MEASURING AND MODELING THE EFFECT OF SNOW ON PHOTOVOLTAIC SYSTEM PERFORMANCE

Loren Powers, Jeff Newmiller and Tim Townsend
BEW Engineering, San Ramon, CA, U.S.A.

ABSTRACT

Today's demanding project financing climate requires developers to hone annual photovoltaic (PV) energy estimates with unprecedented accuracy -- and to back the estimates with meaningful long-term performance guarantees. With some snowy locales in the U.S. and southern Canada becoming increasingly popular for MW-scale PV systems, lenders are now requiring that snow losses be estimated as part of their energy simulations. The literature is exceptionally thin on this subject - we have been unable to find even a single side by side study that directly quantifies the difference between an always-clean array versus an identical one left to naturally accumulate and shed snow [1],[2].

This paper describes the design and reports results for a side by side PV test bed installed in California near Lake Tahoe in December 2009. It has been designed to gauge the energy loss due to snow for three common tilt angles. Results from the first winter are presented, with insights for future model development and ongoing measurements.

BACKGROUND

Historically, PV modules installed in snowy climates have been part of small, off-grid arrays mounted at very steep tilt angles. This is done both to shed snow quickly and to maximize winter output. Unfortunately, this concedes too much annual energy to be a good design strategy for larger contemporary systems. Today's snowy climate PV systems tend to be installed at angles shallow enough to make them prone to snow loss.

Both weather and array design factors influence the amount of snow loss. Weather factors include the quantity and quality (moisture content) of the snow, the recurrence pattern of storms, and the post-storm pattern of temperature, irradiation, wind speed, wind direction, and relative humidity. Array design factors essentially boil down to orientation (fixed or tracking, tilt, azimuth, and tracker rotation limits) and the surrounding geometry, that is, open rack or building integrated. Building features can either help (e.g., melt) or hinder (e.g. dam up or drift) natural snow shedding.

Figure 1 illustrates how roof tilt and features can influence whether a series of snowfalls will shed or accumulate. This roof is in Truckee, CA, with the photo taken three days after a December snowfall. The steeper pitch of 35-40° is clear, while the shallower 18-23° section has retained several separate layers of snow and has effectively become a shallower "winterized" slope with each successive event. On the left side, the extra drifted snow from the valley and higher roof segment illustrates what could happen if a PV array were present.

Figure 1. Influence of tilt angle on snow retention

The National Renewable Energy Laboratory's (NREL) 30-year TMY-2[3] database is widely used by solar researchers, and for many sites, includes two snow-related data columns. Unlike the *hourly* data it lists for solar and weather variables, *daily* data are listed for:

1. Snow depth (cm)
2. Number of days since last snowfall

Lacking field measurements of snow loss, BEW developed an analytical model in 2008 to make use of NREL's data. The estimates we have prepared have fallen in the 2-5% annual loss range. These results are not huge, but are not negligible. Our experience includes a mix of ground-mounted tracking arrays that are subject to heavy snows but which shed them rapidly by virtue of the tracking mechanism, along with others in less snowy areas that may experience comparable percentage losses because they are oriented at shallow fixed tilts. Our coarse snow loss estimates contrast sharply with anecdotal reports of larger snow losses for some fixed tilt arrays. For example, NREL's PVWATTS program advises that 70% winter month reductions were noted in Minnesota for a fixed 23° tilt array and 40% losses were noted even for a 40° tilt array[4].

One compensating aspect of snowy climates is they do tend to have minimal soiling losses in the summer months due to regular year-round precipitation. In the southwest U.S., summertime dust losses can reach 20%, causing annual energy losses of 5% or more in the absence of manual washing. For snowy climates, operators are faced with parallel questions:

what is the value and cost of manual snow removal? While the cost of snow removal is outside the scope of this paper, the value of snow removal is a key objective of our ongoing work.

