nical Memorandum ERL ARL-73

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

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Air Resources Laboratories
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Abstract. The distribution of Relative Effective Solar Space Heating is displayed on maps of the contiguous United States for January and for the November through April heating season. These maps make use of the increased energy obtained by solar collectors that are tilted southward at angles designed to maximize the total collection of solar energy during the heating season. Relative Effective Solar Space Heating is defined, for use here, as the ratio of the maximized solar energy to the heating demand (heating degree days), at a location, where both elements have been normalized to values found near the northern border of the United States. Therefore, Relative Effective Solar Space Heating has a value between one and two in the northern states and increases to the south. It was found, on the average, that effective solar heating in January, for example, was six times greater in southwest Arizona and eight times greater in Brownsville, TX, than at Pittsburgh, PA, or International Falls, MN. Further, over the 6-month heating season, average solar heating was as effective in south-central Montana as in southern Indiana or eastern Kentucky. The 40-fold increase, over these northern cities, in effective solar heating at Miami, FL, may not be relevant to heating applications because of the generally warm winter temperatures there.

The solar heating maps are based on climatological data updated to 1976 and flat solar energy collectors tilted southward at angles of location latitude plus 10 degrees where average ground reflectivity is assumed. The computed energy obtained by collectors so-tilted ranges from 125% along the Gulf Coast, to 225% along the Canadian border, of that falling on horizontal surfaces at those respective latitudes. The optimum tilt angle and azimuth for a particular solar collector should take into account the local climatology (diurnal cloudiness patterns, persistent winter snow cover, etc.), the ground reflectivity and the intended use (heating, cooling or both).

The average surface wind speeds over the USA for January and for November through April are shown because of the additional heating load imposed on structures by wind. The heat loss appears generally to be proportional to the first power of the wind speed but can range down to about the one-half power for buildings in clusters. The wind-induced heat loss is considered, from actual experiments, to be small in comparison with the loss due to colder outside temperatures.

1. INTRODUCTION

Widely-publicized predictions of an impending shortage of fossil energy sources has stimulated considerable effort in a search for alternative energy supplies. One such alternative energy source is the Sun. In spite of the technical difficulties caused by the need for storage of this intermittent energy, and the high capitalization costs for collectors and storage facilities, the amount of energy available from the Sun over the United States is immense. Because of the large amount of cost-free energy "constantly" available, it was deemed appropriate to show potential solar energy users the distribution over the USA of Relative Effective Solar Space Heating where the additional energy resulting from the use of fixed southward-tilted collectors is employed in the calculations. This information can be used for estimating the feasibility of employing solar heating in different regions of the United States.

Relative Effective Solar Space Heating is defined, in this study, as the ratio of the solar radiation, obtained from southward-tilted collectors, to the heating demand (heating degree days), at a location, where both elements have been normalized to values found near the northern border of the United States. The results are based entirely on climatology and do not account for solar heating system efficiency.

Climatological heating degree days are used as indicators of energy demand since they have been found to be proportional to the heating energy requirements of structures. Further, they are in quite general use by the heating and air conditioning industry (Baldwin, 1968). The solar energy data used in this study have been updated through 1975 (Environmental Data and Information Service, NOAA, 1978).

Average wind speeds over the USA are shown for the purpose of estimating enhanced heat loss from structures due to wind.

2. DATA SOURCES AND ADJUSTMENTS FOR UPDATING

Daily totals of solar energy (monthly means) falling on a horizontal surface (global) and normal heating degree days per month[†] (HDD) were taken from the Climatic Atlas of the United States (Baldwin, 1968) published by the Environmental Data and Information Service (EDIS) of the National Oceanic and Atmospheric Administration (NOAA). For the approximately 90 stations reporting solar radiation that were used in this analysis, record lengths average 11 years and range from 2 to 39 years. The Atlas used solar radiation through 1962. All solar energy data reflect the effects of cloudiness and atmospheric turbidity and were measured in, or reduced to, the International Pyrheliometric Scale of 1956. The heating degree day records are for the 30 years prior to 1961 for the 265 temperature-recording stations used in the analysis.

[†] Monthly accumulations of the negative differences between 65° and the daily mean temperature (°F).

Since solar radiation data in the Climatic Atlas ended 17 years ago, more recent solar radiation data were incorporated into the analysis in order to reflect recent climatological trends. The updated records consisted of solar radiation data from 26 stations distributed rather evenly over the conterminous USA, with long solar radiation records, that were "rehabilitated" by the Environmental Data and Information Service (1978) and were also brought up to date for almost 25 years prior to 1976. The rehabilitation in part consisted of making corrections to the data of the 26 stations by use of an atmospheric transmission model based on clear-sky solar noon observations of solar radiation with precision, and quality-controlled, equipment (EDIS, 1978). These 26 stations are located at the dots in Figure 1.

The hourly solar radiation data (global) at the 26 stations where rehabilitation was accomplished were checked for obvious errors and missing observations by examining original stripchart records. Missing hourly observations were estimated and filled in to make the records of solar radiation data homogeneous. To accomplish this, relationships were established between solar radiation and meteorological variables, such as duration of sunshine, cloudiness amounts, time of day, etc., at these stations by means of multiple regression analysis. The missing hourly solar radiation data were then estimated from the regression equations. Where meteorological observations were unavailable, climatology and interpolation were used to estimate hourly values of solar radiation. In general, the rehabilitated and updated solar radiation values at the 26 long-record stations were lower than values published by EDS in 1968 for the same stations. The average decrease over the November through April heating season was about 9%. The solar radiation values at the remaining 64 stations were adjusted by linear interpolation to conform to adjacent rehabilitated and updated stations on the assumption that climatic trends changed them in the same sense and proportion as the adjacent rehabilitated stations were changed.

