Stochastic PV Performance/Reliability Model
Preview of Alpha Version

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Problem Statement

- **Uncertainties in PV system performance and reliability impact business decisions**
  - Project cost and financing estimates
  - Pricing service contracts and guarantees
  - Developing deployment and O&M strategies
- **Understanding and reducing these uncertainties will help make the PV industry more competitive**
- **Performance has typically been estimated without much attention to reliability of components**
- **Tools are needed to assess all inputs to the value proposition (e.g., LCOE, cash flow, reputation, etc. …)**

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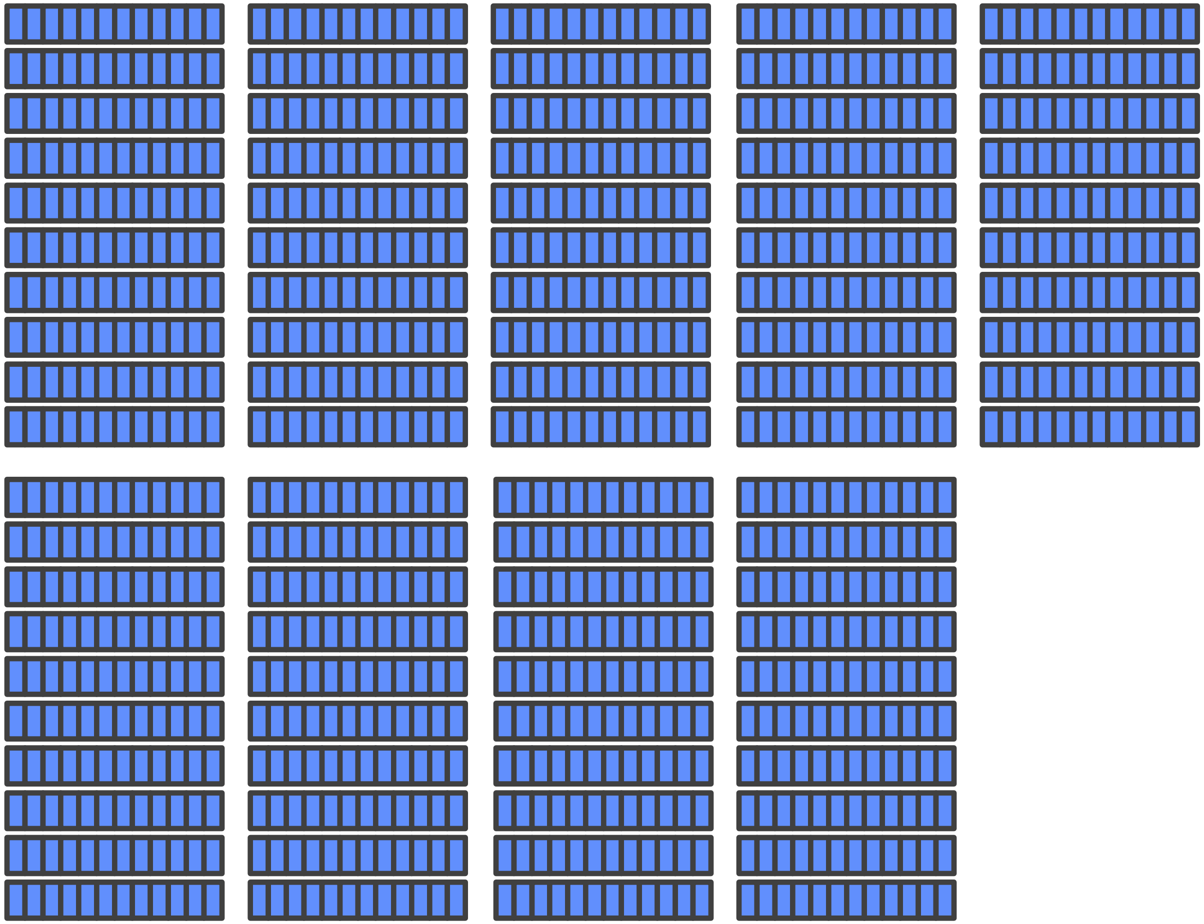
Goals and Objectives

- **Develop a stochastic simulation model (in GoldSim) that can represent PV system performance as a function of system design, weather, reliability, and O&M policies.**
- **Evaluate performance for an example system to quantify sources of uncertainty and identify dominant parameters via a sensitivity study.**
- **Example System:**
  - 1 inverter
  - 225 kW DC Array latitude tilt (90 strings of 12 modules {1080 modules})
  - Weather from Tucumcari, NM (TMY2 with annual uncertainty)

