EVALUATION OF SNOW REMOVAL METHODS FOR ROOFTOP PHOTOVOLTAICS

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ABSTRACT: Avoiding snow on photovoltaic (PV) installations is motivated for two reasons: to decrease power losses from shading, or to decrease mechanical loads to avoid damage to the PV-installation and the underlying construction. We experimentally investigated the effectiveness and suitability of four different snow removal methods at our facility in the north of Sweden (Piteå, 65°N), throughout three winters. The layout of a PV installation and the underlying roof, together with meteorological conditions and snow characteristics, impact which methods are best suited for snow removal. A simple roof rake with a rectangular toolhead works well when the snowpack is compact and not too thick, whereas a roof rake with a slide works better when the snow is dry and packed. Neither the investigated passive hydrophobic surface coatings, nor the active forward bias electrical heating methods induced shedding of the accumulated snowpack in our experiments without additional intervention. At our test facility in Piteå, the roof rake with a slide was the most effective and user-friendly snow removal. Despite maximum snow loads of approximately 1 kPa, far below the modules' rating, cell damage was observed for both snow removal groups (except for the slide roof rake group) and the control group.
Keywords: Durability, Snow, Evaluation, Electroluminescence, Rooftop

1 INTRODUCTION

In regions that regularly experience sub-zero temperatures and snowfall, avoiding snow on photovoltaic (PV) installations is typically motivated for two reasons: to decrease power losses from shading, or to decrease mechanical loads to avoid damage to the PV-installation and the underlying construction.

Both snow loads and snow removal might contribute to an accelerated degradation in PV-modules. Cells might crack under heavy loads or careless snow removal, frames might loosen across many thaw-freeze cycles, and modules might delaminate. Studies have indicated that a single exposure to temperatures below -20°C can significantly increase a glass/backsheet-module's susceptibility to crack formation under relatively low mechanical loads [1]–[3]. As a PV-module has an expected technological lifespan of 25 years minimum, initial small cracks are likely to grow larger across multiple winters and snow-load-cycles. If they are a common occurrence in cold climates, their prevention further motivates snow removal, even at low snow loads. The most commonly used standard for mechanical load testing, IEC 61215 [4], is based on laboratory conditions and does not consider low temperatures, inclined modules, or in-homogenous loads that are to be expected for real world applications. IEC 62938 tests in-homogenous loads, but also at room temperature [5].

To avoid snow on PV installations, the PV installation can either be constructed to avoid any snow accumulation, or snow accumulating on the installation can be removed. There is however no clear consensus of how snow should be removed, if at all. Some methods might cause more harm than they prevent by exerting additional stress or coming into direct contact with the modules; some methods could put the user at risk, for example, if performed at height; and some methods might be inaccessible due to high costs or limited availability.

Snow removal is a problem that largely remains unexplored when it comes to side-by-side tests. This study aims to evaluate the performance of different methods and investigate whether they cause or prevent damage to the PV-modules in real-world conditions.

1.1 Background

In the literature, often proposed methods for removing snow includes snow and ice repelling coatings [6]–[8] and electrical heating [9]–[12]; whereas, based on user testimonies, what is typically used on-site at residential installations is an assortment of commonly available tools such as shovels, brooms, or roof rakes that mechanically removes snow.

Many coatings based on different technologies have been tested in literature [6]–[8]. Due to limited performance gain or low mechanical durability, many of these coatings are not yet ready for market.

Forward bias electrical heating applies an electrical current in the opposite direction of what the module typically delivers. This results in heat generation due to resistive heating. In literature, there are predominantly two different outcomes from using this method. Either the snow is melted away completely, or the meltwater lowers the friction between the snowpack and module sufficiently for the modules to shed the snow entirely. The latter requires less energy and is generally considered the desired outcome [9]–[10].

The use of mechanical snow removal tools is generally discouraged in literature as they risk to permanently damage the PV-modules [12], [13]. Some commercially available tools might minimize these risks and could offer an attractive solution to the problem for residential installations.

In a pre-study, different snow removal methods were compiled from literature as well as through interviews with early adopters of solar PV in northern Sweden. In addition, commercially available methods were identified. These methods were evaluated by their expected performance regarding availability, initial cost, operational cost, labour intensity, risk of module damage, and risk of injury [14]. This evaluation suggested that two types of roof rakes, forward bias electrical heating, and hydrophobic surface coatings were promising for further evaluation in field.

