COO-4094-61
Distribution Category UC-63d

SNOW-COVERING EFFECTS ON THE POWER OUTPUT OF SOLAR PHOTOVOLTAIC ARRAYS

December 1979

Bronwyn L. Brench

Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02173

Prepared for
THE U.S. DEPARTMENT OF ENERGY
AGREEMENT NO. DE-AC02-76ET20279

ABSTRACT

In general, snow covering a photovoltaic panel causes negligible energy loss when the snow is light and melts easily; however, a more serious loss can occur when the snow is heavy and does not quickly melt or shed. In order to examine the effects of snow cover on the output energy available from photovoltaic modules, a small-scale snow-shedding experiment was conducted during the winter of 1978-79 at the Natural Bridges National Monument in Utah. This site was chosen since it was the planned location for a 100-kWp flat-plate photovoltaic power system. Daily array power output and weather measurements were recorded by a data logger, and time-lapse photographs were taken of the array. This report discusses the analysis of this data and conclusions concerning the dependence of power loss on type of snow, weather conditions, and panel angle.

TABLE OF CONTENTS

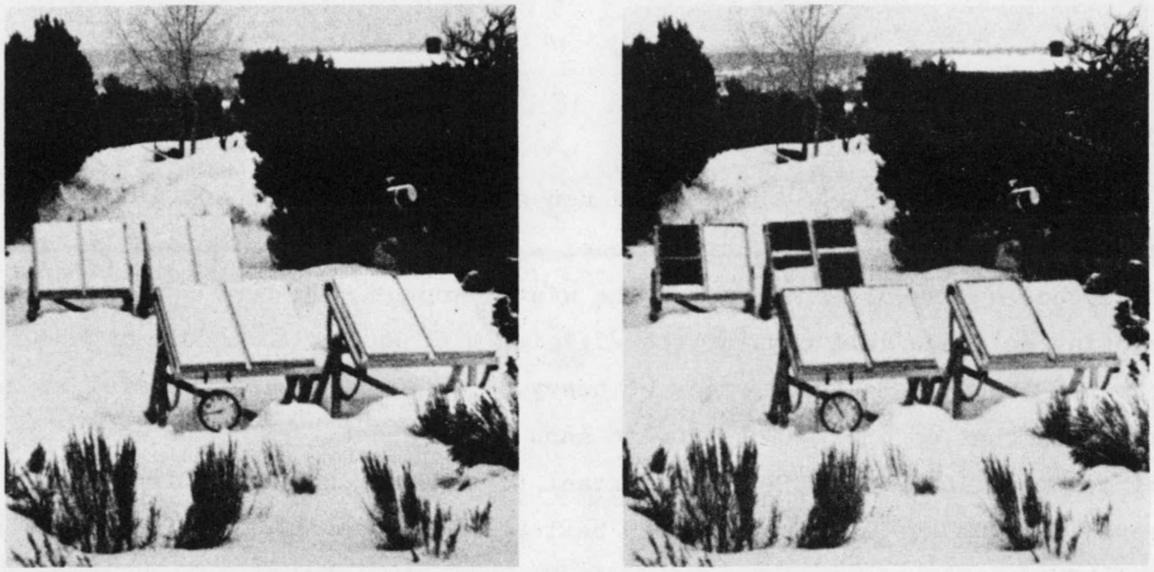
LIST OF FIGURES

1.0 INTRODUCTION

In many areas of the world where non-concentrating photovoltaic modules are now being installed, the presence of a snow covering on the modules can reduce the energy collected during the winter months. In some instances, snow shadowing only one cell can cut the efficiency of an entire module by a considerable amount. In those areas of heavy snowfall it would be useful to measure the amount of energy loss due to snow cover and to determine ways to minimize this loss. It is also important to consider the economics of snow removal weighed against creating the best possible operating efficiencies in costly PV installations.

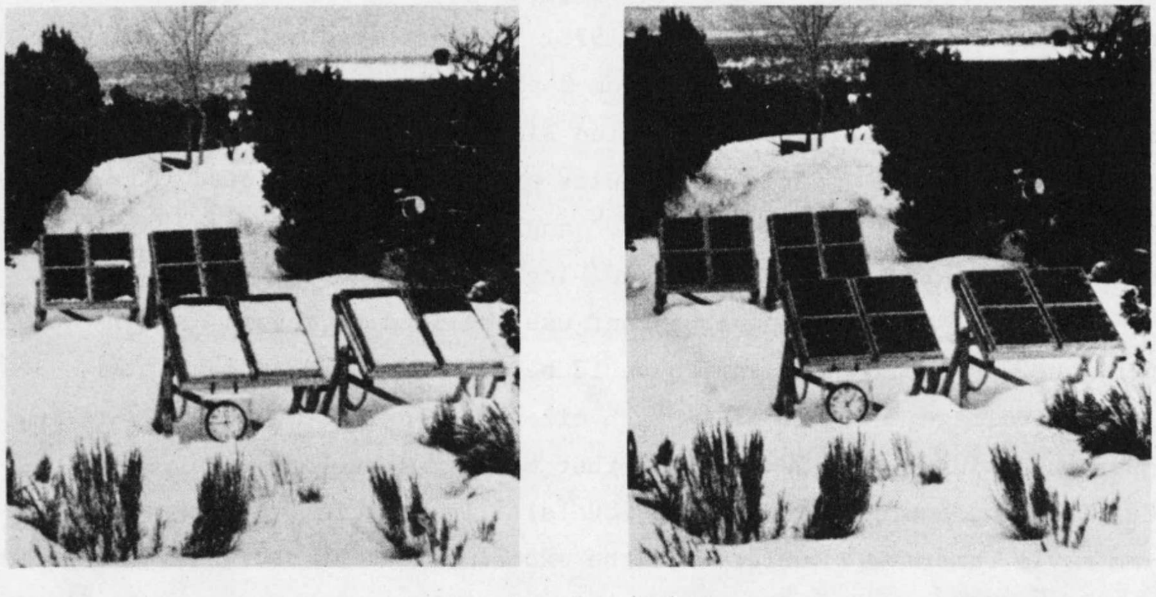
The photovoltaic system being installed at Natural Bridges National Monument was chosen to be the site of a "snow-shedding" experiment designed to explore these problems. A small-scale version of the photovoltaic array was designed and installed in December, 1978. A shunt regulator was utilized to maintain a constant output of 40V from 2 paralleled branch circuits. Each circuit consisted of 8 series-connected Block-III Motorola modules. (These modules each contain 4 parallel circuits of 12 series-connected cells.) The modules in circuit A were set at a 30° angle from the horizontal, and the modules in circuit B were set at a 40° angle.

