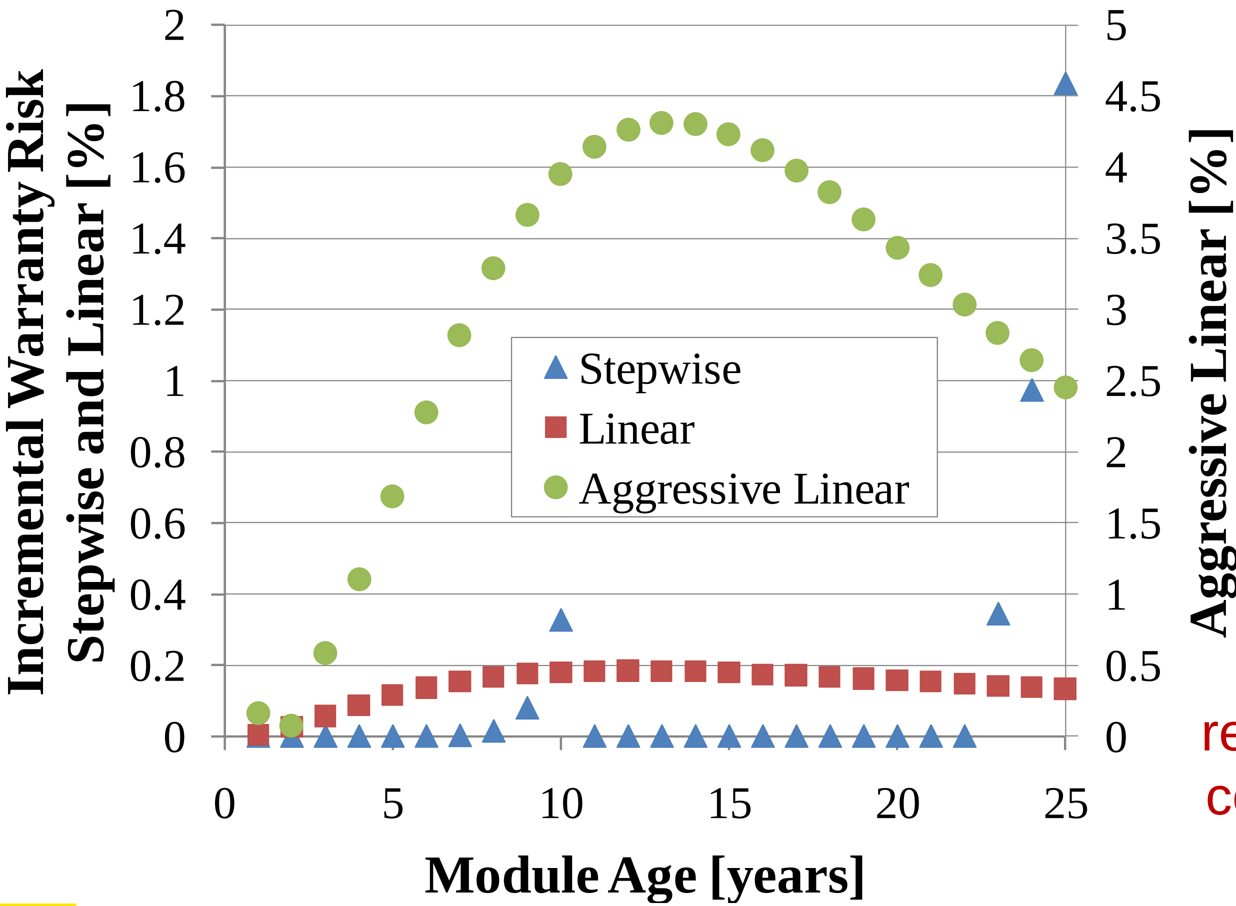


Linear decrease:
0.71%
0.5%

Roessler and Sauer, Modeling of PV Module Power Degradation

Application: **Incremental Warranty Risk**

- "Incremental warranty risk" = percentage of modules underperforming for the first time at a given module age