Example PV Array



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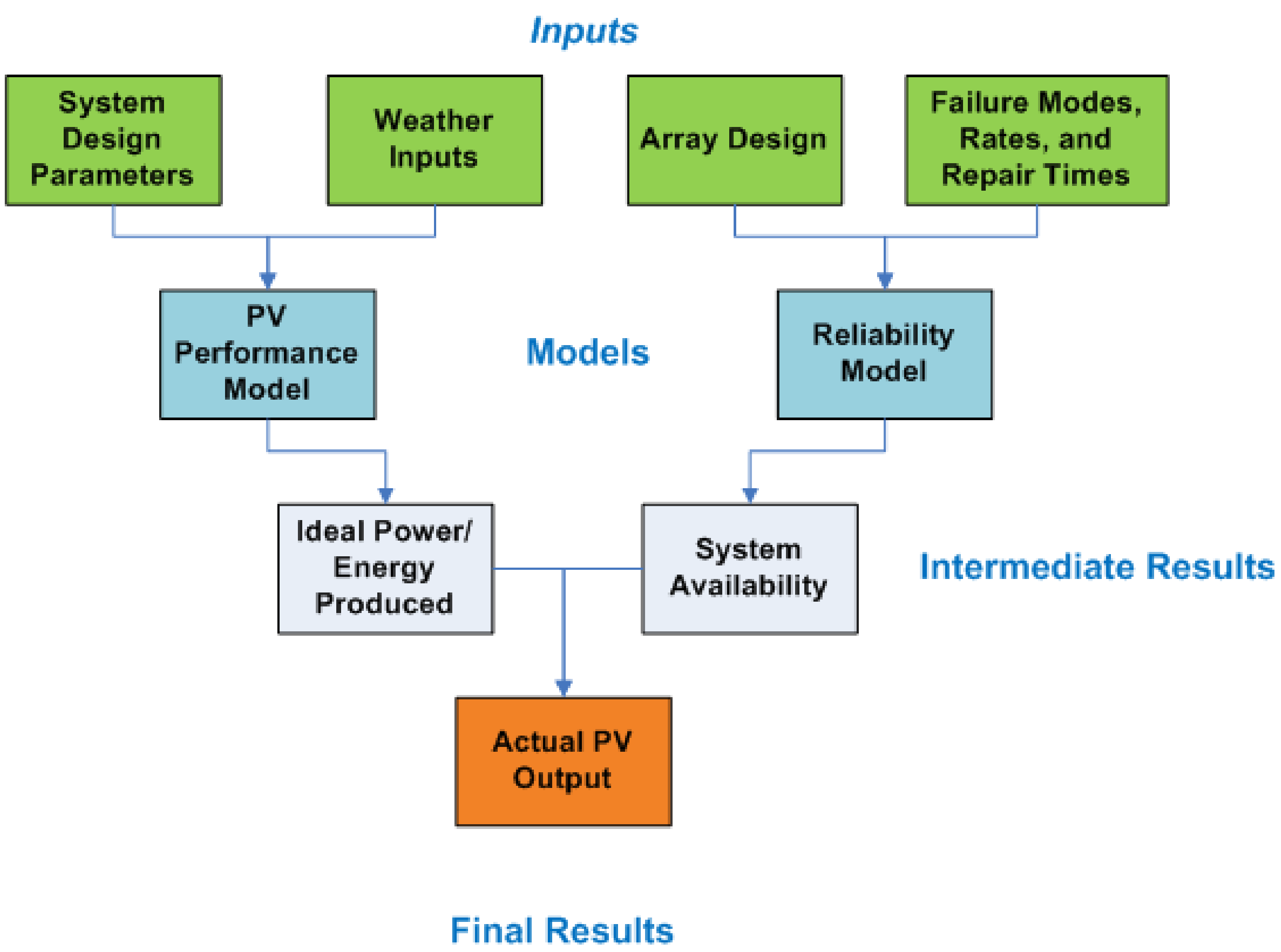
Model Design



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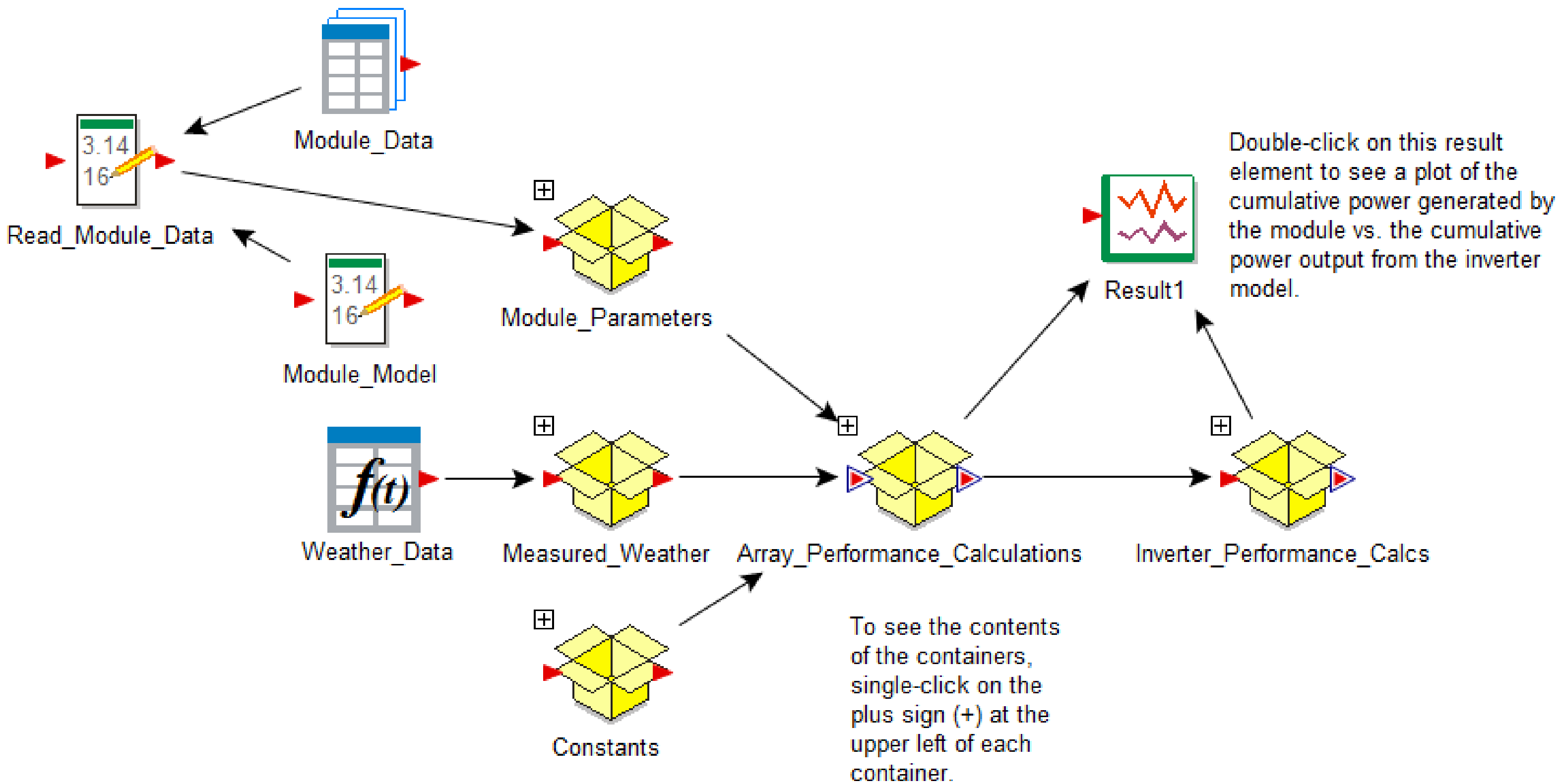
PV Performance Model