A variety of monitoring equipment was utilized to record data on the experiment, as human intervention would be minimal. A data logger was used to record voltage and current in each circuit, module temperatures, ambient temperature, insolation level, and other weather data (dew point, wind, precipitation, and more insolation levels). In addition, a time-lapse 16-mm movie camera was included in the experiment to record snowfalls as well as snow-shedding rates. The picture rate was set at one frame every five minutes, and strobe lights were set up to allow the camera to record 24 hours a day. Figure 1 shows a series of photographs of the arrays under varying stages of snow cover; the 30° panels are those in the foreground.



08:45: ALL PANELS ARE COVERED.

11:00: 40° PANELS PARTIALLY CLEAR, 30° PANELS STILL COVERED.



11:45: 40° PANELS ARE CLEAR, 30° PANELS ARE BEGINNING TO SHED.

13:30: ALL PANELS ARE CLEAR.

SNOW-SHEDDING EXPERIMENT AT NBNM, UTAH, 1978-1979

Fig. 1. Snow-shedding sequence.

The winter of 1978-79 produced an unusual number and variety of snowstorms which contributed to a comprehensive set of results. Despite many problems, enough data were gathered to yield significant conclusions. These data were tabulated and examined for patterns which would determine what type of snowfall produced what amount of energy loss. The resulting tables are shown in Appendices A, B, C and D.

In general, it was found that energy loss is greatest when the day following the storm is cloudy or cold. On sunny days, the snow melts quickly and little energy is lost. Panel angle is an extremely important energy-loss factor; 85% of the time the 40° panels shed more quickly and had less energy loss than the 30° panels. The ideal sun-collecting angle is dependent upon the latitude of the photovoltaic arrays and, in regions of significant snowfall, a trade-off must be made to determine the best compromise panel angle.

2.0 DETAILS OF THE EXPERIMENT

2.1 Standard Cell vs. Pyranometer

In order to determine the amount of energy lost when a photovoltaic module is covered with snow, the amount of energy that would have been available if there had been no snow must be determined. At present, there are two instruments which can be used to evaluate this quantity: a standard PV cell and a pyranometer. The standard cell in order to be useful must always be clear of snow so that its power output can be measured. This can then be compared with that of the panels covered with snow. The problem is that standard cells are presently made only for laboratory use and have no sealed protective housings for field testing.

The second instrument is the pyranometer which responds to the insolation level. A relationship can be determined between the pyranometer output and the solar array power output on snow-free days which would provide the necessary basis for energy-loss meaurements. The difficulty here is in correlating temperature-difference effects and spectral effects between solar cell output and pyranometer readings. Since at the time of the experiment there were no standard cells available and two pyranometers were already in use, the pyranometer was chosen as the reference instrument from which to calculate energy losses. The pyranometer was tilted at an angle of 30°.

2.2 Array Output vs. Insolation

Figure 2 shows the relationship between the array power output and the corresponding recorded insolation. The dashed line is the actual curve used to calculate the power loss from the array on snowy days. This line was plotted through a set of points taken from five separate days (both sunny and cloudy combinations). The recordings from these five days are shown in total in Fig. 3.

The scattering of points along the insolation axis of Fig. 3 is due to early-morning and late-afternoon shadowing effects. As can be seen, these shadows caused a reduction and even an elimination of the power output, and therefore were ignored in order to obtain a practical and usable relationship

C74-840

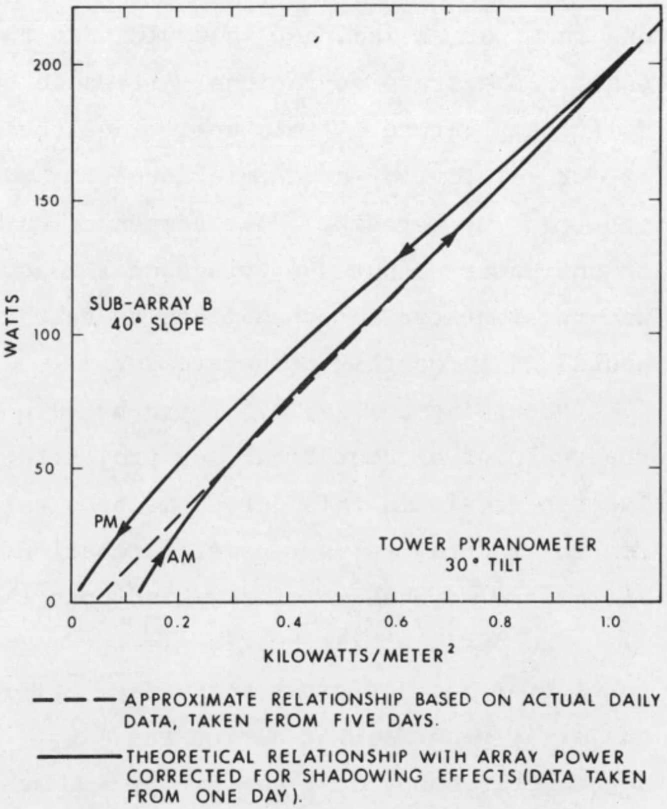
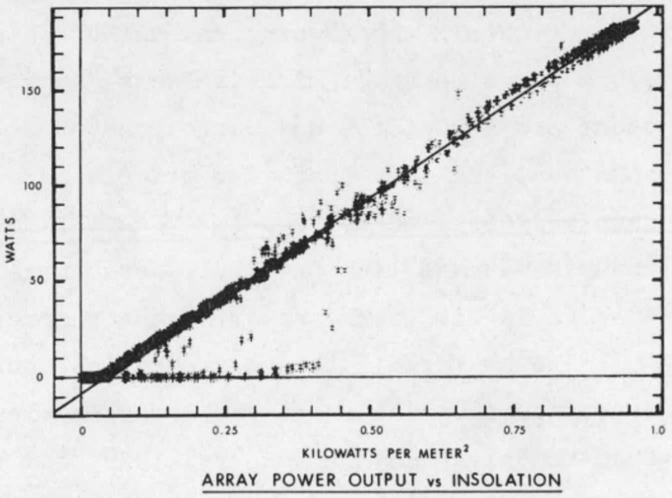


