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Uncertainty in Annual Yield: Conceptual Approaches and Implementation in SAM

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Outline

- What is uncertainty in annual yield (energy) and how is it quantified?
  - P90, i.e., 10^{th} percentile of future annual energy
- Typical practice to calculate P90
- An alternative structured approach to uncertainty
- Quantifying uncertainty

What is P90?

Future annual yield is uncertain: next year's weather, uncertainty in data and models

P90 is the 10th percentiles of the distribution of annual yield (energy)

Used to assess investment risk – a factor in the assessment of risk of loan repayment

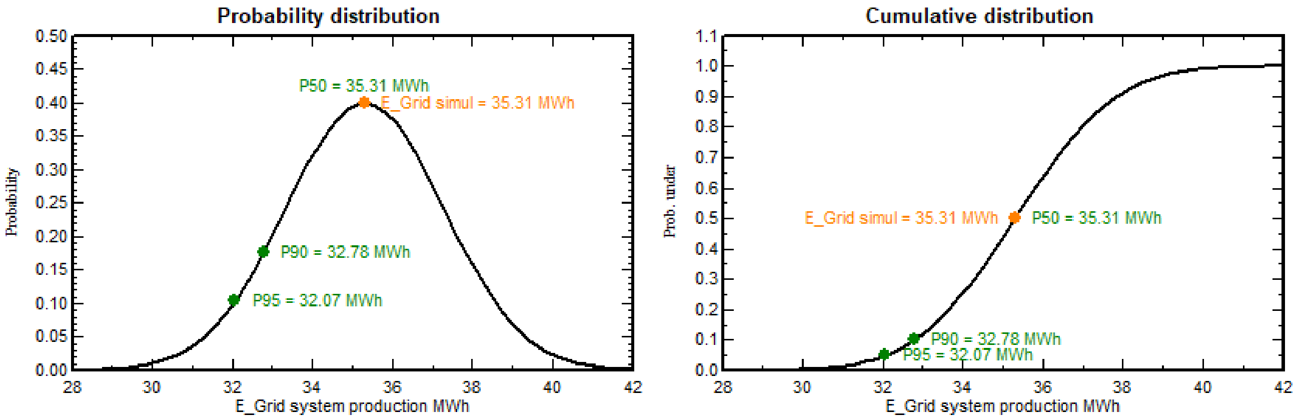


Figure courtesy of PVsyst, https://www.pvsyst.com/help/p50_p90evaluations.htm

What is P90, formally?

Future annual energy is uncertain due to uncertainty in:

- Future weather <- MOST SIGNiFICANT FACTOR
- Historical weather data (when used to represent future weather) - data have measurement (or modeling) uncertainties
- Models and parameters that are used to translate weather to annual energy

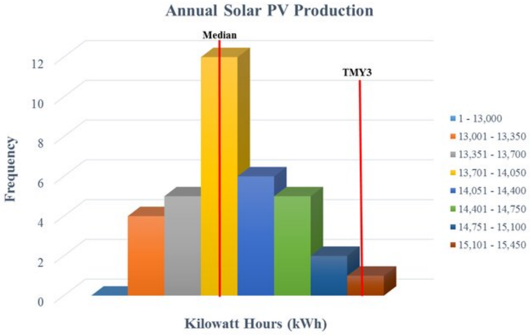
Future annual energy Y is a random variable: $Y = \sum_{t_i} f(W(t_i); \mathbf{p}) \times \Delta t_i$

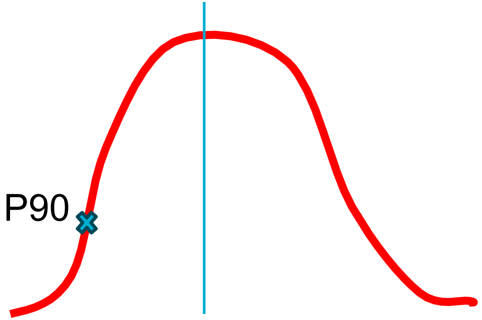
- f : performance model (usually a sequence of models) that translates weather $W(t_i)$ (irradiance, temperature, wind, etc.) to power at each time t_i
- $\mathbf{p}$: a vector of parameter values for the performance model(s), e.g., module parameters at STC, surface tilt and azimuth, incident angle modifiers