2 METHOD

The test facility, presented in Figure 1, is located in Piteå, Sweden, at 65°N; where the snow depth on average

peaks at 70 cm each winter and roofs are built to withstand a snow load of 3 kPa [15], [16]. The test facility consists of a 12 m × 5 m construction with a 14° single pitch corrugated steel roof. A low inclination was chosen to promote snow accumulation and represent an installation where snow removal might be necessary. The roof was fitted with 20 framed monocrystalline glass/backsheet 60-cell PV-modules (*Longi LR6-60BP 305M*) divided into five equal groups mounted on a rail and clamp system (*Schletter Solo* and *Rapid*). The modules had a mechanical load rating of 5.4 kPa according to *IEC 61215*. Four of the groups were designated snow removal methods, whereas the centre group was the control. Cable connections were accessible from within the facility, enabling on-site electroluminescent (EL) imaging. The modules were stored at open circuit as mechanical degradation was the focus of this study. Time-lapse images were recorded with a surveillance camera throughout the second and third winter (*Reolink Go PT*).

Figure 1. The test facility in november 2021. Module groups from left to right: heated, coated, control, roof rake with slide, and rectangular roof rake.

2.1 Snow removal methods

For this study forward bias electrical heating, hydrophobic surface coatings and two types of roof rakes were tested, based on the pre-study described in Section 1.1.

The first coating tested (*Nanoflex VP20*) was a hydrophobic coating claiming to be suitable for PV, although not specifically for snow repulsion [17]. After the first winter these modules were exchanged to another set of modules (*SoliTek Standard M.60-B-310,* with a mechanical load rating of 3.6 kPa*)* that had been treated with a different coating developed in the project *Super PV*. This coating had indicated an improved snow performance for modules at higher inclination than what is examined in this study [18].

The forward bias electrical heating employed a DC power supply (*EA-PS 9200-25 T*) to deliver 1200 W to the four 305 W modules connected in series. Heating was performed up to 8 hours.

For this study two different toolheads were tested. One was designed to be pushed up from the roof eave through the snowpack and cut out blocks of snow. The blocks would then slide down a plastic tarpaulin off the roof. The steel toolhead was mounted on plastic wheels to keep some distance between the it and the underlying surface. The other rake featured a simple rectangular toolhead in hard plastic designed to pull and scrape down snow off the roof. One long edge was fitted with less abrasive cell foam. The toolhead must be lifted above the

snow and lowered with sufficient force to grab it, before pulling it off the roof. Both roof rakes are presented in Figure 2.

Figure 2. The two roof rakes.

As the coated and control groups required no active snow removal their snow covers were left untouched during the winter seasons. The active snow removal groups (roof rakes and electrical heating) would at the project's start be cleared from snow once they had accumulated more than 10 cm, unless more snow was expected within the coming days. This was done regardless of other external conditions to encompass a variety of ambient temperatures, snow characteristics and times of year. As testing proceeded, at what conditions to perform snow removal was adapted based on preliminary results. E.g., it was quite quickly found that electrical heating was not feasible at very low temperatures. Prior to each snow removal event, the entire test facility was photographed by drone or from the ground. Snow depth at the eave below each module group was measured and snow density measurements would be made on the ground depending on the availability of untouched snow. The snow was characterised (e.g., dry, wet, packed, loose, crusty), and after snow removal the facility was photographed again. The subjective relative effort required (low, medium, high) to perform the active snow removal methods, respectively, was also estimated.

2.2 Module inspection

Visual inspections and EL imaging were performed between each winter. Visual inspections looked for module damage such as damaged glass, frames, or contacts, as well as damage to the mounting system and the facility in general. EL imaging was used to identify cracks or otherwise defective and non-active areas of the solar cells.

