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Analysis of the Impact of Decentralized
Solar Technology on Electric Utilities:
Comparison and Synthesis of Models

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Analysis of the Impact of Decentralized Solar Technology on Electric Utilities: Comparison and Synthesis of Models

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Abstract

This report describes the validation of the physical submodels of three solar-electric utility interface models. The validation problem is divided into two components, the accuracy of the submodels themselves and the accuracy of the data typically used to run these models. The data set required to study these problems with respect to utility requirements is discussed and its collection in the Philadelphia Metropolitan area described. The instrumentation employed in the gathering of the data is covered. Error statistics of data and submodel accuracy are presented and the current status of the study is presented.

Introduction

The solar-electric utility interface study is an attempt to validate and corroborate the models and techniques used to predict the impact of solar technologies on electric utilities and their customers. Traditionally, the cost effectiveness of solar heating and hot water systems has been approached from the perspective of consumer economics. However, as solar space and hot water heating systems are typically designed for solar fractions of 40 to 70%, and will use electric backup for periods of insufficient solar radiation, the cost effects on the electric utility must be included in the economic analysis. As penetration of the heating market by solar systems occurs, the load curves of utilities and hence their financial picture could be substantially affected.

This study examines three of these models as well as the data used to run them. The three models are the Feldman-Anderson Model, the Brookhaven Model and the A.D. Little Model. Each of these models is composed of two major parts, a physical model that simulates the required electric backup of a solar system, and an economic model that translates the electric demand into costs. As the number of space heating systems in the study local is considerably less than the number of hotwater systems, the validation will be performed using only domestic solar hot water (DSHW) systems.

In the discussion that follows, data will refer to either input or output variables that change with time. Input

variables fixed in time will be termed parameters.

The first part of this study, now underway, is specifically concerned with validation of the physical submodels used to simulate the electric backup demand and the problems with the data used to run these submodels. Simulation can, of course, be a much more cost effective method of system evaluation than actual measurement. This is especially true as the range of possible solar system designs and climates present a large number of permutations to the evaluators. However, the value of the simulation to the evaluator rests on its ability to accurately predict system performance. As the model is a simplification of the real world, it cannot be expected to duplicate the real world in every aspect. For a model to be judged valid, it is sufficient that it accurately predicts only the variable in question. The validation criteria used for this evaluation is quite straightforward. Actual operating DSHW systems will be monitored to obtain input and output data. The input data and system parameters will be used to run a simulation of that specific system, and the resulting model output will then be compared with the observed output. In this case, output data will be the electric backup consumption. The accuracy of the simulation will be measured by the accuracy with which electric backup is predicted.

Two types of information are required to run DSHW simulation models, input data and system parameters. Input data can be divided into 3 categories, weather information,

hot water demand schedules and inlet water temperature. Weather information is usually obtained from Solmet tapes. Solmet weather tapes, constructed for 222 major cities across the country, are the most widely available meteorological data base in existence. Hot water demand schedules information is usually based on past studies. Typically an average daily curve is chosen, or the demand is just assumed constant. Inlet water temperature is usually assumed to be constant.

In general two classes of problems result from the use of the above data; errors in the accuracy of prediction and lack of load diversity information. Both of these problems originate with the poor data resolution that exists in space and time with respect to utility requirements. In terms of using a single set of weather inputs, accuracy is suspect due to missing the possibly significant microclimatic variations across the utility service area. Load diversity that would have resulted from the inclusion of the missing weather variations will, of course, also be absent. In terms of using a single hot water load schedule, the primary concern is the loss of load diversity. Overall consumption accuracy will be a less significant problem, assuming a large enough sample, as consumption will be random across individual households. This is not the case with local weather temperature variations as significant blocks of utility service area will jointly experience this variable. Variation in wind, as with

water consumption, will be random on the scale of the household and hence will average out. Wind variation will contribute to load diversity, but the effect due to wind will be small in comparison to the effect due to water consumption.

The other type of information required for the DSHW system simulation are the system parameters. These consist of steady state values such as collector area, circulation pumping rate, hot water temperature set point, etc. These are normally known quite accurately, but of course any variation in value from that assumed for the simulation will introduce modeling errors.

