Reports

Solar Availability for Winter Space Heating: An Analysis of SOLMET Data, 1953 to 1975

Abstract. *Solar availability for space heating on coldest-weather days has been determined from an analysis of SOLMET data tapes. The tapes contain hourly readings of insolation and ambient temperature over the period from 1953 through 1975. Scatter diagrams of insolation versus heating degree-days, compiled on a daily basis, indicate a wide variation in the insolation level, even during coldest-weather periods. For all but one of the eight sites studied, the peak-day backup energy requirement of the solar system was in excess of 85 percent of the peak-day energy requirement of the conventional (nonsolar) heating system.*

The day-to-day variation in insolation observed at most locations in the United States is a serious problem for solar system designers. In most solar applications, an auxiliary or backup system is required if the load is to be met reliably during extended periods of cloud cover. In space heating applications, this usually entails the addition of a backup furnace adequate to supply the design day heating load. Although the auxiliary system, by itself, is usually a relatively minor component of the capital cost of the total system, the cost of energy supply to the auxiliary system can be high. In particular, if the backup system is electric, the demand component of cost, including the utility investment in "standby" generating and distribution capacity, can be substantial (*1*).

The impact of space heating on the utility depends upon whether the utility's peak load occurs during the winter or the summer. If the utility is summer-peaking, neither a solar system nor a conventional heating system will contribute to the utility's generation and transmission capacity requirements. On the other hand, if the utility is winter-peaking, the utility's capacity expansion requirement will be largely determined by the peak space heating loads. In this case, the impact of the solar system may differ significantly from that of a conventional heating system, depending upon the level of insolation on the coldest-weather days (*2*).

Two recent studies have examined solar availability on peak heating days (*3*, *4*). The conclusion of one study, of the Philadelphia area, was that the solar system's auxiliary power (demand) requirements were the same as those of a conventional furnace (*3*). The other study simulated the peak-period performance of both solar heating and cooling systems at several U.S. locations. For the two northern sites—one in New England, the other in Wisconsin—there was evidence of substantial solar availability on peak heating days (*4*). This finding led to speculation that in certain climatic regions a correlation may exist between high insolation levels and low outdoor temperatures. A more conclusive assessment of the solar availability question would require more data from more sites for longer periods of time.

The release of the SOLMET data tapes by the National Climatic Center in early 1978 provided an opportunity to examine insolation levels at a number of U.S. locations for periods of over two decades (*5*). In the study reported here we analyzed data from eight SOLMET sites to determine solar availability and daily heating requirements on a seasonal and coldest-days basis.

The SOLMET data are the product of an extensive "rehabilitation" of hourly solar radiation data by the National Climatic Center (*5*). The data are now available for 26 weather stations across the United States. For most locations the period of record extends from 1 July 1952 to 31 December 1975.

