Testing a Method for De-energizing Solar Panels for Firefighting

David Starling
Joseph Ranalli
Kenneth Dudeck
Penn State Hazleton
76 University Dr.
Hazleton, PA 18202
starling@psu.edu
jranalli@psu.edu
ked2@psu.edu

Ron Steber
Hazleton Fire Department
525 E. Broad St.
Hazleton, PA 18201
teachair@live.com

ABSTRACT

Solar power installations present potential electrical hazards during firefighting operations. Even if a building is disconnected from the electrical grid during an emergency, live high DC voltage electrical lines may still be present between the panels and the inverter due to solar irradiance. While newer installations may feature disconnects, they may be located in difficult to access areas (e.g., on the roof). One strategy for eliminating potential electrical hazards is by blocking the panel's solar access using a tarp. However, this process poses a safety hazard. An alternate procedure was developed to test the ability of a common foam agent (fluoro-protein Foam) to de-energize a 2.8 kW solar array under sunny conditions. This agent is carried by almost all firefighting trucks and tankers and can be sprayed through a hose, eliminating the need for firefighters to access the roof of a burning building. The agent can be washed off using water, returning the panels to an operable state. During testing, the voltage and current on both the AC and DC sides of the inverter was recorded to evaluate the effect of the foam on the power output of the array. While the foam did create a dramatic reduction in power, it appears that the reduction was insufficient to eliminate the electrical hazard in the DC lines. Ongoing efforts include testing of the optical properties of the foam to determine whether possible improvements could be made, and testing of other foam agents and foaming strategies.

1. INTRODUCTION

Photovoltaic (PV) energy generation in the US has been on the rise for the past decade (1) with many of the new solar panel installations being residential grid-connected systems. Despite the obvious benefits of such systems, there are a number of safety concerns associated with typical residential power generation.

In particular, there are some issues that arise during firefighting operations (FFOs). These problems have been considered in great detail by the Fire Protection Research Foundation (2). Possible complications during FFOs include structural collapse, electrical shock, battery hazards and melting or vaporizing of carcinogenic materials (e.g., cadmium telluride). The most common issue faced by fire fighters is electrical shock. Concern about these hazards led to large scale loss during a warehouse fire in New Jersey in 2013 (3). However, typical strategies to deal with such hazards are inappropriate in the case of locations powered by solar panels.

When a building catches fire, the standard approach is to cut the AC power to the home before FFOs begin. However, even if the AC power is cut, the house may still be partially energized in standard solar panel installations. Typical, an emergency cutoff is located at the ground, leaving a live DC line from the array to the inverter. Some installations include cutoff switches at the solar panels for maintenance purposes; however, these are typically inaccessible during a fire. A comparatively safer (albeit more expensive) solution involves the use of micro inverters at the PV array. While this eliminates high voltage DC lines within the home, the panel itself is still energized and poses a minimal risk.

The danger to firefighters is therefore platform dependent. In order to mitigate these problems, it is sometimes recommended to cover the solar array with an opaque tarpaulin. This, however, provides its own set of procedural difficulties and risks. For instance, most tarps are not fully opaque and solar arrays may be too large to cover practically. If the panel is near the fire, the tarp may combust. If there is high wind, securing the tarp may be

Fig. 1: Top - application of foam to array. Bottom - measurement procedure.

difficult. Most importantly, this procedure requires firefighters to ascend to the roof of a burning building, which is generally not recommended.

Here, we consider another method of de-energizing a solar panel array during FFOs. Nearly all firefighting trucks and tankers carry fluoro-protein foam used for coating and cooling the fuel in a typical fire. This method has been dismissed as ineffective for solar power applications (2), and yet no detailed testing has been done. Qualitative observation shows that the foam is largely opaque in the visible spectrum and may provide some shielding of a solar panel from the sun when applied liberally. In the following sections, we describe our preliminary experimental testing of shielding a 2.8 kW solar array from the sun using fluoro-protein foam. We include our results and possible future laboratory testing to improve the procedure.

2. EXPERIMENTAL DESIGN

The AC and DC electrical parameters were obtained using standard digital voltage and current meters. These readily available meters did not include a computer data acquisition port to capture the time domain data directly. Instead, we recorded the data from these meters using video to capture the numerical readout of all meter displays. The readout was then coded for post processing.

The array was constructed from sixteen General Electric PVp-200 panels. Each panel was rated at 200 W and 26.3 VDC under Standard Test Conditions (STC = 1000 W/m^2 @ 25ºC). The array configuration consisted of two parallel banks of 8 panels in series combining to a total array voltage of 210.4 VDC and power of 3.2 kW.

The output from the array was connected to an Advanced Energy PVP2800 grid tied DC/AC power inverter. This inverter is rated for 2.8 kW with a DC input voltage ranging from 180 to 450 VDC.

As a control to monitor the solar irradiance, a USB connected silicon photodiode power sensor (Thorlabs S120C) equipped with a 715 nm longpass filter was placed near the panel directed toward the sun (see green curve, Fig. 3). This supplied the solar irradiance baseline to detect cloud cover.