3. ADJUSTMENTS OF DATA FOR TILTED COLLECTORS

Climatological solar radiation data are obtained from instruments measuring the amount of solar energy falling on a horizontal surface (direct plus diffuse radiation). It is obvious that by tilting a solar energy collector so that it faces toward the sun, more energy (particularly from the direct component) will fall on the collector. Balcomb and Hedstrom (1976) have determined that a south-facing solar collector tilted from the horizontal at an angle equal to its position-latitude plus 10°, will generally optimize the collection of solar energy over the heating season at most latitudes in the conterminous USA. Their formula for estimating the amount of solar energy falling on a collector when it is tilted, as noted above is:

$$E_S \approx 1.025Y - 8200$$

where E_S is Total Monthly Radiation in BTU ft^{-2} (1 BTU = 1055 joules) on

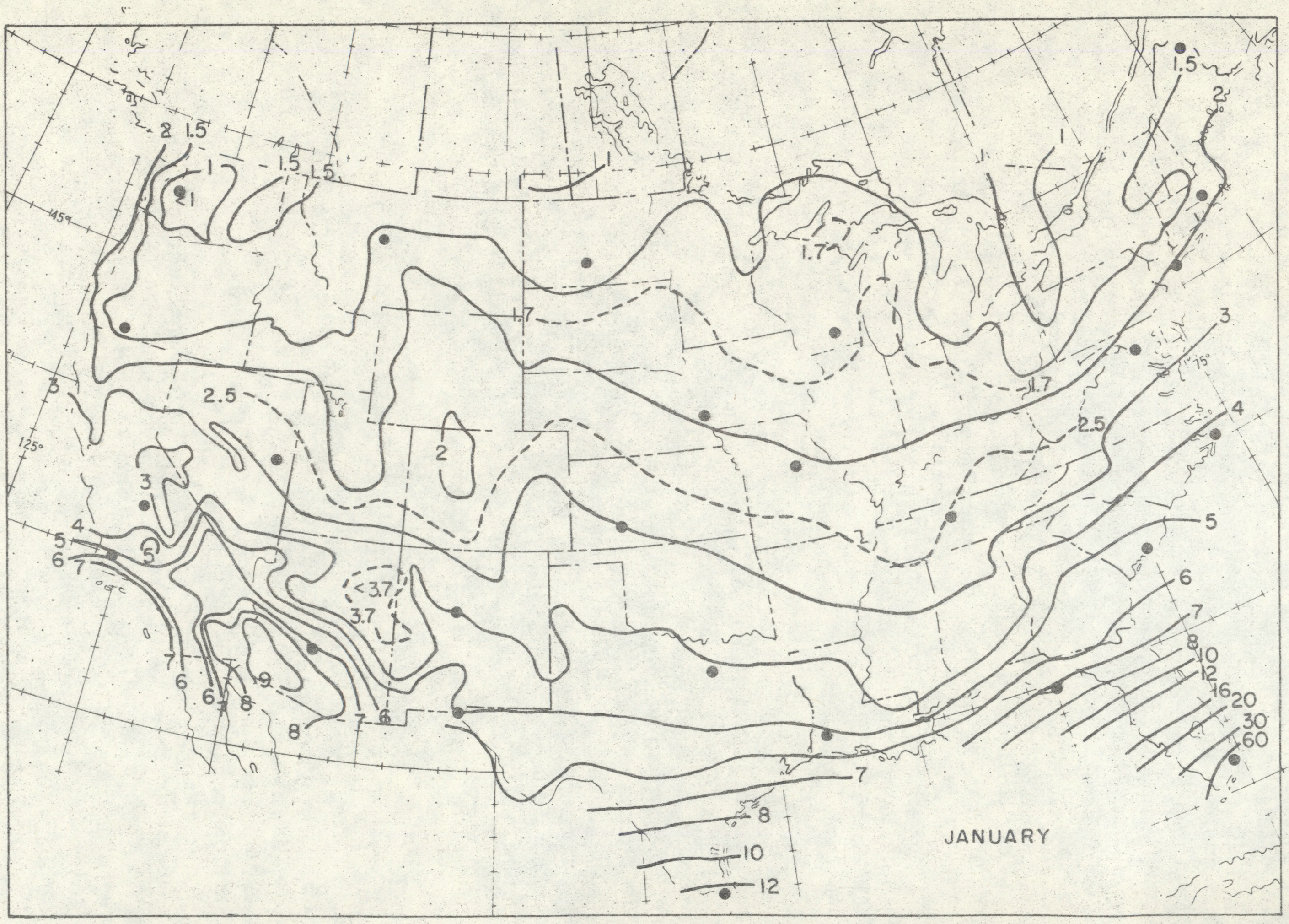

Figure 1. Distribution of Relative Effective Solar Heating (ratio of normalized solar radiation to normalized heating degree days) in January derived from climatological data. Original global solar radiation data were increased to values that result from tilting solar collectors southward at angles of location-latitude plus ten degrees. Large dots show locations where solar radiation data were updated and "rehabilitated." Unit Relative Effective Solar Heating represents 6.278 megajoules per square meter per day and 1300 Heating Degree Days per month.

a surface tilted at Latitude plus 10^{o}, and

$$Y = \frac{\text{Total Monthly Radiation on Horizontal Surface (BTU ft}^{-2}\text{)}}{\text{Cosine (Latitude - Solar Declination at Mid-month)}}$$

$$\begin{array}{l}\text{Total Monthly Radiation} \\ \text{on Horizontal Surface}\end{array} = \sum_{1}^{n} \begin{array}{l}\text{Average Daily Radiation on Horizontal Surface} \\ \text{(BTU ft}^{-2}\text{)}\end{array}$$

(where n = 28, 29, 30 or 31), and Solar Declination at the middle day of each month = 23.45 Cosine (30M - 187), with M = month (Jan. = 1, Dec. = 12, etc.). Dividing E_s by Total Monthly radiation on a horizontal surface (BTU ft^{-2}) gives the gain or benefit in solar radiation provided by a collector tilted southward as noted above. Climatological solar radiation given in joules per square meter (or other units) per day must be converted to BTU ft^{-2} per month for use in the above formula. (One joule per square meter = 8.8114×10^{-5} BTU ft^{-2}).

