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PV-RPM Demonstration Model User's Guide

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Introduction

This model is a simplified "player" version of the Photovoltaic Reliability Performance Model (PV-RPM) currently in development at Sandia National Laboratories (SNL). The PV-RPM is built using the GoldSim™ Probabilistic Simulation Environment. The PV-RPM allows the user to define a PV system (inverters, modules, tracking, etc.) and select or input weather data, and the model will calculate the performance of the system using the SNL *Photovoltaic Array Performance Model* (King, Boyson, & Kratochvill, 2004) and the SNL *Performance Model for Grid Connected Photovoltaic Inverters* (King, Gonzalez, Galbraith, & Boyson, 2007). Of course, there are many other software packages available that can also predict PV system performance (kilowatt-hour output of the system). These performance predictions are actually a prediction for an idealized case where the PV system does not experience component failures or degradation, electrical grid outages, or any other type of disruption.

The PV-RPM is intended to address more "real world" situations by coupling the performance model with a reliability model so that inverters, modules, combiner boxes, etc. can experience failures and be repaired (or left unrepaired). The model can also include other effects, such as module output degradation over time or disruptions such as electrical grid outages. In addition, PV-RPM is a dynamic probabilistic model that can be used to run many realizations (i.e., possible future outcomes) of a system's performance using probability distributions to represent uncertain parameter inputs.

We are currently working on adding a financial component to calculate cash flows based on the sale of energy produced or the energy lost due to component failures. This will include estimates of Operations and Maintenance (O&M) costs (e.g., debt servicing, repair costs, preventative maintenance) into the final cash flow calculation. We expect to develop PV-RPM even further to investigate issues such as module temperature issues such as spatial fluctuations and heat island effects, cost/benefit of different O&M strategies, and inverter size trade-off studies to name a few.

This model is intended to demonstrate the system performance and reliability functionality of the PV-RPM using a free player version of the model. The sections that follow describe how to install the player software and how to use this player model file.

System Configuration

The GoldSim software provides considerable flexibility as to how a system can be modeled. On the other hand, a GoldSim player file is intended to allow a user who does not own a GoldSim license to "play" a model and to change those inputs that the model developer makes available to the user, but the model structure cannot be modified in a player model. Therefore, the model structure here is somewhat generic and is very similar to that described in *A Reliability and Availability Sensitivity Study of a Large Photovoltaic System* (Collins, et al., 2010).

The PV system modeled here consists of these components: inverters, combiner boxes, transformers, AC disconnects, modules, and the electrical grid. While the system setup allows for the selection of single or dual-axis tracking, the reliability model in this demo model does not include failures of the tracking systems. The system configuration is setup in the Model Settings Dashboard which is described in one of the following sections.

GoldSim™ Player

GoldSim is an object-oriented graphical simulation program that can be used to build system models using graphical input elements that can represent data inputs, time series information, equations, stochastic distributions, disruptive events, and much more. This graphical modeling architecture can convey a more easily understandable representation of a complex system model over that which is possible using typical coding methods.

GoldSim can be used to carry out dynamic probabilistic model simulations to predict the possible future performance of the system. Because some model parameters cannot be known with complete certainty, for example the operating lifetime of an inverter or how a module's output will degrade over time; these inputs can be defined using probability distributions. The model can then be simulated many times, each time using a different sample value from those probability distributions, to provide many possible realizations (possible future outcomes) of the system. GoldSim uses Monte Carlo simulation to do this and also includes the option to sample the stochastic variables using Latin Hypercube sampling.

The GoldSim Player is a special version of GoldSim, that can be obtained free of charge (www.goldsim.com), and is used to "play" a specially prepared GoldSim model without having to purchase a license for the GoldSim software. The GoldSim Player can allow a user to make changes to those model inputs that the modeler makes available on specially prepared dashboards, and view results that are also made available via a dashboard. While the user can make changes to selected model inputs, the GoldSim Player does not allow the user to access any of the menu options that are available in the licensed version GoldSim, or to edit the underlying model in any way.

The following sections describe the dashboards in the PV-RPM Web Demo model and how the user can change the model inputs made available on the dashboard and view the results.

Installation of the GoldSim™ Player

The GoldSim Player software has been bundled along with this PV-RPM web demo user's guide, the PV-RPM web demo model, and other necessary DLL files used by the demo model. The GoldSim Player software can also be downloaded free of charge from the GoldSim website (www.goldsim.com). To install the Player, simply double-click on the setup file

(GoldSim_Player_10.5SP1_Setup.exe) and an installation wizard will facilitate the installation process.

After installing the Player, the PV-RPM demo file (PV-RPM Web Demo.gsp) can be opened either by double-clicking on the PV-RPM demo file or opening the GoldSim Player via the Windows Start menu and then navigating to the directory where the PV-RPM demo file was saved.

PV-RPM Player Demo

The PV-RPM player demo will open to an introductory dashboard and the GoldSim Run Controller will also open. This player file consists of four dashboards that provide instructions for using the model, for allowing the user to specify certain model parameter inputs, and for displaying the simulation results. The Run Controller provides the means to start, monitor, and reset a simulation. Each of these dashboards and the Run Controller are discussed in the following sections.

Introduction Dashboard

This dashboard provides a brief introduction to the Demo player file and gives a brief description of the other three dashboards; the Model Settings Dashboard, the Failure Modes Dashboard, and the Results Dashboard.

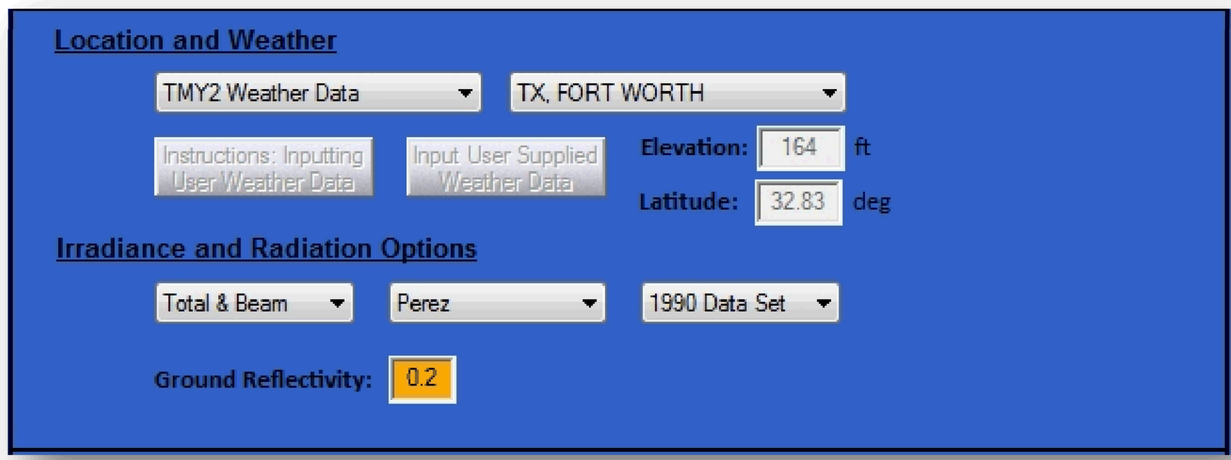
Along the bottom of this and the other dashboards are navigation buttons that when clicked will switch to the dashboard indicated.

Model Settings Dashboard

The Model Settings dashboard is used to define the basic inputs to the model such as: PV site location and weather data, the system setup including tracking options and module orientation, and the model run simulation settings. The subsections below describe how these inputs can be setup to run a simulation.

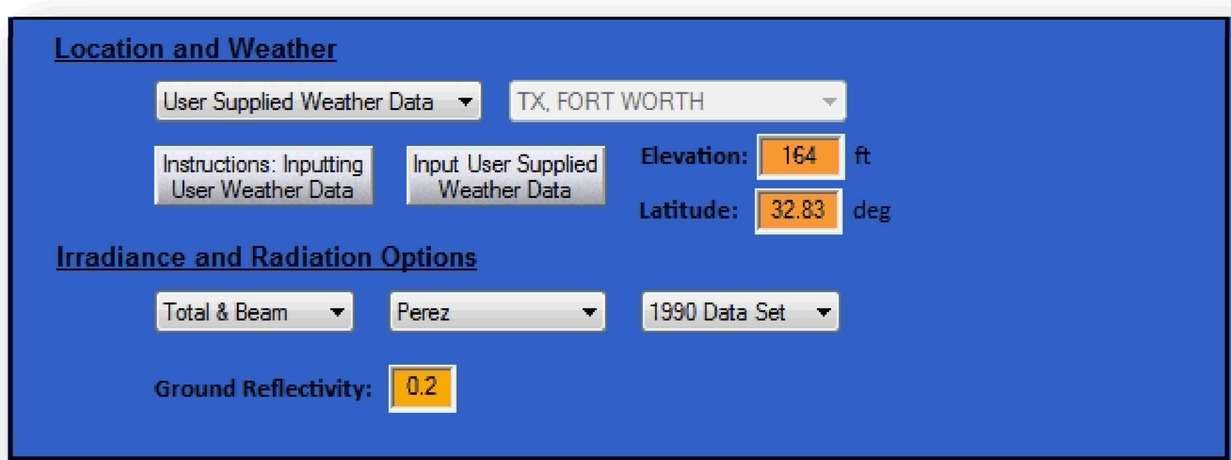
Location and Irradiance Model Inputs

The image below shows the settings options for defining the location and weather information to use for the PV site, and setting options for the diffuse irradiance model , the radiation model (i.e., total and beam, or beam and diffuse), and the desired ground reflectivity value to use in the calculations. Each of these settings is selected via the drop down list, with the exception of the ground reflectivity value which is input directly into the input box.

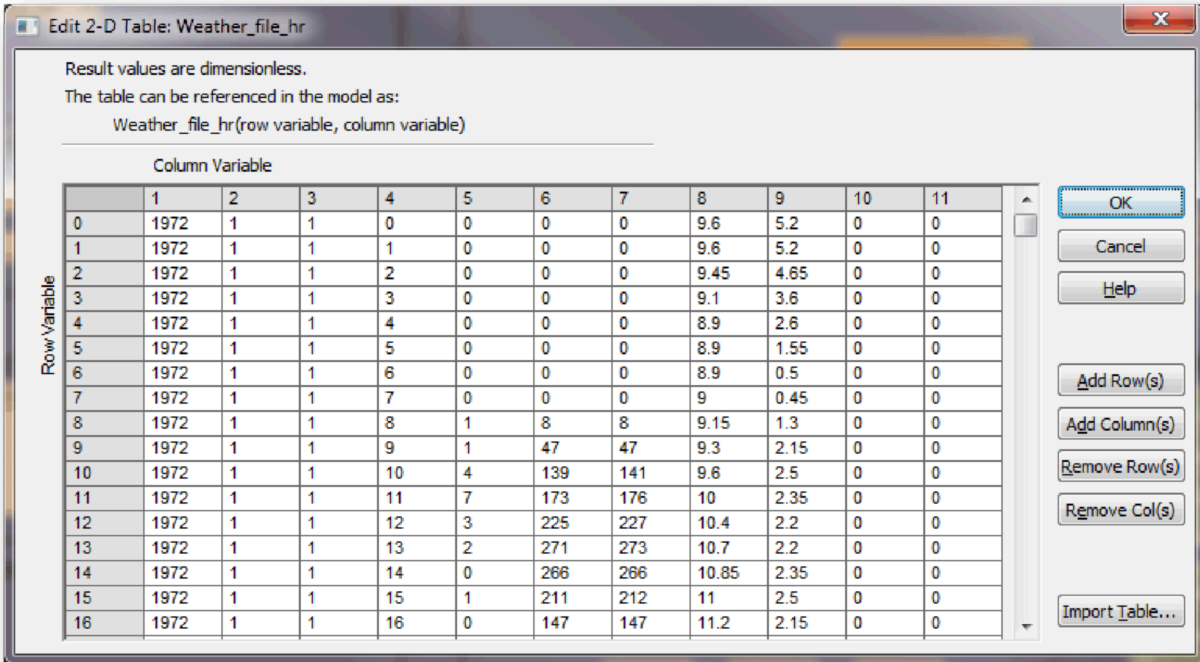


It should be noted that the selection of the "Perez F coefficient" option (i.e., 1988 data set or 1990 data set) is only meaningful if the Perez irradiance model is selected, if some other irradiance model is selected the data set selection option is hidden.