As seen on Figure 1 (bottom), a total of five additional meters were used. Starting from the left, two Extech MA410 Clamp Meters were used to measure the AC current (400-A max.) and AC voltage (600-V max.), respectively from the grid tied inverter. Next, two Fluke 87 VOM meters (10-A max) were used to measure the DC current coming from the PV array. Since the array's electrical ratings indicated an expected current of 15.2 A at STC, two Fluke 87 meters were connected in parallel in order to split the current load and not exceed the 10-A individual meter rating. The readings from both meters were summed to obtain the total array current. Finally, a Radio Shack 22-813 VOM meter (600-V max.) was used to measure the DC voltage from the array.

The DC power from the array was calculated by the product of the DC voltage and current. The AC "apparent" power was calculated by the product of the AC voltage and current from the inverter since the power factor was unknown.

The meters were positioned as shown in Figure 1 such that all the displays could be recorded using a single digital video camera. Another digital camera was set up outside to record the foam application and runoff of the array. A third camera was positioned to record cloud activity by monitoring a separate array (not shown). Each of these cameras recorded continuously (with no breaks) throughout

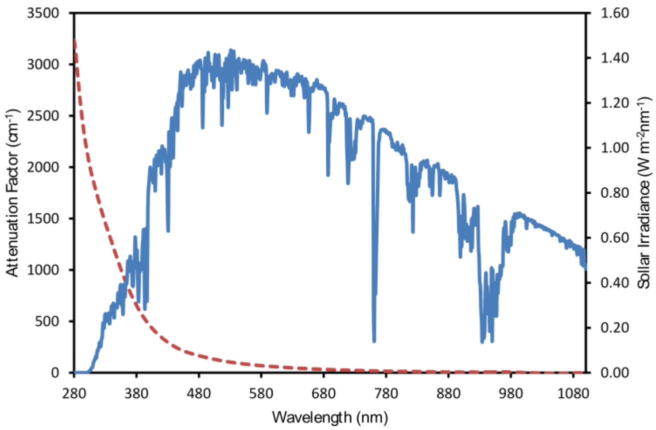

Fig. 2: Attenuation of light from a sample of foaming agent (red dashed) and the mean solar irradiance for the U.S. (blue solid).

the experiment and were configured to display the recording time. To synchronize the recording events, one independent handheld digital stop watch was used to establish the system time. This timer was started together with the baseline measurement and then positioned in front of each camera in turn so that the system time could be recorded and subsequently correlated to each camera's internal recording time. Once this process was completed, the foam was applied to the panel in a series of tests.

The foam used to coat the panels was an adjustable mixture of water and Aer-O-Foam XL-3, a fluoro-protein foam liquid concentrate, composed of water, protein hydrolysate, ethylene and hexylene glycol, ferrous sulfate, zinc chloride and fluoroalkyl surfactants. The foam is considered safe under most circumstances and is only a mild irritant in its concentrated form (4). Standard procedure to address accidental release involves flushing with water. Concentrated disposal into the sewer is not recommended due to high foaming rate but is otherwise not a health or environmental risk.

The spectrum of a diluted sample of the fluoro-protein liquid (non-foamed) was measured using a spectrophotometer (Shimadzu UV-1800). We model the attenuated intensity I of the initial light intensity I_0 at a particular wavelength using Beer's Law as

$$I(\lambda, L) = I_0 e^{-\alpha(\lambda)L},$$

where L is the path length through the material and $\alpha(\lambda)$ is the wavelength dependent attenuation. The factor $\alpha(\lambda)$ is linear in concentration but varies nontrivially with wavelength. The results of the measurement are shown in Fig. 2 along with the mean solar irradiance (AM1.5) for the United States (5). The absorption factor has been scaled to represent an undiluted sample. We find that the attenuation toward the red end of the spectrum is poor. Note that these results do not take into account the scattering behavior of the substance when in its foamed state, which plays an important role.

3. EXPERIMENTAL METHOD AND RESULTS

The solar array produced a total power of approximately 2.75 kW before the testing began. The foam was then applied and the power was monitored both before and after the inverter while the system was grid connected. Several test runs were conducted consisting of foam application, followed by a period of allowing the foam to settle. The results from a single test run are shown in Fig. 3. The data points are separated by 1 s. The green curve, indicating the solar irradiance, is plotted in arbitrary units (scaled from mW) to fit the plot. We have also scaled the DC curve by the average inverter efficiency of 0.92 to see the AC and DC relationship more clearly; however, the numbers used in the calculations below are the true values computed from the measurements of current and voltage.

