SENSITIVITY OF CONCENTRATING SOLAR POWER TROUGH PERFORMANCE, COST, AND FINANCING WITH THE SOLAR ADVISOR MODEL

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Abstract

A comprehensive solar technology systems analysis model, the Solar Advisor Model (SAM) was developed to support the federal R&D community and the solar industry. This model, developed by staff at NREL and Sandia National Laboratory, is able to model the costs, finances, and performance of concentrating solar power and photovoltaics (PV). Currently, parabolic troughs and concentrating PV are the two concentrating technologies modeled within the SAM environment.

The primary function of the model is to allow users to investigate the impact of variations in physical, cost, and financial parameters to better understand their impact on key figures of merit. Figures of merit related to the cost and performance of these systems include, but aren't limited to, system output, system efficiencies, levelized cost of energy, return on investment, and system capital and O&M costs.

SAM allows users to do complex parabolic trough system modeling with an intuitive graphical user interface (GUI). This model has the capability to compare different solar technologies within the same interface while making use of similar cost and finance assumptions. Additionally, the ability to do extensive parametric and sensitivity analysis is central to this model.

1. Introduction

Originally, the Solar Advisor Model (SAM) was developed to meet the needs of the systems driven approach (SDA) that was adopted by the U.S. Department of Energy's (DOE) Solar Energy Technologies Program (SETP).[1] By clearly establishing the connection between market requirements and R&D efforts (and how specific R&D improvements contribute to the overall system cost and performance), the SDA approach will allow managers to allocate resources more efficiently. The data and metrics coming from SDA analysis will provide a more credible and reproducible story regarding the impact of R&D on levelized energy costs. Additionally, the SDA approach will promote the use of a consistent methodology in analysis regarding the impact of R&D activities and non-R&D activities on the costs and performance of solar technologies.

One aspect of the systems driven approach is the creation of analysis tools that promote this consistent methodology of analysis across all solar technologies. To capture the goals of the SDA, SAM is able to integrate the financing, costing, and performance of systems. Additionally, it must be possible to apply consistent financing and cost assumptions across all solar technologies. Although eventually all solar technologies (including solar water heating) would be available, the technologies implemented to date are photovoltaics (using a variety of models) and parabolic trough concentrating solar systems. This paper will focus on the discussion of the implementation and use of parabolic troughs in SAM.

2. General SAM features

One primary goal of the user interface is the ability to efficiently conduct complex sensitivity analysis. One aspect is the ability to have multiple "cases" within a project (Figure 1). This is very similar in concept to Microsoft Excel allowing the user to have multiple worksheets within a workbook. Each case contains a specific technology system

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[1] http://www.eere.energy.gov/solar/systems_driven.html

and inputs for the related performance, cost, and financing parameters. A case may be created by duplicating (or copying) an existing case or, in future versions, from a series of pre-existing templates.
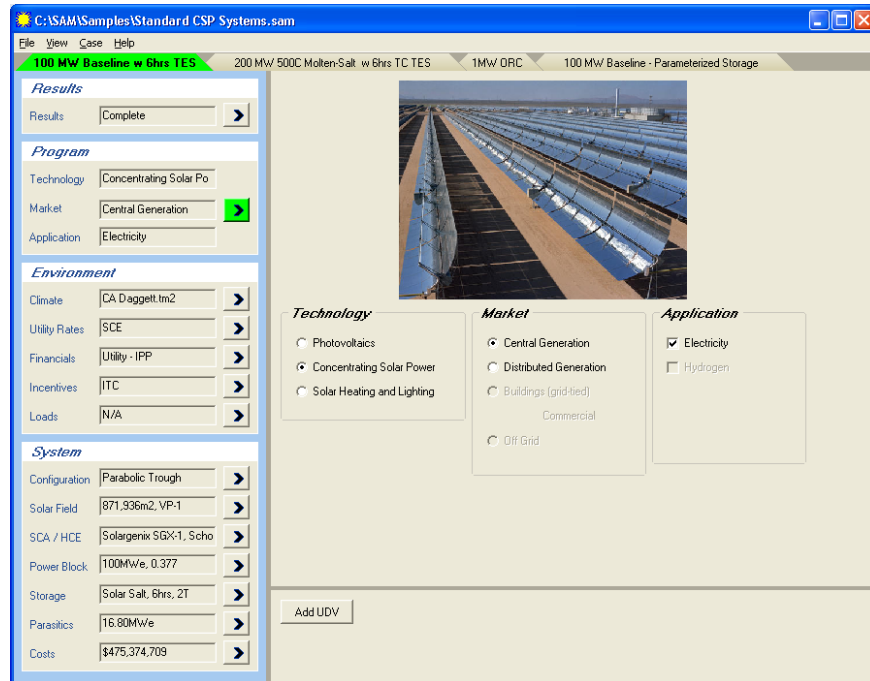