All the solar radiation data were converted to the increased values resulting from collectors tilted toward the south at an angle of location-latitude plus 10 degrees using the above formula.

4. DETERMINATION OF RELATIVE EFFECTIVE SOLAR HEATING AND DISCUSSION OF RESULTS

Isolines of average daily solar radiation for January falling on collectors tilted southward at position latitude plus 10^{o} were drawn on a map of the USA. This map was superimposed on another map showing isolines of January monthly average accumulations of heating degree days (HDD). The region having the smallest ratio of tilt-increased solar radiation to heating degree days was found to be near Lake Ontario where 6.278 megajoules per square meter (MJm^{-2}) per day (150 Langleys per day) fall on a tilted collector and heating degree days amount to 1300 per month. Unit Relative Effective Solar Heating was defined as existing wherever the ratio, $MJm^{-2}Day^{-1}/HDD$ per month, equaled 6.278/1300. Therefore, Relative Effective Solar Heating over the United States was computed at the intersections of other combinations of average daily solar radiation and average monthly heating degree days by the expression:

$$\begin{array}{l}\text{Relative Effective} \\ \text{Solar Heating}\end{array} = \frac{\text{Solar Energy (MJm}^{-2}\text{ per day)/6.278}}{\text{Heating Degree Days per month/1300}} = \frac{\text{Solar Energy} \times 207.1}{\text{HDD per month}}$$

The distribution of ratios computed by this expression for January is shown in Figure 1 where generally east-west-lying lines connect points of equal ratios of solar energy to heating demand. Thus, a line labelled 4 would either have 4 times more solar energy available for the same amount of heating demand or the same amount of solar energy but only one-fourth the demand, or as usually is the case, a combination of the two such that the ratio of solar energy to heating demand is 4 times greater than the ratio, 6.278 x 207.1/1300, from the above formula.

Deviations of the isolines from the zonal (east-west) pattern appear especially in the western high plains and the desert southwest where effective solar heating can be one and one-half to two times greater than that in the Mississippi Valley for the same latitude. These deviations are almost entirely due to non-zonal northward extensions of the solar radiation pattern. Unfortunately, solar radiation data are not as spatially homogeneous or dense as heating degree day data so most of the fine details shown in Figure 1 (and 3) are due to the closely-spaced temperature recording stations.

Figure 1 can be used quantitatively in the following manner. Knowing the percentage of a structure's heating requirements that solar energy can normally furnish at a given location with a given collection system, one can estimate the expected percentage of solar heating available at another location for the same kind of structure and collection system by a simple application of the ratios in the figure. For example, if solar energy furnished 50% of the January heating requirements of a building in St. Louis, MO (isoline labelled 2), it would furnish, other things being equal, the same percent of heating for the same building and solar collector in south-central Montana even though the Montana location (Lewistown) is 8° latitude (890 km) farther north. Figure 1 shows also that effective solar heating is six times greater in southwest Arizona and eight times greater in Brownsville, TX, than in Pittsburgh, PA, or International Falls, MN. The 40-fold increase, over Pittsburgh, in effective solar heating at Miami, FL, may not be of great importance to heating applications because of the warm average winter temperatures there.

The solar energy collecting advantage of the tilted collector (location latitude plus 10°) in January is not evident in Figure 1. For the convenience of the reader, ratios of solar energy collected on surfaces tilted as noted above, to energy collected on horizontal surfaces of the same area, were computed and their distribution over the United States is shown in Figure 2. Gains range from a factor of 1.25 in the southern USA to a factor of 2.25 in the northern states.

Relative Effective Solar Heating was also computed for the cool season, November through April inclusive. Daily (monthly average) solar radiation falling on a horizontal surface was averaged at each station for the six months. This was converted by the Balcomb and Hedstrom (1976) formula to the quantity falling on a collector tilted southward at location latitude plus 10° using, in the formula, the mean of the six mid-month Solar Declination angles applicable to each station. A test on stations at high and low latitudes showed a 10% loss in computed energy gain, at both latitudes, from the gain that would be obtained if each station were computed separately each month, using individual mid-month Solar Declination angles, then averaged. Therefore, 10% was added to the values computed by the Balcomb and Hedstrom formula where the six-month mean Solar Declination angle was used.