Typical practice to calculate P90 ("All-in" approach)

1. Model future weather, by assuming either:
   A. Multiple years of historical weather
   B. A typical year of weather
2. Select models (and parameters) and calculate yield from modeled energy
3. Account for model/data uncertainties
   A. Form a distribution with the "typical" annual energy as a central value
   B. "Widen" the distribution using a variance

$\sigma = \sqrt{\sum_k \sigma_k^2}$, where σ_k is the variance of annual energy attributable to some source of uncertainty





https://eepower.com/technical-articles/understanding-the-role-of-uncertainty-in-pv-energy-production
https://solargis.com/blog/best-practices/how-to-calculate-p90-or-other-pxx-pv-energy-yield-estimates
https://www.pvsyst.com/help/p50_p90evaluations.htm

Challenge and Consequences of the “all-in” approach

How does one enumerate and quantify the variances σ_k ?

- Units of annual energy
- Typical σ_k :
  - Variance in annual energy from weather variability
  - Uncertainty of models?
- Assumed to be “independent”

P90 conflates risk from future weather with uncertainty in models and data

- The P90 value is not uncertain, only imprecise
- “All-in” provides no basis for quantifying the lack of precision in P90
- Difficult to judge the value of reducing epistemic uncertainties

A structured approach to uncertainty

Aleatory *(inherent, random)* uncertainty that cannot (practically) be reduced by better measurements or models

- Future weather is inherently variable and (at some precision) unknowable

Epistemic *(state-of-knowledge)* uncertainty that could, in principle, be reduced by more accurate measurements, better models, more data, etc.

- E.g., a temperature coefficient could be known more precisely with more data, or, variation among PV modules could be quantified with more testing.

Commonly used in environmental and engineering risk assessments

Structured uncertainty yields same P90 but with more information

Models and data are epistemic uncertainties

Future weather is an *aleatory* uncertainty

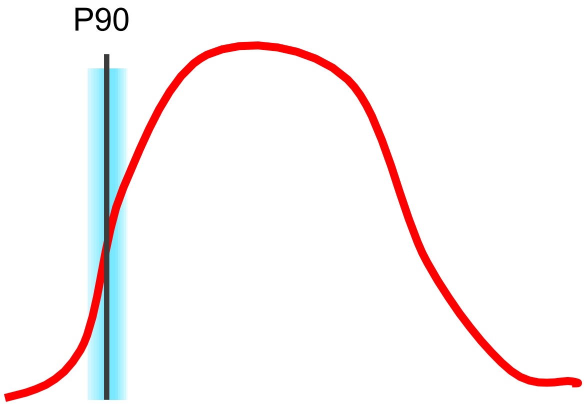
$$Y = \sum_{t_i} f\left(W\left(t_i\right);\mathbf{p}\right) \times \Delta t_i$$

Can compute a distribution of annual energy considering only uncertainty in future weather, **conditional** on models, parameters, and data

- Expresses risk of not meeting energy yield (revenue) due to future weather

Can compute a "best" estimate with uncertainty resulting from incomplete models and data

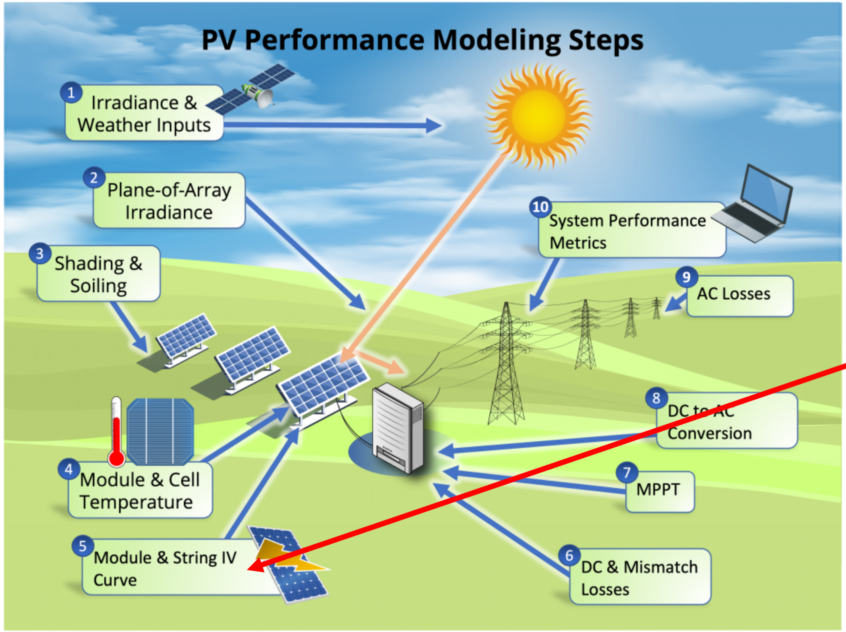
- The value of improving models and data can be quantified