Fig. 2. Array output vs. insolation.

C74-842



Note: DATA TAKEN FROM DAYS 1-5, January 1979

Fig. 3. Array power output vs. insolation.

from the insolation level. Further deviations from the straight line could be due to minor or indirect shadowing but for the most part were due to the daily panel temperature variations. It would be possible to take into account the daily temperature effects but, since these effects were so minimal and because of our relatively large tolerances, it was considered acceptable to ignore the resultant hysteresis. Some compensation was provided, however, for the effects on the power output due to seasonal changes. The straight-line approximation was recalculated for each month to take into account the changes in daylight hours and in monthly temperatures.

Returning to Fig. 2, it can be seen that the dashed line falls within the realm of a theoretical, or projected, array power vs. insolation relationship. The hysteresis in this curve has been called theoretical since it shows what the solar array vs. pyranometer relationship would be within a given day if there were no shadows of any kind upon the photovoltaic modules.

The basis of the hysteresis curve was formulated from a set of points taken from one perfectly sunny day. Figure 4 shows the actual insolation and array power output during that day. Note that the insolation curve shows a perfectly sunny day, yet Fig. 4B shows jagged power curves which would normally imply clouds. These aberrations are the effects of shadows on the panels (with a greater number of shadows on circuit A) caused by nearby trees which are between the array and the sun throughout the day.

To obtain the theoretical set of points used in the hysteresis curve, the array power curve of circuit B was "smoothed out" and projected through to the start and end of the day corresponding to those of the pyranometer day. In this way, the tree-shadowing effects were eliminated and a theoretical relationship was obtained for the array output vs. insolation. The shadowing effects upon the dashed line in Fig. 2 were therefore successfully eliminated as the line falls within the realm of the theoretical curve.

The hysteresis in the theoretical curve would normally be due to the daily temperature variation of the array modules. This hysteresis curve was taken from the first day of January, 1979, and the average temperature difference between the modules in the morning and afternoon was -3°C to +5°C, or 8°C (the peak module temperature reached 15°C in the early afternoon with an ambient temperature of -12°C). If temperature was the reason for the hysteresis, it

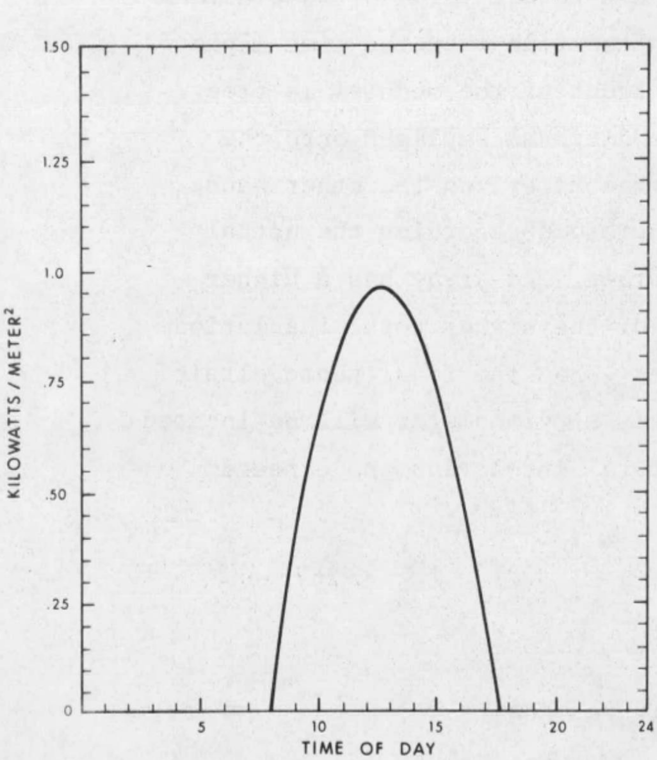


Fig. 4A. Insolation.