As before, the region having the smallest ratio of solar energy per day (tilted collector) to heating degree days per month was near Lake Ontario where the 6-month average of 8.371 megajoules per square meter (MJm^{-2}) per

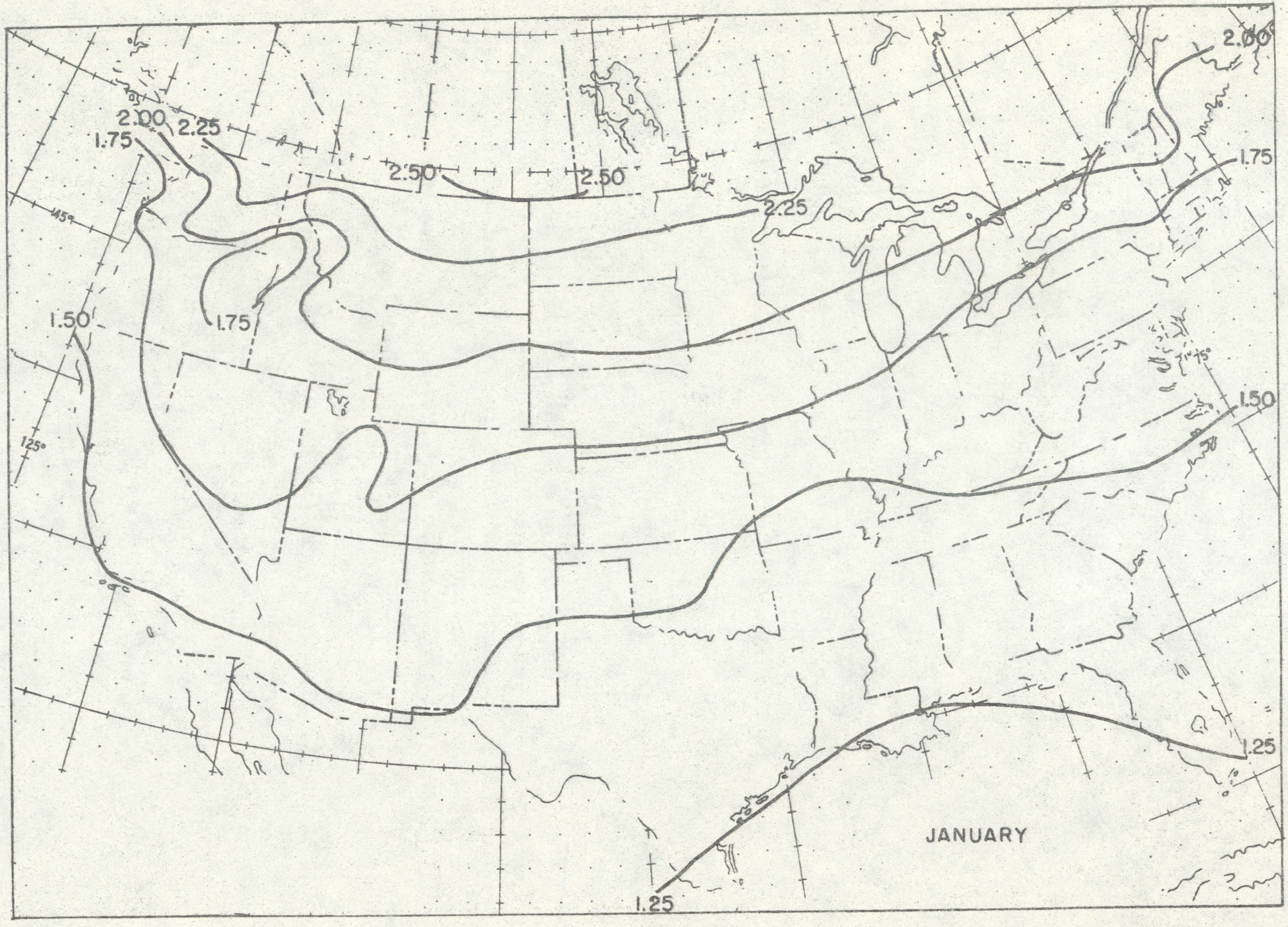

Figure 2. Distribution over the conterminous United States in January of ratios of solar energy received on south-tilted collectors to that received on horizontal surfaces. Solar collectors were tilted as specified in Figure 1.

