Dynamic Snow Loss Model in PVSim: Modeling Impact of Snow on PV Production

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***Abstract*—Snow coverage on PV panels can significantly decrease annual energy production. This reduction is dependent on local snow behavior, system configuration and O&M practices. In some regions where PV is commonly installed, annual energy losses can be 5% or more. Accurate prediction of expected loss due to snow is of significant value in annual energy estimates and performance guarantees for a project. Multiple years of production data from over 30 sites that experience mild to significant snow have been used to validate a snow loss model used in SunPower's PVSim simulation engine. These sites include a wide range of system types including tracker, roof mount and ground fixed tilt ranging from 0-25°. The model uses hourly data for snow depth on the ground, which can be acquired from historical, typical, or measured sources. The model translates this ground snow depth data into accumulation on the panels and allows for the two primary modes of snow removal, sliding and melting. All of these behaviors are weather- and system-dependent.**

***Index Terms*—snow, soiling, losses**

I. Introduction

PV system installation is becoming increasingly common in areas with significant winter snowfall. While PV systems can produce energy year round, snow can accumulate on PV panels during these winter months and limit production. Estimating this loss is complex; there is no obvious relationship between snowfall and PV power output nor has the impact been studied as extensively as other areas of PV modeling.

The effect of snow on PV modules has been reported in several papers [1-5]. Andrews *et al.* describe two primary mechanisms, sliding and melting, for snow to clear from PV. This study used a multi-orientation fixed-tilt panel test setup to correlate power loss and time-to-clear with tilt angle, but did not clearly associate behavior with snow depth or amount of snowfall. They also discuss previous studies showing that approximately 20% irradiance will be transmitted through a 2-cm snow depth. Townsend *et al.* used both a test array and larger operational systems to develop a model for monthly snow loss as a function of snowfall, weather and system geometry. They show that for snow to slide off of the modules, sufficient space for the snow to accumulate is necessary. Becker *et al.* indicated that power loss is more influenced by fresh snow then by amount of accumulated snow on the ground. They also notice that slipping is not highly dependent on ambient temperature, observing that slipping occurred at ambient temperatures of 10°C. Marion *et al.* (NREL) looked at six operational systems and performed detailed data collection to determine conditions necessary for sliding to occur. They propose a method to calculate daily output based on hourly updates to the amount of sliding expected to have occurred, and estimate the coefficient of static friction between panel and snow to establish a critical angle for sliding of 8-10°. They suggest that roof systems do not allow sufficient space for significant sliding to occur in general, and that module frame and glass type do not have a significant effect on sliding behavior. A few methods are available in industry modeling tools for incorporating snow losses into a PV energy model. PVSyst allows users to manually enter monthly "Soiling" values, which are meant to represent both winter snow losses and year-round losses from soiling and debris accumulation on modules. BEW Engineering developed a generalized monthly snow loss model which uses aggregated monthly snowfall data as inputs [4] and returns monthly snow loss values for use in PVSyst. An updated version of Marion's snow loss model has been implemented in NREL's Solar Advisor Model (SAM). This method calculates the percentage of a PV array that will be covered by snow given daily snow depth and system tilt. Snow sliding is considered to be the dominant removal process; it depends dependent on plane of array irradiance and ambient temperature, but does not account for snow melting or wind removal [5]. Unlike static snow models based on monthly aggregates of snowfall, the PVSim method utilizes a dynamic model that evaluates system snow coverage at each hour of production. We studied production data from 60 operational PV systems across 22 snow-prone locations to investigate the effect of snowfall on system output. The sites consisted of roof mount, tracker, and ground fixed-tilt racking systems with a wide range of tilt angles. The resulting analysis was used to develop and validate a dynamic snow model, which has been implemented into SunPower's PVSim simulation tool. This implementation utilizes hourly ground snow depth data and allows for system dependent accumulation, melting and sliding. An additional validation study was conducted on operational data to see how well the model estimated losses on an annual basis. We evaluated the model for 10 systems with multiple years of data, and compared the modeled snow losses using snow data for that location and year with the measured snow losses from the operational data.