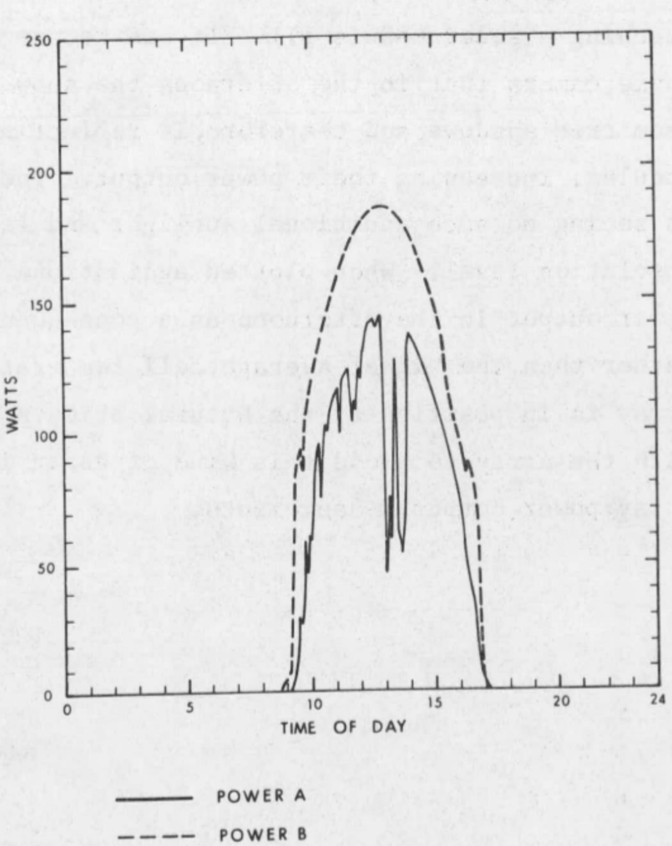


Fig. 4B. Array power circuits A & B.

appears from Fig. 2 that the solar cells operate more efficiently at higher temperatures during the relatively cold winter months. This contradicts normal thinking in regard to cell output as a function of temperature, i.e., as cell temperature rises, the power output decreases for a given insolation. A possible explanation for this anomaly is that the modules received a greater insolation relative to the pyranometer due to an added amount of snow-reflected light.

Figure 5 shows the actual location of the pyranometer with respect to the photovoltaic modules. Note that while the modules are surrounded with snow, the pyranometer is mounted approximately 20 ft. in the air on a tower. It is known that the sun reflecting off the snow can add to the value of insolation reaching a solar module (1). It can be seen in the film from the time-lapse movie camera that in the afternoon the snow in front of the modules is free from tree shadows, and therefore, is reflecting additional sunlight onto the modules, increasing their power output. The pyranometer, on the other hand, is seeing no such additional sunlight and is therefore recording the actual insolation level. When plotted against one another, the array has a higher power output in the afternoon as a consequence of the higher total insolation rather than the higher average cell temperature. When the final photovoltaic array is in position at the Natural Bridges site, a pyranometer will be located with the array to avoid this kind of error in total insolation and expected array-power-output measurements.

CP267-4622

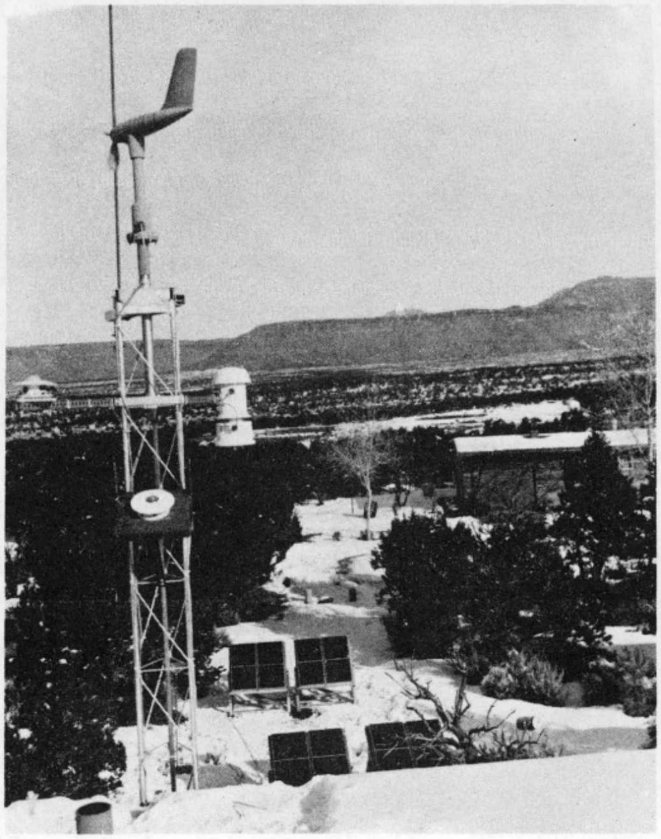


Fig. 5. Pyranometer at NBNM.

2.3 Further Comments on the Use of a Pyranometer

Once data became available for analysis, it was soon discovered that the pyranometers were frequently giving incorrect readings. This was the result of either snow or frost covering the pyranometer sensor. Out of the 30 snow days monitored, 40% were eliminated due to false readings. An additional 14% were eliminated because of faulty data logger operation or power cuts. It would be useful in the future for a heating element to be secured around the pyranometer sensor during the snowy months in order to prevent snow and frost from accumulating. Care would also have to be taken to maintain the pyranometer's internal temperature compensation.

From the remaining 46% of the data (of which there were only 14 snow days), charts were made to present the following: 1) energy loss vs. amount of snowfall, 2) insolation level during shedding, 3) time taken for the modules to clear, 4) ambient and module temperatures during shedding, 5) wind conditions, and 6) module angle. Through these charts, as given in Appendices E and F, an overall viewpoint of the complete experiment can be gained.

3.0 DISCUSSION OF RESULTS

3.1 Energy Loss

Some difficulties are presented in determining the meaning of "energy loss" due to snow covering the solar panels. One might wish to determine what percentage of the energy was lost during the whole winter or how much was lost on a daily basis for a given storm, or even how often the back-up power source had to be utilized because of snow accumulation.

To determine the total energy loss during the winter months (or the whole year), a study of the average annual snowfall would have to be made and compared with the specific year under experimentation in order to get any usable results. For this particular experiment, the total amount of snowfall far exceeded the average annual snowfall for the area, which would result in a higher average annual energy loss due to snow accumulation. Therefore, this study was concentrated on the energy lost on a daily basis for the individual snowstorms.