Initial EL imaging was performed indoors, prior to installing the modules. Subsequent EL imaging was performed without removing the modules from the roof installation to minimize risks related to handling the modules. A DC power supply (*EA-PS 9200-25 T*) was connected to one module at a time and delivered a maximum of 45 V or 4.5 A. An InGaAs-sensor camera (*WiDy SenS 640V-ST*) with a 1 100 nm high-pass filter was used for imaging together with an 8 mm short wave infra red (SWIR) lens (*VS Technology),* 1.5 mm of spacer rings were used to increase sharpness. Exposure time typically varied from 2 – 10 ms. Imaging was performed

at dusk or after sunset, when ambient noise was minimal. Whole modules were photographed and close-ups were taken of noticeable defects.

3 RESULTS AND DISCUSSIONS

The first winter, of 2019–2020, received atypically little snow fall and the temperature often fluctuated above and below freezing, almost no substantial snow accumulation occurred on the test facility. This resulted in a single snow removal event. The winter of 2020–2021 instead featured atypically heavy snow fall and the final winter of 2021–2022 was more ordinary, and the temperature was consistently below freezing. This encompasses a large variance in snow accumulation and conditions for the timeframe of the study. Most snow removal occurred during the latter two winters.

The single-pitch roof typically accumulated snow unevenly. Less snow gathered along the top and sides, meaning that the thickest part of the snowpack typically was slightly above the eave at the centre of the roof. An example of how the snowpack thickness varied along the height of the roof is presented in Figure 3.
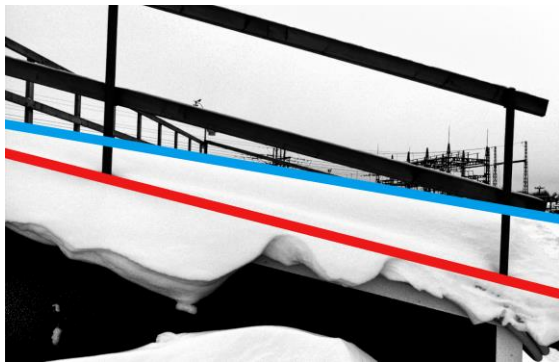

Figure 3. Blue, snowpack inclination; red, roof inclination.

3.1 Hydrophobic coatings

The coatings tested in this study did not indicate any decrease in snow accumulation or increase in snow shedding performance compared to the control group. The second set of coated modules performed worse in terms of snow accumulation and shedding, which was likely not due to the coating itself but rather the sharp edges of the frame-edge where it meets the glass, compared to the Longi modules. For the SoliTek modules, that edge was a sharp right angle protruding 2 mm from the glass surface, for the Longi modules the edge also protruded 2 mm but featured a smooth curved edge. Figure 4a shows an occurrence when the frame likely inhibited snow shedding and Figure 4b the end of one winter where the coated modules (*SoliTek)* showed no distinct difference from the control modules.

It is possible that better performance could be discerned with a higher inclination or frameless modules. The Super PV-coating has shown improved snow performance for higher inclination modules that were less susceptible to edge effects [18].

3.2 Electrical heating

Forward bias electrical heating would consistently initiate melting but was by itself insufficient for inducing snow shedding. Since this test limited the use time to 8

Figure 4. Coated SoliTek module group marked with red. a) Module frames likely preventing snow shedding. b) Snow still covering parts of the coated and control groups at the end of winter.

hours, unless all snow was removed, what meltwater remained in the snowpack would refreeze. To isolate factors that might have prevented shedding, other than the low inclination, the snow on the eave below the modules was removed as seen in Figure 5. This was done on multiple occasions, and in this case, after 6 hours of heating, the snowpack still showed no signs of shedding.

Figure 5. Snow unable to shed after 6 hours of heating with no snow on the roof eave.

On two occassions the snow cover was also cut along the side edges of the module group, which enabled snow shedding as seen in Figure 6. The ambient temperature was on this occasion above melting. Thus, shedding was found to be possible under certain circumstances.

Forward bias electrical heating, although theoretically possible, does not seem like a practical or economical solution at this point for the residential market; as it requires additional hardware such as a large DC power supply, and a more involved electrical installation. Efficient use also likely requires the entire snow layer to be removed in one go, as to prevent otherwise unnecessary thaw-freeze cycles. It is likely beneficial to use the method in conjunction with mild weather, as to direct more energy towards melting rather than heating. A net benefit from electrical snow removal would require it to either increase the energy yield to a point that surpasses the energy used for heating, negate the costs or labor required to remove the snow by other means, or

prevent costly damage to the installation.