II. Snow Loss Model Overview

The SunPower snow loss model is based on basic engineering principles and validated against operational site data. The model accounts for snow accumulation on the panels and ground, and snow dispersion through melting and sliding off the glass surface. Based on the accumulation and dispersion of snow calculated by the model, the depth of snow remaining on the module at every time stamp is determined. If the depth is great enough all of the energy produced in that hour is lost, otherwise the system performs normally.

A. Snow Data

Ground snow depth data is more commonly available than snow fall data. Historical snow depth information is available in specific locations through sources such as the NOAA Global Surface Summary of the Day (GSOD) and Global Historical Climatology Network (GHCN) databases (this is usually daily information), and from 3Tier (hourly). These historical data sources were used for analysis and validation of the model against operational data.

For predictive simulations that are performed in PVSim, typical year estimates of snow depth are used, similar to the use of TMY estimates for irradiance temperature and wind-speeds. The primary source of typical snow depth in PVSim comes from Meteonorm7 which offers global snow information.

B. Snow Accumulation and Melting

The change in snow depth is determined as new accumulation (positive change) or amount melted (negative change). The amount of snow that accumulates on the PV (normal to the surface) is assumed to be directly correlated to the amount of snow accumulated on the ground:

$$\Delta SD_{PVaccum} = \Delta SD_G \times cos\beta \ (\Delta SD_G > 0) \quad (1)$$

where ΔSD_G is the change in snow depth on the ground, and β is the slope of the PV from horizontal (for tracker systems this will vary with time).

Melting is assumed to be a function of the PV orientation relative to the sun:

$$\Delta SD_{PVmelt} = \Delta SD_G \times \frac{cos\theta}{cos\theta_z} \ (\Delta SD_G < 0) \quad (2)$$

where θ is the incidence angle between the sun and normal to the PV, and θ_z is the solar zenith angle. This is effectively a ratio of the energy the PV sees vs the ground. This is to account for snow melting at a higher rate on the panel due to it receiving more light relative to the ground.

Combining (1) and (2), the snow depth on the PV is tracked over time as the snow depth on the ground changes:

$$SD_{PV} = SD_{PVprevious} + \Delta SD_{PVaccum} + \Delta SD_{PVmelt} \quad (3)$$

Where SD_{PV} is the current snow depth on the PV, and $SD_{PVprevious}$ is the snow depth on the PV during the previous hour.

C. Snow Sliding

If the PV slope exceeds a predetermined threshold, then sliding may occur. If the panel does not exceed this slope, then sliding does not occur in the model. Tracker systems tend to exceed this slope every day during non-stowed operation, and were found to generally clear themselves within hours of a new snow event.

D. Available Shed Pile Volume

In addition to the critical tilt angle, it is also necessary that there be sufficient available volume below the array for the snow to fill. This is modeled by determining the remaining volume of snow on the panel and the unfilled volume available below the array. If the available volume is greater than the volume of snow on the PV, then it will slide; otherwise no sliding will occur (Figure 1).

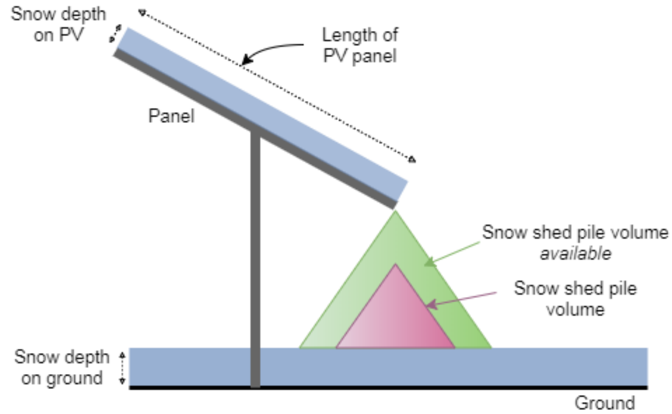

Fig. 1. Available volume for snow shed pile to determine if snow will slide off module

The linear volume of snow on the PV is simply equal to SD_{PV} times the length of the panel (L_{PV}).