Another question that might be asked is how much more often the back-up power source would have to be operated due to the snow covering the panels. "Energy loss" could then be defined as the amount of diesel fuel needed to compensate for the temporary hold on the operation of shadowed solar cells. To answer this, a more detailed study would have to be made of the operation of the stand-by diesel generator and its probable operating time during and after each snowstorm, a procedure beyond the scope of this experiment.

It was finally considered most useful to view the raw data from each of the snowstorms and to determine how much energy was lost over the whole day following (or during) the storm (and not just the part of the day when snow covered the panels). With this method, the various types of snowfalls and weather conditions during shedding could be analyzed individually and the percentages of energy losses occurring throughout each day could be found and tabulated.

3.2 Panel Angle

The most significant factor affecting energy loss from the arrays was the panel angle, since it had the greatest effect upon the time it took the panels to clear. For the 40° slope, an average of 26% of a day's total energy was lost due to snowfalls of over 1.0 inches, while 45% was lost from the 30° panel slope. Snowfalls of 1.0 inches and under resulted in an average of a 5% energy loss from the 40° slope, and an 11% loss from the 30° slope. These figures can be found in the summary table of Fig. 6 where further comparisons are made for cloudy and sunny conditions following the snowstorm. (Fig. 6 was derived from Appendices E and F.)

PANEL ANGLE:	30°		40°	
SNOWFALL:	OVER 1"	UNDER 1"	OVER 1"	UNDER 1"
AVERAGE ENERGY LOSS/SNOWFALL:	45%	11%	26%	5%
CLOUDY WEATHER, AVERAGE ENERGY LOSS/SNOWFALL:	56%	14%	33%	4%
SUNNY WEATHER, AVERAGE ENERGY LOSS/SNOWFALL:	27%	10%	15%	5%

Fig. 6. Energy loss summary.

3.3 Insolation

For any given cloudy day following a snowstorm, it was calculated that 56% of the day's total possible energy was lost by the panels at the 30° slope, while 33% was lost from those at the 40° slope (considering the heavier snowfalls). On a sunny day following a storm, these figures were roughly halved. (A sunny winter day was considered to be one which accumulated over 2.5 kWh/m^2 of integrated solar radiation from sunrise to sunset.) The higher daily percentage loss of energy of a snow-covered module on a cloudy day is due to

a) the longer period of time that the snow remains upon the modules on the cloudy day and b) the relatively small amount of insolation that is eventually received after the snow has shed from the panels on that cloudy day. However, because the actual amount of energy produced by the array during a cloudy day is small compared to that produced during a sunny day, the effect of the 56% daily energy loss is small when considering what would have been available on a sunny day.

For example, from 0 to 400 Wh might be available from the 30° experimental array on a cloudy day, but only from 0 to 175 Wh would be realized due to the 56% loss (with a heavy snowfall). For a sunny day, from 500 to 1300 Wh might be available, but only from 365 to 950 Wh would be realized due to the 27% loss. It can be seen from this example that the energy available on a cloudy day is similar to that available on a sunny day with snow on the modules (400 Wh $\approx$ 365 Wh). It can be concluded, therefore, that the effective energy loss due to a cloudy day is nearly equivalent to the loss resulting from a snow covering on a sunny day. Since the back-up power source would probably be operating under these conditions, it can be seen that the energy loss due to snow cover on a day with a low insolation level will have a small effect on the overall state of the photovoltaic system as compared to the effect of a snow cover on a day with a high insolation level.

3.4 Snow Density

Snow density is a factor that should be considered if comparisons are to be made with other sites. Whereas the snow at the Utah location (freshly fallen snow) is approximately 0.05 to 0.10 g/cc, in New England the snow can be as dense as 0.40 to 0.60 g/cc (2) and even higher if any rain has mixed with the snow. In general, the denser the snow, the more sunlight will get through due to the large crystalline structure of the snow. The less dense the snow, the greater is the occurrence of light scattering and consequent absorption within the snow layer (3).

In fact, the amount of sunlight which penetrates a layer of snow is not necessarily a direct effect of the density of the snow nor does it necessarily have a direct effect upon the power output of the photovoltaic modules since the solar cells absorb only a certain portion of the light spectrum. The difficulty lies in the fact that as the snow melts, its water content increases and causes a non-uniform snow density. The water-snow interface causes a greater degree of light scattering. The photovoltaic cells add to the problem by generating heat as they absorb the solar radiation that does reach them. This heat increases the amount of melted snow on the module surface.

A good example of this non-uniform snow density can be seen in Fig. 7, illustrating an experiment made on two Motorola Block-III modules in the Lincoln Laboratory Rooftop Array. The snow that had accumulated during the night had mixed with rain which resulted in a layer of ice and snow on the module surface by morning, as seen in the figure. This layer varied in depth from 0.32 to 1.9 cm, had a density of 0.59 g/cc, and reduced the (instantaneous) power output of the modules by 70%! This higher-than-expected loss was probably due to the non-uniform nature of the snow cover.

CP267-4579

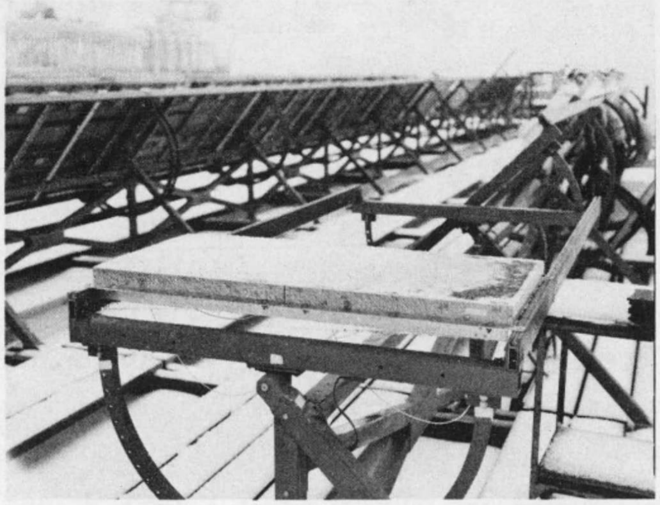


Fig. 7. Snow and ice combination.