The selection of the weather data options requires further explanation. If "TMY2 Weather Data" is chosen from the drop down list, then the desired TMY2 location should be chosen from the next drop down list. If the user has a full year (8760 hours) of weather data and would prefer to use that instead of TMY2 location data, then the "User Supplied Hourly" option should be chosen from the weather data dropdown list. When the "User Supplied Hourly" option is selected, then the TMY2 location selection is disabled and the buttons and input boxes at the bottom become active as shown in the image below:



Input the elevation and latitude for the site where the user supplied weather data was collected in the input boxes. Click the "Input User Supplied Weather Data" button and a table will open as shown below.


Edit 2-D Table: Weather_file_hr

Result values are dimensionless.
The table can be referenced in the model as:
Weather_file_hr(row variable, column variable)

Column Variable

Row Variable	1	2	3	4	5	6	7	8	9	10	11
0	1972	1	1	0	0	0	0	9.6	5.2	0	0
1	1972	1	1	1	0	0	0	9.6	5.2	0	0
2	1972	1	1	2	0	0	0	9.45	4.65	0	0
3	1972	1	1	3	0	0	0	9.1	3.6	0	0
4	1972	1	1	4	0	0	0	8.9	2.6	0	0
5	1972	1	1	5	0	0	0	8.9	1.55	0	0
6	1972	1	1	6	0	0	0	8.9	0.5	0	0
7	1972	1	1	7	0	0	0	9	0.45	0	0
8	1972	1	1	8	1	8	8	9.15	1.3	0	0
9	1972	1	1	9	1	47	47	9.3	2.15	0	0
10	1972	1	1	10	4	139	141	9.6	2.5	0	0
11	1972	1	1	11	7	173	176	10	2.35	0	0
12	1972	1	1	12	3	225	227	10.4	2.2	0	0
13	1972	1	1	13	2	271	273	10.7	2.2	0	0
14	1972	1	1	14	0	266	266	10.85	2.35	0	0
15	1972	1	1	15	1	211	212	11	2.5	0	0
16	1972	1	1	16	0	147	147	11.2	2.15	0	0

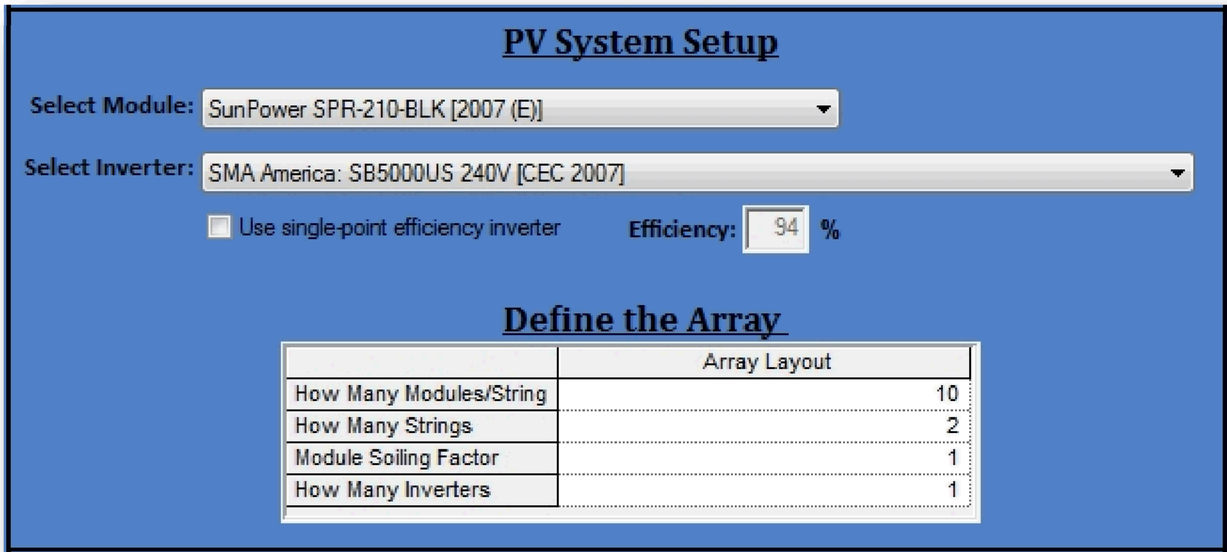
OK
Cancel
Help
Add Row(s)
Add Column(s)
Remove Row(s)
Remove Col(s)
Import Table...

The user supplied weather data can be pasted in this table, but it should be arranged in the following 11 columns: Year, Month, Day, Hour, DNI, DHI, GHI, Ta, WS, Zenith, and Azimuth, respectively. The first row should start at 0 hr (this can be a copy of the 1st hour) followed by 8760 hrs (1 yr) of data for a total of 8761 rows. Note that for the user supplied weather data, inputs for zenith and azimuth (columns 10 and 11) are not needed since this information will be calculated by the model.

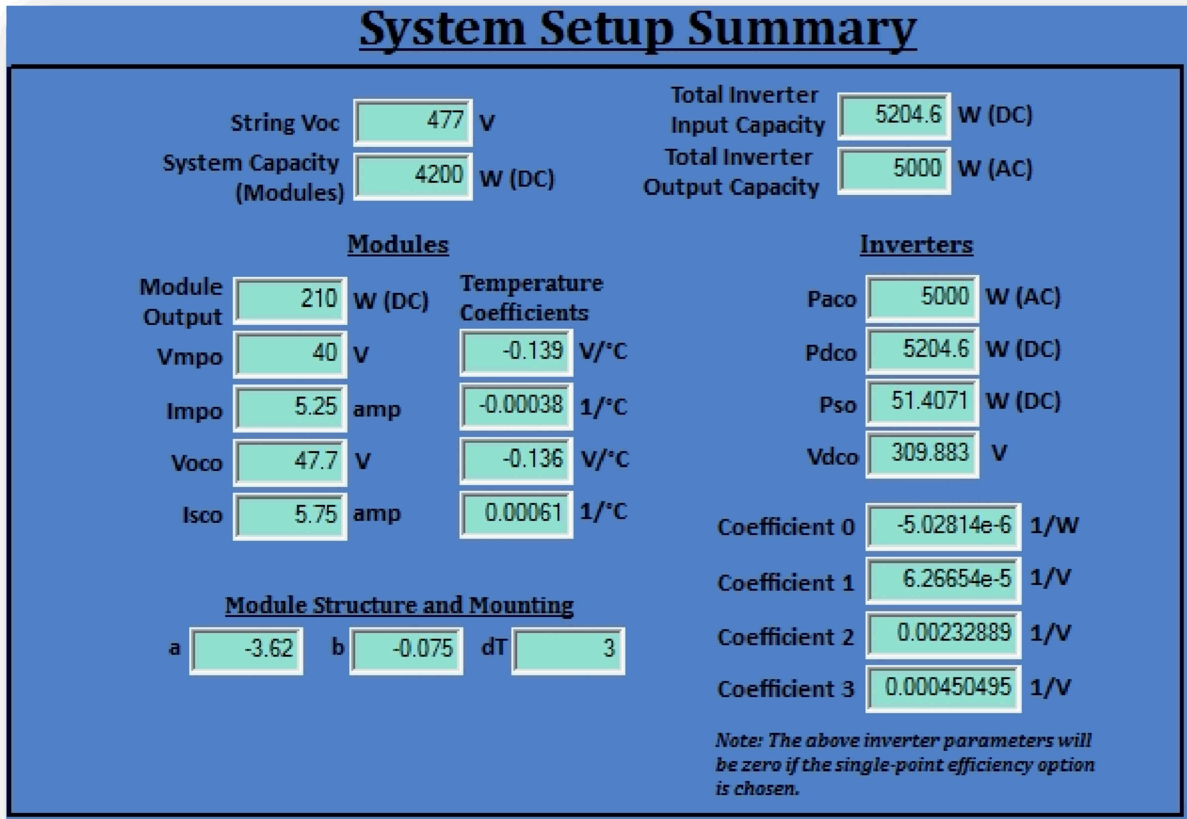
The TMY2 database provides weather data for the "typical" year, but for PV performance calculations the period of interest is typically much more than one year. To provide some variability in the weather data after the first year, the TMY2 data, as well as the user input weather information if used, is multiplied by a variability factor. This variability factor is based on the uncertainty values listed in the National Renewable Energy Laboratory publication *Solar Radiations Data Manual for Flat-Plate and Concentrating Collectors* (National Renewable Energy Laboratory, 1994).

PV System Setup and Tracking

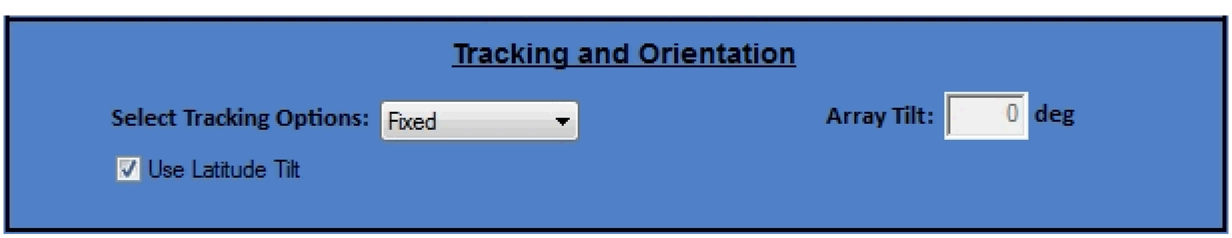
Here is where the PV system is defined. There is a drop-down list for selecting any PV module in the Sandia National Laboratories Module database. This demonstration model assumes that the whole array consists of the same type of module. Similarly, there is a drop-down list for selecting the desired inverter from those in the Sandia Inverter database, and it is assumed that if there is more than one inverter, they are all the same model. The user has the option to forgo selection of a particular inverter, and chose to use a "single-point efficiency" inverter with a user defined efficiency.