PV Array Performance Model

Uses an empirical PV performance model with hourly weather data to calculate the ideal (no system component failures) system output from a module (or array of modules). An inverter performance model is included to determine the expected AC output of the system.



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Sandia Array Performance Model

This series of calculations determines the power at maximum-power point, *Pmp*, for the particular module defined by the module parameters input.

Reference Sandia Report SAND2004-3535, *Photovoltaic Array Performance Model* (King, Boyson, and Kratochvill) for a detailed discussion of the parameters and empirical equations used for calculating the power at maximum-power point.

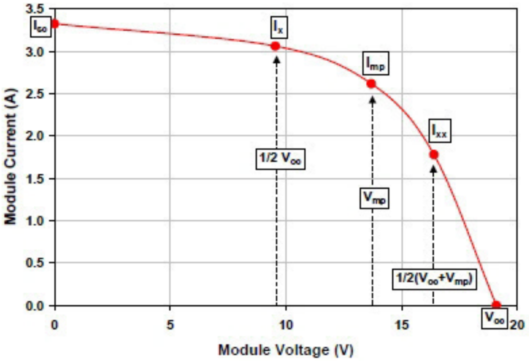
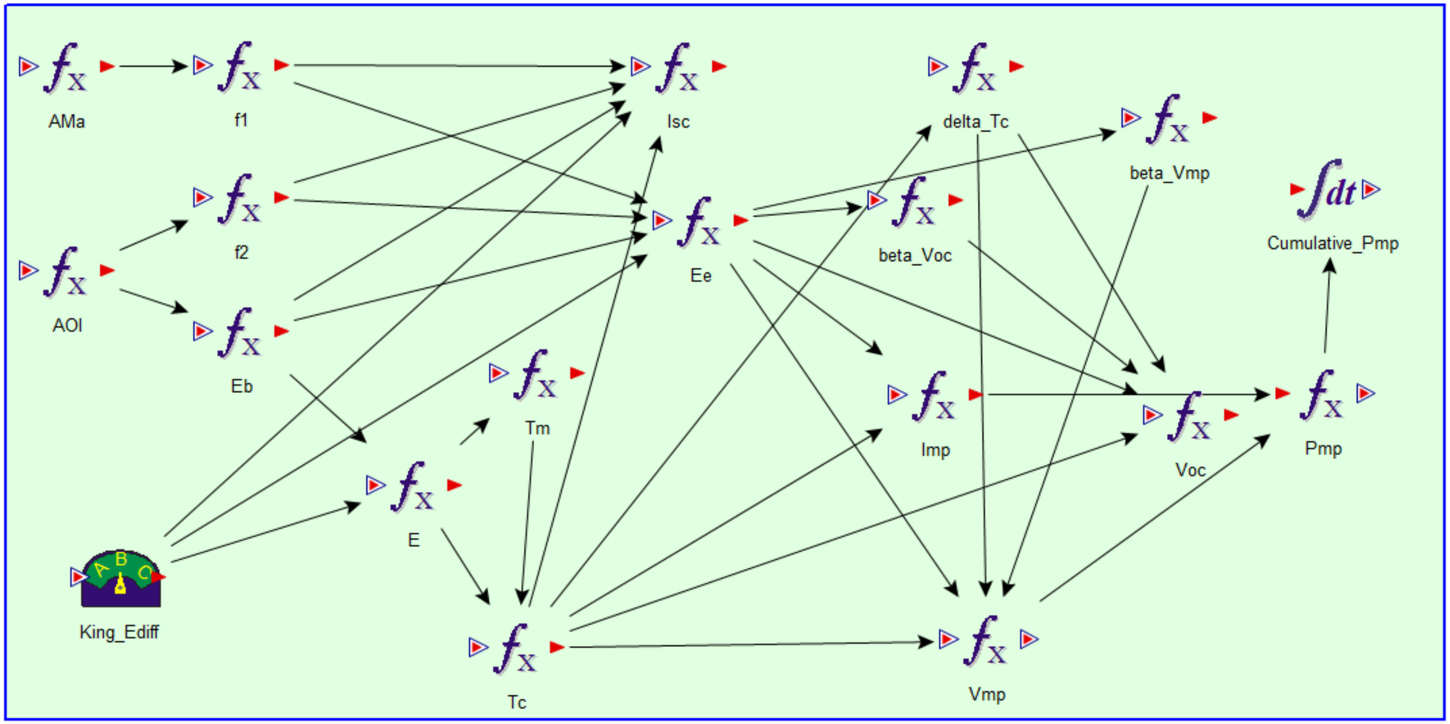


Illustration of a module I-V curve showing the five points on the curve that are provided by the Sandia performance model.
(Source: SAND2004-3535, *Photovoltaic Array Performance Model* (King, Boyson, and Kratochvill).