HYPOTHESIS

The state of the art in predicting annual energy losses can be improved by applying results from a side by side PV module test bed to generalized simulations. It should be possible to estimate the *annual* energy impact of snow to within ±1%. This will require carefully controlled field measurements, with the understanding that the permissible uncertainty for predicting *monthly* snow losses may still be more than an order of magnitude higher than the desired annual uncertainty. The reason this comparatively large error is tolerable is because the sensitivity of annual energy forecasts to a single winter month's production is low – often, less than 5% of annual production occurs in a winter month for a low-slope array. Therefore, relatively large errors in estimating snow losses will not necessarily spoil the accuracy sought in annual revenue forecasts.

Monthly and annual snowfall varies widely from year to year, even in consistently snowy locations. This large natural variability makes precise determinations for a specific year unnecessary and probably misleading. BEW feels an appropriately realistic goal in developing snow loss estimates is to produce monthly snow loss reference tables with as much as a ±20% uncertainty for a given climate, as that level of monthly uncertainty still translates to a much smaller annual uncertainty of about ±1% after seasonal radiation weighting is accounted for.

SITE AND TEST BED CONSIDERATIONS

Our goal with the first of what we hope to be a network of snow test beds has been to measure the most significant variables that can be readily correlated with reduced PV output. Candidate variables in approximately decreasing level of significance include:

1. Snowfall/snow depth
2. Structure orientation (fixed or tracking with tilt, azimuth, and rotation angles as applicable, and open-rack or building integrated mounting)
3. Visual record of snow buildup
4. Air and module temperatures
5. Plane of array irradiation
6. Wind speed and direction
7. Snow moisture content
8. Relative humidity

It was felt the first five items in the list could be addressed within our first-time private budget and our ability to make good use of the data; we did not feel ready to commit the funds to perform a comprehensive test covering a multitude of tracking, building integrated, and off-azimuth systems, nor to collect a wealth of micro-climate specific data such as wind, snow moisture, or humidity.

Instead, we found a host operator in Truckee, CA (near Lake Tahoe) who was willing to both place the 12'x35' test bed on a flat, unobstructed parcel and to keep one set of modules and irradiance sensors clean. The Truckee test bed's results will be used to calibrate (or refine) the analytical model and to develop simpler empirical models, if feasible.

A custom Campbell-based datalogger and camera with a cell modem and web display interface was designed and fabricated. The data acquisition system (DAS) is equipped with six sensors to record short-circuit currents (as a proxy for power) for three pairs of cleaned and snowy PV modules, as well as several temperature and irradiance sensors. The three tilt angles include 0° (flat, as a worst-case), 24° (latitude minus 15°), and 39° (latitude). While one steeper pair at 54° (latitude plus 15°) was also considered, we reasoned it would be unnecessary to simply find that, as we neared the 55° critical angle for point release avalanches[5], the amount of lost energy would be negligibly small. Plus, there are virtually no commercial arrays placed at such steep tilt angles and comparatively little value to obtain such data.

Truckee, California, is a high-altitude (≈6,000'/1,800 m) location with an average of 200 in./500 cm. of snow per year. However, a 50^+ year database[6] shows the standard deviation is ±37%, with extremes ranging from 50-200% of normal. Monthly data vary even more than the annual totals. January, the snowiest month, accounts for one-fourth of the annual total. However, January's 48 in. average also exhibits a standard deviation twice as large as the annual deviation (±73%) and has exhibited a range of near zero to over 300% of normal. Given this high degree of variability, simple monthly snow loss estimates to the nearest whole percentage point seem more than adequate.

The Lake Tahoe area is not a prominent solar market, though the Truckee Sanitary District installed a 125 kW_P 35° fixed tilt array in 2009 and there are several other commercial PV installations in the Lake Tahoe region. Compared to Truckee's 200"/yr, the following well-established commercial solar markets and their average annual snowfall include[7]:

1. Denver, 60 inches
2. Milwaukee, 47 inches
3. Boston/New England, 43^+ inches
4. Detroit (and Ontario Canada), 42 inches (and much more going eastward toward Buffalo)
5. Chicago, 38 inches
6. Mid-Atlantic region, 20-30 inches

Figure 2 shows the most recent year's snowfall trend as a solid bold line, with dashed lines showing the monthly averages and their normal 1-std. deviation envelope. **From June 2009 through May 2010, the snowfall of about 190 inches was 96% of average, so our first year's results should be very representative for this location.** February 2010 was notably dry, receiving just 48% of its average snow, yet this was still well within the bounds of the *normal* year to year variation for that month. In the past year, only May 2010 fell outside the normal range, with 12 inches received instead of the average 4 inches.