Once the modules and inverter(s) are selected, the input table can be used to input the specifics of the system such as the number of modules per string, the number of strings, the number of inverters, and the module soiling factor. This demo model assumes that each inverter carries an equal share of the system input power. Once these options are chosen, a simple system summary is displayed at the bottom right of the dashboard. See the figure below as an example of a system summary. Note that, with the exception of utility applications, the string voltage should notexceed 600 V.

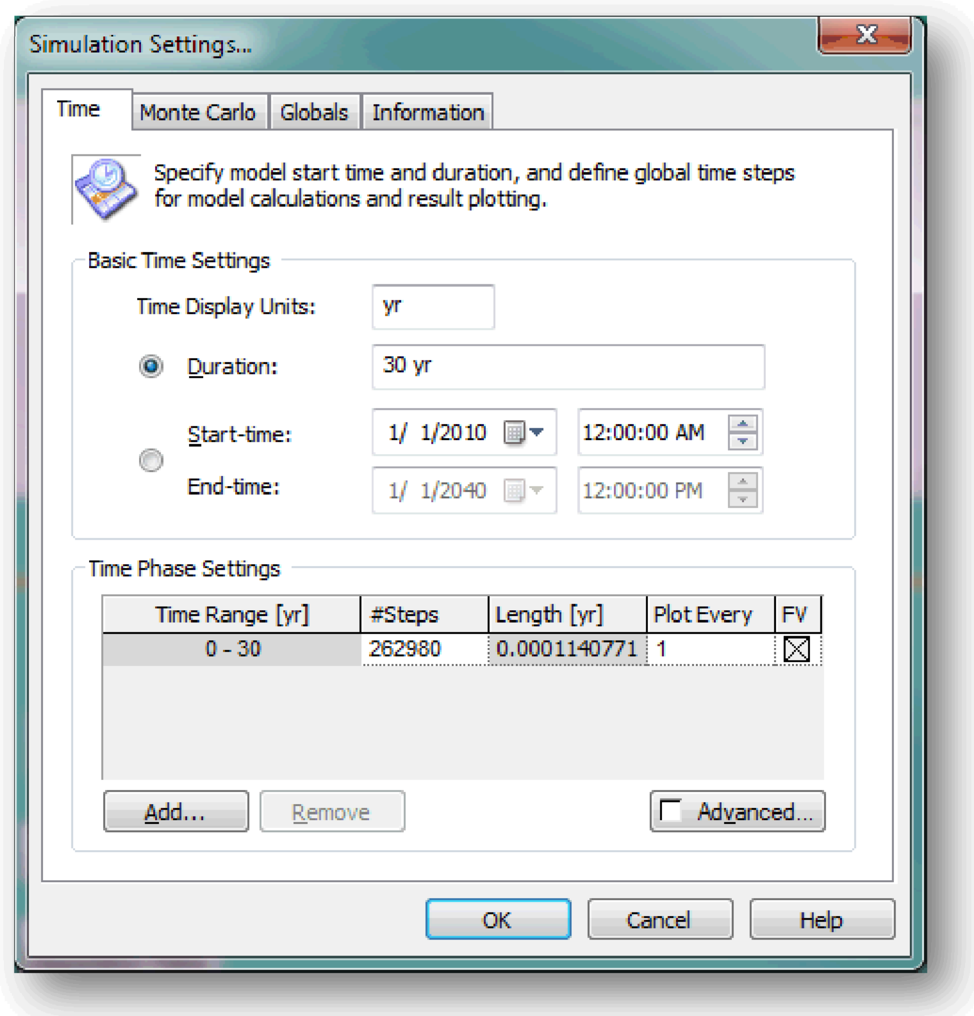


The tracking and orientation options settings are shown below. The tracking options are fixed, single-axis tracking, or dual-axis tracking. The fixed array is assumed to be pointed due south, and the array tilt angle can be input by the user. Latitude tilt is a common orientation for a fixed system and there is a check box to select that option. If that check box is not selected, then the array tilt angle input box becomes active for user input. An array tilt angle of 0 degrees would indicate a horizontal orientation of the modules, such as on a flat roof, and a 90 degree angle would be used for a vertical application, such as on a building wall. The single-axis tracker is assumed to have its axis of rotation pointed due south and rotates from east in the morning to west in the evening to track the movement of the sun across the sky. The two-axis tracker allows a tracking motion such that it can always be pointing directly at the sun.



Model Run Simulation Settings

In order to correctly run the model, the simulation settings must first be configured. To access the model simulation settings, click the "Simulation Settings" button on the dashboard The Simulation Settings dialog opens with the *Time* tab active as shown below.

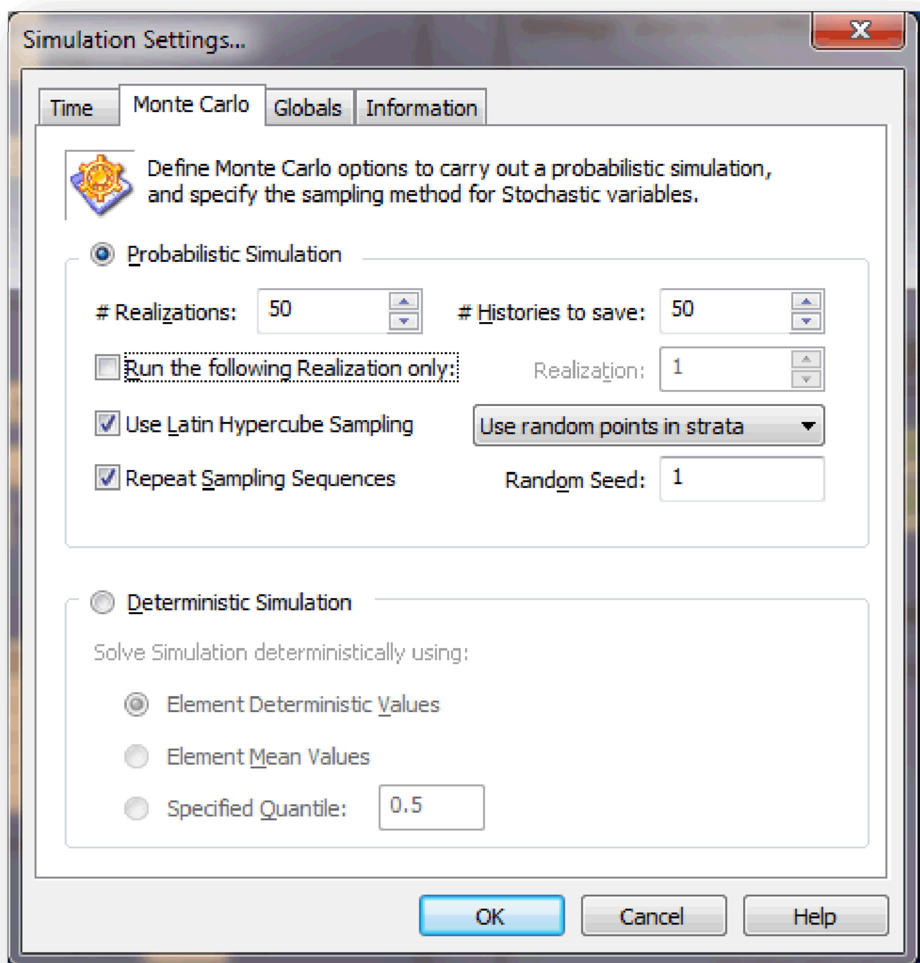


In this dialog window, the simulation duration and the number of timestepsare specified. The time step length should ideally be set such that it equals one hour to match the hourly TMY2 weather data interval. As an example, here is how the time settings would be specified for a 30 year model simulation:

1) in the *Time Phase Settings* box set *Time Display Units* to yr,
2) set *Duration* = 30 yr, and
3) set *#Steps* in the *Time Phase Settings* box to 262980 (30 yr * 365.25 days/yr * 24 hr/day = 262980 hr)

By default, GoldSim saves time histories by saving the values of outputs at every timestep. You can instruct GoldSim to only save results at selected timesteps (for example, every tenth timestep) by specifying the *Plot Every* in the *Time Phase Settings* section. If *Plot Every* is set to 1, every timestep is saved; if it is set to 2, every other timestep is saved, and so on. This can speed the simulation and reduce the final file size, particularly with longer simulation durations and small timesteps such as with this 30 year, 1 hour timestep example (there would be 262,980 plot points for every time history output). If the output of interest is a cumulative result (e.g., total energy output) or an average operational availability output, then reducing the number of time steps saved can significantly speed the simulation and reduce the file size (e.g., *Plot Every* could be set to 10 or 100). If it is desired to have an output that shows the result for every hour of the day or where it is desired to show finer details in a plot (e.g., many electrical grid failure events could be missed if the *Plot Every* setting is set too high), then this *Plot Every* value should remain as 1.

The final simulation settings that need to be specified are found under the *Monte Carlo* tab. This is where the Monte Carlo options are specified for carrying out a probabilistic simulation, and for specifying the sampling method for stochastic variables. The Monte Carlo input options are shown in the figure below.



Select the *Probabilistic Simulation* radio button (if it is not already selected) to activate the input options. Then input the number of realizations (*# Realizations*) and the number of time histories to save (*# Histories to save*). Typically, the number of histories to save will be equal to the number of realizations chosen. You may choose to save fewer time histories than the number of realizations run to save hard disk space for example.

The manner in which the Monte Carlo sampling of stochastic elements occurs is controlled by the *Use Latin Hypercube Sampling* and *Repeat Sampling Sequences* options. The LHS sampling method divides a probability distribution into equally likely intervals which has the effect of ensuring that the area of the distribution is uniformly sampled. This technique can more efficiently sample the low probability tails of a distribution over that possible using traditional random sampling. The default setting is to *Use Latin Hypercube Sampling* and *Use random point in strata*. The option to *Repeat Sampling Sequences* provides for the repeatability of a simulation. If this option is selected (the default setting), then a repeatable random number sequence is used based on the specified *Random Seed*. This allows the simulation to be repeated exactly. If *Repeat Sampling Sequences* is not selected, then the random number sequence will be different every time the model is run, resulting in a different result each time.

Failure Modes Dashboard

The Failure Modes Dashboard is where the user can specify inputs for the reliability model. There are many failure mode types available in GoldSim to define a component failure. Additionally, up to ten different failure modes can be defined for each component. While all the components in this demonstration example model have failure modes defined along with the input parameter values, this dashboard gives the user the ability to change the failure rate and repair time values for the modules and inverters.

In this dashboard, the user can select one of two failure mode distributions (Poisson or Bathtub Curve) to represent the failure of modules, and specify the failure rates as well as repair times and input an annual degradation rate for the modules. For the inverter(s), the user can specify the inverter failure rate and the inverter repair time.