Figure 1. Solar Advisor GUI demonstrating multiple cases and program selection

Another feature is the ability to construct complex parametric analysis within each case. Each variable available to the user within the GUI – financial, cost, or performance – can be parameterized. These parametric values can be created using an equation, typed in individually, or "linked" from another parameterized variable. A "linked parametric" is typically used when a relationship between variable values should be maintained for all parametric cases. For example, if the amount of thermal storage (hours) is parameterized, the user would want to make sure that an appropriate amount of losses from the storage tank is used in each parametric run. Therefore, the storage size should be "linked" to the storage losses (see Linkage 1 in Figure 2). Additionally, the cost of the solar plant should scale with the size of the solar field, which happens automatically as the cost is entered as a function of field size. Of course, it is possible to parameterize two or more variables independently of each other and do all combinations of these parametric values. Figure 3 illustrates the results screen from Solar Advisor, demonstrating a sample result of the impact on the levelized cost of energy due to varying both the amount of thermal storage (in hours) and the size of the solar field.
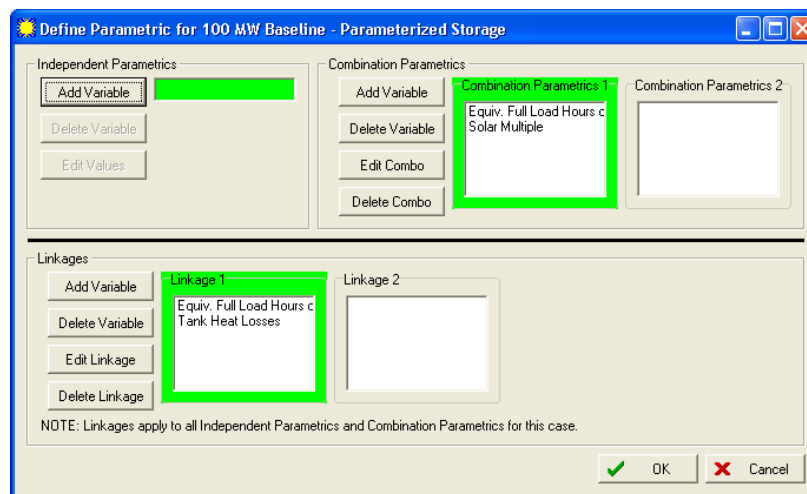

Figure 2. Parametric dialog box demonstrating "linked parametrics"