$$SD_{PV} * L_{PV} \quad (4)$$

The linear volume available for snow to slide into is assumed to be a triangle with a height, h, equal to the distance between the lower lip of the PV and the top surface of the snow on the ground, minus a similar triangle with a height, $h_{previous}$, containing the snow that slid off previously. The angle of the triangles with the ground can be assumed to be the angle of repose, which is the maximum angle at which a pile of debris will stabilize (e.g. grain, sand, snow) [6]. A conservative angle of repose of 45° is used in this model for simplicity. Thus, the area of the triangle representing snow shed pile volume will be 1/2 h^2. Therefore, the available room for the snow shed pile to fall is:

$$1/2 * (h^2 - h^2_{previous}) \quad (5)$$

Combining equations (4) and (5), the snow will slide from the panel to the ground if the following condition is true:

$$SD_{PV} * L_{PV} < 1/2 * (h^2 - h^2_{previous}) \quad (6)$$

Otherwise, the model assumes that snow cover remains on the module and limits all production until there is sufficient clearance for it to slide.

III. Validation

The methods in the model described above were validated in two phases with operational data from short periods of winter snow build up: (1) identify that the mechanics and assumptions incorporated in the snow model are valid, and (2) assess how well the model predicts system energy loss on an annual basis. For this energy study, operational data was examined for complete years and compared to the modeled loss for 10 sites.

Historical snow depth information was obtained near each installed system from sources such as the NOAA Global Surface Summary of the Day (GSOD) and Global Historical Climatology Network (GHCN) databases (this is generally daily information).

A. Methods and Snow Behavior Validation

The previous study conducted as part of the development of the snow model examined 60 systems from 22 sites located in snowy climates. These sites include a variety of roof, fixed-tilt and tracker systems with multiple years of operational data. For each site, fifteen minute average irradiance and temperature as well as inverter energy for each inverter were obtained around the time of each snow event. A simple performance ratio (PR) was calculated for each inverter to indicate gross under-production:

$$PR = \frac{P}{Irr} \times \frac{Irr_{max}}{P_{max}} \quad (7)$$

where P and Irr are the power and irradiance at each 15-minute interval and P_{max} and Irr_{max} are the maximum power and maximum irradiance, respectively. An example of data for a 10° fixed-tilt site in New Jersey with three inverters is shown in Figure 2. The system is considered to be clear of snow if either the median PR is greater than 50% or if there is no snow on the ground, and is otherwise considered to be covered in snow. In this example there are many days during which snow exists on the ground but PR has returned to 100%.

