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A FEASIBILITY STUDY OF PHOTOVOLTAIC SNOW MITIGATION SYSTEMS FOR FLAT ROOFS

STUDIUM WYKONALNOŚCI FOTOWOLTAICZNYCH SYSTEMÓW OGRANICZANIA ŚNIEGU DLA DACHÓW PŁASKICH

Abstract

A new photovoltaic system combining electrical power production with snow mitigation intends to reduce the snow load on flat roofs. Applying electrical power to PV modules causes heat production on the module surface, allowing the ablation of snow. This study combines measurements and theoretical analysis to investigate which conditions are favourable for snow load reduction and discusses the system's feasibility to perform a controlled snow load reduction in a heavy snow load scenario for buildings with flat roofs. Both melting and sublimating of snow are investigated as means to reduce the load. The results show that the potential for load reduction is highly dependent upon weather conditions and snowpack characteristics during system operation. The refreezing of meltwater and water saturation of snow are identified as phenomena potentially preventing sufficient load reduction in cold conditions. Due to such temperature sensitivity, the system is likely to be more suitable for warm climates occasionally experiencing heavy snow loads than for climates with long and cold winters.

Keywords: snow, PV systems, load reduction, roofs, reliability, climate robustness

Streszczenie

Nowy system fotowoltaiczny łączący produkcję energii elektrycznej z ograniczaniem śniegu ma na celu zmniejszenie obciążenia śniegiem na dachy płaskie. Zastosowanie energii elektrycznej w modułach fotowoltaicznych powoduje wytwarzanie ciepła na powierzchni modułu, umożliwiając ablację śniegu. Niniejsze badanie łączy pomiary i analizę teoretyczną w celu zbadania, które warunki sprzyjają zmniejszeniu obciążenia śniegiem i omawia możliwości systemu w zakresie kontrolowanej redukcji obciążenia śniegiem w scenariuszu dużego obciążenia śniegiem dla budynków z płaskimi dachami. Zarówno topienie, jak i sublimacja śniegu są badane jako sposób na zmniejszenie obciążenia. Wyniki pokazują, że potencjał zmniejszenia obciążenia zależy w dużym stopniu od warunków pogodowych i charakterystyki śniegu podczas pracy systemu. Ponowne zamoczenie wody morskiej i nasycenie wody śniegiem są identyfikowane jako zjawiska potencjalnie uniemożliwiające wystarczające zmniejszenie obciążenia w niskich temperaturach. Ze względu na taką wrażliwość na temperaturę system może być bardziej odpowiedni do ciepłych klimatów, czasami doświadczając większych obciążeń śniegiem niż w klimatach o długich i zimnych zimach.

Słowa kluczowe: śnieg, systemy PV, redukcja obciążenia, dachy, niezawodność, odporność na klimat

1. Introduction

Due to climate change and the continuous updating of design standards, parts of the existing building stock are not well adapted to the environment in terms of reliability. Increased knowledge of the environmental loads imposed on buildings is the driving force for updating standards to better represent the actual loads occurring. The development of standards has led to many existing buildings being regarded as under-designed in the current design regulations. The temporal change of the ground snow load in Norway is an example which illustrates how increased knowledge influences our design standards. Meløysund et al. [17] describes how the ground snow load has developed from a general load with little variation, to a load varying with the local topography and the local climate. This is exemplified through the development of the ground snow load in Norway, which has evolved from being 1.5 kN/m^2 for the whole country in 1949 to ranging from 1.5–9.0 kN/m^2 in the current national annex [23]. The differentiation of the snow load results in many existing buildings being regarded as under-designed in the current regulations. Meløysund [16] states that 4.5 % of the total bulk of buildings in Norway may have too low a capacity according to current regulations.

In addition to the under-design of the existing building stock, a change in the environmental loads is expected due to climate change [3, 14, 21, 24, 25]. The global trend of climate change is that we will have increased winter temperature and winter precipitation. The increase in temperature will determine whether the precipitation falls as rain or snow, and will influence the change in the snow load [21]. For this reason, the snow cover in climates with mild winters should be more sensitive to an increase in temperature than climates with colder winters [15]. However, it is the case that even if the increased temperature leads to more precipitation falling as rain, it will not necessarily lead to a reduction of the snow load. This is due to the effect of snow absorbing the rain and increasing the load as a consequence [25]. Although it is predicted as a global trend that snow cover will reduce [11], several studies show that snowfall is expected to increase in cold areas [13, 22]. Croce [3] states that the sensitivity of snow cover to precipitation and temperature is highly related to topographic features such as the elevation aspect and terrain shading. On this basis, it is reasonable to assume that the change in snow load should be estimated on a regional scale. A report on the expected change in the characteristic ground snow load for Norway in the period 2071-2100 predicts that the snow load will be reduced for most municipalities, but thirty-four municipalities expect a significant increase in the load [14]. The authors of the report recommend that the characteristic snow load for the thirty-four municipalities should be increased.

The historical updating of standards due to increased knowledge of environmental loads together with the expected change in climate signifies a future discrepancy. Buildings are designed with a long life cycle of 50-100 years and are likely to experience a different environmental impact than what they are designed for.