The tapes contain hourly readings of global solar radiation incident on a hori-

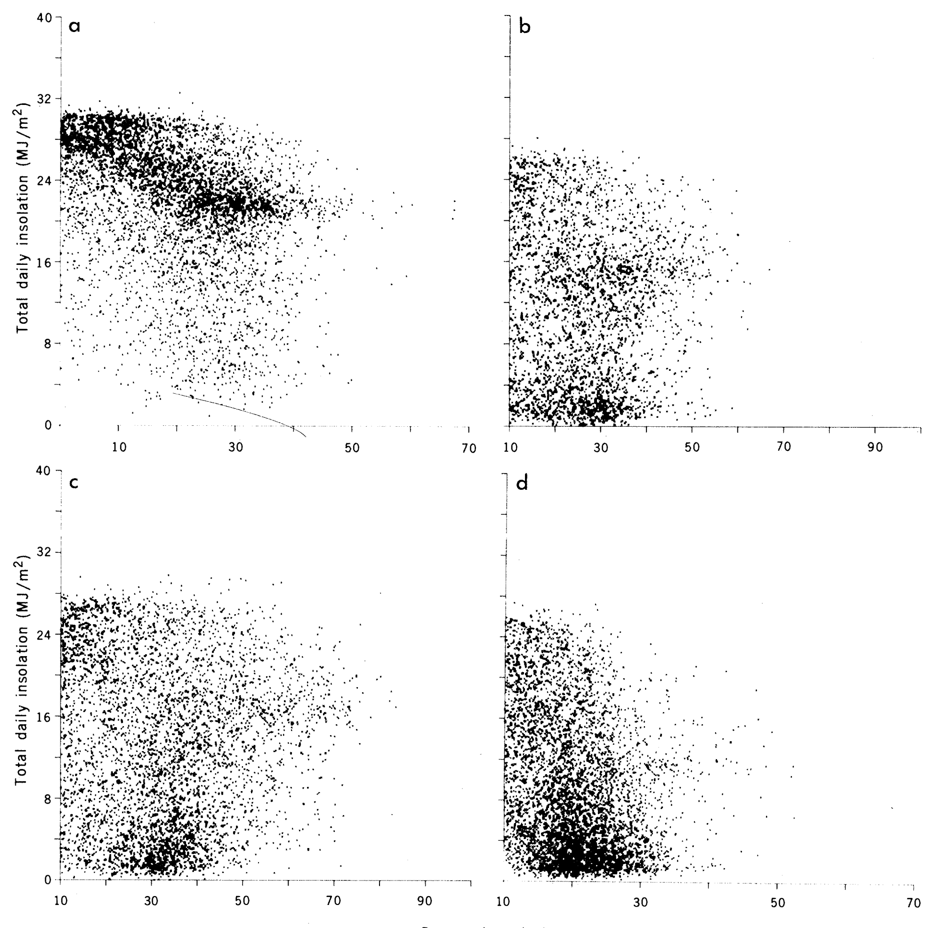

Fig. 1. Scatter diagrams of daily insolation versus heating degree-days for the four locations: (a) Albuquerque, New Mexico; (b) Boston, Massachusetts; (c) Madison, Wisconsin; and (d) Seattle, Washington. Plots show all points corresponding to days with heating degree-day values greater than cutoff values (0° or 10°F).

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zontal surface as well as readings of certain surface weather variables including wind speed, atmospheric pressure, and ambient temperature. The recorded insolation is the total of direct and diffuse radiation received on a pyranometer, integrated over the hour; the readings of the surface weather variables represent instantaneous measurements. In addition to the raw solar radiation data, the SOLMET tapes contain two types of rehabilitated radiation data, the so-called "engineering-corrected" data and the "standard-year-corrected" data.

The National Climatic Center recommends the standard-year-corrected data as the most reliable of the data fields. Accordingly, the results presented in this report are based on these data. A complete description of the raw data and of the techniques and procedures used to construct the standard-year-corrected data are presented in the SOLMET manuals (*6*).

We analyzed data from eight SOLMET sites selected to span the range of climatic and geographic conditions for locations with solar space heating potential in the United States. The sites are as follows: Albuquerque, New Mexico; Bismarck, North Dakota; Boston, Massachusetts; Caribou, Maine; Columbia, Missouri; Madison, Wisconsin; Seattle, Washington; and Sterling, Virginia.

Our only modification to the standard-year-corrected data was to adjust insolation for collector tilt. We computed the adjusted insolation values, using the standard Liu and Jordon relation for dividing the global insolation into diffuse and direct components. According to the method, the diffuse component was assumed to be isotropic and the direct component was estimated by simple cosine projection onto the collector surface. The method, as applied to hourly data, is described in (*7*).

Plots of insolation on the collector surface as a function of heating degree-days, for individual days, are shown for four sites in Fig 1, a through d. [Results for all eight sites are given in (*8*).] The heating degree-day values are calculated relative to a reference temperature of 65°F (18.3°C). The collector tilt angle is set equal to latitude. The points in the scatter diagram represent all days within the 23-year period on the SOLMET tapes—1 January 1953 through 31 December 1975—except for Boston where the period of record ended in 1968.

Although each of the scatter diagrams exhibits its own unique structure, all indicate a wide variation of insolation levels for each degree-day value. Even the subset of 230 coldest days at each site includes a number of days with insolation levels less than 20 percent of the clear-day level for the site.

To obtain a quantitative measure of the correlation between solar availability and coldest-day temperature, we performed, for each of the eight sites, a least-squares linear regression of daily insolation on daily degree-days for the coldest 230 days in the 23-year sample. The calculated correlation coefficients ranged from −0.0044 for Bismarck to +0.189 for Seattle. When the data sample was not restricted to coldest-weather periods but included all days having a space heating requirement, the correlation coefficients were found to be negative for each of the sites.