Another method for conducting sensitivity analysis is by using the "slider" bars on the results screen (Figure 3). Because the data in the graphs is dynamic and tied to the current inputs, the user can obtain near-instant graphical feedback on the impact of varying the slider values. Typically, the user would vary financial items – such as the inflation rate – to observe the sensitivity of the results.
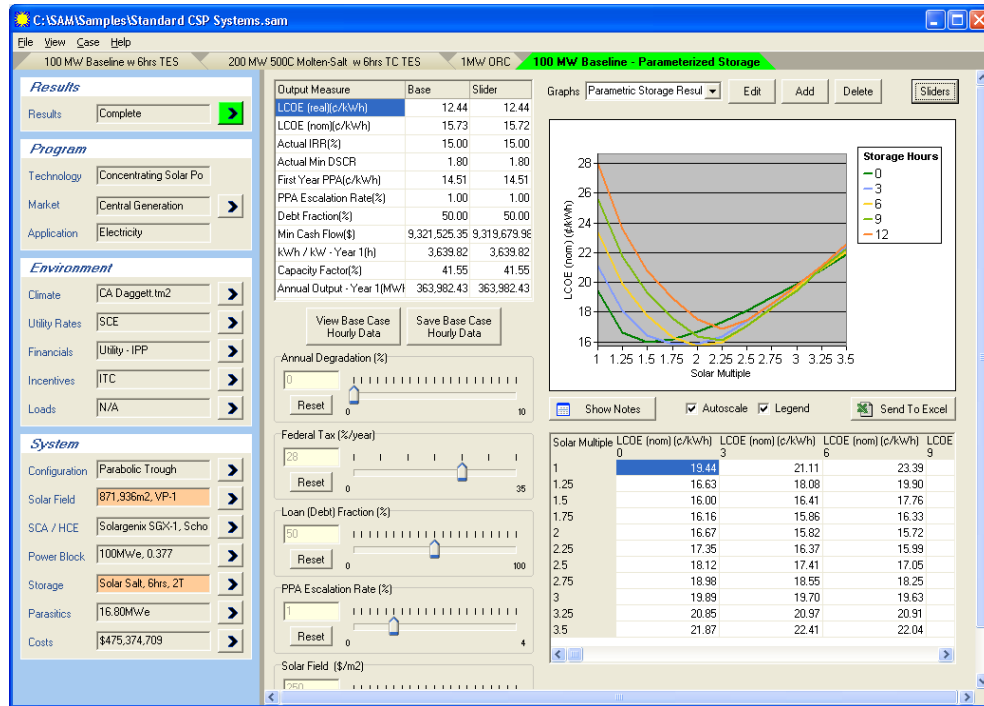

Figure 3. Results page and solar multiple vs. hours of storage parametric results

The financial model within SAM uses values from the performance model and the cost model along with specific financial inputs to determine the appropriate financial output metrics. One of the unique aspects of SAM is that the financial engine allows for a variety of standard financing scenarios eventually allowing for residential, commercial, and utility-scale project financing – specifically, utility-scale investor owned utility (IOU) and independent power producer (IPP) financing options. The calculated financial metrics include annual cash flow throughout the project life, the levelized cost of energy for the system, tax payments, the net present value of the system, and the internal rate of return. For utility-scale systems using the perspective of the independent power producers (IPPs), the model calculates the necessary power purchase agreement (PPA) value and future escalation rate that's needed to make the project viable.