Data

To study the problems indicated above, the first requirement was to collect an appropriate data set. Specifically, to study the accuracy of the physical sub-models, the input data set of solar radiation, ambient air temperature at the collector, inlet water temperature and hot water demand must be recorded. In addition, to compare the predicted electric consumption with the actual, electric demand is needed. To study microclimatic variations, completely, records of solar radiation, air temperature, wind speed and wind direction would have to be recorded at several different points. This was beyond the financial resources of this study. Temperature is believed to be the most important microclimatic variable on the scale of the utility, as significant variations can be expected across the service area, and yet the rate of variation will not be so rapid as to cancel out the service area. Fortunately, hourly temperature data is being taken at several sites in the local utilities service area and using this data microclimatic temperature effects will be studied.

Radiation data may also be an important source of model error for the utility but not because of variation across the service area. Rather the problem is with the manner in which local solar data, i.e. Solmet tapes, is generated. While Solmet tapes are created for 222 sites around the country,

solar radiation is only measured at about 10% of these sites. The solar data for the other 90% of the sites are generated from cloud cover data. On a yearly basis, the accuracy of solar insolation predicted in this way is quite good. But on an hourly basis, even the Solmet authors feel the errors could be as high as 30%. Solar data for this study will be collected locally. Unfortunately, Solmet data is not available until several months after it is actually taken. This will preclude a comparison between actual insolation measurement generated for this study and the corresponding Solmet data.

In accord with the requirements of the data set, monitoring of DSHW systems is being performed as shown in figure 1, and in a geographical arrangement illustrated in figure 2. Figure 1 shows a typical DSHW system consisting of solar panels, a heat exchanger, a solar preheat tank, circulation pump, expansion tank, and hot water tank with auxiliary heater. The monitoring system consists of an ambient air temperature sensor mounted behind the solar panel, water temperature sensor mounted on the inlet pipe, a water meter mounted in the inlet water pipe, and an electric meter mounted in the auxiliary heater circuit.

Figure 2 indicates the location of data sites in the Metropolitan Philadelphia area. Potential participants for this study were obtained from a list of recipients of solar energy grants. This list of people with solar systems was

Figure 1: Typical Domestic Solar Hot Water System

FIGURE 2

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METROPOLITAN PHILADELPHIA AREA

sorted geographically by zip codes. Concentrations of solar grant recipients were then matched with sources of hourly temperature data, with the 3 cluster sites shown on the map being selected. Hourly temperatures at these three sites are being provided courtesy of Philadelphia Electric Company. Using the temperature from the solar system sites, the cluster centers, and from Philadelphia International Airport, where Solmet data for Philadelphia originates, three levels of microclimatic temperature data have been established.

In addition to the sites indicated above, temperature data will also be obtained from Northeast Philadelphia Airport, the U.S. Naval Air Station at Willow Grove, and another PECO site not shown on the map. These extra sites may provide some additional insight into temperature variations.

Data will be collected simultaneously from each of the DSHW system sites, in a cluster for approximately one month. At the end of the month, the equipment will be removed from the first cluster, installed in the second, and left to collect data for another month. After data has been collected from the third cluster, the instruments will be moved back to the first cluster for one final month. This will insure that data from the same location is obtained with large weather variations.

Two variations to the data monitoring scheme outlined above may occur as information becomes available. The first concerns

the measurement of inlet water temperature. Domestic water supplies fall into 2 categories, wells and distributed systems. Well water temperature is expected to remain constant year round. If measurements verify that DSHW systems are receiving constant temperature water from wells, well water will not be monitored on subsequent installations. The temperature of water in a city distributed water system is known to vary during the year, but it may be constant across the service area, as the ground acts as a temperature averaging mechanism. If this proves to be the case then only one distributed water source need be monitored. The temperature monitoring equipment that would be freed in the above situation will be used to monitor the temperature of the preheat tank water. This temperature will serve as a delimiter for system performance. Errors in system simulation could then be separated into the solar subsystem (collector and preheat tank) and the auxiliary system (electric water heater) by noting whether the preheat tank temperature is properly simulated.

Instrumentation

Site instrumentation is based on Westinghouse W31-A magnetic tape event recorders, that have been modified for battary operation in instances of power failure. Sensor systems for temperature, water consumption and electric consumption were designed to interface with these recorders. The W31-A is a two-channel recorder with one channel for timing information and one channel for data. The recording format is of the simplest possible type: simple pulses spaced along the magnetic tape in an event format. Pulse height and spacing carry no information. At one-half hour intervals, as determined by a synchronous clock motor, a pulse is placed on the time channel. The information obtained from the data channel is simply the number of pulses on the data channel between half-hour time pulses.

