SOLAR INDEX PREDICTION METHODOLOGY

FOR

EARLY DELIVERY

MASTER

by

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Abstract

Since the beginning of the Solar Index project in 1978, it has been one of the primary objectives to deliver the Indices in mid-afternoon local standard time. This was desirable because it would make it possible to have the numbers broadcast in the early evening news. This paper presents a short description of the current project and then gives a summary of the work that led to the early delivery of the Solar Index.

Project Overview

The Solar Index is a number between 0 and 100 which represents the percentage of energy made available by a solar system that is used to heat an 80-gallon per day service hot water load for a given geographic location and given day. For example, if the Solar Index is 70 for a given day, it means that a solar service hot water system could provide approximately 70 percent of the heat needed to boost 80 gallons from ground water temperature to 120°F. The Solar Index is much like the pollen count, wind chill factor, and air quality index, in that it can provide more useful information than can be provided by observations such as ambient temperature or carbon monoxide concentrations.

The objective of the Solar Index[†] effort is to increase public awareness. Approximately two years ago it was decided within a U. S. interoffice committee that an index, general in nature, would increase public awareness of solar energy. Several indices were investigated and it was decided that the Index should provide an indication of what the sun can do for the individual rather than to simply state how much solar radiation is available. That is why the

[†] Additional information, general in nature, can be obtained by writing to Solar Index, Conservation and Solar Energy, U. S. Department of Energy, Forrestal Building, Washington, D.C. 20585.

current definition of the Service Hot Water Solar Index has been adopted-- because it does give an indication of what the sun is capable of doing for the individual. The solar service hot water system was decided upon as a base because it appears to be one of the most commercially viable and is the most easily defined and most frequently installed solar system in the country at the present time. Also, the average hot water usage for a service hot water heating system is fairly constant throughout the country.

In order to obtain the Index, a set of simplified and representative systems must be defined for computer modeling purposes. These systems were defined in the following manner. They are to be representative of service hot water systems which would be designed for the specific city of interest. In the south, drain-down systems, with water being the collection fluid, were modeled; while in the northern climates, heat exchangers were employed with an antifreeze agent in the collection loop. Furthermore, the systems were sized, with the storage being sized approximately $1\frac{1}{2}$ gallons per square foot of collector, since it has been determined that this is a cost effective storage size. The collector area is determined so that the system will be capable of providing approximately 70-75% of the annual service hot water heating load for an 80-gallon per day consumption rate. Consequently, there is a different system size for each city. In the south, the collector area may only be 40 - 50 square feet; while in the north, the area may very well exceed 90 square feet.

In the beginning of the project, initiation of the Solar Index for any given city required that the media in that city request the Solar Index. At the present time, cities which are prime market areas are being added to the list whether or not the media have shown interest. Media interest, however, will increase the motivation for inclusion. After deciding to possibly include

a site in the effort, the SOLCOST Service Center[†] selects the appropriate solar system type and determines the availability of weather information. Weather service information is essential.

Once it has been ascertained that all necessary information is available, the computer files required for generation of the daily Index are created. This is accomplished with SOLCOST, which is a computer program used to analyze prospective solar energy systems of various types on the basis of economics and thermal performance. It is basically a design tool which provides the user with the necessary information to facilitate decisions regarding a solar energy system. As pertaining to the Index, SOLCOST is used to size the system and then produce a data base of performance values based on historical weather data. The inputs to the program are: location, orientation, size of specific components, the load, and the location's weather history.

A simplified data base is created with the two inputs being average ambient temperature and percent sunshine with the output being the Solar Index. This may be accomplished either by tabular or graphical means. Both methods of analysis are easily implemented.

The Solar Index process is two-phased. The first phase is setting up and the second phase is execution. Involved in setting up is the decision to include a location. Then if weather service information is available, the necessary computer files are created for execution of the Index procedure on a daily basis. Execution of the Index on a daily basis requires utilization of computer files, which has already been defined in the setup phase.

[†] Technical responsibility for the Solar Index is provided by the SOLCOST Service Center, 2524 E. Vine Drive, Fort Collins, Colorado 80524. Specific technical questions not addressed by this paper should be addressed to Loren J. Lantz at the above address.