Recently, an ability to add financial incentives to the system has been added. Figure 4 shows the interface elements for the incentives. All standard federal and state-level incentives can be included. For example, the 30% federal investment tax credit (ITC) for CSP systems that is currently in place is included below. The tax implications and final impact on the SAM outputs will be included both in the annual cash flow and the resultant levelized cost of energy. Likewise, the user can input values for a production tax credit, an investment-based incentive (a flat rebate would fall here), a capacity-based incentive (a buy-down in $/W would fall into this category), or a production-based incentive (a REC would fall into this category). The tax implications of each of these incentives vary with location and will be subject to future changes. Therefore, it is possible to adjust the default values for the tax impact of these incentives by changing the taxable status of the incentive, if the incentive reduces the ITC basis or if the incentive reduces the depreciation basis. Because federal, state, and utility incentives are often critical financial components to both PV and CSP systems and system siting, this is an important component of SAM and opens its use to various solar policy analyses.
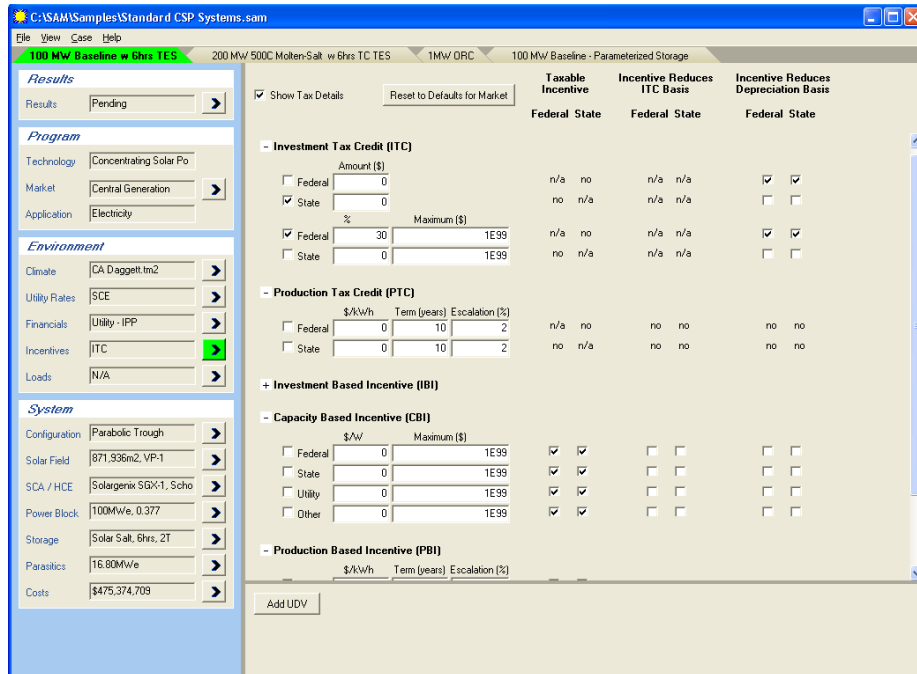
Figure 4. SAM Incentives Interface

The simple cost model currently implemented allows for a relatively simple cost breakdown including direct systems costs such as the solar field, storage, and the power plant. The cost page also includes indirect costs and O&M costs (see Figure 5). Only the O&M cost is a recurring cost through the project lifetime. Most of the direct costs are input as a function of the solar plant size, so that it automatically sizes with the plant. Of course, this is important for parametric analyses with SAM. This simple structure allows for a variety of cost and financial analysis – however, most solar analysts use complex spreadsheets as cost models. SAM allows for easy linking with Excel "named ranges" to pass values back and forth between the GUI and spreadsheet. The goal is to reduce the amount of recoding necessary and to allow the analysts to continue updating and improving their external cost models independently of the GUI.
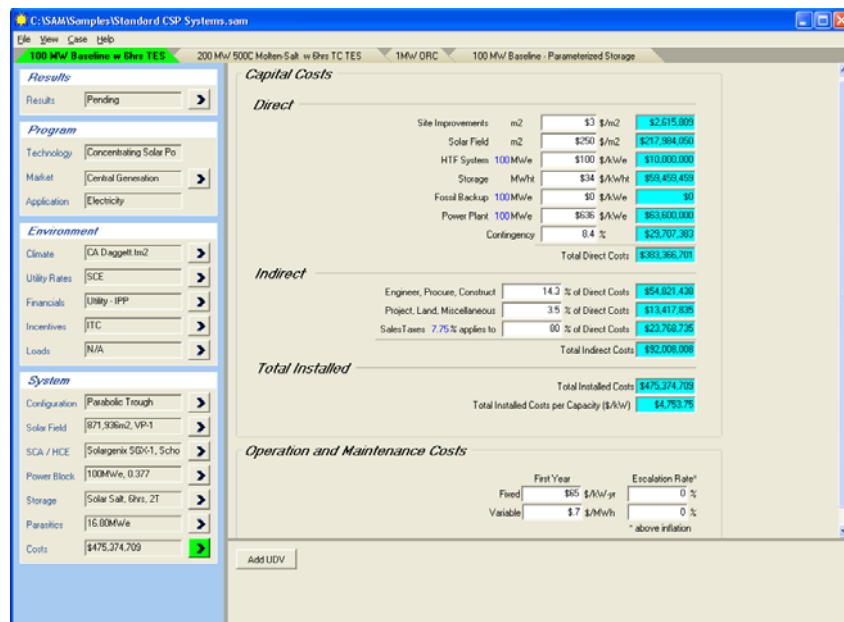