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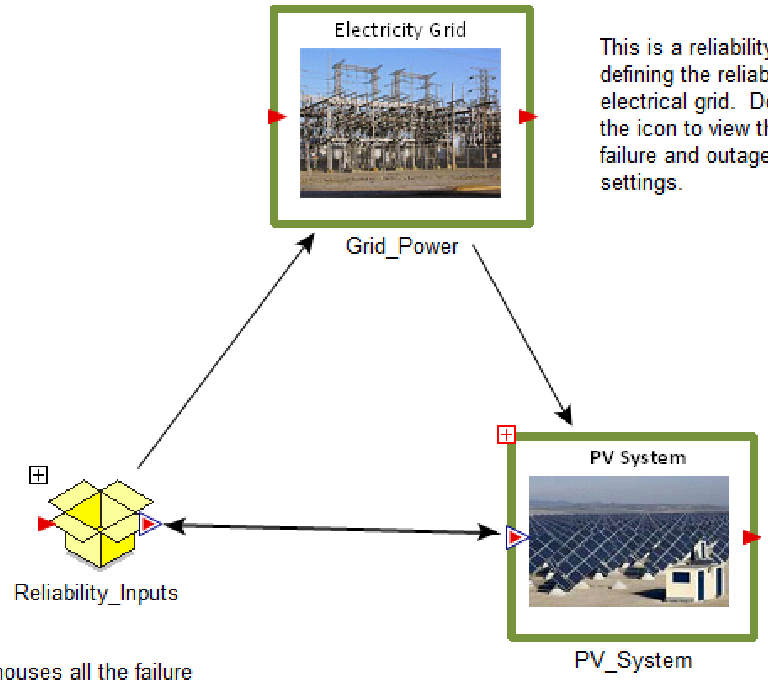
Reliability Model Structure

Reliability Model

The reliability model begins here. Refer to the notes given below. To delve right into the reliability model, enter the PV_System container shown below.



This is a reliability element for defining the reliability of the electrical grid. Double-click on the icon to view the elements failure and outage duration settings.

Single-click on the plus sign (+) at the upper left of this container icon to drop down into the container to begin to examine the details of the PV system reliability model.

This container houses all the failure rate and repair time elements used in the reliability model. Single-click on the plus sign (+) at the upper left of the container icon to drop down into the container an view those elements.

PV Inverter Level

PV System Description

This example model consists of one inverter, nine string blocks each with 10 strings, and each string consists of 12 modules. Total: 1080 modules.

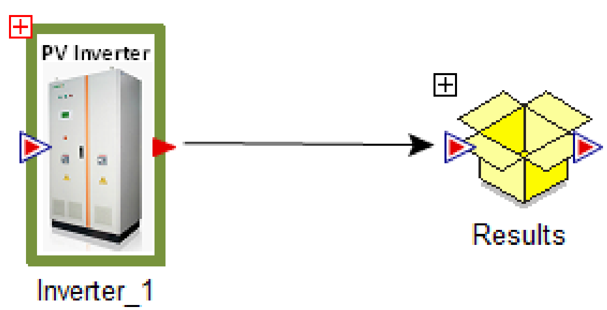
Inverter

The inverter in this example is given one simple failure rate (exponential/Poisson). Upon failure of the inverter, repair is automatically initiated and the repair time is determined by sampling on a lognormal distribution. The inverter also has the external requirement that the electrical grid is available. Thus, if the grid is unavailable, the inverter cannot operate.

String Block

Each string block in this example is given a simple rate (exponential/Poisson). Upon failure of the string block, repair is automatically initiated and the repair time is determined by sampling on a gamma distribution.

Double-click on the inverter icon to see the failure mechanisms defined for the inverter. Single-click on the plus symbol on the upper left of the inverter icon to drop down into the inverter container where the string blocks are contained.

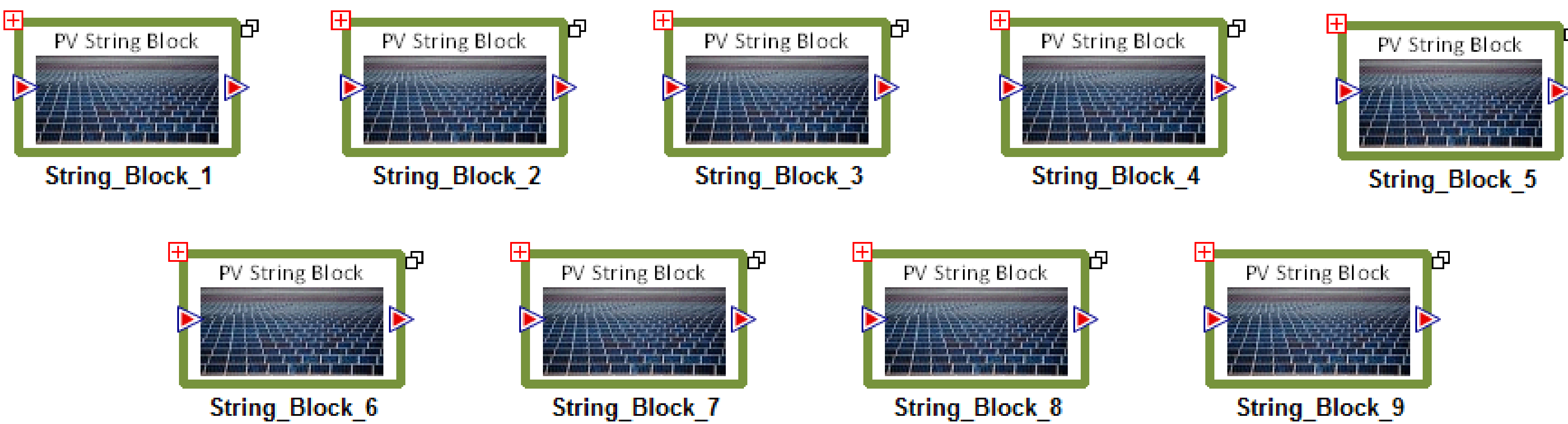


Single-click on the plus symbol on the upper left of the Results icon to drop down into the Results container. There you will find other containers that give results at the inverter, string block, string, and module levels.