3.5 Other Factors

The remaining factors affecting array energy loss, tabled in the comparison charts shown in the Appendices, have been significant at other sites but were found to be less important at the Natural Bridges site. For example, the average wind speed was measured at 7 mph, and gusting was not common; therefore, snow rarely was blown from the panels as had occurred in the Mead, Nebraska, agricultural site (4).

Temperature was a factor, but for the year considered the cell temperatures during the period of snow shedding were between 0° and 7°C, while the ambient temperatures were between -12° and +2°C. Because the cell temperatures were so low and within a range similar to that of the ambient temperature, the need for a correction factor was greatly reduced. The different reactions of the array power output and the pyranometer readings to temperature would be almost negligible since the major effects occur at high cell temperatures vs. ambient temperatures. Some energy losses due to temperature effects were experienced later in the winter, ranging from a 2% daily loss in January to a 10% loss in April. These losses, however, were not included in the losses due to snow covering.

The losses due to tree or building shadows on the panels created some problems. However, as mentioned in Section 2.2, these losses were compensated for where possible from the snow data and were not included in the Fig. 2 relationship. The daily loss caused by these shadows was from 6% to 22%, depending upon which month and which of the angled panels were being examined.

The final point considered was the time of day that snow shedding occurred. It was found that shedding at the Natural Bridges site was for the most part a function of the time of the actual snowfall and the day's insolation level. Most of the storms occurred during the night and snow was shed between 9 and 11 a.m., leaving the greater part of the day for the modules to receive sunlight. A storm occurring during the day caused a relatively low insolation level throughout the day (little power available due to the clouds), therefore, shedding would also occur during the low insolation level and even less power would be produced due to the longer shedding period.

The longer shedding period is basically due to the lack of sunlight and heat to melt the snow. If the ambient temperature is above freezing, the snow tends to melt rather than shed off the panels. If the temperature is below freezing, as it is most of the winter, the physics of shedding relies heavily upon the sunlight filtering through the snow layer on the panels. When the light reaches the modules, and is absorbed by the solar cells, the module begins to heat up. As the panel temperature rises above freezing, the snow on the surface of the panels melts and, with the weight of the remaining snow layer, the snow begins to slide off. It can be understood easily that the less sunlight (insolation level) there is, the longer it will take for the modules to heat up and the snow to shed. Hence it can be seen that the daily insolation level holds the key at the Natural Bridges site to the possible power available from the array.

Another factor which has not yet been considered is the effect of partly cloudy conditions at high elevations. It has been found that when the sun shines through gaps in the clouds there is an added amount of solar insolation due to cloud reflection. Measurements were made at an elevation of 6365 ft. (1940 m) at Obergurgl, Austria, of instantaneous values of as much as 1.566 kW/m^2, which is 112% of the solar constant (4). It should be noted here that the Natural Bridges site in Utah is at an elevation of 6500 ft. (1981 m). We are faced with the same problem found when the solar radiation was reflected off the snow: What part of the reflected light spectrum is absorbed by the solar cells? Is the whole spectrum reflected so that the cells absorb an equivalent percentage of the reflected light, or does scattering occur? Differences in slope exposure are also significant at high elevations. The higher the elevation, the greater are the extremes of radiation conditions. Although measurements have not been made to discover how photovoltaic modules are affected under these more unusual conditions (and hence were not considered in this report), much can be learned by those studies of solar radiation which would enhance the present solar cell technology.

4.0 CONCLUSIONS AND FURTHER WORK

During the winter when snow shedding was investigated at the Utah site, 30 snowfalls were noted and recorded. Although not all of them contributed towards energy loss data due to the problems discussed, significant conclusions were made concerning the effects of snow and weather conditions on module output. It was discovered that, in general, snowfalls under one inch produced a relatively insignificant amount of energy loss, whether it was cloudy or sunny on the day following the snowfall. The biggest factor contributing to loss at the Natural Bridges site was the many cloudy days following heavy snowstorms. An average of 56% of a day's potentially available energy (if no snow had covered the panels, <u>and</u> taking into account the low insolation level due to the cloudy day) was lost from the 30° angled panels; 33% was lost from the 40° angled panels. Low insolation is, of course, bad for any photovoltaic site but, if the day following the storm is only partly cloudy, the panels will still take a longer time to shed thus reducing the available time for the modules to absorb the higher insolation during those periods when the sun appears from behind the clouds.

The second point to be noted is that snow conditions at the Utah site are not severe and that little if any human effort need be expended to keep the panels clear of snow. Summing up the total losses from the winter snow coverings (30 days), 31.8% of the energy was lost from the 30° angled panels and only 17.8% was lost from the 40° angled panels. Even though the 40° panels suffered less loss, the shallower angles are better year-round for catching the sun at that latitude. Considering the time and money involved in changing the panel angles twice a year, relative to the difference in the total energy losses (which occur for an equivalent of only one month out of the year), the decision was made to use the 30° angle.

It should be noted that the figures in this report refer to the site at Natural Bridges National Monument only and that tests made in other localities will vary as much as weather conditions vary throughout the country. For example, it has been observed that snow-shedding characteristics at the Mead, Nebraska site depend greatly upon the wind conditions and that snow drifts tend to build up to and across the panels rather than to shed (4). In New England, the snow tends to be denser due to higher humidity and accumulations are more frequent and heavier.