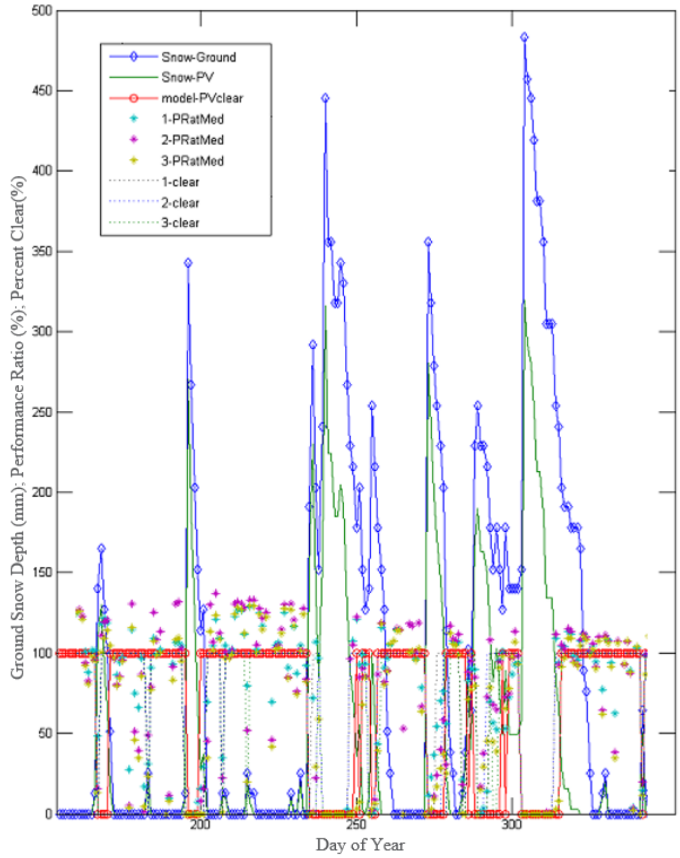

Fig. 2. Analysis data example for 3-inverter site. A single y-axis is used to represent snow depth information (mm), performance ratio (%) and percent clear (%). The dark blue line indicates the daily snow depth on the ground obtained GSOD/GHCN, the three sets of asterisks indicate the daily median performance ratio for the three respective inverters (PRratMed), and the three dashed lines indicate whether each of those inverters is considered to be clear of snow (100%) or not (0%)

The green line in Figure 2 indicates the snow depth on the panel predicted by the model and the red line indicates whether the model considers the PV to be clear (100%) or not (0%). The model generally predicts that the modules will be clear of snow before the ground is clear of snow, and predicted clear state (red line) tends to coincide with the measured PR at values returning to 100%.

The final model was obtained by tuning several parameters such that that the difference between predicted and actual number of days lost due to snow for all inverters analyzed was minimized. These parameters include an Accumulation Acceleration Factor, Melting Acceleration Factor, critical angle, and snow depth on PV threshold. A few parameters in the model were selected and tuned based on the site data. These are the values used in PVSim. However, a user can change them.

- Angle of Repose - 45°: For simplicity, the angle of repose used is 45°: The angle of repose for snow is approximately 38°, although this will depend on the particular snow characteristics (i.e. dry/wet, temperature) [6]. In addition, if the pile is generated from a slide from the upper portion of a module, then the resulting impact on the pile will result in a lower angle.
- Critical Angle - 5° . This is the critical tilt angle at which sliding can occur. The threshold can be determined through simple statics to be $\beta_{crit} = tan^{-1}(\mu_s)$ where μ_s is the coefficient of static friction. Townsend *et al.* indicated a reasonable coefficient of static friction of 0.14 for snow on PV module glass. The 0.14 coefficient corresponds to a critical angle β_{crit} of 8°, while our study conducted on fleet data supported using a value of 5°, independent of module type and system configuration.
- Snow Depth on PV Threshold - 0.05 meters. If there is more than this depth of snow on the PV, then there is a 100% loss, otherwise there is 0% loss. Andrews et al [1] indicated that 2cm of snow still lets 20% irradiance through.
- Accumulation Acceleration Factor - 0.8 (unitless). This is an unitless parameter applied to Equation 1. Observation from numerous sites indicated that accumulation on panels (even flat ones) is lower than on the ground. This

seems physically realistic due to snow wanted to go to lower potential especially with the aid of wind.

- Melting Acceleration Factor - 1.0 (unitless). This is a unitless parameter applied to the Equation 2.

B. Annual Snow Loss Model Validation

The second phase of validation evaluated the model on an annual basis by running the model for that year and comparing the modeled loss to the measured annual snow loss. Operational data from 10 sites in the North East US were used for this part of the study: five ground-mount and 5 low-tilt rooftop systems, with several sites having up to 4 years of data. In addition to measured power data, we calculated expected power from either on-site meteorological stations or satellite data from SolarAnywhere.

The modeled snow losses were obtained by running the snow loss model with inputs of system configuration and historical daily ground snow depth data for that location. For each day the model determines if there was sufficient snow to block production. Then the energy for all days with snow cover–the sum of hourly expected power for that day–was used to calculate the total energy lost to snow for that year.

The measured snow losses were obtained by identifying snow outages in the production data. A snow outage was defined as a day during which snow depth on the ground was greater than 2.5cm and the system produced at least 25% less than the expected power. 25% and not 100% was used to flag a snow outage to capture events where a portion of the array was covered with snow but not all. If this condition is satisfied for more than one hour during the day, the entire difference between measured and expected power was taken as the total energy loss for that day. The total for the year of energy loss during snow outages was then divided by the total expected energy for the year to obtain the Measured Snow Loss Percentage. Figure 3 shows that the measured snow losses have good agreement with the modeled snow losses (0.08% MBE, 0.9% RMSE), and that the model works just as well for rooftop systems as it does for ground mount systems.