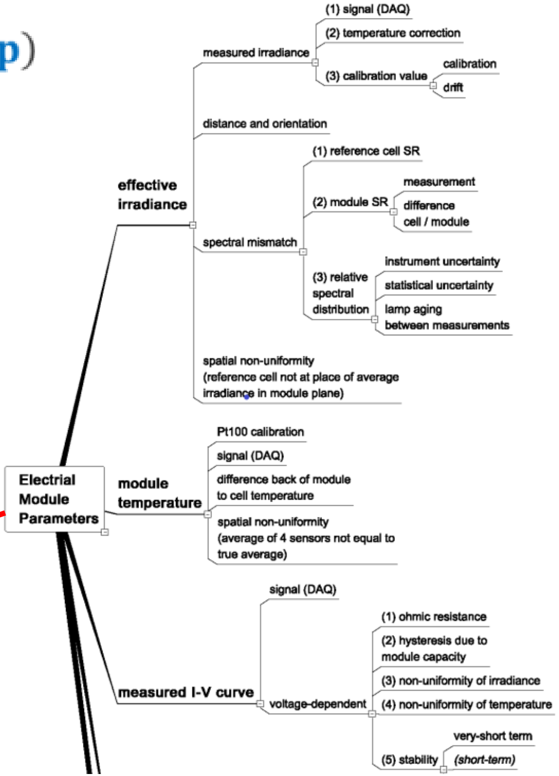


Quantifying epistemic (model, parameter) uncertainty

Quantify uncertainty in each component of $f(W; \mathbf{p})$

"Bottom-up approach" is <u>impractical</u>





D. Dirnberger and U. Kräling (2013)
doi: 10.1109/JPHOTOV.2013.2260595.

Top down "annual energy factors" approach

"Annual factors" approach recommended by IEA PVPS Task 13 [1]

Combined with the structured approach for uncertainty (implemented in SAM) [2]

Annual variability in weather is separated from all other uncertainties

- For each year of weather W :
- "Base" annual energy $\bar{Y}$ (using "best estimate" models)

$$\bar{Y}(W) = f(W; \mathbf{p})$$

- Apply a set of "uncertainty factors" F_k to generate a distribution Y of annual energy

$$Y(W) = \bar{Y} \times \prod_k (1 - F_k)$$

- Repeat for all years W (e.g., when using historical data)

1. "Uncertainties in PV System Yield Predictions and Assessments", Reise et al. (2018), IEA-PVPS T13-12:2018 https://iea-pvps.org/wp-content/uploads/2020/01/Uncertainties_in_PV_System_Yield_Predictions_and_Assessments_by_Task_13.pdf
2. "Quantifying Uncertainty in PV Energy Estimates Final Report", Prilliman et al. (2023), NREL/TP-7A40-84993 https://www.nrel.gov/docs/fy23osti/84993.pdf

What are "uncertainty factors"?

Each $\boldsymbol{F_k}$ quantifies uncertainty in the base annual energy from some component model or parameter in the performance model chain.