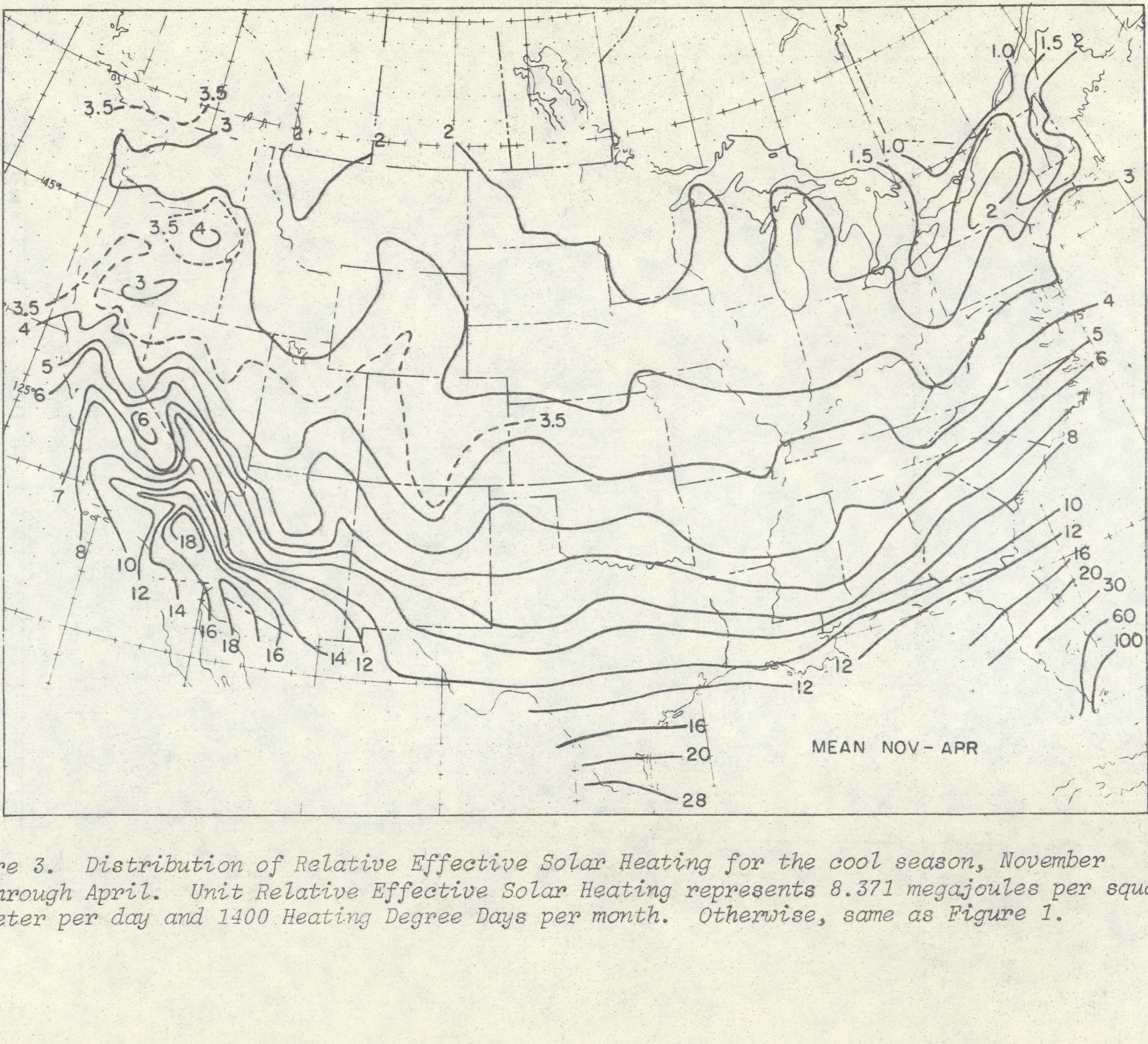

Figure 3. Distribution of Relative Effective Solar Heating for the cool season, November through April. Unit Relative Effective Solar Heating represents 8.371 megajoules per square meter per day and 1400 Heating Degree Days per month. Otherwise, same as Figure 1.

day (200 Langleys per day) and 1400 heating degree days per month was found. Unit Relative Effective Solar Heating was defined as existing wherever the ratio, $\mathrm{MJm^{-2}\ Day^{-1}/HDD}$ per month, equaled 8.371/1400. Therefore, Relative Effective Solar Heating values for the November through April season were determined from:

$$\text{Relative Effective Solar Heating (Nov.-Apr.)} = \frac{\text{Average Solar Energy (Average } \mathrm{MJm^{-2}\ Day^{-1}}\text{)}/8.371}{\text{Average Heating Degree Days per month}/1400}$$

$$= \frac{\text{Average Solar Energy} \times 167.2}{\text{Average HDD per month}}$$

The distribution of Relative Effective Solar Heating for the season, November through April, is displayed in Figure 3. Note that the effective heating increases almost twice as much from the northern to the southern USA for the season as it does for January alone. The northward extension of greater values of effective solar heating is again evident in the western plains and the desert southwest.

Figure 4 shows the distribution of the seasonal gain resulting from tilted instead of horizontal collectors. The gain in solar heating increases to the north, as before, ranging from a factor of 1.2 in the southern USA to about 2.0 near the Canadian border.

5. WIND SPEED DISTRIBUTION OVER THE UNITED STATES AS RELATED TO HEAT LOAD OF BUILDINGS

It is known that the heating demand of a structure or group of buildings is greater in windy conditions than it is when calm prevails. Therefore, additional solar collector area should be allowed in climatologically windy regions to provide for this additional heat load. Figures 5 and 6 show the average surface wind speeds (10 m above ground) over the USA for January and for the November through April heating season, respectively (Baldwin, 1968). Both figures show that the windiest region extends in a belt in the Great Plains from southern Oklahoma to central Montana. Other windy regions extend from the eastern Dakotas across north-central Minnesota to Lake Superior, from central Illinois to Lake Ontario and along the eastern part of New England.

The amount of heat loss due to wind is extremely variable from one structure to another, according to the literature. Variations result from insulation factors, cold air infiltration through cracks and other openings in the structures and cold air induction into ventilation systems, among others. Experiments by Murphy (1960) and Nozaki (1973) and a report by Kusuda (1975) suggest that, generally, heat loss from buildings is proportional to approximately the first power of the wind speed. However, Nozaki (1973) also found that the proportionality trended toward the one-half power of the wind speed for buildings in a cluster (college campus) particularly as the number of buildings increased. Although they give no actual heat loss numbers, Murphy and Nozaki conclude from their experiments

