MITIGATING SNOW ON ROOFTOP PV SYSTEMS FOR HIGHER ENERGY YIELD AND SAFER ROOFS

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This study investigates the potential and technical limitations of applying a controlled forward bias on photovoltaic (PV) modules for snow mitigation on building-applied photovoltaic (BAPV) systems installed in regions with substantial snowfalls. Mitigating snow on BAPV systems has a twofold purpose: to reduce the mechanical stress on the PV modules and the building structure itself, as well as to limit shading and thus increase the overall PV energy yield in the winter months. The technology is tested in both a climate chamber and under field conditions in an operating, commercial rooftop PV system covered with snow in Oslo, Norway. Payback time calculations for the snow mitigation is done both in terms of energy and economy, with the latter taking the national power tax into account.

Both in the climate chamber and initial full-scale rooftop PV system tests, the system was successfully demonstrated. Energy calculations show that there is large potential for optimization of the snow mitigation process to boost the PV system's energy yield in the spring. Hence, active snow mitigation can be a beneficial solution not only for necessary snow mitigation, but also for boosting the yield of PV systems.

Keywords: PV System, Rooftop, Safety, Snow

1 INTRODUCTION

In Norway, like in the rest of the world, the installed photovoltaic (PV) capacity is growing at an impressive rate. According to the International Energy Agency (IEA), 11.4 MW_p was installed in 2016, corresponding to a 366 % increase compared to the 2015 figures, giving a total accumulated PV capacity of 26.7 MW_p [1]. The largest part (7.4 MW_p) of the installed capacity in 2016 is made up of PV systems installed on roofs and facades of commercial/industrial buildings while the rest refers to residential and off-grid PV systems.

With regard to the Norwegian climate, there are several challenges that PV asset owners and operators are faced with. Snow during the winter is one of these. This is especially an important concern for PV systems installed on flat roofed commercial buildings, since many of these are under-dimensioned for carrying large snow loads during winter. Normally, manual snow removal is required to reduce the load, but when a PV system is installed on the roof, the process becomes more complicated and expensive. Rooftop PV systems in Norway are often installed with low tilt angles (in an east-west configuration), which will reduce the accessibility to large parts of the roof. Additionally, manual shoveling increases the risk of damaging the PV modules. Manual mechanic snow removal will be expensive, and is not recommended for PV systems [2]. In addition to being a risk for the building structure itself, large snow loads can also lead to physical failures and performance losses in PV modules [3].

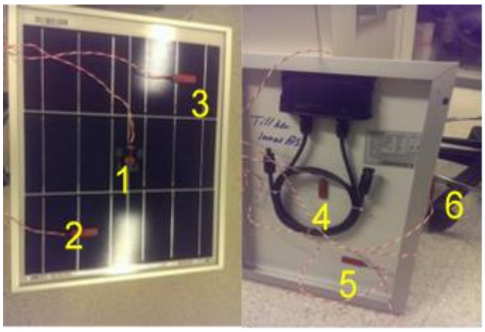
To solve these challenges the Norwegian supplier Innos [4] has introduced a snow mitigation system, WeightWatcher, which uses the heat generated by forward-biasing the PV arrays for melting and removing the snow from the modules' surface. Today, this system is primarily marketed for reducing the snow loads on the roof and the consequent risks for the building structures. However, it is well-known that snow reduces the power production in winter time significantly [5,6], due to reduced transmission and significant shading effects on the affected PV modules or arrays. The latter is known to increase the risk of follow-up hot spot effects. This raises the question of whether it is possible to optimize the snow mitigation process to reduce PV production losses from shading, and thus increase the net PV energy yield in the winter months.

In this study, the forward-biased PV modules' capability of melting snow is assessed. The temperature increase of a forward biased module is measured for different ambient temperatures and applied currents in a climate chamber. The technology is also tested under field conditions in an operating rooftop PV system covered with snow. To investigate the potential of using the system to increase PV generation in addition to load reduction, the energy consumption for heating up the PV modules and adequately melting the snow is calculated. Based on this, the potential of such snow mitigation practice for increasing the system's energy yield is quantitatively evaluated.