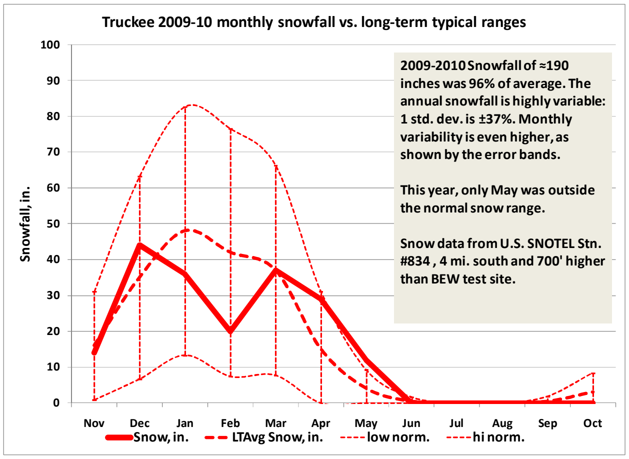

Figure 2. Truckee monthly snowfall trends

ARRAY DESIGN

The Truckee test bed consists of three pairs of south-facing Mitsubishi 175 W_P poly-Si modules portrait-mounted at 0°, 24°, and 39° tilt angles. One of each pair of modules is manually kept clean of snow and frost. Each module has an inactive 18" border of similarly textured and colored material to minimize edge effects. The module pairs are spaced far enough apart to prevent row shading, even on the winter solstice. Air and module temperatures are recorded, along with module current. The modules are short-circuited, producing up to 8 amps of dc current at 1,000 W/m^2.

Three Licor pyranometers are also used, one on each plane, with a fourth pyranometer mounted facing downward from the rear side of the 39° tilt plane. This sensor was put in to help characterize the radiation received from ground-reflected and north sky sources[1], but from its snow-protected position, later proved invaluable in helping identify and rehabilitate the roughly 5% of records that were compromised by snow accumulation on the "clean" side modules, since it was never obscured by snow. Our hosts made over two dozen service log entries over the winter, yet there were still some occasions when otherwise clear conditions were not captured by the test bed. We relied on a combination of camera evidence and data screening to identify and adjust anomalous records using quality-checked data to scale and replace errant records. For future studies, we intend to outfit the clean side modules with thermostatically controlled, insulated electric heat tape on the module backsides. This will ensure rapid melting of snow and ice and minimize both the cleaning labor and the likelihood of anomalous data points.

Figure 3 illustrates the test bed design. Concrete ballasts are used to anchor the Unistrut, aluminum stock, and 4x4 lumber framing. Pro Solar racking is used to mount the modules. A plexiglass on blue-painted OSB laminate is used to border the modules. The data logger and current shunt sensor enclosure is mounted on the north side of the assembly, and poles to show snow depth and to mount the camera are located nearby. This view is to the NW.

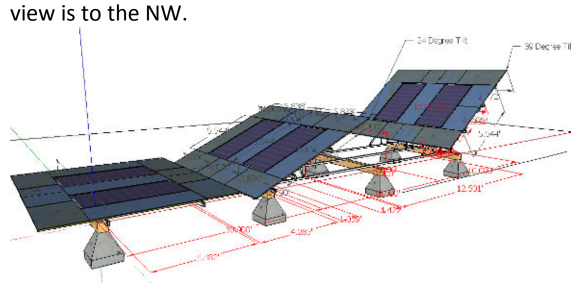
Figure 3. Test bed design

INSTALLATION AND OPERATION

The test bed was installed over a dry three-day period at the beginning of December 2009 and was up and running just a few hours before the season's first major storm hit. Figures 4 and 5 show the installation's progress.