PV String Block Level

String Blocks

Here are the reliability elements for each of the string blocks. You can double-click on any string block element to view its attributes. You can single-click on the plus sign (+) on any of the string block elements to view the system of string modules for that string block (note: all string blocks are similar).



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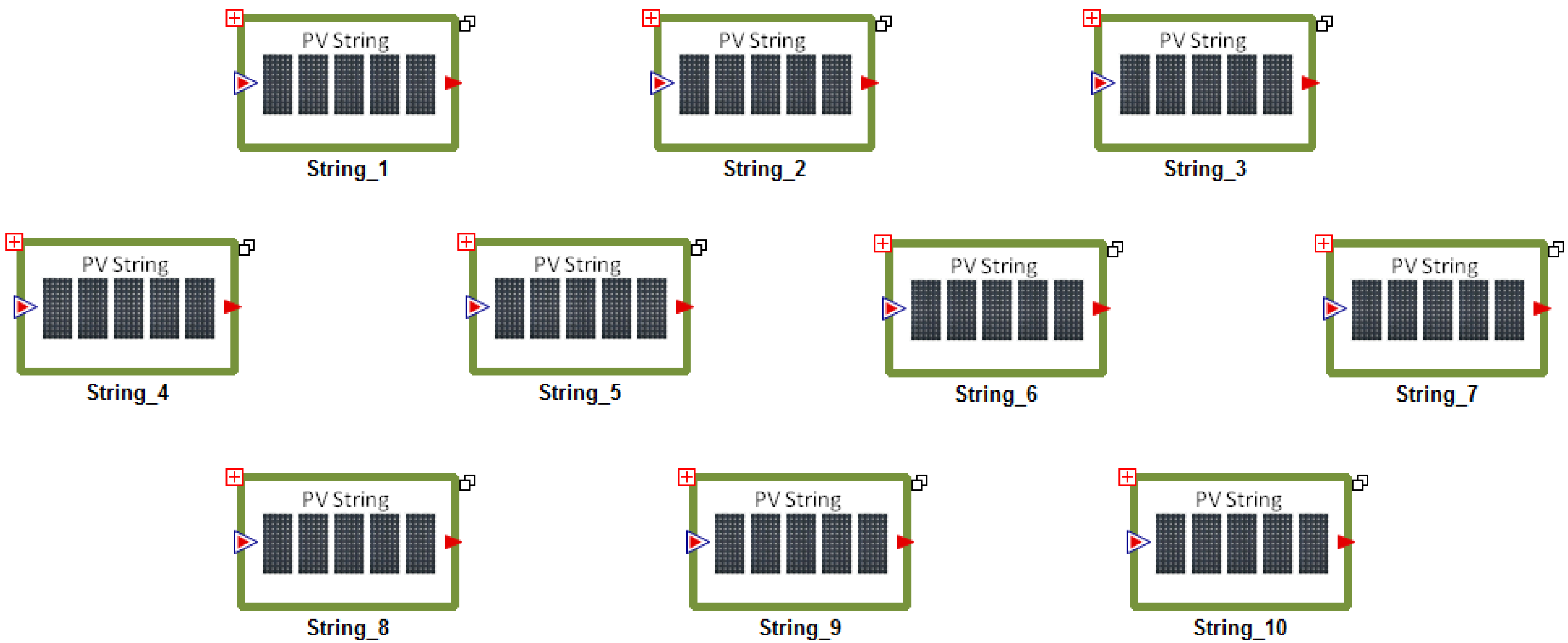
PV String Level

Strings

Here are the reliability elements for each of the strings within a string block. You can double-click on any string element to view its attributes. You can single-click on the plus sign (+) on any of the string elements to view the individual modules in that string (note: all strings are similar).