2 METHODS

2.1 Climate chamber tests

The technology was tested in a climate chamber set-up, at different ambient temperatures (+25°C, -1°C, -5°C and -10°C) and at different levels of current bias (10 A, 15 A and 19 A), provided by an external power source, to investigate the increase in temperature as a function of both variables. The tested module was a specially designed mini-module (prototype), consisting of 2×3 c-Si solar cells, with seven individual PT100 temperature sensors, to provide the module's thermal response at different positions (Figure 1).



Sensor	Position
1	Between cells, front
2	Middle of cell, front
3	Middle of cell, front
4	Between cells, back
5	Middle of cell, back
6	Frame
7	Ambient

Figure 1: Image of the test module with temperature sensors.

2.2 BAPV snow mitigation system

The WeightWatcher BAPV snow mitigation system was tested at a site in Oslo, Norway, installed at ASKO Norge by INNOS AS and Solenergi FUSen AS. In the WeightWatcher system, the PV modules are heated up by applying forward bias through an external power source. The system consists of 260 W multicrystalline and 300 W monocrystalline silicon modules, and is installed on a flat roof commercial building, where the modules are installed in an east-west configuration with a tilt angle of 10°. The installed capacity of the PV system with WeightWatcher technology is 1 MW_p. The applied current through the modules is 10A, which corresponds to approximately 45V per module depending on the modules' temperature. Heated channels are used to drain off the melting water from the roof. To avoid icing on the roof and on the modules during the melting process, the system is normally used when the ambient temperature is above -5°C.

2.3 Energy calculations

The energy calculations were done using clear sky modelling from the commercially available PVsyst software with the Meteonorm weather database [7] and subsequent analysis of melting energy obtained from field test data. In the PVsyst calculations the modelled PV-system was a miniature of the real system described above, with 20 x 260 W mc-Si modules in total, using an azimuth matching the real system. A clear sky model was used, with additional weather data from the Meteonorm database, using the systems coordinates in the Oslo-area.

To estimate the minimum payback time, the energy and economic calculations use the number of *consecutive clear sky days* (CCSD) needed to break even in terms of energy used and money spent on melting.

2.4 Snow mitigation test under field conditions

A field test of the snow mitigation solution was performed in December 2017, when there was a thin layer of snow on the PV modules (~1cm (1 kg/m^2)). The test involved 360 modules, with 20 modules per string. The temperature on the back and front surface of the modules was measured before and after melting. The back-surface temperature was measured with a portable TRI-SEN sensor from TRITEC with an accuracy of ± 3 %, and the front surface temperature was measured using a FLIR E-series IR camera.

An additional run was done in late March 2018, with a larger accumulated snow load, and the snow load sensors in place.

3 RESULTS

3.1 Climate chamber temperature tests

The average increase in temperature in measuring point 2 and 3 for different applied currents at different ambient temperatures is given in Figure 2.

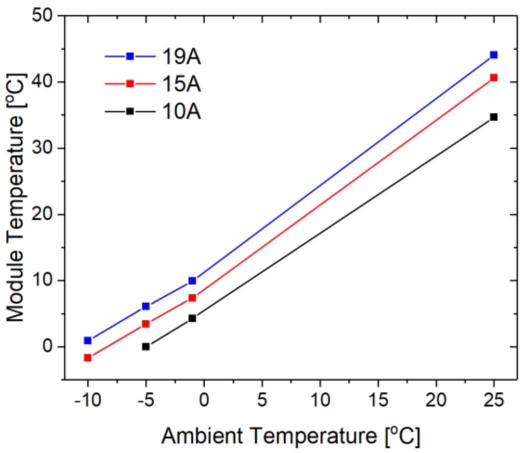


Figure 2: Temperature increase of the test module at different ambient temperatures and at different applied currents.

As expected, forwards bias heats up the module. The module temperature correlates positively with the applied current and increase in ambient temperature. The typical heating process of the module is shown in Figure 3. After a steady increase for approximately 1000 seconds, the module temperature saturates. The cooling of the module happens within the same time frame as the heating.

The temperature increase measured at the positions given in Section 2.1 for the investigated PV module at 10 A and different ambient temperatures, is presented in Figure 4. There are low temperature differences between the front and the back of the module, and in the middle and between cells. The low temperature of the frame might reduce the efficiency of the snow melting, as this might refreeze the melting water at low ambient temperatures.