Further testing should be done on larger module groups and regard electricity use (and possible subsequent production gain), both for complete melting and for enabling snow shedding. To make the method accessible for the residential market, it would also be of interest to explore implementations that removes the need for an external DC power supply to deliver the required power, for example an adapted hybrid inverter.
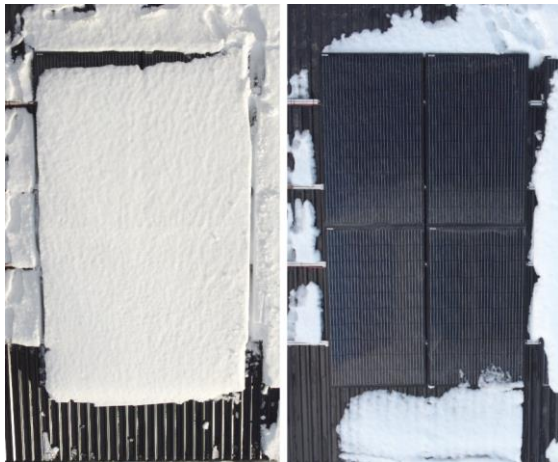

Figure 6. March 2nd, 2022, the ambient temperature ranged between +4–7°C. Left, snowpack separated from anchor points prior to heating. Right, successful snow shedding after heating.

3.3 Roof rakes

Both types of tested roof rakes could often remove most of the accumulated snow from their respective group. The roof rake with a slide did not completely remove snow due to the gap between modules and toolhead formed by the plastic wheels. The wheels and general design did however make it easy to use in most cases, but certain types of snow proved problematic. This included when snow was loose and grainy, very icy, or wet and compact. These conditions made it problematic to get the toolhead underneath the snow cover, especially with a fully extended telescopic handle, and very icy crusts made it difficult to cut through the snow. The rectangular roof rake also struggled in certain conditions. Dry and wind-packed snow often adhered especially well to the glass surface of the modules, which increased the required effort for snow removal markedly, especially with a fully extended handle, see Figure 7 for an example of performance in such conditions. Both methods struggled with snow that had experienced multiple thaw-freeze cycles and had icy crusts. The roof rake with a slide removed the snow without exerting significant stress on the modules. On the other hand, the long handle in combination with the weight at the toolhead of the rectangular roof rake made it difficult to handle and increased the risk of damaging the modules. In one case, the tool head was hence dropped above a module, resulting in a cracked cell wafer, see Section 3.5.

Figure 8 presents the experienced effort required for snow removal at different snow densities. At high snow densities, when the snow is very wet, the rectangular roof rake required less effort since the snowpack more easily slipped downwards at these conditions, whereas the slide roof rake was difficult to force through the dense snowpack. At lower snow densities, the slide roof rake in general required less effort.
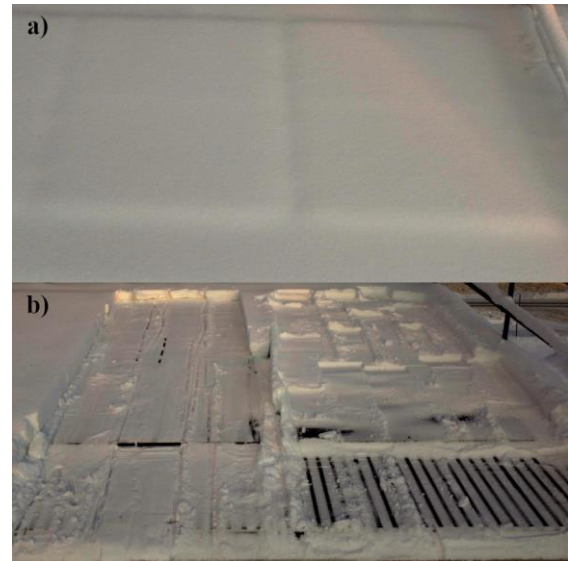

Figure 7. a) The roof rake groups prior to snow removal on December 15th 2021 and b) after snow removal. Left group, roof rake with slide, and right group, rectangular roof rake. Snow was dry and wind packed.
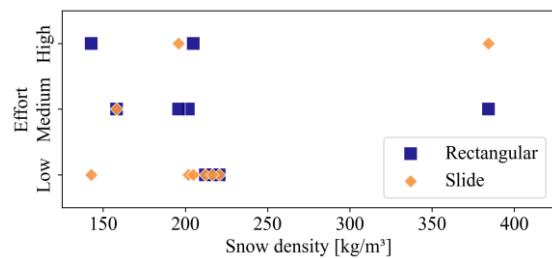

Figure 8. The effort required to remove snow of different densities with the two roof rakes.