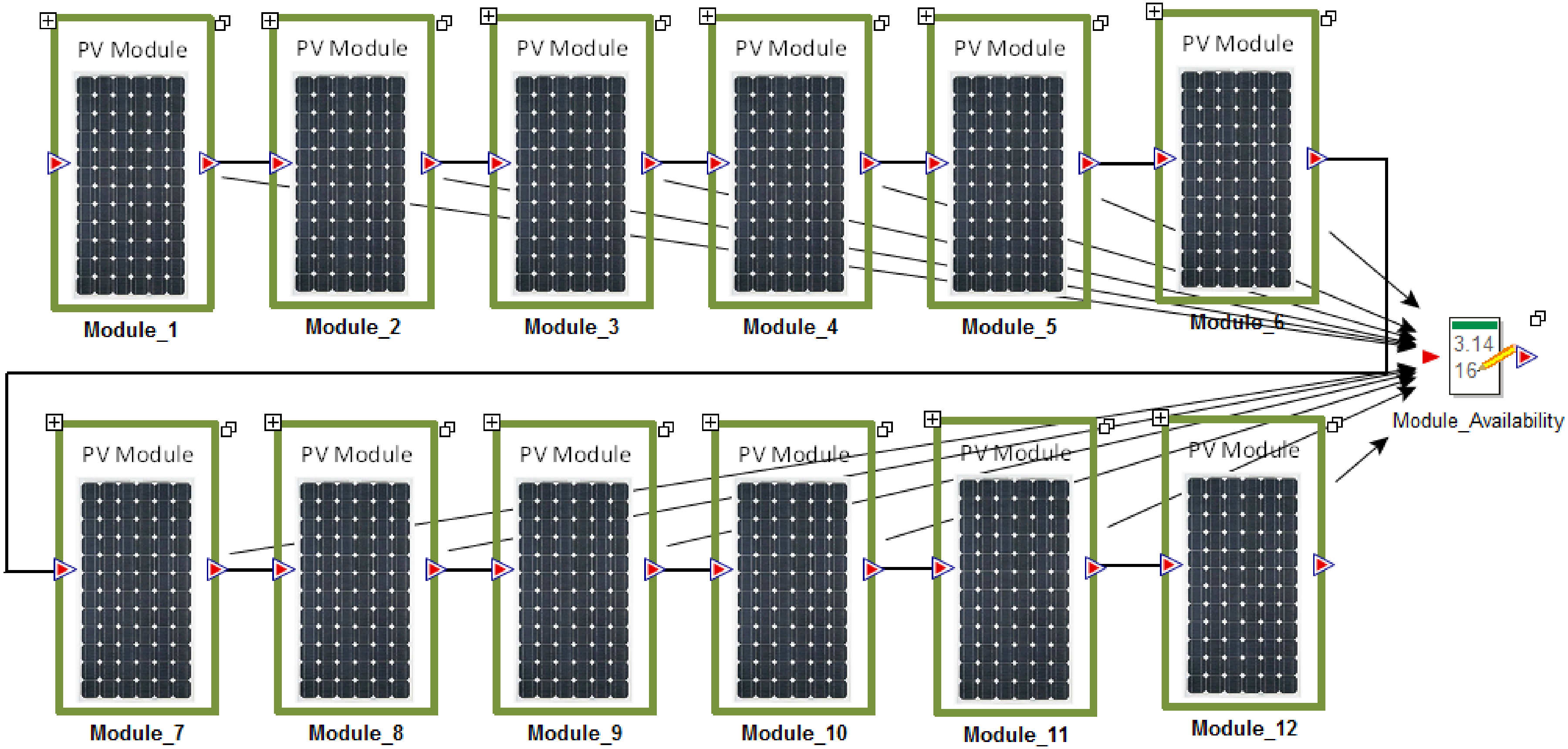


Each string reliability element contains one simple failure mode (exponential/Poisson). A repair time is also defined upon the occurence of a string failure. Additionally, the string is also defined as failed when any of its modules experience an open-circuit failure. In that case, the string remains in the failed condition until the module has been repaired/replaced.

PV Module Level

Modules

An open circuit failure in a module is assumed to fail the entire string, and is therefore, repaired. Each bypass dioide failure in a module is assumed to reduce module output by 25%, but no repair is initiated.



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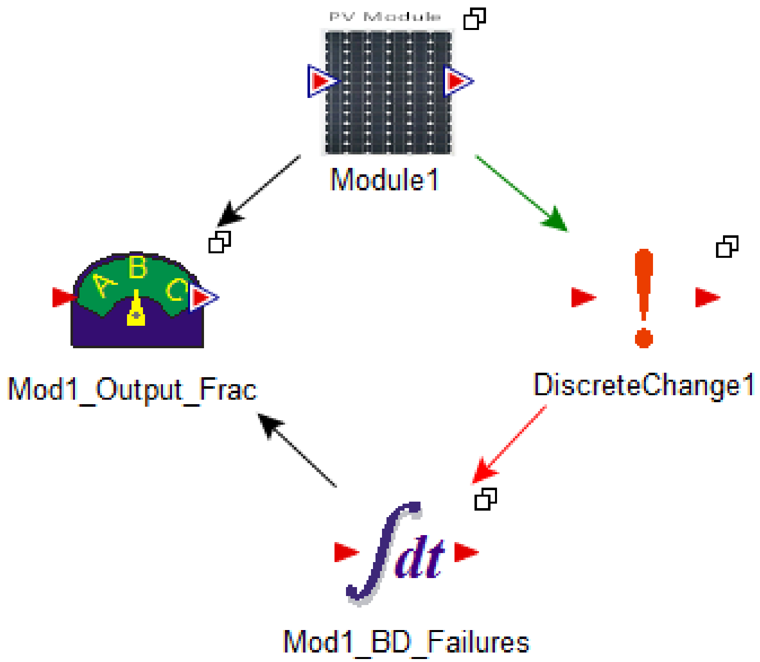
PV Submodule Level



As the simulation progresses, the discrete change element (*DiscreteChange1*) receives a signal from the module reliability element each time a bypass diode failure occurs. When the discrete change element receives such a signal, it sends a signal the the integration element (*Mod1_BD_Failures*) to increment its count by one. The integration element provides the real-time status of the number of bypass diode failures to the selector element (*Mod1_Output_Frac*) which selects the real-time fractional availability of the module. Also, the module reliability element also sends the selector element a signal if the module has an open-circuit failure, which indicates an immediate failure of the module.