If a study characterizing the snow shedding at any general locality is desired, controlled tests would have to be made to compare the effects of snow coverings for a range of snow densities, depths, insolation levels, wind factors, and panel angles. Studies of solar radiation and how it is affected during its reflection off snow, clouds, glass, and other surfaces, and hence, its effect upon photovoltaic cells, would also add to a detailed report on the environmental conditions affecting array power output. Then, with an analysis of the typical snow and weather conditions at a given location, an estimate could be made of the total amount of array energy loss to be expected under given conditions.

REFERENCES

1. Hopkinson, R. F., "Photovoltaic Power for Grain Drying," MIT LL COO-4094-67, December 1979.
2. Forman, S. E., Themelis, M. P., "Quarterly Report; Solar Photovoltaic Project; Materials, Processes and Testing Activities for the Period 1 January to 31 March 1979," MIT LL COO-4094-55, 30 June 1979.
3. Geiger, Rudolf, The Climate Near the Ground, Harvard University Press, Cambridge, MA, 1965, Chapters 24 and 46.
4. Private Communications with S. E. Forman and R. F. Hopkinson.

APPENDIX A

TABLE OF SINGLE SNOWFALLS: COMPARISON BETWEEN PANEL ANGLES

Day	Amount of Snow (inches)	Integrated 30° Insolation (Day total kWh/m^2)	30° Panels		40° Panels	
			Time to Clear to 5% Snow Covering (min.)	Energy Loss	Time to Clear to 5% Snow Covering (min.)	Energy Loss
12/17/78	4.3	0.6+	∞	(1)	165	(1)
12/19	1.2	3.5	140	31.7 ± 2.4%	90	12.7 ± 1.3%
1/6/79	3.1	0.5+	∞	(2)	60	(2)
1/7	0.7	7.3+	140	(2)	55	(2)
1 /10	trace	4.0	55	13.6 ± 1.3%	25	6.8 ± 0.9%
1 /13	0.5	9.0+	140	(2)	45	(2)
1/15	1.2	1.5	115	20.5 ± 3.6%	110	40.5 ± 0.5%
1/16	6.3	0.9+	200+	(2)	185	(2)
1/19	6.6	2.8+	115	(2)	115	(2)
1/25	1.5	1.2	150	65.4 ± 7.7%	60	35.3 ± 5.4%
1/26	5.9	0.7+	∞	(2)	70	(2)
1/27	trace	8.1+	120+	(2)	35	(2)
2/1	5.3	1.5+	340+	(2)	55	(2)
2/2	1.0	2.3	60	14.5 ± 1.5%	50	3.3 ± 0.8%
2/20	4.2	2.5+	50	(2)	50	(2)
2 /22	2.0	4.5	100	22.6 ± 1.0%	40	12.9 ± 1.4%
2 /24	1.0	7.2	60	9.8 ± 0.6%	40	11.9 ± 1.2%
2 /27	5.3	(1)	150	(1)	50	(1)
3/ 2	1.2	2.3+	190	(2)	20	(2)
3/14	0.5	3.1	185	20.1 ± 4.1%	65	3.3 ± 0.6%
3/20	trace	2.6	70	3.9 ± 1.2%	60	4.6 ± 1.0%
3/21	trace	3.2	95	4.1± 1.0%	75	1.3 ± 0.4%
3/29	2.5	0.5+	140	(2)	35	(2)
3/31	2.2	(1)	230	(1)	110	(1)
4/10	4.5	3.5	270	(2)	40	(2)

(1) No data due to faulty data logger operation.

(2) No data due to snow on the pyranometer.

APPENDIX B

TABLE OF PROLONGED* SNOWFALLS: COMPARISON BETWEEN PANEL ANGLES

			30° Panels		40° Panels	
Day	Amount of Snow (inches)	Integrated 30° Insol. (day total kWh/m^2)	Time to Clear to 5% Snow Covering	Energy Loss	Time to Clear to 5% Snow Covering	Energy Loss
1/12/79	4.3	(1)	snow all day	(1)	snow all day	(1)
1/17	4.2	0.7	2 sheddings(2)	59.1 ± 15.7%	2 sheddings(3)	13.0 ± 4.4%
1/29	1.2	3.2	3 sheddings	26.4 ± 3.8%	3 sheddings	18.3 ± 3.2%
2/21	5.3	1.5	2 sheddings	97.0 ± 11.2%	2 sheddings(4)	48.6 ± 6.6%
2/23	3.1	2.4	3+ sheddings	39.0 ± 0.6%	3+ sheddings	28.4 ± 3.9%

(1) No data due to faulty datalogger operation.

(2) First shedding cleared in 360 minutes.

(3) First shedding cleared in 160 minutes.

(4) First shedding cleared in 165 minutes.

* A "prolonged" snowfall in this case represents periodic or continuous snowfalls throughout the day when either partial or complete snow sheddings from the panels occurred. In the case of a complete shedding (i.e., before the next snowfall covered the panels), data was taken as if only one distinct snowfall occurred.