Figure 4. Installation begins


Figure 5. Installation complete

[1] An interesting side result: the monthly irradiation on the back side of the module was 25% of the front side irradiation when the ground was mostly snow-covered in Dec-Apr, but just 10% when dry ground prevailed for most of May.

Figures 6 and 7 show a typical cleaning episode and hourly snapshot, respectively. The left, or west, side of the array is the manually cleaned side.

Figure 6. Cleaning the array

Figure 7. Webcam snapshot

As these photos show, the snow is deep enough to pile up higher than the 18” low edge of the array and dam up and impede the natural shedding of snow. In retrospect, we should have raised the structure perhaps 2’ higher and spaced the flat array section a foot or so farther from the middle section, and would probably do so in subsequent installations to avoid confounding the results and making the impact worse than it need be. On the other hand, almost all fixed tilt commercial systems are mounted very close to the roof membrane and are spaced closely enough to create exactly this kind of damming, so this geometry may be more realistic for some types of arrays.

RESULTS

The first winter was statistically very normal. The lost energy due to snow buildup in the 7-month winter season ranged from as little as 25% for the 39° tilt = latitude orientation to as much as 42% for the flat orientation. The seasonal results project to losses in annual output of 12%, 15%, and 18% for the 39°, 24°, and 0° tilts, respectively. While these results are hugely significant for this location, it is not clear how well such results should translate to other locations. Some inferences can be made, though.

Table 1. 2009-10 Truckee snow season results

Month	Snow		% loss in generation for each tilt (Nov loss was estimated using similar May data)		
	inches	% avg.	0 deg.	24 deg.	39 deg.
Nov	14	88	10	8	6
Dec	44	126	81	80	79
Jan	36	75	100	90	80
Feb	20	48	93	69	29
Mar	37	100	51	28	17
Apr	29	193	37	20	16
May	12	300	9	7	5
Nov-May	192	96	42	33	25
Annual (estimated)	192^{+}	96^{+}	**18**	**15**	**12**

For example, Denver has a latitude and elevation similar to Truckee, though its average annual temperature is 3.7 °C warmer and it receives only 30% of the snowfall that Truckee gets. However, like Truckee, it:

- receives snow in all but the mid-summer months
- its snowiest month, March, gets about the same amount of snow as Truckee saw this May (12”), and
- has the same average temperature in March as what Truckee recorded this year in May (4 °C)

Based on this, one might infer that the snow losses in Denver in March may be comparable to the 5-9% losses seen in Truckee in May for similarly tilted fixed arrays.

Figure 8 illustrates the table data. The observed energy loss for each month and tilt angle are plotted on the left scale, and the % of average snowfall is shown as a dashed line referenced to the right scale.

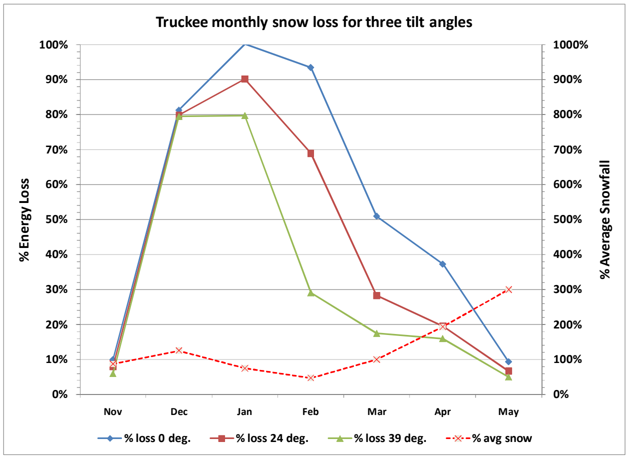

Figure 8. Monthly snow losses for three tilt angles

Figure 9 removes the snowfall data and expresses the losses as a function of tilt angle. Losses are assumed to approach zero in any month as tilt angles approach 60 degrees. This plot offers some thin clues as to what the losses might be for tracking arrays. Actual measurements will need to be made, of course, but casual observations by BEW's staff and discussions with PV operators suggest tracking systems will shed snow similarly to fixed tilt arrays tilted 20-30 degrees higher. For example, a single-axis tracking system inclined at 20 degrees in Truckee might experience snow losses of 8% per year, or about half of the snow loss a fixed 20 degree tilt array may experience.