3.2 Field validation – proof of concept

As shown in Figure 5, during the initial test of forward biasing snow covered modules under field conditions, the temperature of the modules increased, and the snow melted. Before the test, the temperature of the back and front surface was respectively -10.5°C and -10°C. At the end of the test the corresponding measured temperatures were -1°C and 0°C. During the test, the ambient temperature was slightly below what climate chamber tests indicate is necessary for efficient melting, making the process slightly harder than under normal operation. Despite this, most of the snow was removed from the modules within 45 minutes of operation time. Thus, the temperature increase was slightly above what is expected from the climate chamber results for such low ambient temperatures, and is likely due to limited heat transport in the field due to the isolating properties of the snow layer.

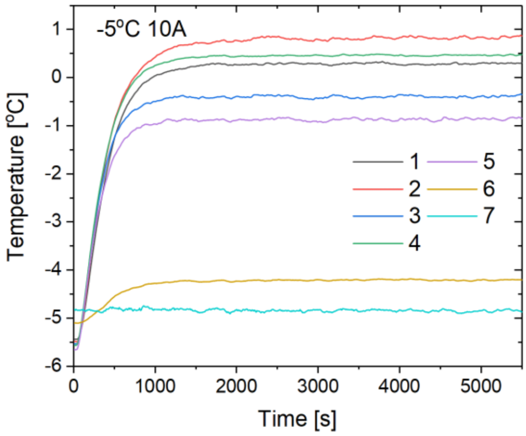


Figure 3: The increase in temperature as a function of time at an ambient temperature of -5°C and an applied current of 10 A.

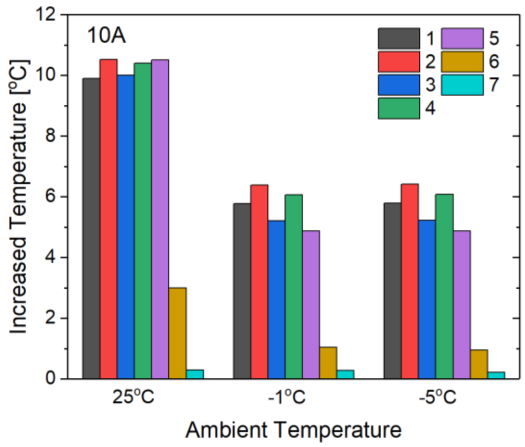


Figure 4: Increased temperature at different ambient temperatures for an applied current of 10 A.

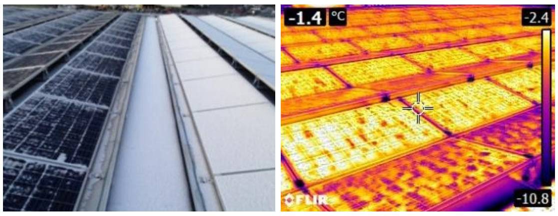


Figure 5: Left: The PV modules in the WeightWatcher system [3] after 30 minutes of forward bias, compared to unbiased modules. Right: IR-photography of forward biased, partly snow covered, modules.

The snow load data recorded by the system before, during and after the melting done in March can be seen in Figure 6. It is compared to snow load estimates from the Norwegian Water Resources and Energy Directorate [8] at the ground level of the site of the system for 2018. The data recording started on February 13th and contains one active melting on March 24th. The measured snow load on the roof is lower than the estimates, which is likely due to an offset in load sensor calibration, and possibly leakage of heat through the roof, causing some of the snow to melt on the hotter days. The active melting makes the roof snow free 25th of March, while the snow remains on the ground until the 15th of April, according to the snow load estimates. This indicates that due to the active melting it was possible for the PV system to produce power three weeks before what would normally be the case. Because the snow load data set only consists of 45 snow days, and system tests have been done on the roof during winter, it is difficult to say how well the snow load estimates from [8] translates to the building roof. It is however, assumed that the estimates are a good approximation of roof snow loads during a normal winter, with no interference from the WeightWatcher system.