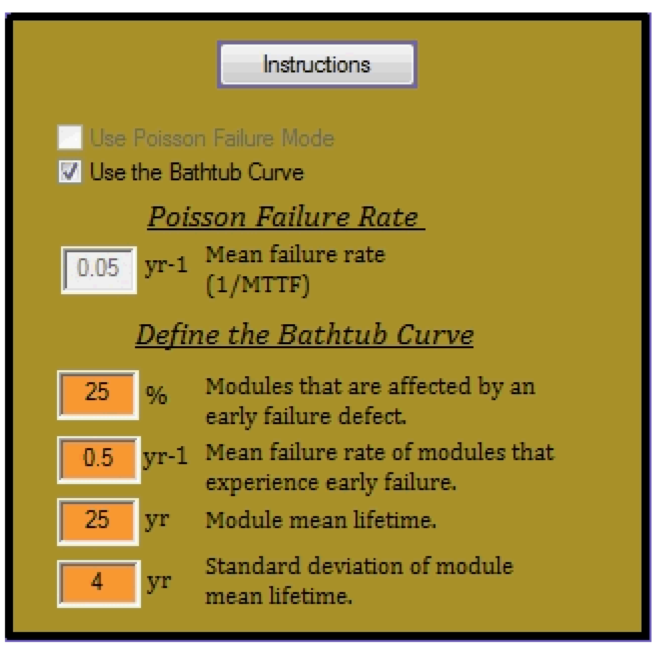
The following subsections describe the options available for modifying the module and inverter inputs for failure rates, repair times, and module degradation rates, and how to set these parameters.

Module Failure Rates

As mentioned above, there are many failure modes available in GoldSim to define a component failure. For the module failure mode for this demonstration model, a choice is given to use either a simple Poisson failure rate, or one that approximates a bathtub curve failure definition. A "bathtub" curve is descriptive term for a curve that resembles the cross-sectional shape of a bathtub and can represent the failure curve of a population of components. The bathtub curve generally shows three features which are: early failures, useful life, and wear-out failures. As the name implies, early failures will show up early in the life of the component and there is typically a high initial failure rate that quickly decreases as the defective components fail (left side of the bathtub curve). Early failures are generally more prevalent in prototype or new model introductions, and are much less common in a mature product or technology. During the useful life stage, the vast majority of the components function as intended with only the occasional random failure, so the failure rate is very low (flat bottom of the bathtub curve). As the components reach the end of their design life, they physically wear-out and the failure rate increases as they fail in greater and greater numbers (right side of the bathtub curve).

GoldSim does not have a "bathtub shaped distribution" to select from on its distribution list, but there are ways to create the same effect with one or more of the available distributions. One way is to use an exponential distribution with a failure rate that varies with time, initially the failure rate would be very high, then the failure rate would drop to near zero, and then increase again as the component nears the end of its design life. For this web-demo example, the bathtub failure rate curve is represented by combining a defective component failure distribution (to represent early failures) and a normal distribution (to represent useful life and wear-out failures). The defective component failure distribution is specifically designed to represent early failures. It only affects the portion of the components (modules in this case) specified by the user. Those components that are affected by the early failure defect fail according to an exponential (Poisson) distribution with a failure rate specified by the user.

To set up the module failure rates in the *Failure Modes Dashboard*, select the checkbox for either the simple Poisson failure rate or the bathtub curve (one option must be selected). Then use the input box(es) to supply the required user inputs as indicated next to each input box.



Module Repair Times

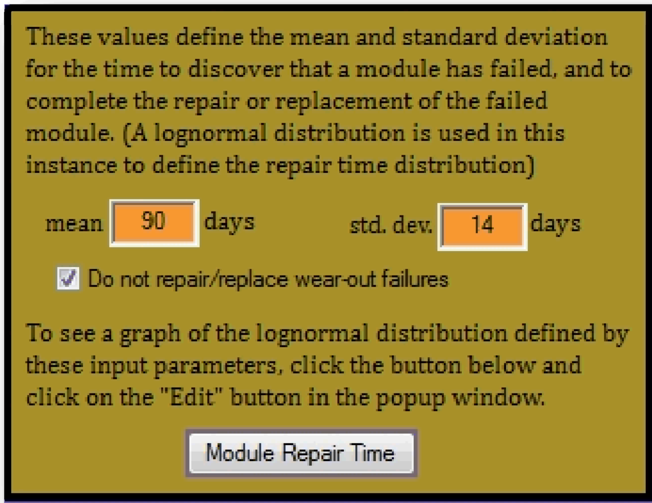
Each failure mode can also have a corresponding failure repair definition to specify when, and to what extent, that failure mode is repaired. The repair is defined by a repair time distribution along with a specification of when the repair is to take place. GoldSim provides the choice of three probability distributions for defining the repair time: Gamma, Lognormal, and Exponential. All three require a "mean delay time until repaired" value, and the Gamma and Lognormal also require a standard deviation. When a failure occurs, GoldSim samples from the chosen repair time distribution to determine when the failure is to be repaired.

The extent to which a component can be repaired can also be specified. For this demonstration model, the repair of the module returns the module to new condition (replacement). GoldSim has the capability to return a repaired component to service in a less than new condition.

Additionally, this demonstration model automatically repairs a failed module when the failure occurs subject to the user defined repair time discussed above. GoldSim has the capability to define a preventative maintenance event where all failed modules are not repaired until the preventative maintenance event occurs. For example, if a preventative maintenance for modules is scheduled to occur at the end of every year, then those modules that fail during the year will remain non-functional until the scheduled preventative maintenance occurs at year's end.

For an active, monitored component such as a motor or pump for example, failure would likely be quickly known. For a passive, typically non-monitored component such as a PV module, it is possible that failure would not be discovered for a relatively long time. Keep this in mind when specifying the module repair time, that is, the repair time should also include an estimate of the time required to discover that the module has failed in addition to the time typically required to repair/replace the failed module.

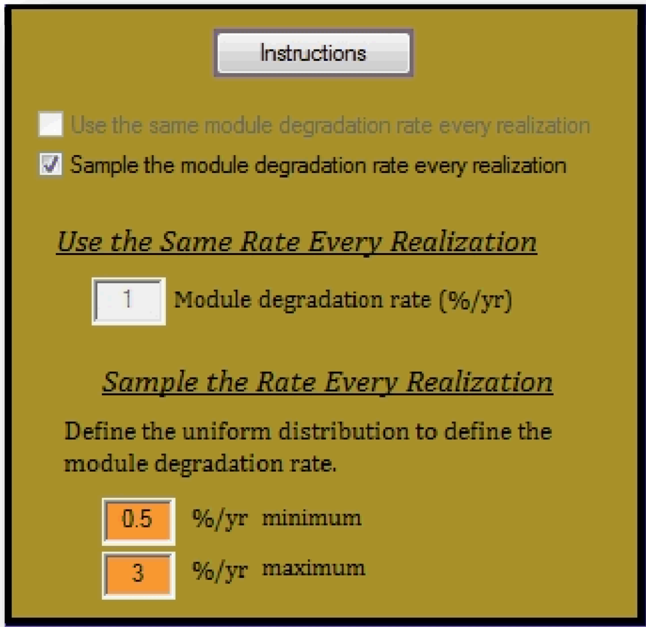
The module repair time distribution input dialog is shown in the figure below. In this demonstration example model, a lognormal distribution is used as the repair time distribution. Input a mean repair time and a standard deviation in days.



A check box option is also provided to give the option of not repairing the wear-out failures. If this check box is selected while using the bathtub curve failure definition, then the early failures defined by the defective component failure mode will be automatically repaired and the later wear-out failures will not be repaired. If this check box is selected while using the simple Poisson failure definition, no module failures will be repaired. The button at the bottom is intended to provide a graphical representation of the lognormal repair time distribution with the user supplied mean and standard deviation values. Click the button and a dialog window will open. Click on the *Edit…* button to open another dialog window where graphs of the PDF, CDF, and CCDF can be displayed.

Module Degradation Rates

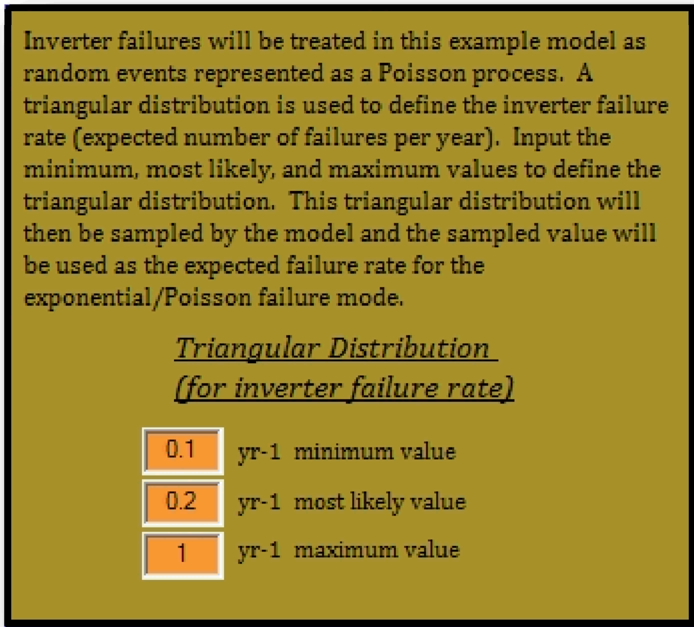
It is generally understood that the average output of a PV module decreases as it ages. Often this degradation is expressed as an average degradation rate for the module in percent per year (%/yr). This demonstration model allows the user to specify a module degradation rate in one of two ways. If one realization is run or if it is desired to run multiple realizations without varying the module degradation rate, then select the appropriate checkbox and input the desired module degradation rate in the input box indicated. If a multiple realization simulation is to be run and it is desired to have a different sampled module degradation rate for each realization, select the checkbox option to sample the module degradation rate. This allows the user to specify a uniform distribution from which the model will sample from for each realization. The user can input the desired range for the uniform distribution in the provided input boxes.



This is only an example of the many possibilities for defining the module degradation rate. In addition to many other stochastic distributions that are available, it is also possible to define the degradation rate with an equation that can vary with elapsed time, or with the occurrence of an external event, for example a nearby lightning strike that causes a surge through the modules.

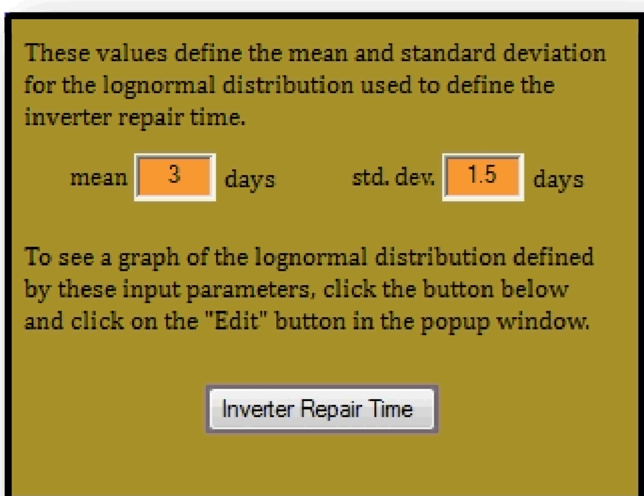
Inverter Failure Rates

Inverter failures will be treated in this demonstration model as random events represented as a Poisson process. A Poisson process implies that if the failure rate is constant, then the time between failures is exponentially distributed. Here, a triangular distribution is used to define the inverter failure rate (expected number of failures per year). The user inputs the minimum, most likely, and maximum values to define the triangular distribution. This triangular distribution will then be sampled by the model and the sampled value will be used as the expected failure rate for the exponential/Poisson failure mode.