Figure 5. Cost model input page

3. CSP Performance Model

The performance model within Solar Advisor performs an hourly transient simulation of the system as defined by the user in the GUI. Because of the extensive existing content and existing validation of individual components, the TRaNsient SYstem Simulation (TRNSYS) program[2] was chosen as the performance engine for Solar Advisor. For example, methods for modeling PV, CPV, and CSP systems as well as the peripheral activities (such as reading weather data and outputting results) currently exist. The performance model works completely in the background, and the user doesn't need to know anything about TRNSYS to conduct any analysis. The systems are pre-constructed and integrated into the Solar Advisor GUI. However, as with the cost model, an advanced TRNSYS user can modify the details of the performance model separately from the GUI. The number of times the performance model is run for each analysis depends on the arrangement of the parametrics for each case. For example, if 10 different thermal storage sizes are chosen, then 10 different runs of the performance model would need to be completed.

The CSP parabolic trough model currently implemented within SAM is based completely on another defacto standard model called "Excelergy."[3] Excelergy is a Microsoft Excel-based tool that includes an hourly performance model, financing options, and costs for parabolic troughs. However, without documentation and lack of wide public distribution, the Excelergy model was difficult for DOE or industry to use without support from NREL. It should be noted that the performance model in Excelergy is based on another previous tool called Solergy.[4] These models are basically energy flow models that calculate the energy captured in the solar field, pass that energy to and from thermal storage via the dispatch logic, and convert that energy into electricity in the power plant. The model is not a complete thermodynamic system and, therefore, the feedback between storage and the power plant back to the solar field performance is not included. This makes certain short-term issues, such as start-up and shut-down effects, difficult to model. Additionally, much of the model is based on curve-fits to real plant operations, making it difficult to model future plants or modify basic physical parameters without having measured data to generate the necessary curve-fits.

The Visual Basic code for the trough plant performance within Excelergy was converted to FORmula TRANslation (FORTRAN) for use with TRNSYS. This code was broken into three modules including the solar field module, the thermal storage and dispatch module, and the power plant module. Each of these modules is briefly summarized below:

- **Solar Field Module –** The solar field module takes various weather and system inputs and calculates the amount of energy collected by the solar field and the outlet temperature from the solar field. The inlet temperature can either be hooked up to the outlet of the power plant steam train or left as a constant. The optical efficiency is determined based on a variety of factors such as twist and geometric accuracy that are input by the user.

  The heat losses from the receiver tubes is determined iteratively, based on a polynomial curve-fit that is determined from measured values for a particular receiver type combined with the integrity of the receiver tube (vacuum, hydrogen, broken, lost vacuum). The model also takes into account high-wind stowing of the array, end losses, and parasitics.

  The properties of various typical heat transfer fluids are included, and others will be added to the heat transfer fluid library as they become prevalent in the marketplace.

  Finally, the model calculates the parasitic power requirements for the solar field, especially the necessary pump power for the heat transfer fluid in the field and the motors to rotate the troughs.