The above mentioned melting was a test run of the system, and the roof snow load was not critical. However, should it be critical in months with less sun than March, a melting in e.g. January would still reduce the roof snow load through the spring months, and ultimately result in snow free modules earlier than natural snow melting. Which means that if a melting during mid-winter results in snow free modules earlier in the spring, there would still be a window, like in Figure 6, where it would be possible to return the energy invested in melting – and possibly even produce more energy than invested.

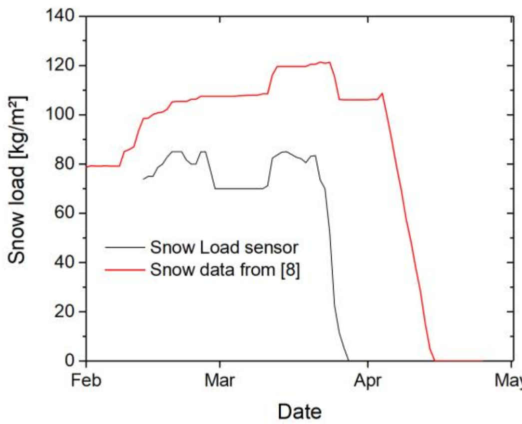


Figure 6: Snow load data from the WeightWatcher system and snow load data from seNorge.no [8] for 2018.

3.3 Energy payback time calculations

The daily clear sky DC energy output per square meter calculated in PVsyst can be seen in Figure 7. Because of the latitude of Oslo, the seasonal variations in production are large, from under 0.025 kWh/(m^2 day) December 22nd, to over 1.1 kWh/(m^2 day) June 1st. From this the *energy payback time* (EPBT) of running the system under different conditions has been calculated below. The metric chosen is *consecutive clear sky days* (CCSD), which, as mentioned above, represents the minimum theoretical payback time. This means that a melting at any given time through the winter and spring will result in a need for a given number of CCSD to return the energy investment. This naturally means that the number of CCSD needed after melting under similar conditions in December and April will result in a larger number for December, due to the low production during a December clear sky day.

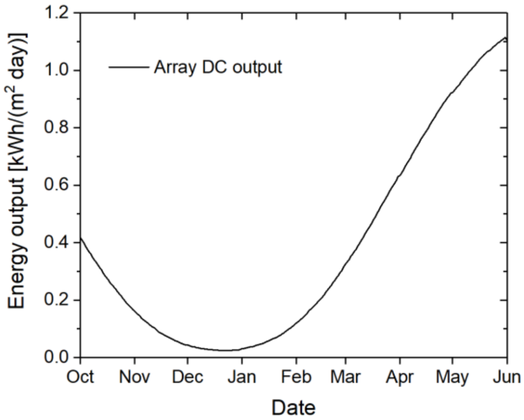


Figure 7: PVsyst clear sky model output through the year.

The number of CCSD needed to return the energy invested in melting 10 kg/m^2 of snow given melting energies of 0.15, 0.1 and 0.05 kWh, a given date from October through May is shown in Figure 8. The melting energy is the amount of energy in kWh needed to melt 1 kg snow. This number is very dependent on conditions when melting. Ambient factors play a large part, where lower temperatures require larger energies like demonstrated by the climate chamber tests above. The same is true for wind, as this will contribute to module cooling. This means that unless the snow load approaches critical values, melting should preferably be done on relatively hot days with no wind, which will also help reduce ice generation on the modules.

Here 0.15, 0.1 and 0.05 kWh/kg is chosen because this is in the range that has been observed in initial melting tests in the field. Since melting energy is directly proportional to the energy needed for melting a given snow load, it largely impacts the CCSD needed to return the energy investment. In the calculations below, 0.1 kWh/kg is used, as this is close to the average observed through the initial testing. More tests should be done under better defined conditions to be able to report more accurate numbers for the melting energy for different conditions.