Inverter Repair Times

Similar to what was used for the modules, the inverter repair time is modeled by using a lognormal distribution as the repair time distribution. The inputs required are the mean inverter repair time and the associated standard deviation.



The button at the bottom is intended to provide a graphical representation of the lognormal repair time distribution with the user supplied mean and standard deviation values. Click the button and a dialog window will open. Click on the *Edit…* button to open another dialog window where graphs of the PDF, CDF, and CCDF can be displayed.

Once the Model Settings Dashboard and the Failure Modes Dashboard have been set up, navigate to the Results Dashboard by clicking the Results Dashboard button at the bottom of the page.

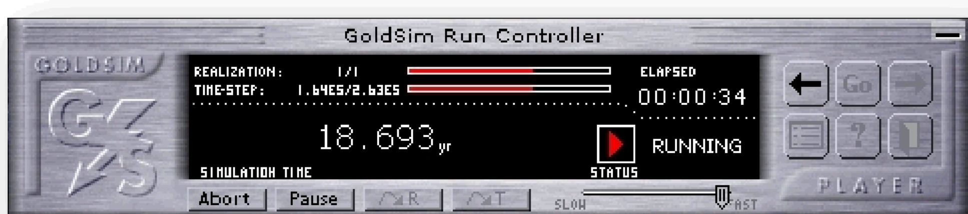
Results Dashboard

This dashboard shows a number of result output boxes and bar displays that will show real-time values as the simulation progresses. In addition, there are also a number of time history plots that can be viewed after the conclusion of the simulation.

Run Controller

There are two ways to start the simulation. One way is to click on the *Run Model* button at the bottom of the dashboard, and the other is to click on the *Run* button at the bottom of the GoldSim Run Controller. An example image of the Run Controller is shown in the figure below before a simulation is started.

While the simulation is running, the Run Controller displays the status of the simulation by showing the current realization and timestep, the simulation time, and the total elapsed time of the run. Additionally, when a simulation is started, the *Run* button changes to a *Pause* button and the *Reset* button changes to an *Abort* button. The figure below shows an example of the Run Controller while a simulation is in progress.



While a simulation is running, the user cannot switch to other dashboards or open time history plots or affect the simulation in any way, with the exception of pressing the *Abort* and *Pause* buttons. If the *Pause* button is pressed, the simulation is paused at its current point and the *Pause* button changes to a *Resume* button. The user can now switch to other dashboards if desired, or open any of the time history plots which will show a time history plot up to the time the simulation was paused. The user can then press the *Resume* button and the simulation will continue on from the point it was paused.

Pressing the *Abort* button at any time while a model is running (or paused), immediately aborts the simulation. If some Monte Carlo realizations have been completed when the simulation is aborted, a prompt window will appear asking if the results for the completed realizations should be saved or discarded. If the results are saved, the completed realizations will be available for viewing.

The slider on the lower right of the Run Controller can be used to slow down the simulation if desired. By default, the slider is set to Fast. The two buttons immediately to the left of the speed controller allow the user to step through the simulation one realization at a time or one timestep at a time. If the button for simulating one realization is pressed, the Player will complete the next realization and then pause. If the button for simulating one timestep is pressed, the Player will complete the next timestep and then pause.

At the completion of the simulation, a small dialog box will pop up indicating the simulation is complete. The Run Controller will then indicate in the status window that there are results. Below is an example of a Run Controller following the completion of a simulation.

After a simulation is complete, and the model contains results, the Player will not allow you to change any of the inputs via the input controls. In order to change inputs, you must first reset the model by pressing the *Reset* button. This clears all of the results and allows you to change input controls and start a new simulation. Pressing any of the other buttons at the bottom of the Run Controller also resets the model.

The top three buttons on the right side of the Run Controller are used to help navigate between the dashboards and are redundant to the buttons provided at the bottom of each dashboard. The lower left-hand button on the right side of the Run Controller (the *Options* button) provides access to a menu for saving the current file or opening another file, view the *About* dialog for Player, and view a dialog listing the model author and a file description (*Model Info*…). The other buttons on the right side of the Run Controller provide access to online help and close the Player.

Real-time Result Displays

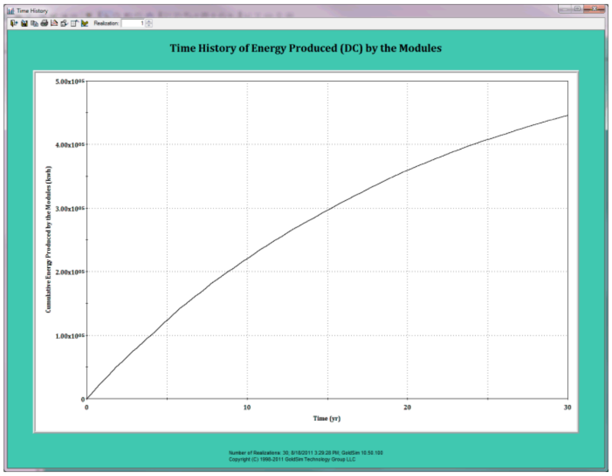
On the upper portion of the Results Dashboard there are a number of display bars and numerical output boxes that will provide real-time output values as each realization in the simulation progresses. At the upper left, there are four numerical output boxes which are intended to provide a comparison of total system output (both DC and AC from the inverter) from a so called "ideal system", and from that same system with component failures and module degradation. The two numerical output boxes on the upper right show the peak string voltage experienced during the simulation (should be less than 600 V for non-utility applications) and the module degradation rate and inverter failure rate used for the realization.

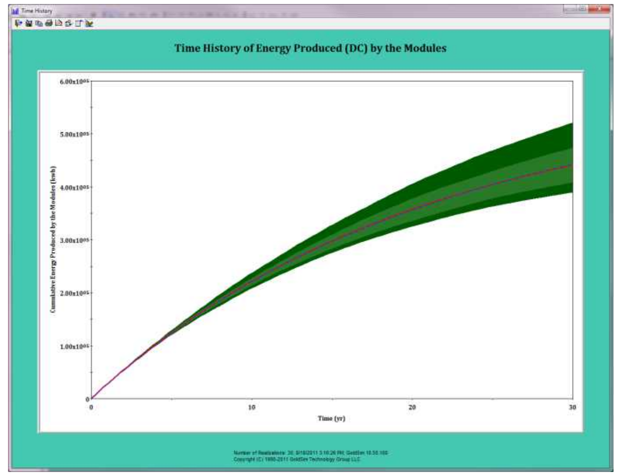
The seven real-time display bars provide the following information:

1. PV System Availability: instantaneous operational availability of the entire PV system.
2. Operational Availability of the Inverter(s): instantaneous operational availability of the inverter(s).
3. Operational Availability of the Modules: instantaneous operational availability of the modules.
4. Module Output Degradation: current fraction out module power output (compared to that of the new module)
5. Inverter Efficiency: real-time efficiency of the inverter(s).
6. System Performance Factor: a measure of the PV system's annual electric generation output in AC kWh compared to its nameplate rated capacity in DC kW, taking into account the solar resource at the system's location.
7. Fraction of Energy Lost (DC): the cumulative total fraction of energy lost due to component failures and module output degradation.

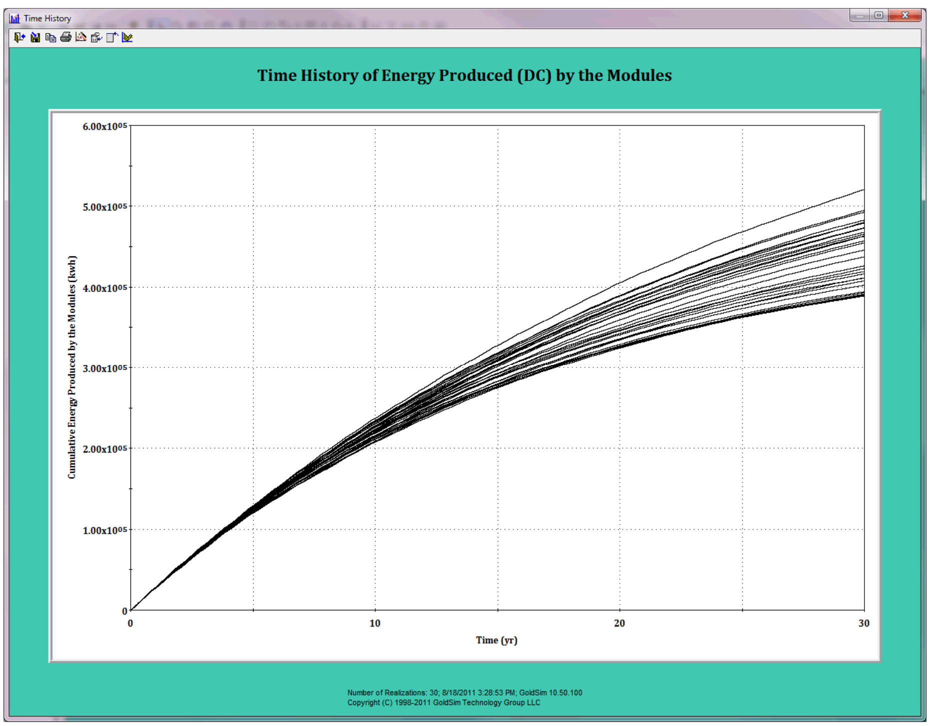
Time History Tables and Results Tables

On the lower portion of the Results Dashboard is a number of buttons that when pressed will open a time history plot (or a tabular output as appropriate) of the output noted on the particular button. If a single realization simulation was run, then opening a time history plot will show the time history for that single realization as shown in the example at the left in the figure below. If many realizations are run, then the time history plot will open showing some statistics for the set of realizations, namely the greatest and least result, and the mean (solid red line) and median (dashed blue line) for the set of realizations, as shown in the right figure below. Other statistics may or may not be present depending upon the number of realizations; 25%/75% requires at least 20 realizations, and 5%/95% requires at least 100 realizations.



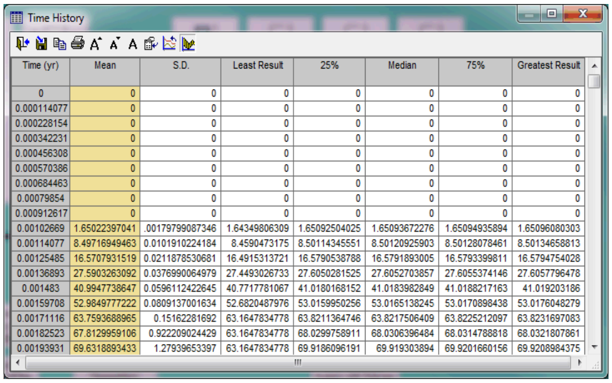


To see all the realizations in a multi-realization run, simply click on the *Probability Histories* icon on the graph menu bar (graph symbol on the right-most side). This will then show the first realization on the plot and the user can scroll through the realizations one-by-one using the *Realization* up/down arrow box that appears to the right of the *Probability Histories* icon. To show all the realizations on the plot, right-click the mouse in the plot area and selecting "Show All Realizations", all the individual realizations will be shown on one plot as shown in the figure below.