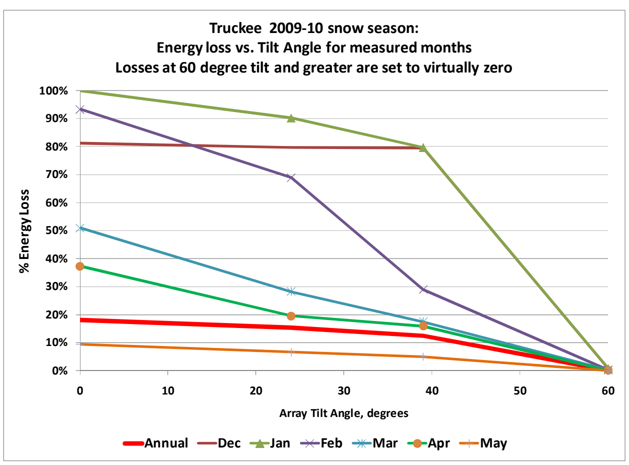

Figure 9. Monthly losses as a function of tilt angle

Figure 10 illustrates the annual snow-related energy loss as a function of tilt angle. Some liberties in extrapolation were taken here. For one, we assume that snow losses become negligibly small at some critical angle, perhaps as low as 45 degrees but conservatively shown here as being reduced to negligibly small at 60 degrees. We also applied long-term average solar radiation data for the Truckee-Tahoe TMY-3 NREL station for the purpose of estimating full-year energy loss since our test bed has only been active for six months.

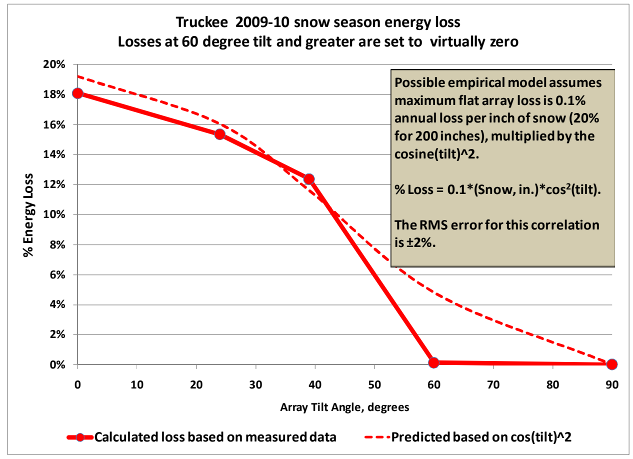

Figure 10. Measured and fitted trends for energy loss as a function of array tilt

Here, we offer the simplified observation that the generalized relationship between losses, snowfall, and tilt angle can perhaps be adequately represented by the equation:

Annual % loss = 0.1 x [Snow, in.] x $\cos^2$(tilt)   Eqn. 1

The first coefficient, 0.1, was not regression-fitted. It carries the implied units of % per inch. It was selected based on the observation that a near-20% annual loss corresponded to a near-200 inch annual snowfall, or 0.1%/yr/inch of snow. This correlation suggests a typical error of ±2% for predicting annual energy loss, with the overall correlation looking pretty good up to about 45 degree tilt angles, and fairly poor for commercially invisible steeply tilted arrays. This is not good enough to call the job done, but, subject to additional data collection at other locations, potentially represents a considerable improvement over the current lack of any simple empirical estimating tools.