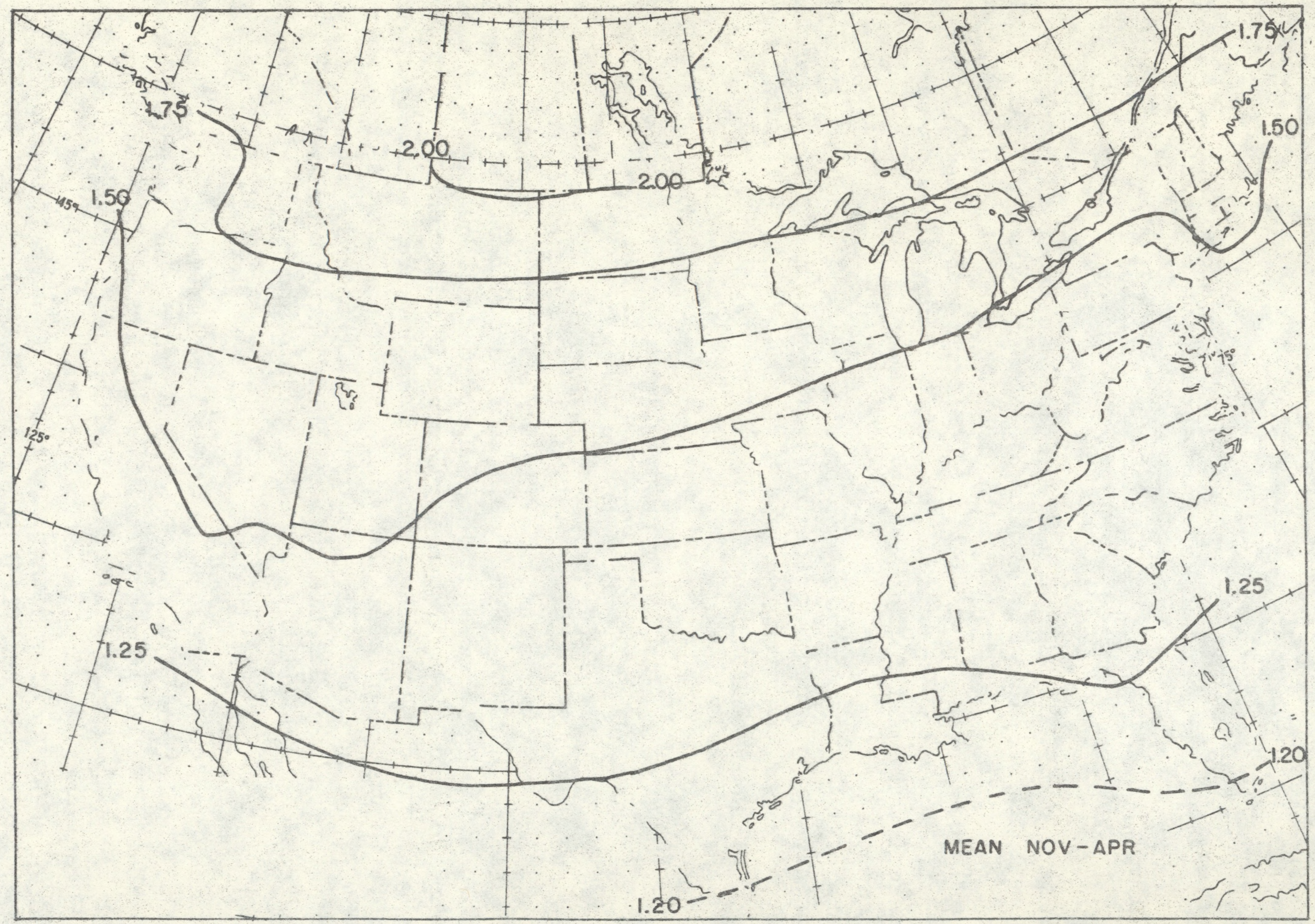

Figure 4. Same as Figure 2 except for the season November through April. See text for details.