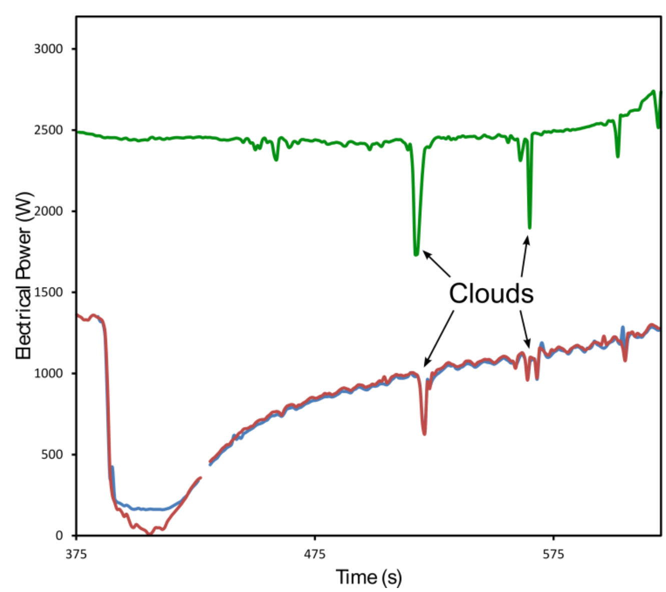

Fig. 3: A single data run is shown with AC (blue) and DC (red) power curves during application of foam. Baseline (green) included for reference with arbitrary units. Foam was applied at t=388 s.

At the beginning of the data run shown here ($t = 375$ s), there was a thin layer of foam from a previous trial. The initial power at this moment was therefore about 1.48 kW, down from 2.75 kW. This thin layer was approximately stationary and reduced the power output by only 46.2%. The foam was then applied in a steady stream and impacted the solar array at $t = 388$ s. The DC power output of the panel dropped noticeably and came to a minimum of 12 W at $t = 406$ s. The foam was continuously sprayed until $t = 409$ s, at which point the foam began to run off the solar array and was not replenished.

From this data, we see that a continuous supply of foam reduces the DC power output by a factor of 230 within 18 seconds. We note here that the AC power stayed high (160 W), perhaps due to the fact that the system was still grid connected. Additionally, the effective half-life of the foam coverage is about $\tau = 40$ s as it slowly rises to its thin-layer maximum of about 1.48 kW.

Other test runs, including foam coverage of a completely clear panel, showed similar results.

4. DISCUSSION

This full scale test of power reduction via the application of a foam fire suppressant indicates that there is potential for this process to be effective in the field.

First, we consider the reduction in the power on the DC side of the inverter. We see from our data that the power drops to approximately 0.44% of its maximum value during continuous application of the foam. While the power is reduced by more than an order of magnitude, with a current down to 60 mA, the safe rating for human contact (with no gloves) requires a reduction to approximately 10 mA (2). Therefore, the power must drop to 0.077% (another factor of 6) of the maximum power for our experimental conditions.

Importantly, while 80 mA is potentially hazardous to humans upon direct contact, it is *not* lethal in most circumstances. It is possible that suitable use of personal protective equipment (PPE) may be sufficient to mitigate the risk posed by the electrical hazards. At this time, while reductions in generated power were clearly seen, further study is necessary prior to recommendations about deployment of this strategy in the field.

Second, we note that the AC power reading is only reduced to 160 W during this procedure. We believe that this is an artifact of our test design due to power drain from the grid; this can be corrected by first cutting the power from the grid and then measuring only the behavior on the DC side of the inverter with an applied load. Under any circumstance, this behavior depends upon the specifics of the inter-grid connectivity of the solar hardware and should be considered to be installation dependent.

Third, the tilt of the solar panel is approximately 36º from zenith (Penn State Hazleton latitude is 40.9589º). Many solar collectors use a shallower tilt angle, for reasons of optimum collection angle, or for convenience of matching the slope of a roof. This shallower angle would result in less foam runoff, providing the possibility for a thicker layer of foam, or a longer effective half-life than what is seen here.

Lastly, this test only includes a single 2.8 kW solar array and a single hose for foam application. Some home installations may have five times this capacity. Such an increase in coverage would demand five times the coverage area and therefore five times the foam used here under the same conditions. However, for solar arrays with less tilt, this problem is minimized as the foam runoff would be reduced.

5. FUTURE WORK AND CONCLUSION

We have shown that the application of a common fluoro-protein foam used during FFOs can serve a dual purpose in the case of structures powered by inaccessible solar panels. The foam reduced the DC power output of the solar array to 0.44% of its maximum while the foam was applied. After the supply of foam was cut, the foam runoff then proceeded such that the power increased up to half of its thin-layer maximum within 40 seconds. We did not explicitly test how long this thin layer remained on the panel, and it is important to note that this thin layer is insufficient for reducing the power output to safe levels.

A number of cost-effective and environmentally friendly measures can be taken to improve the results found here. In a future study, we plan to test other common foams as well as possible additives to the foam solution such as coagulants to reduce runoff and materials to improve absorption at the wavelengths toward the red end of the spectrum (see Fig. 2). Further testing of the effective half-life as a function of panel tilt should also be useful for practical considerations. We hope that this ongoing work will help to establish confidence in the possibility (or impossibility) of this technique as a potential hazard mitigation strategy during firefighting operations in solar powered facilities.

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