If a building is under-designed with respect to snow load, there are certain measures which could be performed in order to increase the reliability of the structure. Structural health monitoring (SHM) can be performed at an early stage to determine the state of the building and provide a basis for further improvements [4]. Retrofitting through upgrading the structural capacity of the building is a permanent measure, but often proves costly for the building owners. Manually removing snow off the roof is a measure which can be performed in the case of heavy snow loads, but relies on knowledge of the snow load on the roof and on having the available labour to remove the snow at the right time. Shovelling snow off roofs is also highly correlated with accidents [2, 12].

Buildings that are under-designed with respect to snow load are often prevented from having PV systems on the roof surface due to the additional weight. Roofs are especially suitable for having PV systems in urban environments due to them being large flat surfaces with high solar irradiation, favourable wind conditions and accessible for maintenance. Roof surfaces are often unutilised, even in densely populated areas.

2. Photovoltaic snow mitigation systems

Photovoltaic snow mitigation systems combine electrical power production with snow removal. If PV-cells are subjected to forward bias, heat is produced due to the electric resistance in the cells. The heat development on the surface of the PV-cell enables the ablation of snow and presents a new application for PV-systems. The photovoltaic snow mitigation system can serve the following three possible purposes:

- as a measure for under-designed roofs to increase snow load robustness,
- releasing roof area for PV-purposes previously indisposed due to limited load capacity,
- increasing yield of PV-systems through melting snow when the typical seasonal snowpack is present.

This study focuses on the first two purposes described above. The latter purpose has previously been briefly researched by Frimannslund [7] and more thoroughly by Aarseth et al. [1].

If the intent of the system is to reduce snow loads on flat roofs; the snow should be kept on the modules. Snow load reduction on flat roofs relies on melting the snowpack from the bottom up, and requires modules with a low angle tilt due to the sliding of snow. For increasing yield through removing snow from the modules, a tilt could be beneficial because sliding snow off the modules requires less energy than melting the entire snowpack.

Applying heat to the bottom of the snowpack will gradually increase the temperature of the snow towards 0°C. A thick snowpack reduces heat loss to the ambient environment, enabling a steady increase in temperature and a gradual melting process on the module surface. For load reduction to be effective, meltwater must be transported off the roof.

Sublimation, the instant transition from solid to vapour, can serve as another means of load reduction when melting is difficult. Sublimation occurs naturally in snow when there is a higher partial pressure of water vapour in the snowpack than in the air. The difference creates a gradient in specific humidity, causing transportation of mass from the snowpack to the air. The natural process of sublimation in the snow can simply be amplified by applying power to the modules when the conditions are right. A formula calculating latent heat flux due to sublimation illustrates the factors influencing the process:

$$Q_{BF} = \rho L_s C_E u_a \left(q_s - q_a \right) \tag{1}$$

where is the air density, is the latent heat of sublimation, is a transfer coefficient of latent heat, is the wind speed, is the specific humidity of the snow and is the specific humidity of the air. In order to induce the sublimation of snow on the PV-surface, the temperature should be close to, but never above, 0°C. Sublimation also occurs above freezing; however, this results in additional melting and necessary transportation of the meltwater. By keeping the temperature of the module close to zero, the partial pressure of water vapour in the snow increases, creating a vapour gradient and transportation of mass from the snow to the air. Sublimating snow is nevertheless far more energy consuming than melting snow. The energy required for sublimating snow at 0°C is equal to the combined energy it takes to melt and vaporise snow at 0°C [19]. The amount of energy required to induce a phase change in water is given by the latent heat constants presented in Table 1.

Table 1. Latent heat constant for phase changes in water [19, 27]

Phase change	Temperature	Latent heat constant [kJ/kg]
fusion	0°C	333.5
vaporisation	100°C	2257.0
sublimation	0°C	2830.0

The latent heat constant for sublimation is approximately 8.5 times higher than the latent heat constant for fusion. This means that it takes 8.5 times as much energy to sublimate water as it takes to melt it at 0˚C. Another way to put it is that you will have 8.5 times less ablation when sublimating compared to melting for the same energy input.

Applying forward bias to PV modules is a common way of checking the quality of the modules for defects in the manufacturing process. This is achieved with a limited electrical effect and is possible for any module regardless of the manufacturer. However, the degradation effects of applying forward bias to PV-modules over a long term is poorly documented.

In order to apply forward bias to PV-systems, rectifiers converting AC-current from the grid to DC-current are necessary. Alternatively, DC-current can be applied directly from batteries. PV modules are commonly designed with bypass diodes to only let the current pass one way, due to the unwanted effect of reverse bias. DC current must therefore be applied in the same direction as when producing power. Rectifiers are in principle the only additional component a normal PV-system needs to induce heat production on the module surface and use it for snow mitigation purposes.

In order for the photovoltaic snow mitigation system to become a widespread solution for under-designed roofs, it must be included in the framework of the international standards for structural design. The ISO standard for the determination of snow loads on roofs [10] provides a framework for reducing the design snow load based on a reliable control device or method able to reduce the snow load. The framework is presented in Annex F, entitled *Snow loads on roof with snow control*. To be able to reduce the designed snow load, the respective system's abilities for reducing the snow load for a given evaluation period must be documented.