During cold winter periods, when daily load exceeds collector output, the action of most solar systems is to deliver available solar energy to load with little or no day-to-day carry-over of stored energy. To calculate the backup requirements on these coldest days, we adopted a simple model of solar collection that assumed no storage carry-over.

Collector performance was modeled with the Hottel-Whillier equation [see (*7*) and references cited therein]. We used a standard hydronic flat-plate collector having a heat loss of 17 kJ m^{-2} $°C^{-1}$ $hour^{-1}$ and an absorptance-transmittance product of 0.73. On the coldest days, collected energy will pass rapidly to load, with the storage temperature and hence collector inlet temperature remaining at a relatively low value determined by the minimum temperature requirements of the load. The constant value of 90°F selected here for the collector inlet temperature is suitable for space heating and will yield an optimistic estimate of collected solar energy.

At each location, collected solar energy on a daily basis was estimated for array sizes designed to supply 25, 50, and

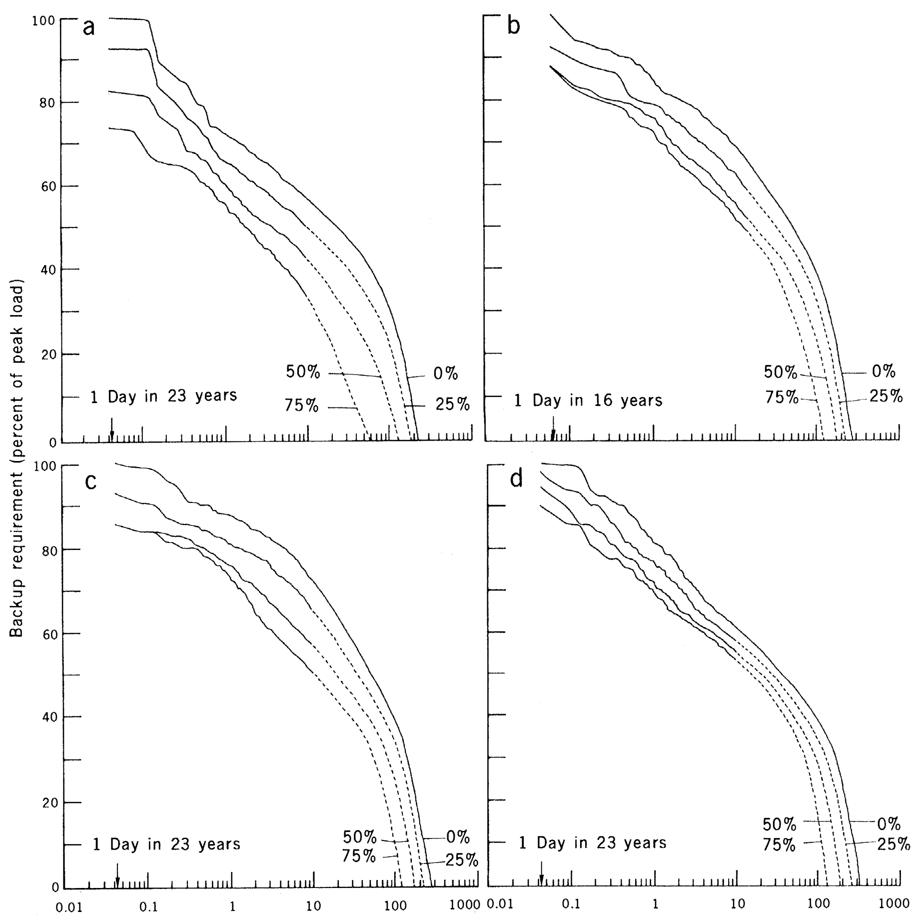

Fig. 2. Load duration curves, or cumulative frequency distributions, of daily backup energy requirements for the following sites: (a) Albuquerque, New Mexico; (b) Boston, Massachusetts; (c) Madison, Wisconsin; and (d) Seattle, Washington. The backup requirements are normalized to the maximum heating load observed over the SOLMET period of record (point corresponding to 1 day in 23 years). The number of occurrences has been divided by the number of years of data to normalize to the 1-year cycle along the horizontal axis. Load duration curves are shown for the nonsolar case and for solar systems sized to meet 25, 50, and 75 percent of the annual heating load.