- **Thermal Storage and Dispatch** – This module tracks the energy injected and extracted from the thermal storage system but, perhaps more important, determines the dispatch control for the thermal storage and the

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[2] Klein et al., 2003 TRNSYS 16, A Transient Simulation Program. Solar Energy Laboratory, University of Wisconsin, Madison, Wisconsin, WI.
[3] A Parabolic Trough Solar Power Plant Simulation Model, H. Price, January 2003, NREL/CP-550-33209
[4] Stoddard, M.C., Faas, S.E., Chiang, C. J. and Dirks, A.J., SOLERGY - A Computer Code for
Calculating the Annual Energy from Central Receiver Power Plants, SAND86-8060 Sandia National Laboratories, Livermore, CA, 1987.

power plant. This is done based on a series of rules entered by the user for up to six different time-of-use periods during the year. The user assigns each hour of the year to a specific time-of-use period and sets the dispatch rules for that period as well. For example, during a summer peak time-of-use period, the power plant will be dispatched either from storage or from the solar field depending on how much energy is still in storage. Conversely, an off-peak period would generally fill the thermal storage before dispatching the power plant (unless the power plant was operating in the previous hour).

The model includes characteristics for a one-tank thermocline storage system or a two-tank system. The storage fluid can be the same or different than the solar field fluid with appropriate use of a heat exchanger. The model allows for losses from the thermal storage but does not do any internal thermodynamic analysis (such as vertical stratification) of either the two-tank or thermocline system. This module also calculates the parasitic losses, especially any backup heating needed for freeze protection of the thermal storage.

- **Power Plant** – The power plant model, which requires a design value, is essentially a part-load curve-fit that converts the thermal energy coming from either the solar field or thermal storage into electric power. There also is an option for temperature correction, based either on the wet-bulb temperature or the dry-bulb temperature, which allows for accounting for using either a dry-cooling or wet-cooling option. A variety of typical power plant designs have already had curve-fits developed – and more will be included in the future.

  The power plant module also has an option to use fossil backup as necessary and will determine the necessary gas input based on a curve-fit determined from measured data.

  Finally, the power plant model also calculates any parasitic energy requirements by the power plant.

In the future, a more complex thermodynamically based model for parabolic troughs will be incorporated, based on existing research done at the University of Wisconsin–Madison.[5] This will allow greater modeling options, especially for thermal storage and dispatch modeling. Power tower technology, dish sterling technology, and other new CSP technologies also will be added.

4. Sample CSP Results

The graphs below demonstrate the type of output available and the possibilities for doing parametric analyses within SAM for CSP models. The use of SAM for photovoltaic analyses has been discussed in other references. The project file on which these samples are based is included in the standard SAM download.

Figure 6 contains the results screen for a project with a standard 100 MW parabolic trough plant with six hours of thermal storage. As shown, one of the most basic standard outputs is the First Year PPA level for this plant in this location (Daggett, California), which is 14.51 cents/KWh with an escalation rate (which is an input) of 1%. This is the levelized payment necessary to make this project economically viable including an internal rate of return (IRR) for the equity partner ("Actual IRR") of 15%. To the right, the levelized cost of energy (LCOE) in real dollars is broken down by the contribution from the different cost components. From this graph, one can see that the solar field is a dominant part of the LCOE stacked bar chart with storage, EPC (Engineer, Procure, Construct) costs, and fixed O&M also being big contributors.

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[5] "Design & Optimization of Organic Rankine Cycle Solar-Thermal Powerplants," M.S. Thesis, A.C. McMahan, 2006, University of Wisconsin-Madison Solar Energy Laboratory
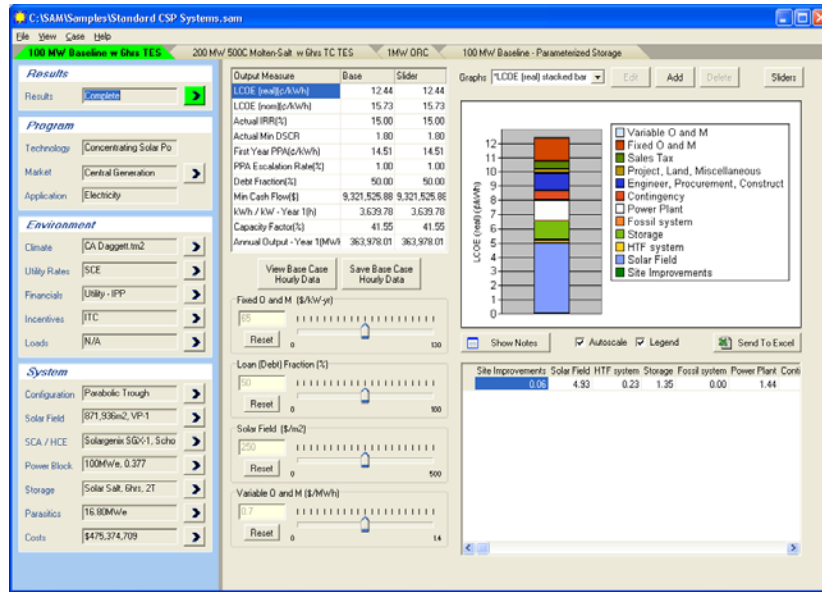
Figure 6. SAM results screen for sample 100 MW CSP plant