Each module has 4 bypass diodes represented

Reliability Inputs

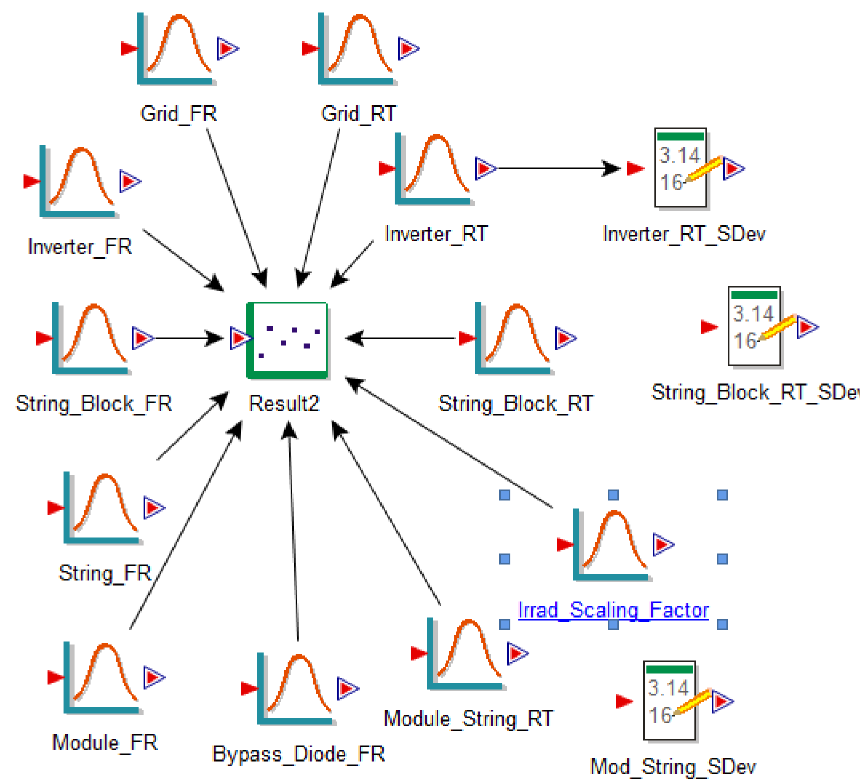
<u>Reliability Model Parameters:</u>

- Failure Rate (Poisson process)
- Repair Time

<u>Represented Components:</u>

- Grid
- Inverter
- String blocks
- Strings
- Modules
- Bypass diodes

These stochastic elements are used as the inputs to the reliability elements for specifying the failure rates and repair times.



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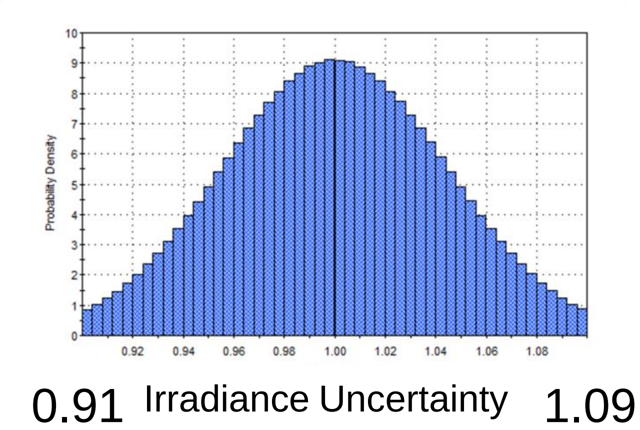
Example Simulation

- **Single inverter**
- **225 kW DC Array**
- **Weather from Tucumcari, NM (TMY2)**
  - Annual uncertainty 95% confidence interval +/- 9%



- **Results are annual energy (normalized to ideal system output)**

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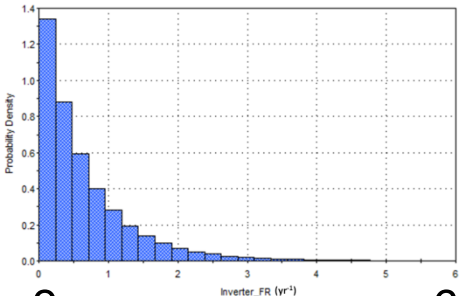
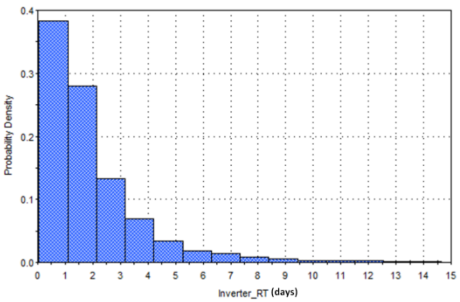
Inverter Reliability

- **Causes**
  - Trips requiring manual resets, capacitor failure, fan, etc…
- **Failure Rate**
  - Distribution: Exponential
  - Mean: Uniform [1/3 to 1 per year]



- **Repair Time**
  - Distribution: Lognormal
  - Mean: Uniform [1 to 3 days] (max simulated = ~15 days)



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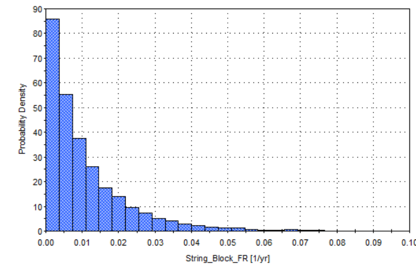
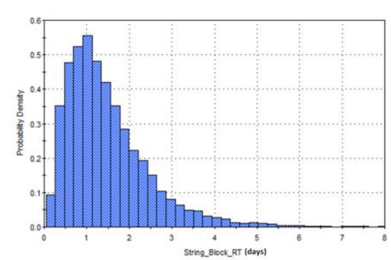
String Block Reliability

- **Causes**
  - Combiner box, connections, fuses, rodent damage…
  - Future runs: tracker problems?
- **Failure Rate**
  - Distribution: Exponential
  - Mean: Uniform [1/270 to 5/270 per year]



