Computer simulation of solar electric generating plants in a utility grid*

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INTRODUCTION
Solar electric power systems have the potential to supply power for industrial, commercial, institutional, and utility applications and to reduce consumption of non-renewable fossil fuels. However, widespread utilization of solar electric technologies in the United States will require that the solar systems be operated in parallel with, or as supplements to, the existing utility grid. For such systems, assumptions regarding future electric energy costs and rate structures have a major impact on solar system design and economics. Thus, in order to fully assess the economic worth of solar electric systems, it is necessary to evaluate their impacts on utility generation characteristics and to determine solar electric system design and cost relations within the context of the overall utility/solar system interaction.

SAI has developed a methodology which evaluates the performance and economics of grid-connected solar electric technologies within the overall utility context. Because solar energy varies both hourly and seasonally, reaching a peak level for only a few hours each year, solar generation is unique relative to conventional generation currently in use by most utilities. The value of solar plants integrated in a utility network consists of both electric generation costs and capacity costs to meet a specified reliability level and depends on a number of variables: the mix and cost of conventional (non-solar) generation; the stochastic coincidence between solar generation patterns and the electric system load shape; the amount of solar penetration; the energy storage capability of the solar systems; and the solar system dispatch strategy. This paper summarizes the various techniques which have been developed and provides initial results for the worth of on-site photovoltaic, wind, and solar thermal electric technologies.

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METHODOLOGY OVERVIEW
Grid-connected solar electric systems have an impact on utility characteristics by modifying the load to be supplied by conventional generation. This provides direct economic benefits to the utility in the form of reduced fuel costs and operation and maintenance costs. In addition, the resulting load may also provide capacity savings in the form of reduced installed capacity requirements, depending on the statistical reliability of the solar generation during peak load periods; and the modified load will affect the appropriate utility generating mix of base, intermediate, and peaking plants. Figure 1 illustrates these impacts and interactions between solar electric power systems and the utility network.

The model developed by SAI provides a comprehensive analysis of the impacts of different solar electric technologies on the utility, and estimates the economic value of the solar plants to the utility, dispersed user, and/or third-party investor. The final output of the model is a set of estimates of the break-even cost for solar electric technologies under different assumptions about ownership, payback period, and return on investment. The model calculates the economic benefits to dispersed users by assuming that the annual cost savings to the utility are passed on to the user via an appropriate rate structure. The precise nature of this rate structure is currently the subject of rather controversial legislation, partly because of the many complex interactions which are involved and which this model is designed to evaluate.

An overview of the model is shown in Figure 2(a). The overall assessment methodology involves five separate model segments: hourly simulation of solar electric system performance; utility load projection and adjustment for the output of the solar plants; capacity expansion and mix adjustment for conventional utility generation; production costing for the resulting conventional utility mix; and finally economic analysis of the solar plant value under different ownership alternatives. Because of the extensive calculations that are involved, the models have been implemented...
with a modular structure so that analysis runs can be made independently of the others. The inputs, outputs, and analysis steps of the various model segments are summarized in Figure 2(b) and described in what follows.

SOLAR ELECTRIC SYSTEM PERFORMANCE MODELS

The solar electric performance models simulate the hourly output of various solar technologies. Separate models are available for photovoltaic, solar thermal electric and wind systems. Each model consists of subsystem component models which are used to compute steady-state efficiencies at each hour. As an example, Figure 3 provides an overview of the simulation model for solar thermal electric power systems. At each hour the model computes steady state energy balances, tracking losses, cosine losses, blocking and shading, reflectivity (or transmissivity), surface error losses, receiver intercept factors, receiver absorptivity, receiver re-radiation and convection losses, thermal transport losses, storage or hybrid energy flows, and part-load turbine generator efficiencies.

Inputs for the various models comprise the following categories:

- Hourly meteorological data on SOLMET tapes
  - Beam and total horizontal radiation
  - Sun position
  - Temperature
  - Wind speed
- Solar electric plant data
  - Type
  - Collector parameters
  - Energy conversion parameters
  - Subsystem efficiencies
- Storage/hybrid configuration
- Dispatch strategy
- Hourly on-site electric demand profiles

Outputs consist of the annual energy flows to/from various subsystems, overall plant performance summaries, thermal energy credits (where applicable), and hourly electric output files for total generation and energy consumed onsite. The model outputs can be used directly for systems analysis and design trade studies, or the hourly output files can be attached for input to subsequent analysis models.

LOAD ADJUSTMENT MODEL

The load adjustment model estimates the impact of the solar electric generation on the overall utility loads. The original loads for the utility are first projected to the time span of interest, and then the outputs of the solar electric plants are subtracted on an hourly basis, taking into account the transmission and distribution benefits of on-site generation. Solar plant outputs are scaled by the number of units and capacities of the various solar systems, and then their hourly outputs are subtracted probabilistically in the sense that various combinations of solar plant outages are considered at each hour in accordance with the forced outages probabilities. The hourly results are then accumulated in the form of load duration curves for each month or season, as indicated in Figure 4. These load duration curves are stored for both the original load projection (without solar) as well as for the solar-subtracted loads. This provides a non-solar reference case which is carried along with the solar case throughout the remaining analysis, so that the differential impacts of the solar generation can be accurately measured.
MIX ADJUSTMENT MODEL

The mix adjustment model performs a capacity expansion analysis to determine the type and number of conventional generating units which should be added to the existing utility mix to meet projected electric demands at minimum total cost. This analysis is performed for both the solar case and the non-solar reference case. Inputs for the analysis include the existing utility system generating plants; the available plants for capacity expansion; characteristics of each plant type, including rated capacity, minimum operating levels, fuel type, heat rates, forced outage probabilities, maintenance requirements, fixed capital costs, and variable O&M costs; utility economic data, such as fuel costs, escalation rates, taxes, discount rate, insurance, etc.; and projected utility load data in the form of seasonal or monthly load duration curves both with and without solar.