- $\boldsymbol{F_k}$ has units of fraction of annual energy
- By convention, $\boldsymbol{F_k}$ is a "loss", i.e., $\boldsymbol{F_k = 0.03}$ means a 3% reduction in annual energy
- Each $\boldsymbol{F_k}$ should be "independent"

$\boldsymbol{F_k}$ are not easy to quantify, e.g., factor for uncertainty in measured GHI (Hansen and Scheiner, 2022)

Perhaps easier than σ_k (prove me wrong)

Bias

E.g., Module rating $\boldsymbol{F_k = N(0, 0.5)}$

Variance

Table 1. SAM Default Distributions for Uncertainty Factors

Factor	Distribution type	Parameters
Irradiance transposition	Normal	$\mu = 11.5$, $\sigma = 2.5$
Horizon shading	Triangular	min.=-1, mode=0, max.=0
Row shading	Triangular	min.=-5, mode=-1, max.=0
Single module rating at STC	Normal	$\mu = 0$, $\sigma = 2.0$
Inverter availability	Triangular	min.=-5.7, mode-2.70, max.=0
Spectral response	Normal	$\mu = -1$, $\sigma = 0.5$
Cell temperature	Normal	$\mu = -2.4$, $\sigma = 1.0$
Mismatch loss	Triangular	min.=-1.8, mode=-0.8, max.=0
DC wiring	Triangular	min.=-2.5, mode=-1.5, max.=-1
Transformer	Triangular	min.=-2, mode=-1, max.=-0.5
Soiling	Triangular	min.=-1.5, mode=-0.5, max.=0

SAM defaults derived from Reise et al. (2018), IEA-PVPS T13-12:2018

Hansen and Scheiner (2022) doi: 10.1109/PVSC48317.2022.9938853

Conceptual implementation in SAM

"All-in" P90 "=" Weather risk "+" Uncertainty in P90

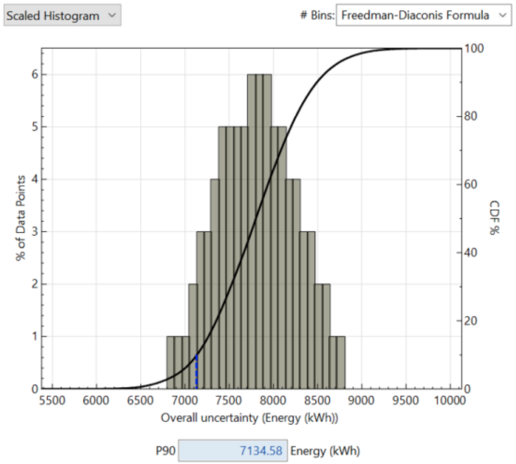


Figure 1. Combined uncertainty graph from SAM uncertainty tool

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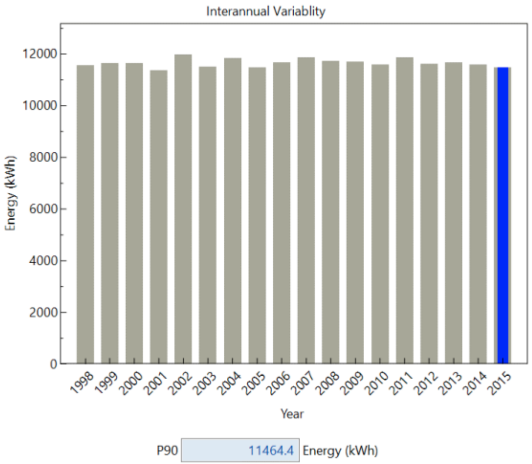

Figure 2. Weather uncertainty graph from SAM uncertainty tool

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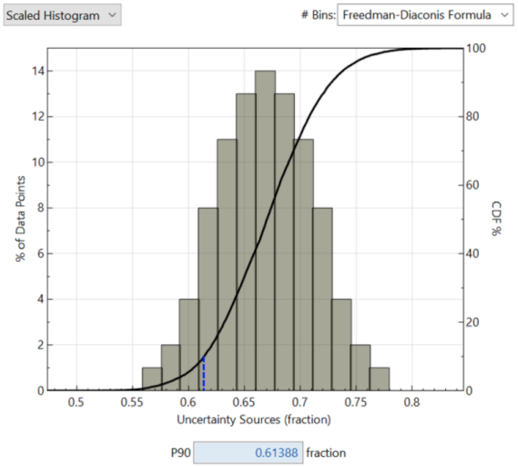

Figure 3. Uncertainty factor graph from SAM uncertainty tool

Summary

Separating weather and other uncertainties:

- Gives same P90
- Quantifies the relative influences of weather variability and model/data uncertainty
- Perhaps easier to quantify annual factors than components of variance