75 percent of the annual heating load (*9*). By comparing the availability of solar energy with total heating requirements on a daily basis, we then computed the daily backup energy requirements for the solar heating systems. The resulting load duration curves (cumulative frequency distributions) of daily backup energy requirements are shown for the four sites in Fig. 2, a through d. The curve labeled "0 percent" corresponds to the conventional (nonsolar) case; the other three curves correspond to solar systems sized to meet 25, 50, and 75 percent of the annual heating load.

In Fig. 2, the backup energy requirement is normalized to the maximum daily heating load observed over the SOLMET period of record (usually the point corresponding to 1 day in 23 years). Although the assumption of no day-to-day storage carry-over, used in the calculation of solar output, is strictly accurate only for the subset of coldest days, the dashed portions of the curves have been included to show the results of a continuation of the same calculation procedure over all days with a positive heating load. The logarithmic scale along the horizontal axis provides greater detail over the period of coldest days.

Except for the Albuquerque site, there is little reduction in backup requirements of the solar systems relative to the power requirements of the conventional (nonsolar) system. Even for solar systems sized to supply 75 percent of the annual space heating load, backup requirements are usually in excess of 85 percent of the peak day requirement for the nonsolar system. For Albuquerque, the capacity reductions were approximately 10, 18, and 25 percent for solar systems sized to supply 25, 50, and 75 percent of the annual heating load, respectively.

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Experimental Coarsening of Antiphase Domains in a Silicate Mineral

Abstract. *Combined annealing experiments and observations by transmission electron microscopy show that in natural pigeonite crystals antiphase domains coarsen approximately according to a rate law in which the tenth power of the average domain size is proportional to time. This result suggests that certain cations (possibly Ca^{2+}) were segregated preferentially onto the antiphase boundaries. The domain size in samples quenched from above the high-low transformation temperature is large and apparently independent of annealing time and temperature. It appears that large domains can be generated either by very fast or by very slow cooling; thus the estimation of geological cooling rates from the sizes of antiphase domains in natural samples becomes rather difficult.*

The low-calcium clinopyroxene pigeonite has been of interest to mineralogists both because of its transformation behavior and because of its potential as an indicator of thermal history for many lunar and terrestrial rocks. Optical and electron optical studies have revealed a variety of fine-scale structures in natural specimens (*1*). Exsolution of augite (a calcium-rich clinopyroxene) is commonly found and may occur by spinodal decomposition or nucleation and growth (*2*). During very slow cooling pigeonite may transform to the low-temperature orthopyroxene structure, but, if this reconstructive transformation fails to occur, then an alternative, displacive transformation takes place which results in a symmetry change from $C2/c$ (high pigeonite) to $P2_1/c$ (low pigeonite) (*3, 4*). The temperature of this high-low transformation is composition-dependent (*5*), and it gives rise to antiphase domains (APD's) related by $^1/_2(\mathbf{a} + \mathbf{b})$ (*3*) which have frequently been observed by transmission electron microscopy (*6*).

Attempts have been made to use the size of APD's as a measure of the relative cooling rates of natural rocks (*7*). Rapid cooling is expected to give the smallest domains because the nucleation rates are higher and the time available for coarsening is less than under conditions of slow cooling. There are, however, several complicating factors. Heterogeneous nucleation of APD's at suitable high-energy sites such as host-precipitate interfaces can give deceptively large domain sizes (*8*). The transformation temperatures vary with composition so that APD sizes may also be composition-dependent. Furthermore, it has been postulated that segregation of Ca^{2+} onto the antiphase boundaries (APB's) may occur (*3*); such a preferential segregation would affect the domain growth kinetics and hence the observed APD sizes. This certainly appears to be the case in slowly cooled specimens (*9*).

I present here the early results of an experimental study that was undertaken in an attempt to shed some light on these problems and to establish a quantitative relationship between thermal history and APD size. There are wider implications, however, in that the kinetics of APD coarsening in ordered metallic alloys have been extensively studied and a simple rate law has been determined (*10–13*), but the same law has not been tested for silicate minerals.

Theoretically, APD's should coarsen according to the relation (*10*):

$$\delta^n - \delta_0{}^n = nK_0 e^{-(Q/RT)} t \qquad (1)$$

where δ is the average domain diameter, δ_0 is the initial domain diameter, K_0 is a constant, Q is the activation energy for domain coarsening, R is the universal gas constant, T is the absolute temperature, t is time, and n is a constant, ideally equal to 2.

Domain boundaries are effectively defects with an associated excess free energy. The driving force for coarsening arises from the decrease in energy

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