To record temperature data on this system, temperature is transformed into a pulse rate. For example, 20° C is equivalent to about 0.2 pulses/sec. Physically, this is accomplished by three major subsystems. First is the sensor itself: a nickel-iron resistive temperature device (RTD) having a resistance proportioned to temperature. Next, a bridge configuration converts the resistance to a voltage. Finally, a voltage-to-frequency converter translates the voltage into a pulse train. The resulting magnetic tape is read by a translator which simply counts pulses on the data channel as

it watches for a pulse on the time channel. Each occurrence of a time pulse causes the recording of the current data pulse count and its resetting to zero. Multiplication of the data pulse count by a conversion factor yields the average temperature over the half hour interval.

Hot water consumption is monitored by a water meter in the cold water inlet line. The water meter is coupled to a contactor, which provides a contact closure with each gallon of water consumed. A voltage source in the W31-A is used to provide a current such that with each contact closure a pulse is placed on the data channel of the tape. The number of pulses in a one-half hour interval gives water consumption directly in gallons.

Electric power consumption is monitored in a manner similar to water consumption measurement. An electric meter is coupled to a pulse initiator that places a pulse on the tape for each unit of power consumed. Multiplication by a conversion factor yields the amount of power consumed in the interval.

This recording system has several advantages. The components are relatively simple and rugged. The relatively high voltage levels, DC nature of the RTD, and pulse nature of the recorder give high noise immunity. The summation of the pulse train in the translation process has the effect of averaging the data over the half-hour interval, which is the form of data required to run the computer simulation. The timing pulses make the system insensitive to absolute tape speed.

However, the system also has several disadvantages. There are no absolute time marks on the tape, only 30 minute intervals. Thus both the absolute time period covered by each tape, and the comparison of two tape periods depends upon hand marking of the tape start and stop times. It is difficult to check the calibration of equipment on site, except in a crude way by counting pulses. The data format used is awkward in that the data requires two translation steps before it is in a form compatible with computer simulation requirements. Finally, only half-hour averages of data are available; it is not possible to obtain any finer resolution in level or time.

As mentioned above site calibration is difficult. However overall temperature calibration will be accomplished by measuring temperatures independently with thermometers at specific times and comparing these results with the data record. Water and electric consumption can only be checked by comparing aggregate totals registered on the meters with the sums of the respective records of half-hour consumptions. Factory meter calibration will be assumed to remain valid. Relative accuracy of the temperature measurement system is believed to be $\pm 0.5^{\circ}\text{C}$.

As microclimatic temperature variations are expected to be relatively small, perhaps 3°C , sensor placement to monitor these effects will be important. The ambient air temperature sensors on site are being positioned a few inches behind the

solar collector panels in their shadow. This should ensure the air temperature indicated by the sensor will reflect the one experienced by the collector. This reading should also reflect any local heating effects caused by the sun warming the roof of the house. One practical difficulty with sensor placement exists where collectors are flat against the roof of the house. In this eventuality, the sensor will be placed in the closest shaded area near the collector. The sensors on the other two microclimatic levels, i.e. Philadelphia International Airport and the cluster centers, are all positioned in standard weather service enclosures a few feet above the ground. This should ensure that readings are both mutually consistent and consistent with Solmet data.

Physical Submodel Validation Procedures

The validation of the physical submodels will proceed largely as indicated in the introduction. Using parameter data gathered from the sites and from the system manufacturers, simulations of the DSHW systems will be setup on a computer. Then employing the measured input data a prediction of electric consumption will be made at one-half hour intervals. An average system error figure will be generated by summing the absolute errors between predicted consumption and observed consumption for each half-hour intervals, and then dividing this total error by the length of the simulation period. This will be done for each DSHW system site. The average system error will provide an indication of the ability of the submodel to simulate different systems, and will also provide a check for any anomalous results.

$$\text{Ave, Sys. Error} = \frac{\sum_{\text{time}} |\text{consumption}_{\text{Obs.}} - \text{Consumption}_{\text{Pre.}}|}{\text{total time}}$$