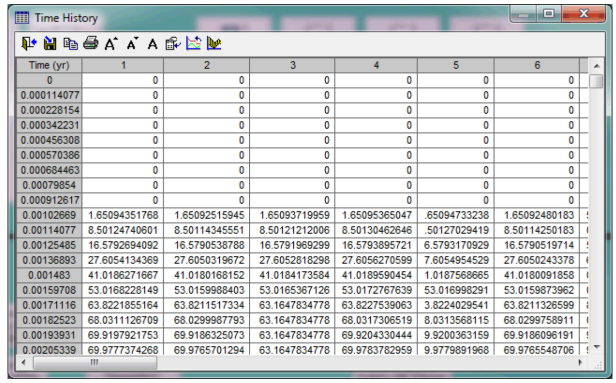
It should be noted that "Show All Realizations" is only available on those plots that display a single output as in the example shown above, two of the plots provided (*Summary* and *Ideal System vs System with Failures*) contain two or more output values. Those two plots can only be viewed one realization at a time or as a Probability History, but with each output in the Probability History represented as a curve of the mean value.

The time histories can also be viewed in tabular form and exported for further analysis if desired. To see the table view of the Probability Histories, press the *View Table* button (immediately left of the *Probability Histories* button) when viewing a Probability Histories Chart, or by pressing the Probability Histories button when viewing a regular time history table. The figure below shows an example of a Probability Histories table (left) and a regular time history table showing the time history for each realization (right).



Time History

Time (yr)	Mean	S.D.	Least Result	25%	Median	75%	Greatest Result
0	0	0	0	0	0	0	0
0.000114077	0	0	0	0	0	0	0
0.000228154	0	0	0	0	0	0	0
0.000342231	0	0	0	0	0	0	0
0.000456308	0	0	0	0	0	0	0
0.000570386	0	0	0	0	0	0	0
0.000684463	0	0	0	0	0	0	0
0.00079854	0	0	0	0	0	0	0
0.000912617	0	0	0	0	0	0	0
0.00102669	1.65022397041	.00179799087346	1.64349806309	1.65092504025	1.65093672276	1.65094935894	1.65096080303
0.00114077	8.49716949463	0.0101910224184	8.4590473175	8.50114345551	8.50120925903	8.50128078461	8.50134658813
0.00125485	16.5707931519	0.0211878530681	16.4915313721	16.5790538788	16.5791893005	16.5793399811	16.5794754028
0.00136893	27.5903263092	0.0376990064979	27.4493026733	27.6050281525	27.6052703857	27.6055374146	27.6057796478
0.001483	40.9947738647	0.0596112422645	40.7717781067	41.0180168152	41.0183982849	41.0188217163	41.019203186
0.00159708	52.9849777222	0.0809137001634	52.6820487976	53.0159950256	53.0165138245	53.0170898438	53.0176048279
0.00171116	63.7593688965	0.15162281692	63.1647834778	63.8211364746	63.8217506409	63.8225212097	63.8231697083
0.00182523	67.8129959106	0.922209024429	63.1647834778	68.0299758911	68.0306396484	68.0314788818	68.0321807861
0.00193931	69.6318893433	1.27939653397	63.1647834778	69.9186096191	69.919303894	69.9201660156	69.9208984375



Time History

Time (yr)	1	2	3	4	5	6
0	0	0	0	0	0	0
0.000114077	0	0	0	0	0	0
0.000228154	0	0	0	0	0	0
0.000342231	0	0	0	0	0	0
0.000456308	0	0	0	0	0	0
0.000570386	0	0	0	0	0	0
0.000684463	0	0	0	0	0	0
0.00079854	0	0	0	0	0	0
0.000912617	0	0	0	0	0	0
0.00102669	1.65094351768	1.65092515945	1.65093719959	1.65095365047	.65094733238	1.65092480183
0.00114077	8.50124740601	8.50114345551	8.50121212006	8.50130462646	.50127029419	8.50114250183
0.00125485	16.5792694092	16.5790538788	16.5791969299	16.5793895721	6.5793170929	16.5790519714
0.00136893	27.6054134369	27.6050319672	27.6052818298	27.6056270599	7.6054954529	27.6050243378
0.001483	41.0186271667	41.0180168152	41.0184173584	41.0189590454	1.0187568665	41.0180091858
0.00159708	53.0168228149	53.0159988403	53.0165367126	53.0172767639	53.016998291	53.0159873962
0.00171116	63.8221855164	63.8211517334	63.1647834778	63.8227539063	3.8224029541	63.8211326599
0.00182523	68.0311126709	68.0299987793	63.1647834778	68.0317306519	8.0313568115	68.0299758911
0.00193931	69.9197921753	69.9186325073	63.1647834778	69.9204330444	9.9200363159	69.9186096191
0.00205339	69.9777374268	69.9765701294	63.1647834778	69.9783782959	9.9779891968	69.9765548706

The results provided are time history plots and tables as follows:

Time history plots:

1. Inverter operational availability.
2. Module operational availability.
3. Electrical grid operational availability.
4. A summary plot showing the overall system availability.
5. Total energy produced by the PV modules during the realization.
6. A summary plot with three curves showing theoretical cumulative output of the system (Sandia Array Performance model), cumulative output with component failures and module degradation (kW DC), and cumulative output with inverter efficiency losses (kW AC).
7. The number of modules operable at any time during the simulation.
8. Module output degradation curves.

Results tables:

1. Sampled module degradation rates (for multiple realization runs).
2. Sampled inverter failure rates (for multiple realization runs).
3. Summary of the component failures during the simulation period.

Glossary

Availability

The probability that a component or system performing its required function at any given time. Operational availability represents the probability that the component will be operating at any given time. (GoldSim Technology Group LLC, 2010b)

Bathtub curve

Bathtub curve is a descriptive name for a curve, or set of curves, that represents the lifetimes of a population of components. Early in the life of the components the failure rate can be high due to an inherent product defect, and then the failure rate decreases as those defective components fail. There are relatively few failures as the remaining components perform as designed during their intended design life. Finally, the failure rate increases again as the components wear out at the end of their design life.

Dashboards

Specialized user interfaces that can be built into a Player file. Dashboards look like "control panels", with buttons, sliders and display panels, and provide a mechanism by which inputs to a model can be modified within the Player.

Latin Hypercube Sampling

A sampling procedure that, because of its efficient stratification properties, provides a more efficient means of ensuring that the sample space of a parameter distribution is uniformly spanned. LHS is very popular for use with computationally demanding models because its efficient stratification properties allow for the extraction of a large amount of uncertainty information with a relatively small sample size (Helton, Johnson, Sallaberry, & Storlie, 2006).

Monte Carlo Simulation

A Monte Carlo simulation is a method for propagating uncertainties in model inputs into uncertainties in model results by repeated random sampling of the uncertainty distributions that represent the uncertain model inputs.

Player file

A player file is a special file format (with the extension .gsp) that can be created by GoldSim and can only be read by the GoldSim Player.

Poisson distribution

A discrete distribution most often used to calculate the probability of occurrence of a random event over a specific time interval when the average probability of occurrence is known.

Realizations

A realization is a single model run within a Monte Carlo simulation. It represents one possible path (or future) the system could follow through time. (GoldSim Technology Group LLC, 2010b)

Reliability Modeling

Analyzing the ways that systems can fail (and be repaired) in order to increase their design life, and eliminate or reduce the likelihood of failures, downtime and safety risks. The output of these models typically consists of predictions of measures such as reliability (the probability that a component or system will perform its required function over a specified time period) and availability (the probability that a component or system is performing its required function at any given time). (GoldSim Technology Group LLC, 2010b)

Run Controller

A dialog used to control the manner in which a GoldSim simulation is run. (GoldSim Technology Group LLC, 2010a)

Stochastic

An element that can be used to quantitatively represent the uncertainty in a model input. (GoldSim Technology Group LLC, 2010a)

Timestep

A discrete interval of time used in dynamic simulations. (GoldSim Technology Group LLC, 2010a)

TMY2

A Typical Meteorological Year (TMY) is a data set of hourly values of solar radiation and meteorological elements for a 1-year period (8,760 hours). It consists of months selected from individual years and concatenated to form a complete year. The TMY2 data sets have been derived from the 1961–1990 National Solar Radiation Data Base (NSRDB) which was completed in March 1994 by the National Renewable Energy Laboratory (NREL).

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Helton, J. C., Johnson, J. D., Sallaberry, C. J., & Storlie, C. B. (2006). *Survey of Sampling-Based Methods for Uncertainty and Sensitivity Analysis.* Sandia Report: SAND2006-2901. Albuquerque: Sandia National Laboratories.

King, D. L., Boyson, W. E., & Kratochvill, J. A. (2004). *Photovoltaic Array Performance Model.* Sandia Report Number: SAND2004-3535. Albuquerque: Sandia National Laboratories.

King, D. L., Gonzalez, S., Galbraith, G. M., & Boyson, W. E. (2007). *Performance Model for Grid-Connected Photovoltaic Inverters.* Sandia Report Number: SAND2007-5036. Albuquerque: Sandia National Laboratories.

National Renewable Energy Laboratory. (1994). *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors.* NREL Report Number: NREL/TP-463-5607. Golden: National Renewable Energy Laboratory.

Screenshots of PV Reliability Performance Model

Version 1.0

Joshua Stein, Steve Miller, and Jennifer Granata

Sandia National Laboratories

GoldSim Player - PV-RPM Web Demo.gsp

PV-RPM Demonstration Model

Introduction Dashboard

This demomstration model is a simplified "player" version of the Photovoltaic Reliability Performance Model (PV-RPM) currently in development at Sandia National Laboratories (SNL). The PV-RPM allows the user to define a PV system (inverters, modules, tracking, etc.) and select or input weather data, and the model will calculate the performance of the system. The PV-RPM is intended to address more "real world" situations by coupling the performance model with a reliability model so that inverters, modules, combiner boxes, etc. can experience failures and be repaired (or not). This "player" version is intended to demonstrate the system performance and reliability functionality of the PV-RPM using the free GoldSim Player software.

This player file consists of several dashboards that allow the user setup a PV system by specifying the number and type of modules and inverters, chose a site location and weather data inputs, specify module and inverter failure and repair rates, and run a simulation with multiple realizations.

Refer to the included user's guide for more detailed instructions.

Model Settings Dashboard

The Model Settings dashboard is used to define the basic inputs to the model such as: PV site location and weather data, the modules and inverters from a database, the system setup including tracking and module orientation, and finally the model run simulation settings.

Failure Modes Dashboard

The Failure Modes Dashboard is where the user can specify inputs for the reliability model. The user can select one of two failure mode distributions (Poisson or Bathtub Curve) to represent the failure of modules, and specify the failure rates as well as repair times and input an annual degradation rate for the modules. For the inverter(s), the user can specify the inverter failure rate and the inverter repair time.

Results Dashboard

This dashboard shows a number of result output boxes and bar displays that will show real-time values as the simulation progresses. In addition, there are also a number of time history plots that can be viewed after the conclusion of the simulation.