APPENDIX C

TABLE OF SINGLE SNOWFALLS: GENERAL COMPARISONS DURING SHEDDING

Day	Clearing Period to 40% Snow Covering (Hrs.)	Average Panel Temp. (°C)	Average Ambient Temp. (°C)	Average Wind Speed (mph)	Average Insolation (kW/m^2)
12/17/78	1320 - 1545	(1)	0	12	0.06+
12/19	0940 - 1130	2	-1	9	0.44
1/6/79	1125 - 1230	2	-2	4	0.08+
1/7	0915 - 1110	5	-7	3	0.32+
1/10	0935 - 1020	2	2	0	0.56
1/13	0900 - 1030	0	(1)	9	(1)
1/15	1920 - 1045	4	-1	9	0.23
1/16	0800 - 1045	3	0	4	0.02+
1/19	0955 - 1110	2	-3	0	0.03+
1/25	1040 - 1245	3	-5	2	0.23
1/26	1005 - 1300	1	-7	7	0.06+
1/27	0830 - 1130	2	-10	1	0.15+
2/1	0920 - 1255	6	-4	8	0.18+
2/2	1030 - 1120	4	-5	(1)	0.14
2/20	0945 - 1035	6	-3	3	0.10+
2/22	0955 - 1045	7	-2	14	0.90
2/24	0920 - 1015	16	-2	8	0.79
2/27	0930 - 1100	(1)	(1)	(1)	(1)
3/2	0855 - 1045	3	-1	2	0.07+
3/14	1545 - 1730	2	2	2	0.16
3/20	0800 - 0845	2	0	9	0.11+
3/21	0855 - 1000	1	0	(1)	0.14
3/29	0910 - 1120	4	-1	10	0.03+
3/31	0855 - 1120	(1)	(1)	(1)	(1)
4/10	0810 - 1045	7	-2	12	0.20+

(1) No data due to faulty datalogger operation.

APPENDIX D

TABLE OF PROLONGED* SNOWFALLS:

GENERAL COMPARISONS DURING SHEDDING

Day	Average Clearing Period to 40% Snow Covering (Hours)	Average Panel Temp.	Average Ambient Temp.	Average Wind Speed (mph)	Average Insolation (kW/m^2)
1/12/79	0600 - 1800	0°C	0°C	2	(1)
1/17	0830 - 1300 (2)	1°	0°	19	0.08
1/29	0800 - 1215 (3)	-4°	-12°	6	0.18
2/21	0955 - 1800 (4)	2°	-1°	12	0.19
2/23	1000 - 1100 (5)	7°	-2°	13	0.37

(1) No data due to faulty datalogger operation.

(2) Average clearing time of first shedding.

(3) Average clearing time of the combined first two sheddings.

(4) Average clearing time of the combined two sheddings.

(5) Average clearing time of first shedding.

* A "prolonged" snowfall in this case represents periodic or continuous snowfalls throughout the day when either partial or complete snow sheddings from the panels occurred. In the case of a complete shedding, (i.e., before the next snowfall covered the panels), data was taken as if only one distinct snowfall occurred.

APPENDIX E

EXAMINATION OF THE ENERGY LOSSES FROM THE 30° PANELS

Energy Loss 30° Panels	Day	Snowfall (inches)	Time to Clear (min)		Daily Total Insolation (kWh/m^2)	Energy Loss 40° Panels
			30° Panels	40° Panels		
97.0 ± 11.2%	2/21/79	5.3	235+(1)	165(1)	1.5	48.6%
65.4 ± 7.7%	1/25	1.5	150	60	1.2	35.3%
59.1 ± 15.7%	1/17	4.2	360	160	0.7	13.0%
39.0 ± 0.6%	2/23	3.1	(2)	(2)	2.4	28.4%
31.7 ± 2.4%	12/19/78	1.2	140	90	3.5	12.7%
26.4 ± 3.8%	1/29/79	1.2	(3)	(3)	3.2	18.3%
22.6 ± 1.0%	2/22	2.0	100	40	4.5	12.9%
20.5 ± 3.6%	1/15	1.2	115	110	1.5	40.5%
20.1 ± 4.1%	3/14	0.5	185	65	3.1	3.3%
14.5 ± 1.5%	2/2	1.0	60	50	2.3	3.3%
13.6 ± 1.3%	1/10	trace	55	25	4.0	6.8%
9.8 ± 0.6%	2/24	1.0	60	40	7.2	11.9%
4.1 ± 1.0%	3/21	trace	95	75	3.2	1.3%
3.9 ± 1.2%	3/20	trace	70	60	2.6+	4.6%

(1) Time of first shedding.

(2) 3+ sheddings occurred throughout the day.

(3) 3 sheddings occurred throughout the day.

NOTE: The dashed line separates the snowfalls into two distinct categories, those over an inch in depth and those under an inch in depth.

APPENDIX F

EXAMINATION OF THE ENERGY LOSSES FROM THE 40° PANELS

Energy Loss 40° Panels	Day	Snowfall (inches)	Time to Clear(min)		Daily Total Insol (kWh/m^2)	Energy Loss 30° Panels
			30° Panels	40° Panels		
48.6 ± 6.6%	2/21/79	5.3	165(1)	235+(1)	1.5	97.0%
40.5 ± 0.5%	1/15	1.2	110	115	1.5	20.5%
35.3 ± 5.4%	1/25	1.5	60	150	1.2	65.4%
28.4 ± 3.9%	2/23	3.1	(2)	(2)	2.4	39.0%
18.3 ± 3.2%	1/29	1.2	(3)	(3)	3.2	26.4%
13.0 ± 4.4%	1/17	4.2	160	360	0.7	59.1%
12.9 ± 1.4%	2/22	2.0	40	100	4.5	22.6%
12.7 ± 1.3%	12/19/78	1.2	90	140	3.5	31.7%
11.9 ± 1.2%	2/24/79	1.0	40	60	7.2	9.8%
6.8 ± 0.9%	1/10	trace	25	55	4.0	13.6%
4.6 ± 1.0%	3/20	trace	60	70	2.6+	3.9%
3.3 ± 0.8%	2/2	1.0	50	60	2.3	14.5%
3.3 ± 0.6%	3/14	0.5	65	185	3.1	20.1%
1.3 ± 0.4%	3/21	trace	75	95	3.2	4.1%

(1) Time of first shedding.

(2) 3+ sheddings occurred.

(3) 3 sheddings occurred.

NOTE: The dashed line separates the snowfalls into two distinct categories, those over an inch in depth and those under an inch in depth.