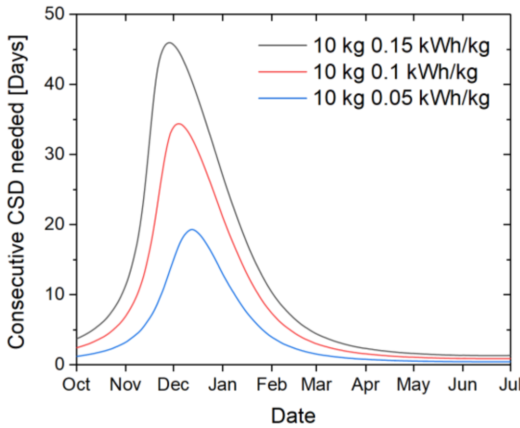


Figure 8: The number of clear sky days with varied melting energy needed per kg.

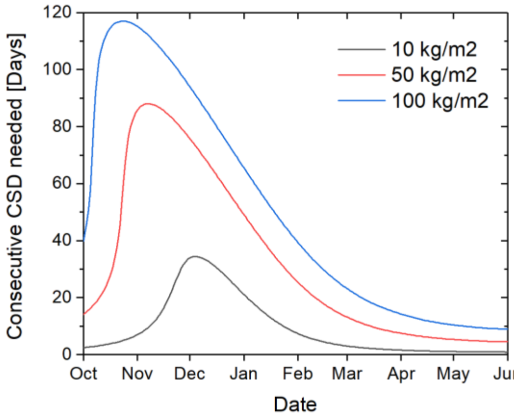


Figure 9: The number of clear sky days needed for melting every day through the winter.

Another important factor in the EPBT calculations is the snow load melted. Figure 9 shows the number of CCSD needed to melt a snow load of 10, 50 and 100 kg/m^2. Naturally, an increase in snow load increases the EPBT and shifts the worst melting date from early December to late October. For 10 and 100 kg/m^2 the number of CCSD needed after melting is just above 30 and 115 days in early December and late October, respectively. However, the 1st of April less than two CCSD are needed to return the energy for 10 kg/m^2. For a larger snow load of 100 kg/m^2 the number is 14 days, which still is a commercially interesting number compared to the test data for the spring of 2018, where the use of the snow mitigation system potentially allowed for increased production for 21 days.

Since the WeightWatcher system first and foremost is a system installed for safety, in order to mitigate snow from under dimensioned roofs before, during or after heavy snowfalls, and keep the roof from collapsing, the need for an active melting event mid-winter is to be expected. This would lead to large CCSD numbers with regards to the EPBT. Potentially, the larger the snow load melted mid-winter, the earlier the roof will be bare compared to the surroundings, and the larger the window for power production in the spring could become. It should also be noted that to have the shortest payback time, weather forecasts for temperature, wind, and snow precipitation should be utilized, to avoid ending up having to melt excessive snow loads in cold or windy weather, and ultimately increase the power investment needed.

3.4 Economic Payback time

The economic payback time of melting snow is a complex calculation and is done here in a somewhat reduced form. The extra installation cost of the power supply for the system is not considered, and neither is the potential savings from not having manual snow removal from the roof. In other words, these calculations only show the potential economic gain due to increased energy generation, given that the system already is installed because of necessary load reduction. In addition, the calculations assume that all the generated power is used in-house, and not exported to the grid. The price for importing power from the grid is much higher than the price received for export, meaning that the payback time could potentially be considerably longer.

The most important factor for economic payback time for melting in Norway is the monthly Power Tariff (PT) cost. This is calculated from the monthly peak power point times the PT rate. The PT rate varies through the year, which is illustrated in Figure 10. Here the y-axis shows the full Power Tariff cost of turning on the melting system, per square meter, while the real PT rate is shown below each step in the graph. The price per square meter is calculated using the system module voltage and current, divided by the module area. As the figure shows the PT rate is at its highest during winter.

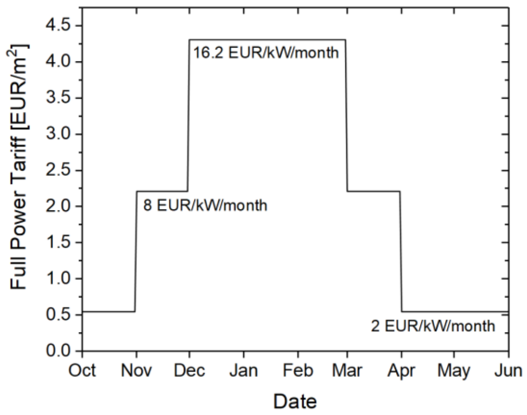


Figure 10: Power Tariff costs through the year. The y-axis represents the full power tariff cost for melting per square meter, while the EUR/kW/month values in the plot represent the base power tariff cost.