A second error figure, average aggregate error, will also be generated to yield an aggregate error for the submodel. A utility is not particularly interested in errors at the individual household level, as it is not supplying electricity to individuals but aggregates of individuals. It is, however, concerned with errors on an hourly basis, as demand varies on

this scale. To reflect this in the error figure, predicted consumption will be summed algebraically over the different sites for each half hour interval. This will have the effect of averaging over the different households. The observed consumption will be similarly treated. Then for each half hour interval, the absolute value of the difference between aggregate predicted and observed consumption will be obtained and these figures will be summed over the total time. Taking the absolute difference every half-hour preserves the error information on the fines time scale. This double summation is then divided by the total time and number of sites to yield the average error per site per unit time.

$$\text{Ave. Aggr. Error} = \frac{\sum_{\text{time}} \left| \sum_{\text{sites}} \text{consumption}_{\text{Obs}} - \sum_{\text{sites}} \text{consumption}_{\text{Pre.}} \right|}{\text{total time} \# \text{ of sites}}$$

This error represents the uncertainty the utility could expect in its load curve predictions using the respective submodel. In addition to proving a useful form of validation information to the utility, the average aggregate error tends to reduce random modeling errors in the simulation output yielding a more accurate result.

Data Dependent Errors

As outlined in the introduction data errors will be of two types, accuracy of prediction errors and load diversity errors. Prediction errors due to data can be handled in a fashion similar to modeling errors. Again as the utility is not particularly interested in variations on a household level, aggregation will be performed over sites. To see variations between data sets, predictions using different data sets will be explored. The absolute differences between predictions using site data as a base line and the other two data sets will be calculated.

Ave. Aggr. Error (Site vs Cluster)

$$= \frac{\sum_{\text{time}} \left| \sum_{\text{sites}} \text{Consumption}_{\text{site temp}} - \sum_{\text{site}} \text{Consumption}_{\text{cluster temp.}} \right|}{\text{total time \# of sites}}$$

Ave. Aggr. Error (Site vs. Solmet)

$$= \frac{\sum_{\text{time}} \left| \sum_{\text{sites}} \text{Consumption}_{\text{site temp.}} - \sum_{\text{Solmet}} \text{Consumption}_{\text{Solmet temp.}} \right|}{\text{total time \# of sites}}$$

The error or change in load diversity is difficult to quantify without resorting to cost of generation considerations. This will be left to the second part of the study. For the

purposes of this portion of the study, comparisons of load diversity will be based on the load factor, the ratio of the peak electric demand to average electric demand over the average daily load curve. The average daily load curve is obtained by aggregating over sites and over days. Thus the load curve, instead of consisting of one number, will comprise 48 numbers, one for each half hour in the day. Clusters will not be combined in this calculation as different sites also represent different months, and common utility practice is to generate a load curve for each month.

$$\text{Ave. load curve} = \sum_{\text{days}} \sum_{\substack{\text{sites of} \\ \text{1 cluster}}} \text{consumption}$$

Load curves will be generated for predicted consumption using site temperature data, cluster center temperature data, and Solmet temperature data keeping other inputs the same. Then using on site temperature data, load curves with fixed hot water demand schedules and the observed hot water demand schedules will be generated. Comparison of the resulting load curves will be accomplished by calculating the respective load factors.

Current Status

Several of the above mentioned tasks have already been completed or are underway. All the equipment has either been purchased or borrowed and is on hand. Necessary modifications are complete. The selection of participants for clusters 1 and 2 is complete, with the selection for cluster 3 underway. Data collection in cluster 1 for the first month was completed as of October 13th. The translation of this data from the Westinghouse W31-A format to model compatible format is underway. Installation in cluster 2 began on October 19th, with data collection commencing as the instruments are installed.

Acquisition and preliminary running of TRNSYS, the physical submodel for the Feldman-Anderson and Brookhaven models, has been completed. The reduction of the DSHW systems of cluster 1 to computer models is the next task to be completed. In conjunction with this work, the manufacturers of the DSHW systems of cluster 1 will be contacted to complete the parameter set for each system.

Other tasks to be completed in the next month are the acquisition of the A.D. Little model, so that simulations using its physical submodel can commence, and of course the completion of cluster 2 data set. After simulations of DSHW systems using both physical models are running, work will commence on the second part of the study, the corroboration of the economic sections of the solar-electric utility interface models.