Acknowledgement and Disclaimer

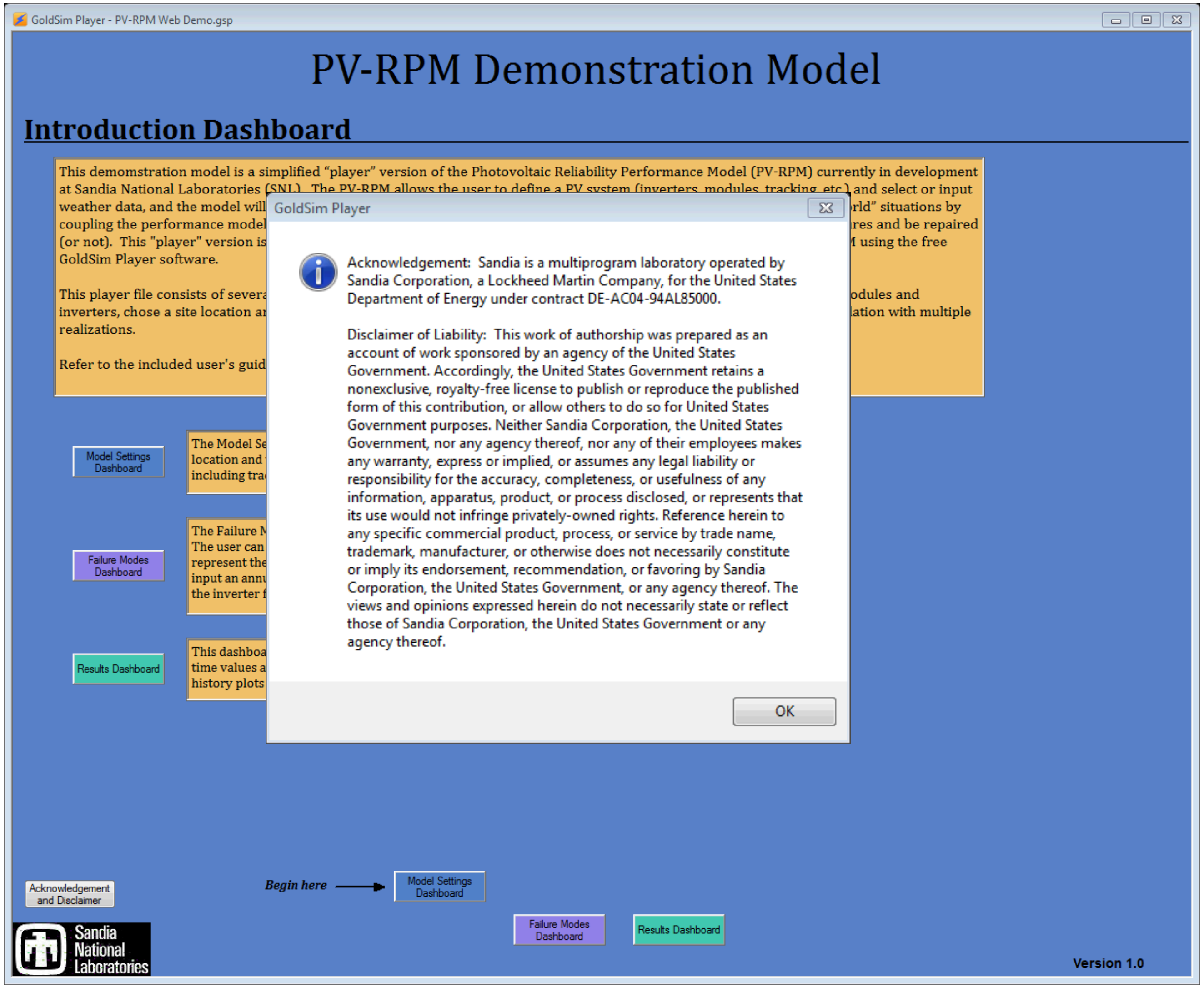
Begin here → Model Settings Dashboard

Failure Modes Dashboard

Results Dashboard

Sandia National Laboratories

Version 1.0


GoldSim Player - PV-RPM Web Demo.gsp
PV-RPM Demonstration Model
Introduction Dashboard
This demomstration model is a simplified "player" version of the Photovoltaic Reliability Performance Model (PV-RPM) currently in development
at Sandia National Laboratories (SNL). The PV-RPM allows the user to define a PV system (inverters, modules, tracking, etc.) and select or input
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coupling the performance model
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(or not). This "player" version is
1 using the free
GoldSim Player software.
This player file consists of severa
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inverters, chose a site location a
lation with multiple
realizations.
Refer to the included user's guid
Model Settings Dashboard
The Model Se
location and
including tra
Failure Modes Dashboard
The Failure M
The user can
represent the
input an ann
the inverter f
Results Dashboard
This dashboa
time values a
history plots
GoldSim Player
Acknowledgement: Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.
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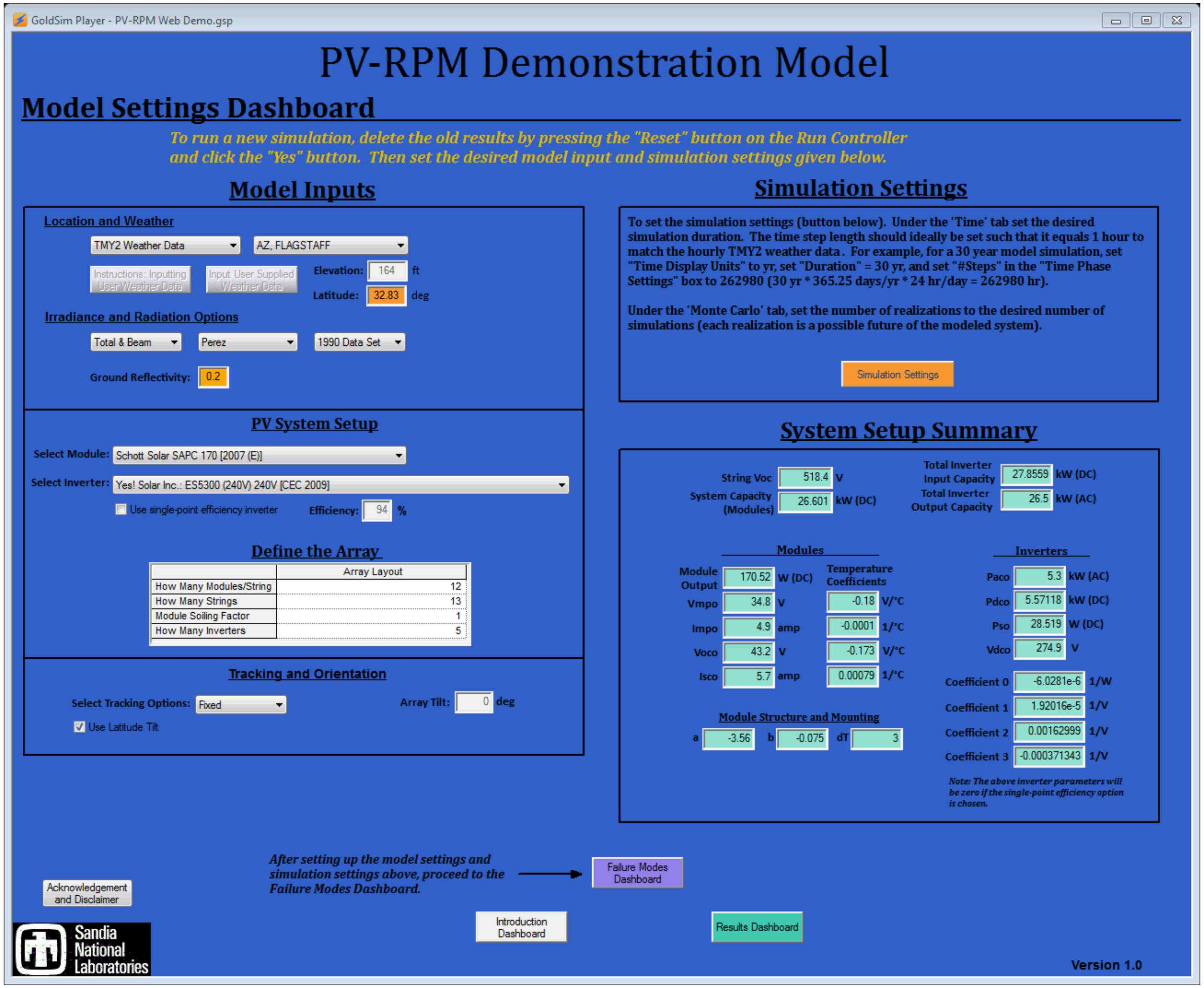
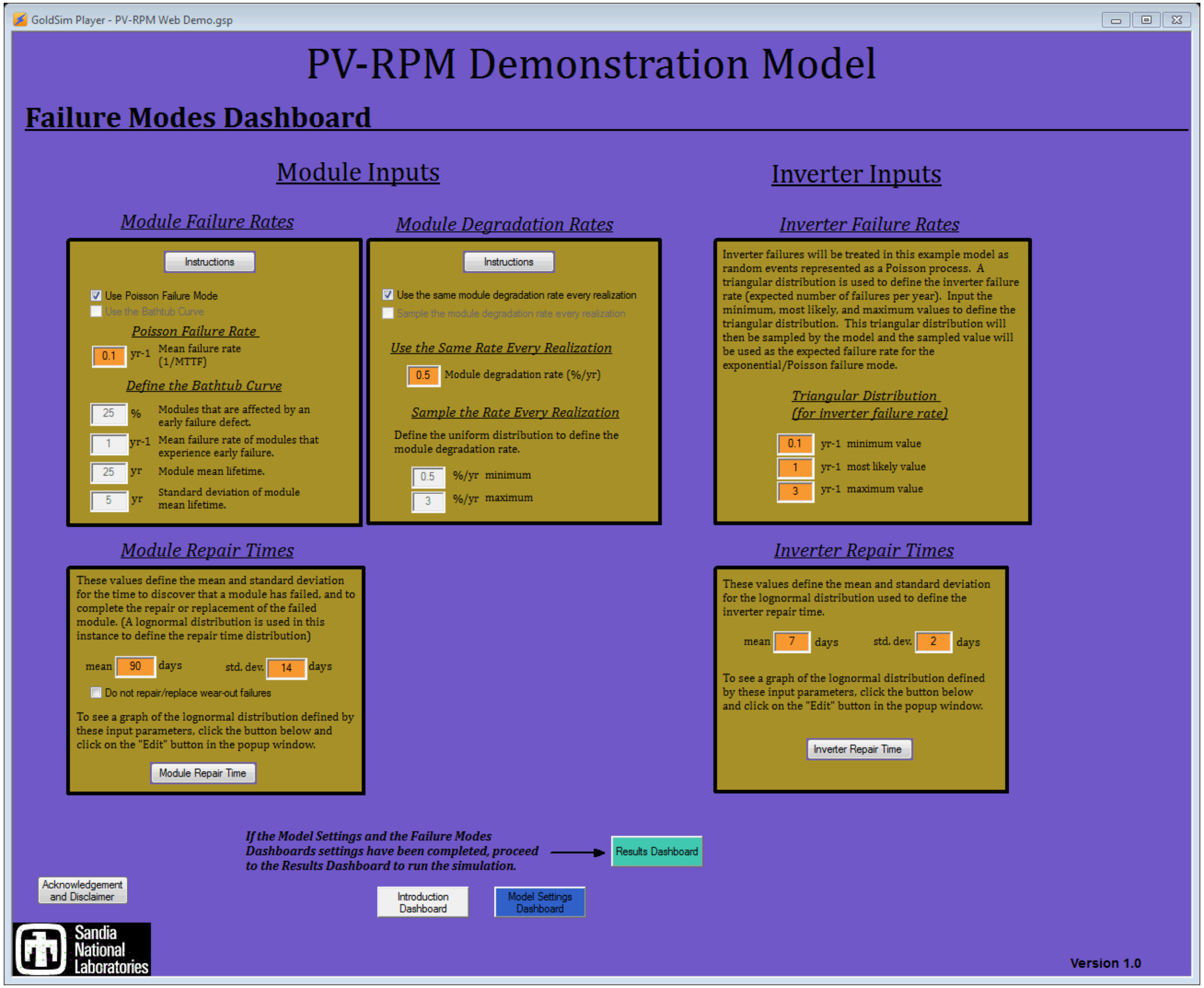
OK
Acknowledgement and Disclaimer
Begin here
Model Settings Dashboard
Failure Modes Dashboard
Results Dashboard
Sandia National Laboratories
Version 1.0