How the PT rate affects the cost of melting snow can be seen in Figure 11. It can be seen that the price of just turning on the system is 4.3 and 2.2 EUR/m^2 in Dec-Feb and Mar/Nov, respectively, if the entire power consumption from melting increases the monthly peak load value. Surprisingly the energy cost is close to negligible compared to the initial PT cost, using a power price of 0.063 EUR/kWh (0.6 NOK/kWh). This implies that to cut melting costs it is paramount to have exact control of peak loads and avoid melting when the melting power consumption will increase the monthly peak load.

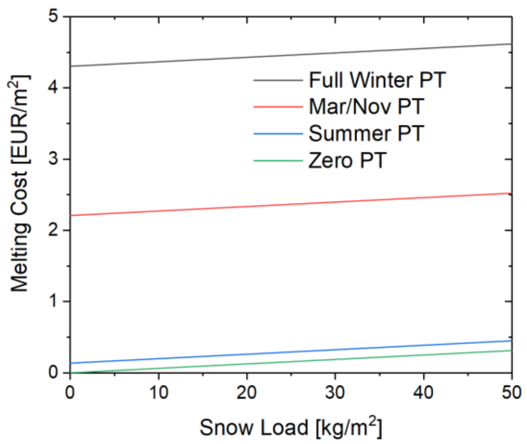


Figure 11: The price of melting snow as a function of snow load, with the different PT rates represented by each line.

Figure 12 shows the number of CCSD needed to pay back the snow mitigation, given the different PT rates though the year. As can be seen, melting done at times where the monthly peak load is increased, increases the CCSD needed. If melting triggers full PT costs during winter (1st Dec-28th Feb), the CCSD needed in early December becomes 170 days. Interestingly, this also gives an CCSD number of over 90 in early March and over 60 in the end of May. This means that the modules would have to become and stay snow free three clear sky months before they naturally would in March. For the Mar/Nov PT rate, the CCSD number is just below 60 in early March, and just above 30 in the end of May, which is better, but still kills a lot of the profitability of both the melting, and the PV system in general. However, if the melting is done without raising the monthly peak load, the CCSD needed becomes the same as in Figure 9, and for 10 kg/m^2 this means 3 days in early March. The short payback time for no PT makes it possible to forecast based on weekly weather forecasts, whether a melting at a given day would be profitable.

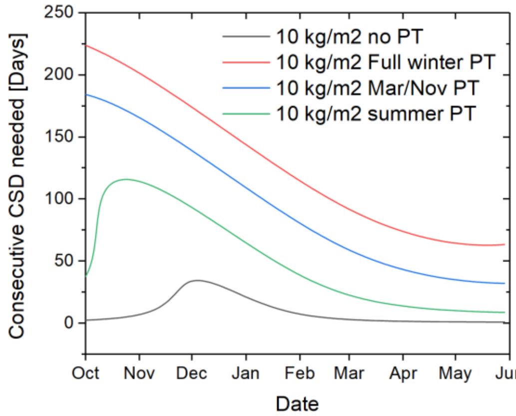


Figure 12: The number of CCSD needed to pay back the money invested in melting snow, given the different PTs through the winter.

4 CONCLUSIONS

In this work a snow mitigation solution and its application potential for rooftop PV systems has been presented and assessed. The discussed application is based on forward-biasing and thus heating up snow-covered modules, until they get snow-free. The concept was validated both in a climatic chamber under controlled ambient temperature and forward-bias (on a mini-module prototype), and under real-field and full-scale conditions, on a rooftop PV system. In addition, calculations on the energy – and economic payback time show that it is possible to return both energy and economic investment of the snow mitigation, and that it is possible to earn money by mitigating the snow to increase PV production, given that the system is already installed because of necessary load reduction. This does, however, require delicate peak load control and utilization of weather forecasts, to hinder that power used to mitigate snow does not increase the monthly peak load of the facility or require more energy than potentially needed.

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