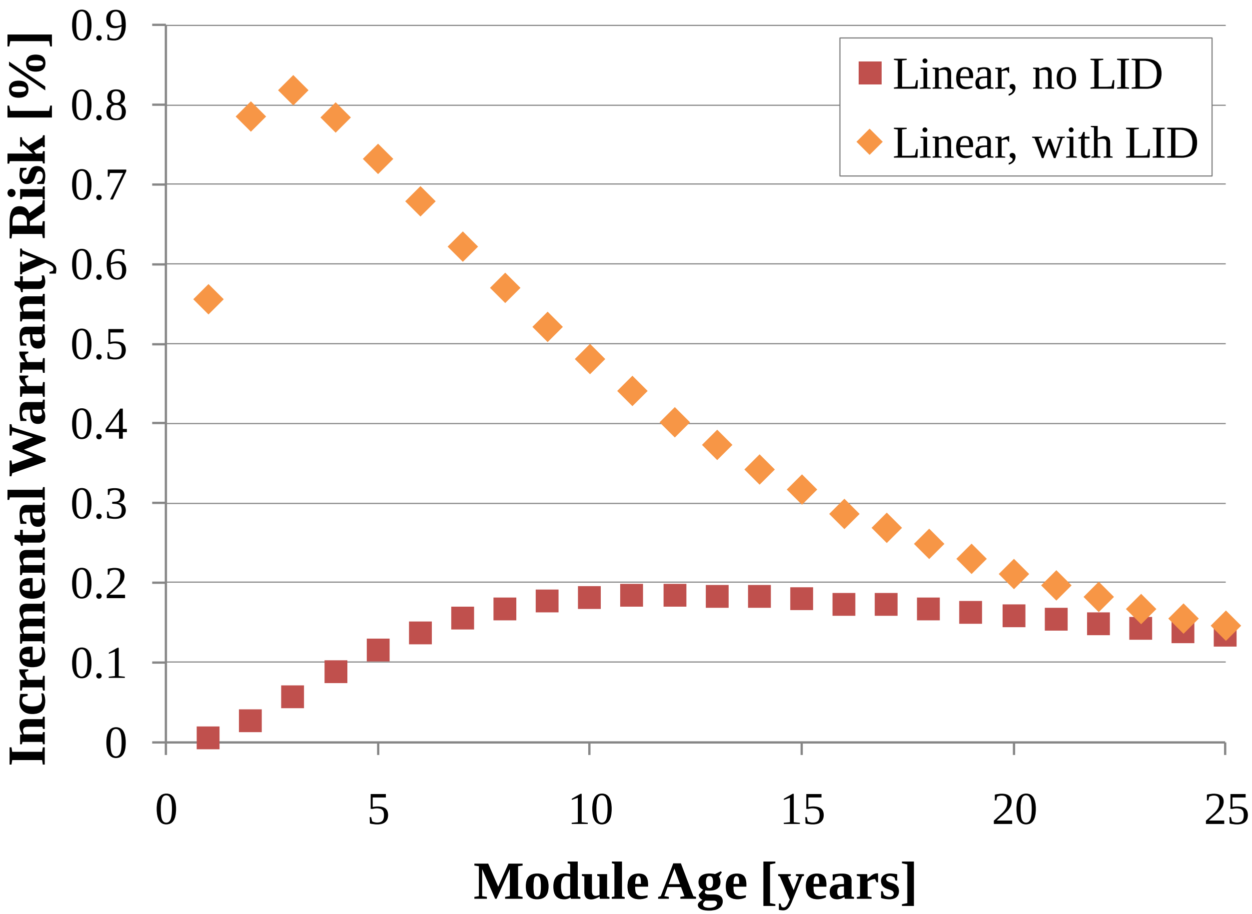
Total warranty risk:
3.6%
3.6%
74%!!!

Higher cost of replacement, tighter control over system performance

Roessler and Sauer, Modeling of PV Module Power Degradation

Application: **Influence of Light-Induced Degradation**

- LID: Gaussian with average 1.3%, std. deviation 0.24%



Total warranty risk:
3.6%
10%

Summary and Outlook

- Summary:
  - ✓Two systematic and general approaches for time evolution of module power distributions presented
  - ✓Simple application to comparison of incremental warranty risk for different warranty terms demonstrates basic utility
  - ✓Effects of LID easily incorporated
- Outlook:
  - ✓Use actual distributions for module power & degradation rates
  - ✓Consider module volume from different production years
  - ✓Consider time dependence of cost of module replacement
  - ✓Time dependence of degradation rate distributions?

Thanks for your attention!