The test facility proved to be especially well suited for these ground-operated methods due to the low roof eave. The use of telescopic tools is possibly only feasible for single-story roofs as longer handles are difficult to operate, thus increasing both risks and required effort. The underlying principles behind each method can however still be applied to other types of installations and tools but would require risk assessments and feasibility studies.

Removing snow completely with these methods proved difficult. The adhesion of cold snow to the modules' glass is significant. Complete snow removal was most easily achieved during mild and sunny days as snow which was wet from melting was far easier to remove, especially with the rectangular rake. However, leaving a few cm of snow can be beneficial since it reduces the risk of damaging the module during the final snow removal, and the thin cover was found to come off during sunny days. Leaving just a small part of the black modules bare would accelerate snow melting during sunny days as their surface would absorb more light than the surrounding snow and therefore heat up. Performing this kind of mechanical snow removal in conjunction with a snowmelt period could therefore have two benefits: avoiding crust formation and accelerating ambient melting.

Due to the risks of mechanical snow removal and the

labour intensity of complete snow removal, it might be preferential to focus on reducing loads, not removing them entirely.

3.4 Reasons for snow remaining on PV installation

The snowpack seemed to remain on the PV-installation for several different reasons. Snow on the roof eave below the modules might hinder snow shedding, as seen on the control module group in Figure 4b, likely due to more friction on the roof than the modules. Figure 5 indicates that this alone cannot explain why shedding did not occur for thicker snowpacks. The relatively small module groups as compared to typical PV-installations gives a proportionally large circumference relative to the area. This means that edge effects from frames, rails and neighbouring snow – that the snowpack can cling to - might have a larger than typical impact when the snowpack is thick enough to drape over the module groups' edges. Throughout thaw-freeze cycles these effects will likely grow more prominent. Figure 6 shows that once the snowpack was separated from these points of attachment, snow shedding could occur for the heated group. Lastly the frame edges also affect snow remaining on the PV installation through obstruction, as seen in Figure 4a, where the sharp edges of the SoliTek modules' frames are believed to prevent snow shedding.

This signifies the importance to consider the reasons for snow to remain on the PV installation, and how they affect performance, when designing and constructing a PV installation in a snow rich climate.

The increase in ambient melting from a partly exposed solar cell surface, as observed for the roof rakes, should be generally applicable regardless of what method is used. Thaw events might hence assist in snow removal, but subsequent refreezing is likely to further cling a remaining snowpack to the modules. It might therefore be less labour-intensive to remove snow prior to or in conjunction with a thaw event.

3.5 Crack formation

Modules on the lower row and not directly next to the roof edge would be subject to the largest snow depth and load. The largest snow load, estimated from snow depth and density, occurred on February 25th, 2021, and measured approximately 1 kPa near the heated, coated and control groups' lower modules. As snow had routinely been cleared from the roof rake groups, they did not exhibit the same load.

As previously mentioned, snow removal with the rectangular roof rake caused an entirely cracked cell. No further cracks were detected on any of the modules belonging to the roof rake groups. The modules of the lower row of the other groups did however all have cracks. They show a slight tendency of following an "X-pattern", which is associated with load related cracks [19]. The cracks imaged with EL in May 2022, their module group, and their relative position superimposed on a 60-cell module is presented in Figure 9 along an outline of the X-pattern. Cells in the coated modules *(SoliTek)* show crack formation with similar origin points for multiple cells, implying that these might be manufacturing defects that have remained undetected until they propagated to a noticable degree. As mentioned, these modules are rated for a load of 3.6 kPa compared to 5.4 kPa for the other modules *(Longi)*,