One parametric analysis that can be easily done is examining the impact of differing geographic locations within the southwestern United States for the same plant. Figure 7 shows the varying real levelized cost of energy for systems at different locations.
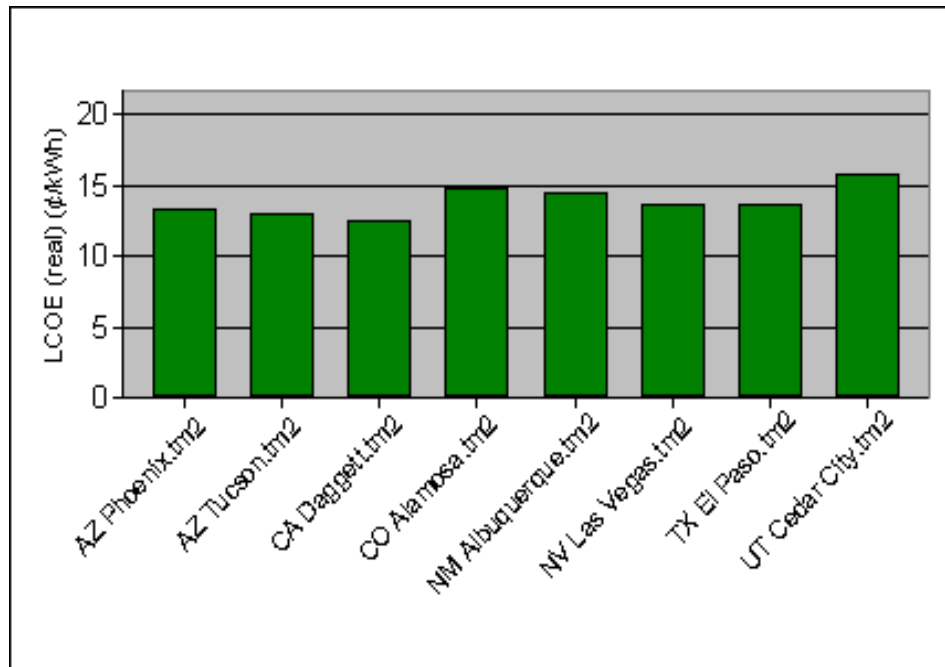

Figure 7. Real LCOE variance by location for a 100 MW CSP trough plant with six hours storage