As the Solar Index project currently stands, the Department of Energy, Conservation and Solar Applications, provides direction for the overall project. There are two prime contractors who provide support to the Department of Energy. They are: 1) SOLCOST Service Center, 2524 E. Vine Drive, Fort Collins, Colorado 80524; and 2) National Solar Heating and Cooling Information Center, 20th and Race Streets, Philadelphia, Pennsylvania 19103.

The SOLCOST Service Center provides technical direction for the project. Its personnel are responsible for determining availability of weather information and setting up computer files for execution of the Solar Index on a daily basis. They are also responsible for delivering the Solar Index in an automatic fashion to the news wire services, which is done at the present time by direct computer ties.

The National Solar Heating and Cooling Information Center in Philadelphia is responsible for delivering the Solar Index to interested parties who do not subscribe to the news wire services. They are delivered each evening by telephone. Individuals at the SOLCOST Service Center phone the Index number to the National Solar Heating and Cooling Information Center each evening for dissemination to those people who wish to receive the number by phone. They are also responsible for tabulating monthly summaries, keeping records, and dissemination of media information to interested parties.

There are two other agencies which are also very important. They are the United Press International, which at the current time is disseminating the Solar Index daily through its wire services, and a computer service agency located in Massachusetts, which collects the weather data each hour from the prime weather wires, including the wires generated by National Weather Service, National Oceanographic and Atmospheric Administration, and the Federal Aviation Administration. The latter is the one that is used primarily in the generation of

the Index. More will be given later about how this weather data is transformed into a Solar Index for a given city.

At the present time, most large metropolitan areas are being serviced by the Solar Index effort. The Department of Energy is constantly striving to inform the media of this new service, especially in the prime solar commercial market areas of the country.

Currently, the Solar Index is generated utilizing established weather wire data which is reduced on an hourly basis to estimates of ambient temperature and total horizontal radiation by computer models which have been thoroughly presented and described in a previously presented paper entitled "Solar Index Generation and Delivery". In the past at sundown each day the average ambient temperature for the day was estimated and the total horizontal radiation summed for the daylight hours and converted into percent of possible sunshine. These two estimates, as well as yesterday's percent of sunshine, were transformed into the Solar Index for the particular day for a particular city. It was desirable to accomplish this task in mid-afternoon for each location and then to disseminate the predicted daily Index so that it can be included in the early evening news broadcasts. The software which sums the total daily radiation on a horizontal from the hourly values has the capability to fill missing data. This is accomplished by utilizing a statistical approach which assumes that the weather does not change drastically from hour to hour. That is, if it is cloudy at 1:00, then it is likely to be cloudy in a similar manner at 2:00. This procedure for filling radiation data has worked well, the ambient temperature on the other hand is handled in a much more continuous manner. The methodology

used for calculating the average daily ambient temperature is to take the average of the minimum and the maximum observed values throughout the day. Even if weather data sets of 20 observed values throughout the day are available, similar results are achieved when averaging the 20 values versus taking the average of the maximum and minimum. However, for certain locations there are systematic weather patterns which occur at sundown. For example: late afternoon cloudiness. The filling technique described could not account for this particular type of systematic behavior for each location. Consequently, it was desirable to develop a methodology which would minimize the mean error and the variance of the individual errors over time.

Possible Methodologies

By utilizing the existing software, estimates are available for expected average ambient temperature for the day, percent sunshine and the Solar Index. Then at the end of the day, after sundown in the evening, updated values of these parameters and final results become available. Following is a description of several methodologies which could be utilized to minimize the error and facilitate delivery of the Solar Index early in the day. Data was collected for various existing Index locations throughout the country so that the errors could be defined and then adjustments could take place. Then an error minimization methodology was adopted, taking into account the cost of implementation. Several methodologies were investigated and they are described briefly in the following pages. A recursive moving average filter which determines the non-stationary mean error was actually implemented. Rationale for this will be given later in this paper.

In an effort to be more specific, predictions exist for each day. They can be expressed respectively in vector form as percent sun, average ambient temperature and the Solar Index;

$$[\%S_p, \bar{T}_p, SI_p]$$

and at the end of the day, the resultant values are obtained and illustrated in vector form as well as the predictions

$$[\%S, \bar{T}, SI] .$$

This can be extended in a vector sense to represent a daily series such as

$$[\%S_p, \bar{T}_p, SI_p]$$

and

$$[\%S, \bar{T}, SI]$$

for example:

$$\%S = \{\%S_1, \%S_2, \%S_3, \dots, \%S_k\}$$

and etc., for the other vectors.