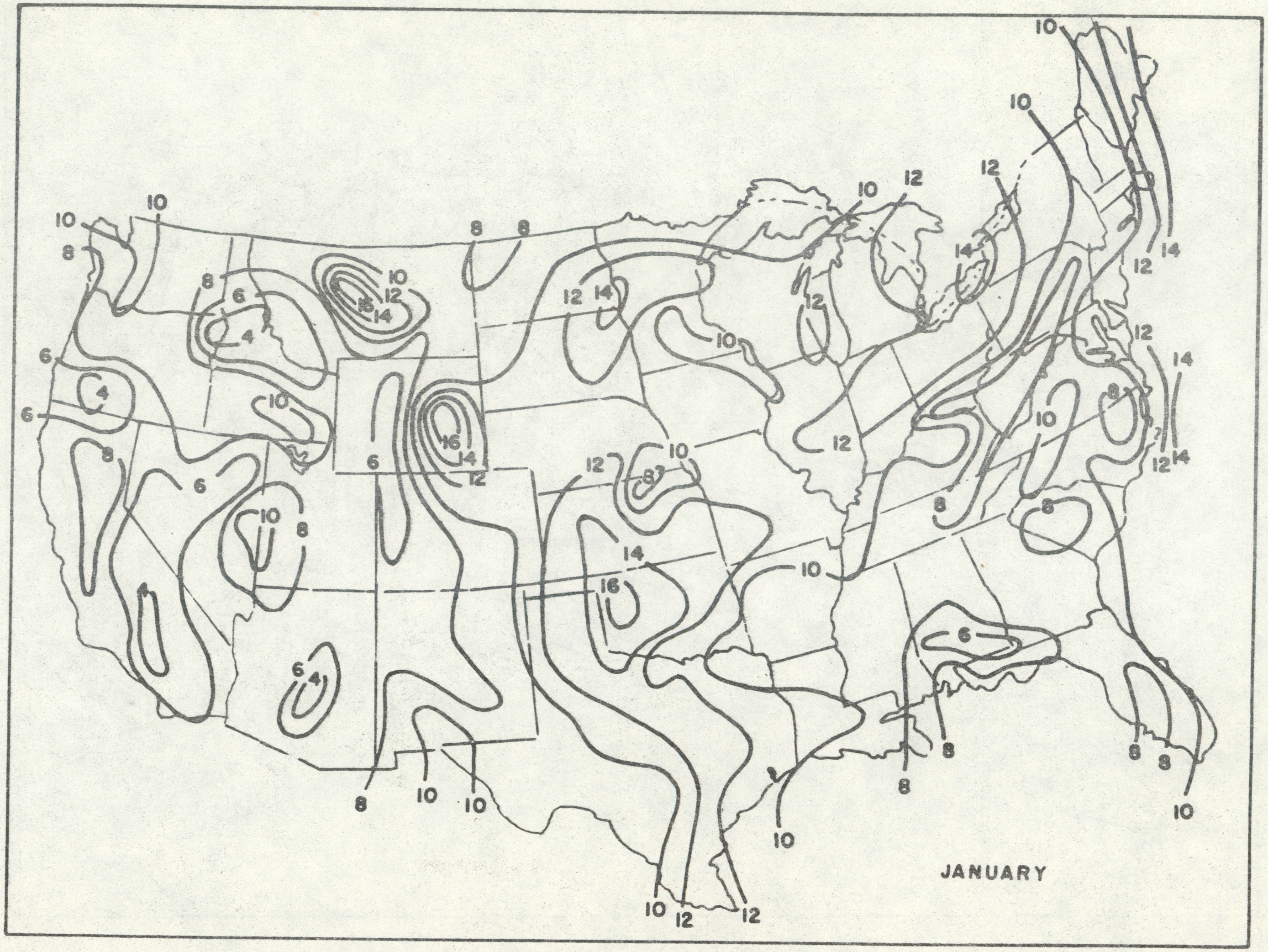

Figure 5. Average wind speed in miles per hour for January.

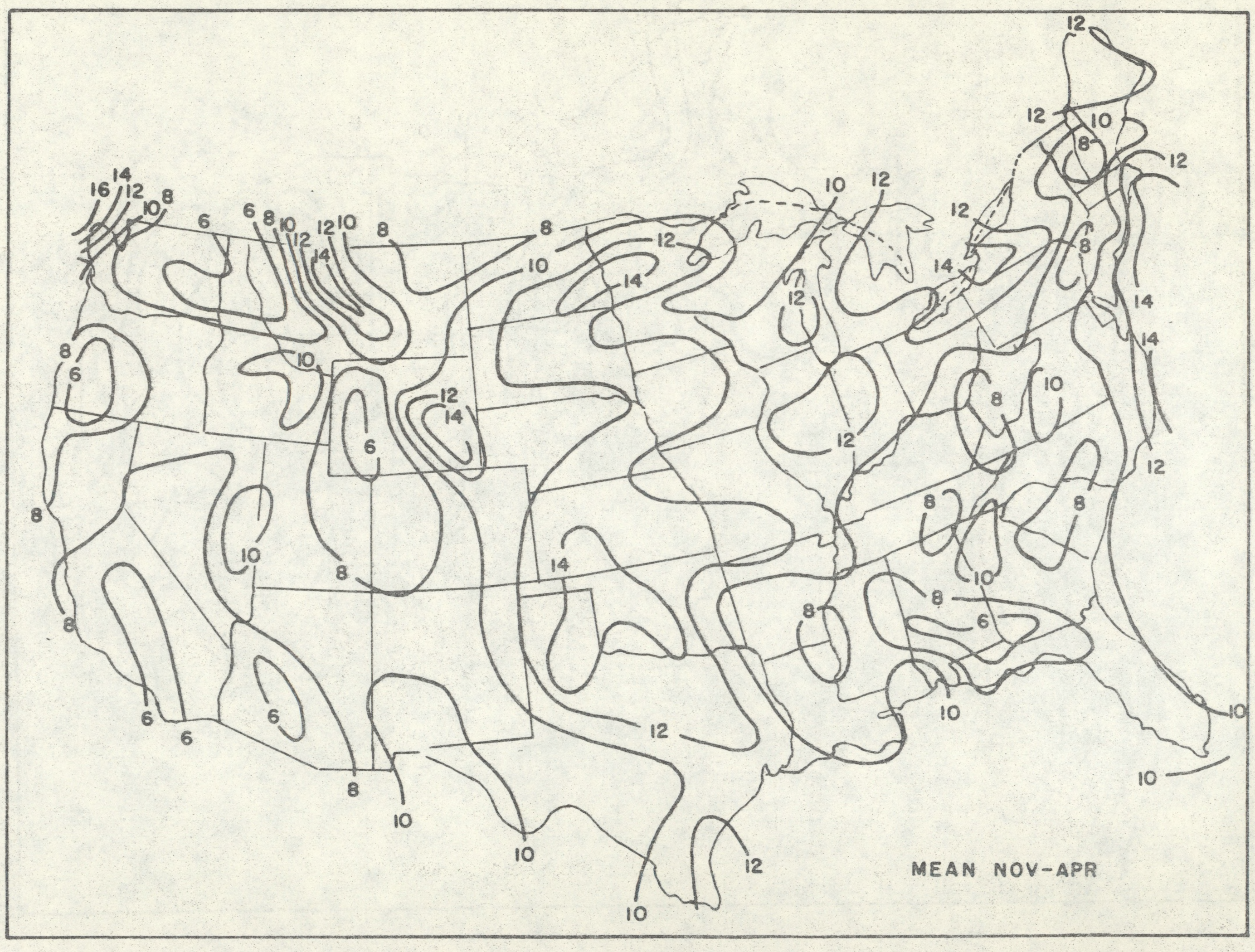

Figure 6. Average wind speed in miles per hour for the heating season November through April.

that the heat loss due to wind is a small proportion of the basic heat load resulting from colder outside temperatures. Nozaki also shows data from Hottinger (1938) on heat loss through an unspecified solid wall as functions of wind speed and wall-air temperature difference. Table 1 shows Hottinger's heat loss data in kilocalories per square meter per minute. A linear relationship exists between heat loss and temperature difference at constant wind speed, but a log-log relationship holds between heat loss and wind speed at a constant temperature difference. The heat loss in Table 1 due to wind for a constant temperature difference is approximated by the expression: Heat loss $\approx 1.7KV^{0.53}$ k cal m^{-2} min^{-1}, where K is the heat loss per square meter per minute at 0.5 m s^{-1} for a given temperature difference, and V is wind speed in meters per second.