It is also possible to vary financial variable parametrically to see what the sensitivity of the cost of energy is to the natural uncertainty in financial variables. For example, one can vary both the required internal rate of return for the investor and the debt fraction (Figure 8). As the required IRR increases and the debt fraction decreases, the levelized cost of energy increases significantly. However, with a high debt fraction (80 % is the maximum in this case); the LCOE is not variable with respect to the required IRR. In this case, the debt service coverage ratio is the dominant constraint.
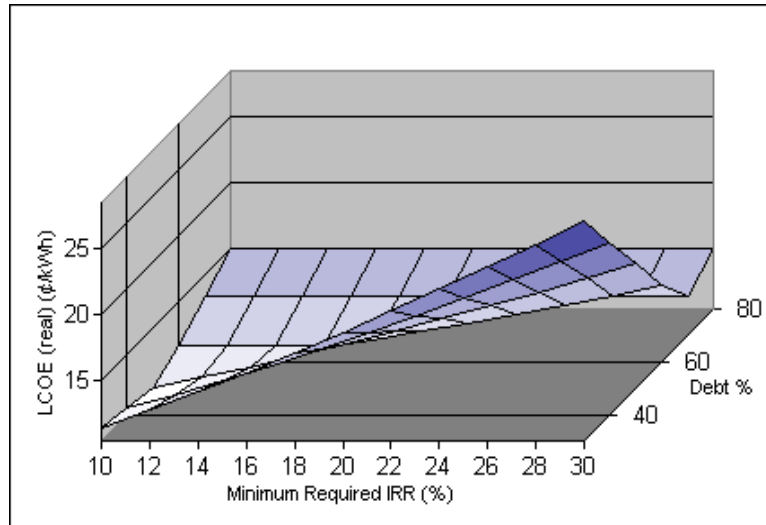
Figure 8. LCOE as a function of minimum required IRR and debt percentage

Finally, analyses can be done for varying levels of incentives. For example, it would be interesting to know the impact of a reduction of the investment tax credit from 30 % to 10 % or even 0 %. Figure 9 shows the cost of energy (divided among the contributing cost components) as a function of the investment tax credit.
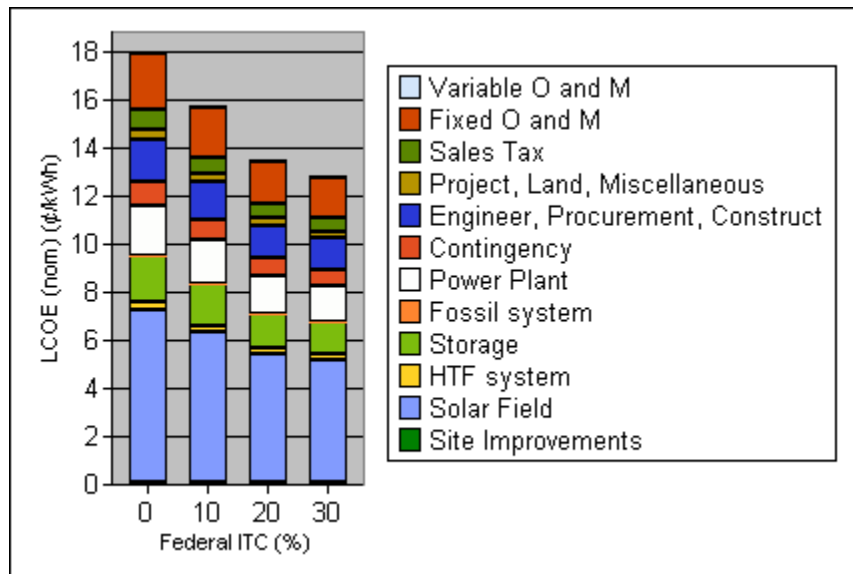

Figure 9. LCOE as a function of federal investment tax credit (%)

5. Conclusions

The Solar Advisor Model (SAM) is a solar technology systems analysis model. Originally developed to facilitate program planning and analysis for the U.S. Department of Energy's SETP, its mission has now been expanded to become an analysis platform for a wide array of stakeholders and decision makers. SAM integrates the modeling of costs, incentives, financial scenarios, and performance of solar technologies – specifically, photovoltaics and parabolic troughs. The primary function of the model is to allow users to investigate the impact of related variations in technology, costs, and financial assumptions to better understand their impact on key metrics. The real value of Solar Advisor stems from the integration of all aspects of the system and ability to do elaborate sensitivity and parametric analysis. The model currently includes parabolic trough technologies, based on previous modeling efforts done at NREL and Sandia. The sample results show the expedience and ease of doing a sensitivity analyses over a wide variety of system inputs – performance, financial, or cost.