Figure 5 presents a screening curve analysis which illustrates the considerations involved in performing the utility mix optimization. The upper curve shows capacity costs for different plant types as a function of the number of hours per year which they are run; the lower curve represents the annual load duration curve. Capital-intensive plants such as nuclear or large coal have high fixed costs but low variable costs, so they are most appropriate when used as base-loaded plants that are run almost continuously. Combustion turbines, on the other hand, have low capital costs but high variable costs, so they are most appropriately used as peak-
Figure 2(b)—Summary of simulation inputs, outputs, and analysis methodology.
Figure 3—Solar thermal electric generating plant model.

Figure 4—Formulation of utility load duration curves.
ing units which run only a few hours per year to meet the highest demand levels. By projecting the intersection points of the plant cost curves onto the load duration curve, as shown in the screening curve analysis of Figure 5, it is possible to estimate the amount of capacity desired for each plant type.

The screening curve analysis does not account for the previously existing plant mix of the utility, the discrete sizes of the available plants, the minimum operating levels of the plants, the spinning reserve requirements to maintain available capacity for meeting sudden load increases, or the probabilistic forced outage characteristics of the various plants. SAI has formulated the basis capacity expansion problem as a mixed-integer linear programming problem which is solved using a standard linear programming package with branch and bound techniques for the integer variables. Figure 6 illustrates the discretization of the load duration curve into demand segments and the variable cost representation of each generator (which allows non-linear heat rates but assumes linear incremental heat rates). The variables for the linear program are the number of plants of each type to be installed, the number of plants of each type which are dispatched in each demand segment (if minimum operating levels are accounted for), and the operating level of each plant in each demand segment. The objective function of the linear program is to minimize the present worth of total fixed plus variable plant costs. Constraints for the problem include the following categories:

- Installed Reserve Margin
- Demand Requirements
- Spinning Reserve
- Plant Capacity
- Plant Availability and Purchase Constraints
- Plant Energy Limits (e.g., Hydro)
- Integer Variable Constraints.

The solution of the linear program provides the basic capacity expansion plan; however it assumes de-rated plant capacities without accounting explicitly for the probabilistic nature of plant forced outages. This is performed in a subsequent analysis step, which estimates loss of load probability (LOLP) using a Gram Charlier series expansion technique to rapidly evaluate convolutions of the demand and plant outage random variables. Peaking capacity is then added or subtracted from the generation mix to meet the required LOLP reliability criterion. Finally, a maintenance schedule is estimated by removing plants according to maintenance requirements so as to levelize the reserve margin defined as total available plant capacity (minus peak demand) over all months. The final output of the mix adjustment model is the adjusted capacity mix (both with and
without solar), the estimated annual production costs for each generator type and fuel type, and an estimate of the present worth of revenue requirements for the utility.

DETAILED UTILITY PRODUCTION COSTING MODEL

A detailed probabilistic production costing model, SYSGEN\(^1\), is used if necessary to provide a refined estimate of production costs based on the modified load duration curves and the optimized conventional capacity mix for both the system with solar generation and the reference system with no solar generation. SYSGEN uses the standard Booth-Bel-eriaux algorithm to account for plant outages, in which the effective load duration curve seen by each generator (or valve point) is expressed as the original load duration curve plus the random outages of previous generators in the loading order. The successive load duration curves are computed using a recursive technique to perform the required convolutions, as described in Reference (1).\(^*\)


ECONOMIC ANALYSIS MODEL

The outputs of either the mix adjustment model and/or the detailed production cost model are then used to provide estimates of the breakeven costs of the solar plants for utility, on-site user, and third party investor ownership alternatives. Additionally, the economic analysis can calculate the net present worth of the solar systems for various solar plant cost assumptions. The key assumption of the economic analysis is that the rate structure applied to solar system investors will reflect the difference in cost of electric service to this customer class, so that the overall savings provided by the solar plants are passed on to the investor.

CONCLUSIONS

The methodology described above provides a comprehensive and consistent analysis of the economic worth of different solar electric technologies operating in a utility network. This is an important consideration in determining solar electric system design and cost relations within the context of the overall utility/solar system interaction. Representative results of the modeling analysis will be presented at the conference for the worth of on-site photovoltaic, wind, and solar thermal electric technologies.
Numerical Methods for the '80s

After more than a decade of emphasis on commercial applications, scientific computing is again emerging as an important area. This session will present two papers, one dealing with methods for making use of the new parallel architectures now being marketed, and the other presenting a language which makes matrix computations accessible to the scientist or casual programmer. The panel discussion will examine a number of issues of current concern in scientific computation and numerical analysis.

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