Table 1. Heat loss from a solid wall as a function of air temperature and wind speed. No details are given on wall construction or the angle at which the wind blew toward the wall. (From Nozaki (1973) as quoted from Hottinger (1938)).

Wind Speed	Air Temperature (^{o}C)						
(ms^{-1})	-20	-15	-10	-5	0	+5	
0.5	4.1	3.3	2.4	1.6	0.7	-0.2	kcal $m^{-2}min^{-1}$ for wall temp. of $4^{o}C$.
5.0	17.0	13.4	9.9	6.4	2.8	-0.7	
20.0	32.1	25.4	18.6	12.1	5.3	-1.3	

Because of the variability among structures of additional heat load induced by wind, no adjustments were made to the maps of relative solar heating (Figures 1 and 3) for wind effects. The interested reader can use the wind speed maps as a guide for planning additional solar energy collector area in windy regions.

6. OPTIMUM ALIGNMENT OF SOLAR COLLECTORS

An optimum tilt and alignment formula for fixed solar collectors applicable to <u>any</u> locality has not yet been established. A part of the uncertainty derives from the partitioning of the total energy received between diffuse and direct radiation (Liu and Jordan, 1960). Other optimum tilt uncertanties are partly a result of local conditions. For example, an optimum tilt angle for solar heating in far northern latitudes in winter based only on the distribution of direct solar and diffuse sky radiation does not consider the reflection of solar energy from snow cover. Such consideration might indicate a larger tilt angle toward the south, where extended periods of snow cover are probable, to take advantage of the additional energy reflected from the snow. Similarly, additional tilt could apply to regions where the ground is highly reflective. Afternoon cloudiness is characteristic of some localities in the far southern USA. A southward-tilted collector in those areas would collect more solar energy over a day if it were also turned somewhat toward the east. Another arrangement suggested by Borgefors (1977), shows significant annual gains in energy collected by southward-tilted collectors (tilt equal to position latitude for this example) that are given some optimum eastward azimuth component in the morning and a similar optimum westward azimuth component in the afternoon. The annual gains, over a collector tilted directly southward at an angle equal to position latitude, range from about 15% at 20°N to 44% at 80°N. Obviously it is much less costly to provide for rotating a collector twice a day from one particular azimuth to another than to provide a continuously-rotating mechanism. Optimum collector tilt and alignment is probably best determined separately for each locality and for each purpose.

7. LONG-TERM VARIATIONS IN SOLAR RADIATION

The Effective Solar Heating analyses presented here are based on solar radiation averaged over the 24 years from 1952 through 1975. Design of solar radiation applications should, however, take into account the expected variations in available solar energy not only for periods of a few days but over periods of years where trends in climate are involved. Angell and Korshover (1975, 1978) provide an insight into probable trends of percent of possible sunshine (PPS) and therefore trends in total available solar radiation. After demonstrating a high correlation between changes in PPS at 100 sunshine-switch stations, and changes in total solar radiation at the 26 rehabilitated stations (discussed earlier) shown in Figure 1, both due primarily to sun-obscuring cloudiness, they show periods between 1950 and 1976 when the annual average PPS over any one of six geographical regions (Angell and Korshover, 1975) of the contiguous USA increased or decreased continuously for periods of two to seven years. Among these six regions (northwest, north-central, etc.) into which they arbitrarily divided the United States, not much similarity existed in either magnitude or sense in the year-to-year variations of regional average annual PPS. As an extreme example, the northeast region showed a 6% total increase in PPS (nearly three-fourths of an hour for a 12-hour day) from 1950 through 1963, a 6% total decrease from 1963 through 1973, then a 2% increase in PPS from 1973 through 1976. Hence, probable temporal variations of PPS and/or solar radiation in regional subdivisions of the contiguous United States should definitely be considered when planning applications of solar energy.

On a seasonal basis, considering the entire contiguous United States, autumn showed the greatest long-term variation in PPS with a 12% decrease from 1953 through 1972. The second greatest variation was in winter with a total 6% increase and then 6% decrease in the same period, by contrast. Finally, cyclic variations in annual average PPS of up to ±7% of the long-term mean (26 year) have occurred over periods of 8 to 22 years in one or another of the six regions. Similar variations in annual average regional solar energy undoubtedly occurred with these variations in PPS. Plans for uses of solar energy should allow for long-term variabilities in solar input of the magnitudes shown above.

8. CONCLUDING REMARKS

Some uncertainties exist in the original solar radiation data of the 64 non-rehabilitated stations used in this study due to lack of quality control, to shortness of record in many instances and to climate trends following 1960. However, by adjusting the radiation data of these 64 stations to conform with solar radiation values of the rehabilitated stations adjacent to them, the magnitudes of the above uncertainties are believed to be considerably reduced. Uncertainties from filled-in data of the 26 rehabilitated stations resulting from regression, expressed as the percent that the standard deviation is of the mean, ranges from less than 7% for monthly values to 1 to 4% for annual estimates (EDIS, 1978).

Before the recent fossil fuel "crisis," little economic value was attributed to solar energy and little use was made of the solar radiation data that were collected; hence, quality control of solar radiation sensing equipment tended to be lax. Conversely, the heating degree day data that were used in constructing Figures 1 and 3, are, and have been, intensively used by the heating and air conditioning industries, as well as others. Therefore these data have been under strict quality control and little or no uncertantity can be attributed to them.

Because of the above uncertainties in the solar radiation data used here, Figures 1 and 3 should be used with some caution in any solar energy design calculations.

ACKNOWLEDGMENTS

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