Now the Solar Index prediction on an average one day has an unknown prediction error (ξ) associated with it.

$$SI_k = SI_{p,k} + \xi$$

This error can possibly be biased and its statistical properties may be non-stationary (vary with time).

The desired properties of the prediction scheme are to force the mean error or expected value to zero; i.e.,

$$E [\xi] = 0$$

and to minimize the variance of the expected error.

$$\min E [\xi - E[\xi]]^2$$

Forcing the mean error to zero is a simple process and can be accomplished by a weighted feedback loop. The feedback function can be allowed to change with time if the process is nonstationary.

If the process is stationary, the estimate of the mean error $\hat{E}[\xi]$ can be calculated recursively.

$$\hat{E}[\xi]_k = \frac{k-1}{k} \hat{E}[\xi]_{k-1} + \frac{\hat{\xi}_k}{k}$$

where

$$\hat{\xi}_k = SI_k - SI_{p,k}$$

If the process is nonstationary, a moving average technique could be employed, such as

$$\hat{E}[\xi]_k = \frac{1}{n} \sum_{i=k-n}^k \xi_i$$

which could easily be accomplished in a recursive manner. Another avenue which will result in a lessening of the error variance as compared to the above method is to calculate, by least squares, the expected error as a function of the inputs when calculating the predicted Solar Index.

$$\hat{E} [\xi]_k = \underline{M} \underline{x}_k$$

where $\underline{M}$ is a vector of coefficients determined by least squares and $\underline{x}$ is a vector of functions of the inputs. One possibility for $\underline{x}$ could be

$$\underline{x}_k = \{\bar{T}_{p,k}^2, \bar{T}_{p,k}, \%S_{p,k}, SI_{p,k}^2, \dots\}$$

As above, it will have to be determined whether or not this process is stationary or not and to compensate accordingly.

One additional procedure to minimize the variance of the error would be to implement a Kalman filter, which is an optimized procedure for accomplishing this task. The filter, however, may offer little benefit as compared to the least squares procedure described above. The Kalman filter is also expensive to implement and can be very tricky (easily becomes numerically unstable).

Model Selection

The first stage of the project was to ascertain what the errors were for various locations and the spread about that error. Data were collected for a month for approximately 20 locations and the mean error and standard deviation for those locations was determined. The Indices were to be calculated using incomplete data sets at 3 p.m. local time for each time zone. The error is the difference from what would be calculated at the end of the day. The error was generally overpredictive in nature and its mean value for most locations ranged from 1 to 2 percentage points and its standard deviation was on the magnitude of 2 to 3 percentage points. Since the resultant error was small and its standard deviation was similarly small, the Kalman filter was immediately ruled out because of its cost of implementation and likely instability. This left a choice of least squares, moving average error estimation or stationary error estimation. For those locations for which data was collected for the

month, least squares estimation techniques were employed to see what could be done to minimize the resultant error and minimize the spread about that error. Recursive moving average techniques were also used. Both gave similar results, with the auto recursive moving average technique being by far the cheapest to implement. Both methodologies resulted in producing a mean error close to zero and actually reducing the spread about that mean error somewhat, but not significantly. There was not enough data available to determine whether or not the moving average technique would eventually reduce into a stationary mean error which would be good for all time. The current methodology calculates a moving average over a 20 day period and the mean error is updated once a week. This particular methodology seems to be quite stable and is inexpensive to utilize as compared to least squares methodologies. Currently, the Solar Indices are calculated at 3 p.m. local time for each time zone and disseminated to United Press International as has been done in the past.

The actual sequence of events is simple. The software that is utilized to fill missing weather information is exercised to create an estimated Solar Index for the day at about 3 p.m. local standard time. The running mean error for that location is looked up and subtracted from that estimate, and the resultant is what is delivered to the media. At the end of the day, the Solar Index is again calculated using a more complete weather data set (see Fig. 1). Both numbers are stored for permanent records. A recursive moving average filter used to determine the mean error is executed once a week.

The end result is that a Solar Index, which deviates only slightly from the end of day resultant Solar Index, is delivered to the media in a timely basis so that it can be included in the early evening news and also possibly evening local newspapers. It is expected that this will increase dissemination significantly and further help to enhance public awareness of solar energy usability.

Figure 1. Solar Index Daily Procedure