C. Inter-annual Variability

As a primary input to this and many other snow models is snow data, the expected snow losses on a PV System are contingent on the inter-annual variability of snow patterns. If one year has significantly more or less snow than the previous, a large change in the production losses can be expected. To asses this variability, the snow model was run using 30 years of snow data. The annual losses for one site in Massachusetts are shown in Figure 4. The mean annual snow loss for this site was 2.8% but the losses over 30 years range from 0.5-8%.

The plots in figure 5 show the distributions of 30 years of modeled snow losses for four sites. The mean value and PVSim value (generated by running the model with "typical" snow depth data from Meteonorm) is also included. The mean value matches the PVSim fairly closely, but the actual value could vary by a couple percent depending on how much snow fell that year.

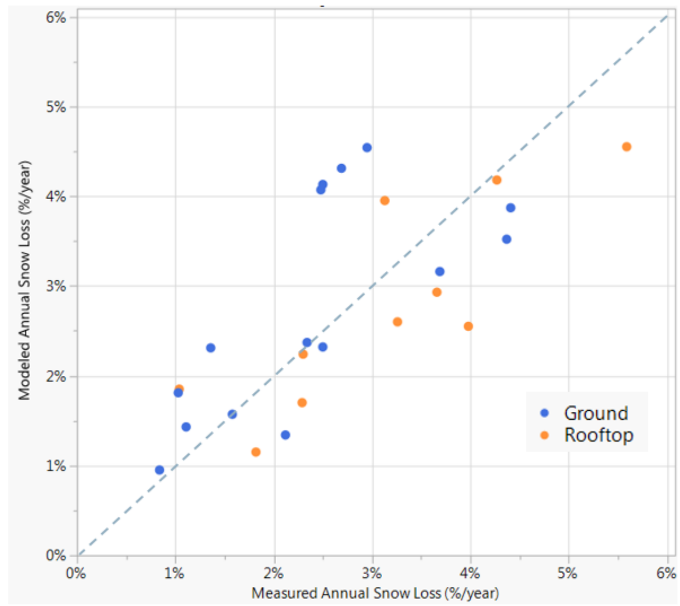

Fig. 3. Measured vs Modeled Annual Snow Losses for 10 sites (with multiple site years).

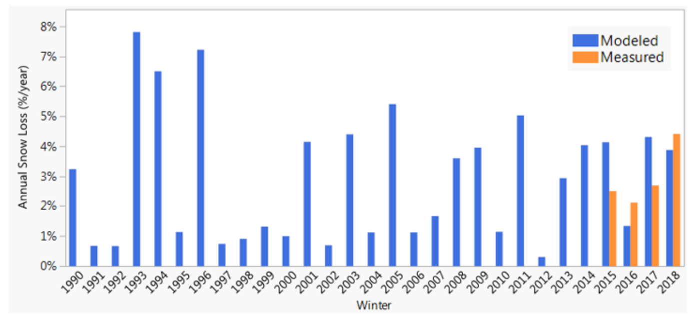

Fig. 4. Modeled snow loss values over 30 years are shown for a single site (25 degree fixed tilt system) in Massachusetts. The measured losses for the last four years with PV operational data are plotted in orange for comparison.

IV. Discussion

The methods in the model presented above glean a fairly close snow loss estimate on the annual basis. The model currently assumes a binary approach to snow losses: meaning that either 100% of product is blocked for the entire system or 0%. In reality, it is not always the case that the entire systems is covered with snow or clear. Snow cover on PV systems has been found to be anomalous in many instances; it is not uncommon for "identical" systems at the same site to recover on different days, likely due to site micro-climate effects.

Furthermore, inter-annual variability poses a challenge to get a "typical" snow loss value for a site's production estimate. As a primary input to the snow loss model is local snow depth data, if the snow changes year to year, annual snow loss can vary year to year simply because snow patterns do.