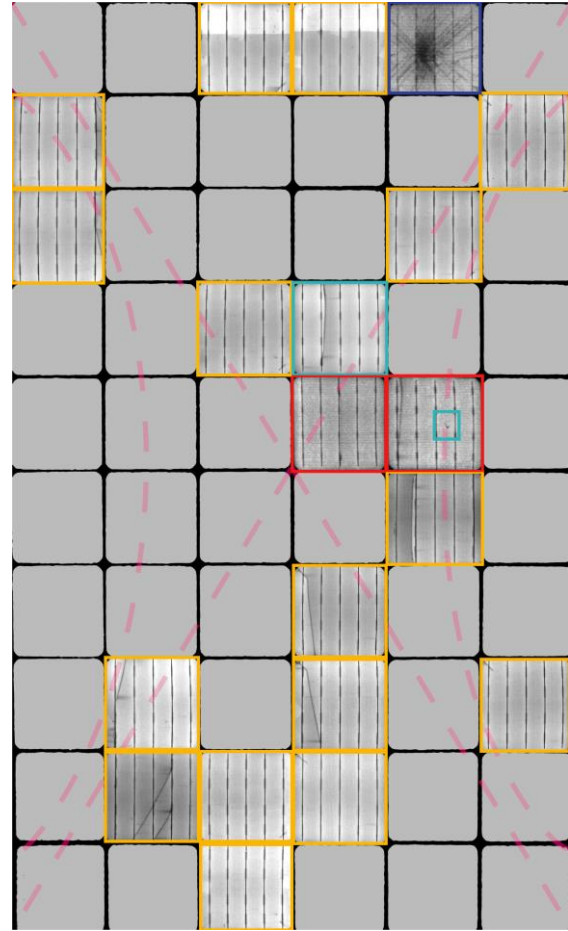which might also explain why more cells from these modules are cracked.

Figure 9. Superposition of cracked cells on a 60-cell module. Orange, surface coated (*Solitek*); red, electrical heating; light blue, control; dark blue, rectangular roof rake. Dashed lines represents the typical *X-pattern* for cracks formed by mechanical loads.

None of the cracked cells, except for the cell damaged by the rectangular roof rake, give rise to dark isolated areas, and might hence not significantly affect the modules' energy output at this point. The cracks might however be likely to grow larger throughout subsequent winters and mechanical load cycles.

It is notable that the heaviest measured snow load of approximately 1 kPa is much lower than what the modules were rated for. Most cracks were detected after the winter that this snow load was observed. Other studies have indicated that glass/backsheet modules are prone to crack formation at seemingly low mechanical loads when exposed to sub -20°C temperatures [1–3]. It is possible that this, plausibly in conjuction with prior defects from manufacturing, have led to the crack formation.

One might expect that it would be sufficient if the modules were rated for mechanical loads similar to or greater than the general construction requirements where they will be mounted. Although we cannot judge in every case for sure why cells have cracked, these results indicate that such is not necessarily the case, and emphasizes the disparity between conditions for certification tests and the real world. We believe that in

the long-term, certification procedures should include realistically low temperatures to better reflect real-world conditions. One way to circumnavigate this issue in the short term is to design PV-installations in such a way that they do not accumulate significant snow loads, for example by mitigating attachment and obstruction of the snowpack as mush as possible or opting for high inclination, with smaller snow depth and higher tendency of natural shedding.

We see a need for development of modules designed specifically for cold conditions, realistic module test procedures, and careful monitoring of the snow loads during operation and maintenance of a PV installation in snow rich locations.

4 CONCLUSIONS

The layout of a PV installation and the underlying roof, together with meteorological conditions and snow characteristics, impact which methods are best suited for snow removal. A simple roof rake with a rectangular toolhead works well when the snowpack is compact and not too thick, whereas a roof rake with a slide works better when the snow is dry and packed. Neither the investigated passive hydrophobic surface coatings, nor the active forward bias electrical heating methods induced shedding of the accumulated snowpack in our experiments without additional intervention. At our test facility in Piteå, the roof rake with a slide was the most effective and user-friendly snow removal method. Despite maximum snow loads of approximately 1 kPa, far below the modules' rating, cell damage was observed for the groups designated a snow removal method (except for the slide roof rake group) as well as the control group.

5 ACKNOWLEDGMENTS

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