We arrived at the $\cos^2$ relationship partly by inspection and partly, as shown below in Figure 11, by optimizing the exponent to minimize the RMS error. While there is a clear relationship between tilt angle and the natural gravity-driven tendency to shed snow, a first-order cosine relationship alone is not aggressive enough to explain the observed loss trend. The upper blue trend line below shows this. The $\cos^2$ relationship works much better, as does the $\cos^3$ form, which actually exhibits the best overall RMS error. We suggest the $\cos^2$ form only because of its closer fit to the observed data for the more common sub-40 degree tilt angles. Higher-order exponents in the proposed $\cos^N$ relationship clearly tend to under-predict relative to the observed bold red trend line.

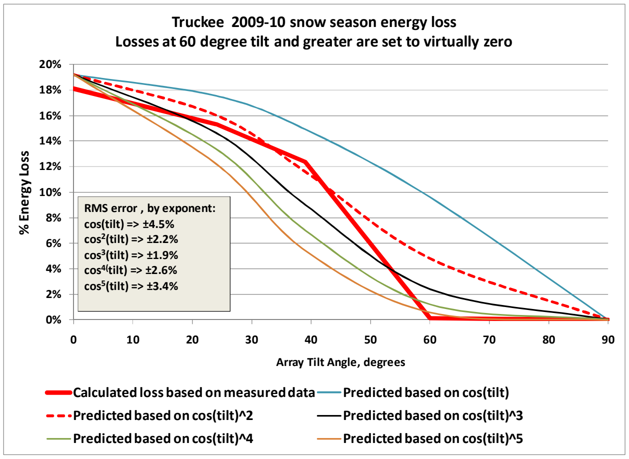

Figure 11. Alternate curve fits to annual snow loss model

CONCLUSIONS AND FUTURE WORK

The first winter of operation has yielded a wealth of significant data on snow-related impact on PV output. For one of the U.S.'s snowiest urban areas, it was observed that annual losses of 12-18% may be expected in a typical year for fixed tilt arrays mounted at tilt angles ranging from 39 degrees to 0 degrees (flat). Monthly losses were substantially higher, with an entire month's output lost for a shallow tilt angle when several feet of snow fell.

A promising simple annual snow loss relationship was posed, which suggests annual energy loss may be estimated as the product of a 0.1% per inch snow loss, multiplied by a $\cos^2$(tilt angle) adjustment factor.

We would like to extend some of our observations for snow loss in the milder winter months at Truckee and apply them to represent more severe months at less snowy locations, and presented such an example for Denver. However, we will await better site-specific data before suggesting the Truckee data can be responsibly applied to other climates.

There is a clear relationship between tilt angle and energy loss, though the relationship will be influenced by factors we did not eliminate in our installation, namely, the damming of snow caused by too low of an array height and too little spacing between rows. BEW plans to modify the Truckee test bed to address these factors for the next winter season, and hopes to find partners to install similar test beds in other snowy areas where photovoltaic systems are being deployed.

REFERENCES

1 Becker, Gerd, *An Approach To The Impact Of Snow On The Yield Of Grid Connected PV Systems,* Bavarian Association for the Promotion of Solar Energy, Munich, 2007.

2 Marion, Bill, *Instrumentation For Evaluating PV System Performance Losses From Snow,* NREL, ASES 2009 conference, Buffalo, NY, May 2009.

3 The National Renewable Energy Laboratory (NREL) published the *National Solar Radiation Database*, also commonly referred to as the Redbook, in 1994 (Bill Marion, principal author), with web address: http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/tmy2/

4 NREL's *PVWATTS* website address is http://rredc.nrel.gov/solar/calculators/PVWATTS/system.html . This PVWATTS citation discusses snow losses in Minnesota.

5 Powers, Phil, *Wilderness Mountaineering*, Stackpole Books, 1993, page 35.

6 Western Regional Climate Center, *Truckee Ranger Station #049043, 1903-2009 data*, 52 valid years for annual snow records, web address: http://www.wrcc.dri.edu/index.html

7 One source for snowfall data has this web address: http://www.currentresults.com/Weather-Extremes/US/snowiest-cities.php