GoldSim Player - PV-RPM Web Demo.gsp
PV-RPM Demonstration Model
Model Settings Dashboard
To run a new simulation, delete the old results by pressing the "Reset" button on the Run Controller and click the "Yes" button. Then set the desired model input and simulation settings given below.
Model Inputs
Location and Weather
TMY2 Weather Data
AZ, FLAGSTAFF
Instructions: Inputting User Weather Data
Input User Supplied Weather Data
Elevation:
164
ft
Latitude:
32.83
deg
Irradiance and Radiation Options
Total & Beam
Perez
1990 Data Set
Ground Reflectivity:
0.2
PV System Setup
Select Module:
Schott Solar SAPC 170 [2007 (E)]
Select Inverter:
Yes! Solar Inc.: ES5300 (240V) 240V [CEC 2009]
Use single-point efficiency inverter
Efficiency:
94
%
Define the Array
Array Layout
How Many Modules/String
12
How Many Strings
13
Module Soiling Factor
1
How Many Inverters
5
Tracking and Orientation
Select Tracking Options:
Fixed
Array Tilt:
0
deg
Use Latitude Tilt
Simulation Settings
To set the simulation settings (button below). Under the 'Time' tab set the desired simulation duration. The time step length should ideally be set such that it equals 1 hour to match the hourly TMY2 weather data. For example, for a 30 year model simulation, set "Time Display Units" to yr, set "Duration" = 30 yr, and set "#Steps" in the "Time Phase Settings" box to 262980 (30 yr * 365.25 days/yr * 24 hr/day = 262980 hr).
Under the 'Monte Carlo' tab, set the number of realizations to the desired number of simulations (each realization is a possible future of the modeled system).
Simulation Settings
System Setup Summary
String Voc
518.4
V
System Capacity (Modules)
26.601
kW (DC)
Total Inverter Input Capacity
27.8559
kW (DC)
Total Inverter Output Capacity
26.5
kW (AC)
Modules
Module Output
170.52
W (DC)
Vmpo
34.8
V
Impo
4.9
amp
Voco
43.2
V
Isco
5.7
amp
Temperature Coefficients
-0.18
V/°C
-0.0001
1/°C
-0.173
V/°C
0.00079
1/°C
Module Structure and Mounting
a
-3.56
b
-0.075
dT
3
Inverters
Paco
5.3
kW (AC)
Pdco
5.57118
kW (DC)
Pso
28.519
W (DC)
Vdco
274.9
V
Coefficient 0
-6.0281e-6
1/W
Coefficient 1
1.92016e-5
1/V
Coefficient 2
0.00162999
1/V
Coefficient 3
-0.000371343
1/V
Note: The above inverter parameters will be zero if the single-point efficiency option is chosen.
After setting up the model settings and simulation settings above, proceed to the Failure Modes Dashboard.
Failure Modes Dashboard
Acknowledgement and Disclaimer
Introduction Dashboard
Results Dashboard
Sandia National Laboratories
Version 1.0


GoldSim Player - PV-RPM Web Demo.gsp
PV-RPM Demonstration Model
Failure Modes Dashboard
Module Inputs
Inverter Inputs
Module Failure Rates
Instructions
Use Poisson Failure Mode
Use the Bathtub Curve
Poisson Failure Rate
0.1 yr-1 Mean failure rate (1/MTTF)
Define the Bathtub Curve
25 % Modules that are affected by an early failure defect.
1 yr-1 Mean failure rate of modules that experience early failure.
25 yr Module mean lifetime.
5 yr Standard deviation of module mean lifetime.
Module Degradation Rates
Instructions
Use the same module degradation rate every realization
Sample the module degradation rate every realization
Use the Same Rate Every Realization
0.5 Module degradation rate (%/yr)
Sample the Rate Every Realization
Define the uniform distribution to define the module degradation rate.
0.5 %/yr minimum
3 %/yr maximum
Inverter Failure Rates
Inverter failures will be treated in this example model as random events represented as a Poisson process. A triangular distribution is used to define the inverter failure rate (expected number of failures per year). Input the minimum, most likely, and maximum values to define the triangular distribution. This triangular distribution will then be sampled by the model and the sampled value will be used as the expected failure rate for the exponential/Poisson failure mode.
Triangular Distribution (for inverter failure rate)
0.1 yr-1 minimum value
1 yr-1 most likely value
3 yr-1 maximum value
Module Repair Times
These values define the mean and standard deviation for the time to discover that a module has failed, and to complete the repair or replacement of the failed module. (A lognormal distribution is used in this instance to define the repair time distribution)
mean 90 days std. dev. 14 days
Do not repair/replace wear-out failures
To see a graph of the lognormal distribution defined by these input parameters, click the button below and click on the "Edit" button in the popup window.
Module Repair Time
Inverter Repair Times
These values define the mean and standard deviation for the lognormal distribution used to define the inverter repair time.
mean 7 days std. dev. 2 days
To see a graph of the lognormal distribution defined by these input parameters, click the button below and click on the "Edit" button in the popup window.
Inverter Repair Time
If the Model Settings and the Failure Modes Dashboards settings have been completed, proceed to the Results Dashboard to run the simulation.
Results Dashboard
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Model Settings Dashboard
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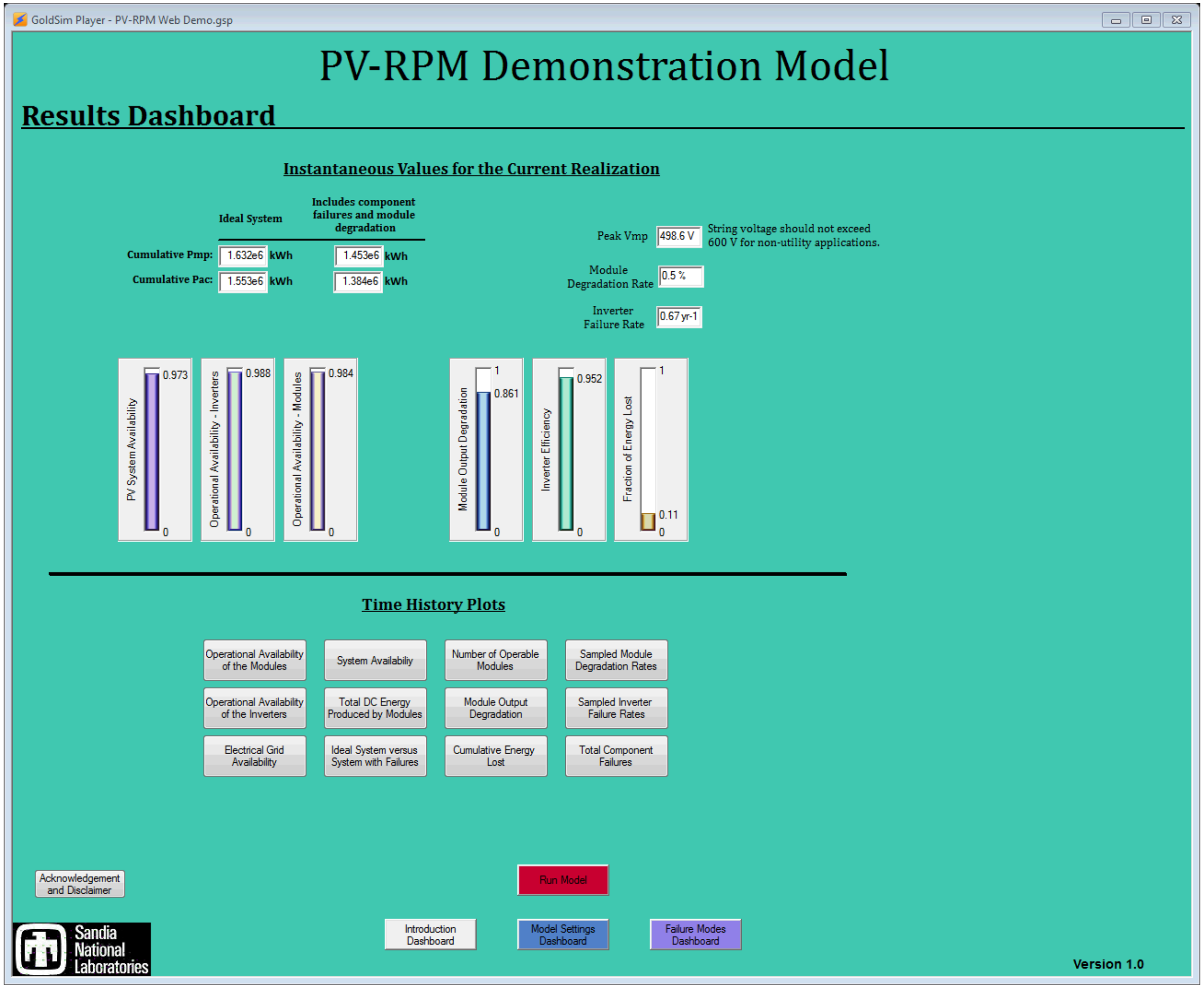
GoldSim Player - PV-RPM Web Demo.gsp
PV-RPM Demonstration Model
Results Dashboard
Instantaneous Values for the Current Realization
Ideal System
Includes component failures and module degradation
Cumulative Pmp: 1.632e6 kWh 1.453e6 kWh
Cumulative Pac: 1.553e6 kWh 1.384e6 kWh
Peak Vmp 498.6 V
String voltage should not exceed 600 V for non-utility applications.
Module Degradation Rate 0.5 %
Inverter Failure Rate 0.67 yr-1
PV System Availability 0.973 0
Operational Availability - Inverters 0.988 0
Operational Availability - Modules 0.984 0
Module Output Degradation 1 0.861 0
Inverter Efficiency 0.952 0
Fraction of Energy Lost 1 0.11 0
Time History Plots
Operational Availability of the Modules
System Availabiliy
Number of Operable Modules
Sampled Module Degradation Rates
Operational Availability of the Inverters
Total DC Energy Produced by Modules
Module Output Degradation
Sampled Inverter Failure Rates
Electrical Grid Availability
Ideal System versus System with Failures
Cumulative Energy Lost
Total Component Failures
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