0 0.1 yr^{-1}

- **Repair Time**
  - Distribution: Lognormal
  - Mean: Uniform [1 to 2 days] (max simulated = ~8 days)
  - *Failure at this level would cause a ~10% reduction in system output and would be noticed in daily monitoring.*



0 8 days

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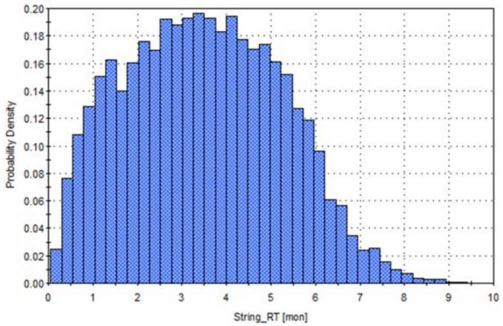
String Reliability

- **Causes**
  - connections, arc fault, fuses, rodent damage,…
- **Failure Rate**
  - Distribution: Exponential
  - Mean: Uniform [1/2700 to 5/2700 per year]
  - Basis: 2700 strings, 1-5 failures a year
- **Repair Time**
  - Distribution: Lognormal
  - Mean: Uniform [1 to 6 months] (max simulated = ~9 months)
  - ***Failure at this level will <u>not</u> be easy to detect except during annual or biannual inspections, thus the long repair times…*

Repair Time Distribution



0 10 months

*** String level monitoring would affect repair time distribution*

Module Reliability

- **Causes**
  - Junction box, physical damage, arc fault, etc.
- **Failure Rate**
  - Distribution: Exponential
  - Mean: Uniform [1/6000 to 1/500 per year]
  - Basis: range found in literature search (MTBF 500-6000 yrs)
- **Repair Time**
  - Distribution: Lognormal
  - Mean: Uniform [1 to 6 months] (max simulated = ~9 months)
  - ***Failure at this level will not be easy to detect except during annual or biannual inspections, thus the long repair times…*
  - *Physical damage may be identified early (not currently represented)*

Bypass Diode Reliability

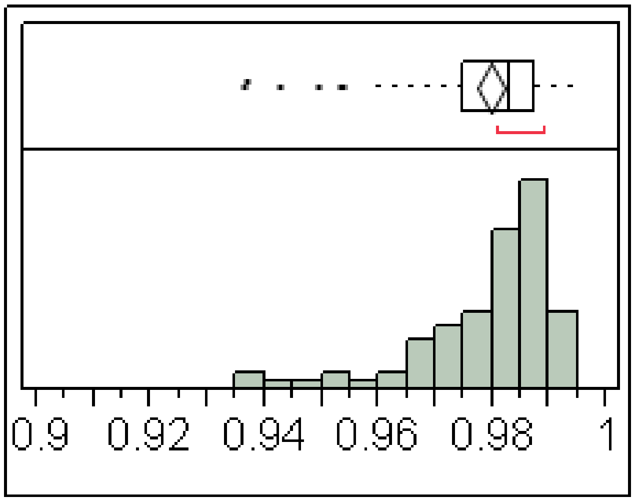
- **Causes**
  - Failure leads to module degradation in increments of 25%
- **Failure Rate**
  - Distribution: Exponential
  - Mean: Uniform [1/200 to 1/50 per year]
  - Basis: Expert guess…
- **Repair Time**
  - No repair is simulated. Is this reasonable?

- ***This failure rate represents module degradation rates from 0.4% to 2% per year***

Example Model Results

- Monte Carlo simulation with 100 realizations
- Result is actual performance / ideal performance

Relative Output



Quantiles

100.0%	maximum	0.99484
99.5%		0.99484
97.5%		0.99336
90.0%		0.99039
75.0%	quartile	0.98735
50.0%	median	0.98319
25.0%	quartile	0.97494
10.0%		0.96548
2.5%		0.93968
0.5%		0.93604
0.0%	minimum	0.93604

Moments

Mean	0.9797103
Std Dev	0.0118507
Std Err Mean	0.0011851
Upper 95% Mean	0.9820618
Lower 95% Mean	0.9773589
N	100

- Uncertainty is evaluated

Sensitivity Analysis

- **Parameter sensitivity was evaluated using stepwise regression techniques.**

Step	Parameter	RSquare	Incremental Rsquare
1	Irrad_Scaling_Factor	0.1456	0.1456
2	Bypass_Diode_FR(1/yr)	0.2555	0.1099
3	Inverter_FR(1/yr)	0.334	0.0785
4	Inverter_RT(day)	0.3874	0.0534
5	Module_FR(1/yr)	0.4131	0.0257
6	Module_String_RT(day)	0.441	0.0279
7	Grid_FR(1/yr)	0.4656	0.0246

•Weather (irradiance) uncertainty, bypass diode and inverter reliability account for almost 40% of variance in performance.

What are the Correct Modeling Assumptions??

- Model results are driven by assumptions and parameter distributions.
- Reliability data from fielded systems is difficult to obtain and share.
- Representing this data as uncertainty distributions may help to uncover sensitivities otherwise obscured by uncertainty.
- How can such a modeling approach add value to the PV industry?

Next Steps

- **Simulate full system lifetime (30 years+)**
- **Examine range of O&M scenarios and policies**
  - Define representative failure rates and repair times
  - Identify correlations between failure and weather conditions?
- **Simulate financial costs and revenues in model**
  - Labor rates, track inventory of spare parts, etc…
  - Include time of use rates
- **Develop derate models (e.g., soiling)**
  - Soiling vs. cleaning frequency
- **Obtain inputs from industry**
  - Very Important!

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Thank You

Questions…