Future work will involve investigating critical angles of various PV products in greater detail, and consider other weather aspects such as ambient temperature and wind loading.

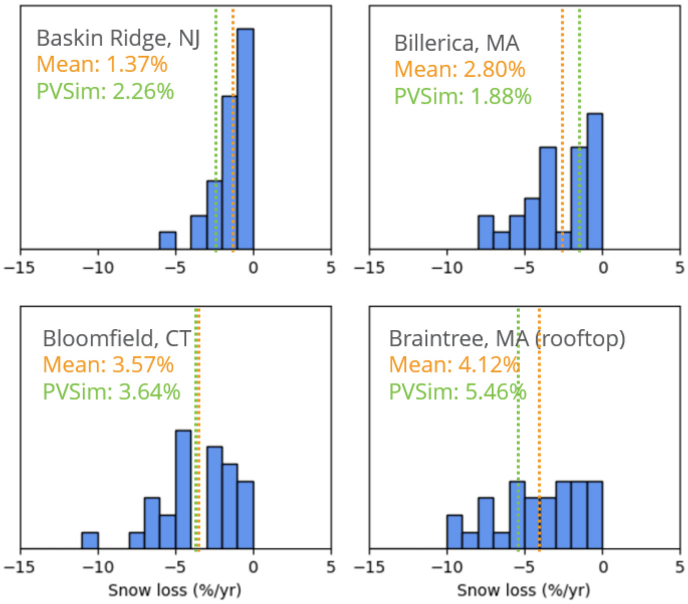

Fig. 5. A long term study was done for 4 sites using 30 years of historical GSOD snow data. Each plot shows the distribution of yearly snow loss and the PVSim results from running the snow model using typical snow data in green. The mean of the modeled data is shown in orange.

V. Conclusion

Assessing the impact of snow on PV production is essential in areas with snowy winters. Snow cover can impact PV system production several percent on an annual basis. A dynamic snow model has been presented to facilitate this analysis and to incorporate expected snow losses into hourly energy model calculations. This model uses simple system characteristics and industry-available hourly snow depth data, and has been validated against over 30 sites consisting of rooftop, tracker and fixed-tilt systems. This model is used within PVSim with Meteonorm typical ground snow depth data.

The validation study discussed above, shows that this model works pretty well to identify snow losses with a MBE of 0.08% given the historical ground snow depth data for that period. In addition to modeling the snow behavior on a PV System accurately, assessing the snow data is also key, particularly due to the large impact of inter-annual variability on snow losses.

References

[1] R.W. Andrews, A. Pollard, and J.M. Pearce, "The effects of snowfall on solar photovoltaic performance," *Solar Energy, 92*, pp.8497, 2013. https://doi.org/10.1016/j.solener.2013.02.014.

[2] T. Townsend, and L. Powers, "Photovoltaics and snow: an update from two winters of measurements in the sierra," *IEEE*, 37th Photovoltaic Specialists Conference,pp.32313236, 2011. http://ieeexplore.ieee.org/document/6186627.

[3] G. Becker, B. Schiebelsberger, W. Weber, C. Vodermayer, M. Zehner, and G. Kummerle, "An approach to the impact of snow on the yield of grid connected PV systems," *21th European Photovoltaic Solar Energy Conf. Dresden Germany*, pp 2732-2735, 2006.

[4] B. Marion, R. Schaefer, H. Caine, and G. Sanchez, "Measured and modeled photovoltaic system energy losses from snow for Colorado and Wisconsin locations," *Solar Energy, 97* 112-121, 2013. http://doi.org/10.1016/j.solener.2013.07.029

[5] D. Ryberg, J. Freeman, "Integration, validation and application of a PV snow coverage model in SAM," *National Renewable Energy Laboratory*, 33 pp. TP-6A20-68705, 2017.

[6] M. Rikkers and A. Rodriguez, "Anatomy of an avalanche". *Telluride Publishing*, 23 June 2009. http://www.telluridemagazine.com/anatomy-of-an-avalanche/