3. Material and methods

3.1. Site description

Photovoltaic snow mitigation systems are a relatively recent invention and only a few buildings are equipped with such systems. One of the first buildings with a photovoltaic snow mitigation system installed on a flat roof was a warehouse building in Oslo, Norway. The system was designed by Innos AS and is called Weight Watcher [8]. The roof with the installed PV system is shown in Fig. 1. The system monitors the snow load imposed on modules through load sensors installed on the module rack. When the load reaches a certain limit, power is applied to the PV system and melting is initiated. The system was used for tests in this study, including a snow load reduction test and an aerial thermography of the system being applied forward bias.

The roof has a surface of approximately 1980 m^2 and is designed for a characteristic snow load of 1.5 kN/m^2. The PV system on the roof consists of 720 modules, orientated 66°/246° (East-North-East, West-South-West), each row facing the opposite direction of the previous row. The modules are tilted at an angle of 10°.

A customised drainage system is installed on the roof, designed for transporting meltwater off the roof surface. The drainage system is made of gutters between the rows of modules as

Fig. 1. The Weight Watcher system installed at the warehouse

illustrated in Fig. 1. Each gutter drains water from two rows and is heated in order to prevent the refreezing of meltwater. The gutters lead to the edge of the roof where water is disposed through scuppers.

3.2. Aerial thermography of a photovoltaic snow mitigation system

Thermography of the PV-system applied forward bias at the warehouse in Oslo was performed using a customised unmanned aerial vehicle with an infrared camera. The intent was to document the temperature distribution across the system and the location of possible hot spots and defects. The thermography was performed without an existing snow cover on the roof. Two maps were made showing the temperatures on the roof when half of the PV-system has forward bias applied. The maps were made by taking many single overlapping infrared images of the roof from heights of 50 and 30 meters. An infrared 3D-model was made by combining individual, infrared images using photogrammetric software for drone-based mapping [20]. The 3D model was then projected into the horizontal plane, creating 2D maps. The maps were calibrated for emissivity and atmospheric radiation [7, pp. 60-61] using FLIR Tools [6]. Calibration points were created on the roof surface, which was necessary to characterise individual modules on the uniform PV-system and to create the infrared 3D model.

3.3. Load reduction test of a full-scale photovoltaic snow mitigation system

A load reduction test of the full-scale facility at the warehouse was performed in February 2017. The objective was to test the performance of the snow mitigation system and to investigate the drainage system. The average snow depth on the day of testing was approximately 5 cm, which was too low to create a continuous snow cover across the modules, thus leaving the panels exposed to the wind. Due to the thin snowpack, the test cannot be said to be a true load reduction test. Load reduction is not usually necessary for snow loads less than the design snow load, which equals 75 cm of snow with an average density of 200 kg/m^3 for the warehouse roof. The test was performed not to reduce the load itself, but with the intent of documenting the physical process occurring when melting snow with PV-modules. The weather conditions on the day of the testing was partly cloudy with a temperature of -7 °C and an average wind speed of 6 m/s. The wind blew perpendicular to the rows of modules, from East-North-East. Three strings of modules were applied power for a duration of 2:00 hours. Temperature and humidity levels on the module surface and in the ambient environment were logged through the test.

3.4. Case study with single modules

In addition to testing the photovoltaic snow mitigation system at the warehouse in Oslo, a case study investigating different possible snow load reduction scenarios was performed. The purpose was to investigate the snow metamorphism occurring on the modules when applying forward bias of different intensities under varying climatic conditions. With three PV-modules, two rectifiers and the required cables, a system was setup in Nordmarka, Norway.

Fig. 2. Setup for the case study – the module to the left is a reference module, while the two to the right are active modules connected to rectifiers able to apply forward bias

Three different snow load reduction scenarios were performed:

- melting old, wet snow in ambient temperatures above freezing,
- melting fresh snow in cold conditions,
- sublimating snow in cold conditions.

The two melting cases were performed with a relatively high effect of 268.8 W/m^2 for the first case, and 762.5 W/m^2 for the second case. Both cases were conducted over the course of 3.5 hours each. Here, snow was shovelled onto the modules. The sublimation case was performed after a fresh snowfall of 14 cm. This case was conducted over a time span of 58 hours with an average effect of 29.8 W/m^2. The average air temperature was -9.3°C and the average humidity was 86.3%. The temperature of the modules was adjusted to be as close to zero as possible, without ever exceeding this limit. For all cases, temperature and humidity was logged in the top and bottom of the snowpack for both the unheated reference module and for the active modules. Ambient temperature and humidity was also logged. Load reduction was calculated using depth and density measurements both before and after applying forward bias.

4. Results

4.1. Aerial thermography of a photovoltaic snow mitigation system

The temperature maps were produced using aerial thermography of the photovoltaic snow mitigation system being applied forward bias. The thermography was conducted at the warehouse in Oslo when no snow was present. The first map provides an overview of the system with its surroundings.

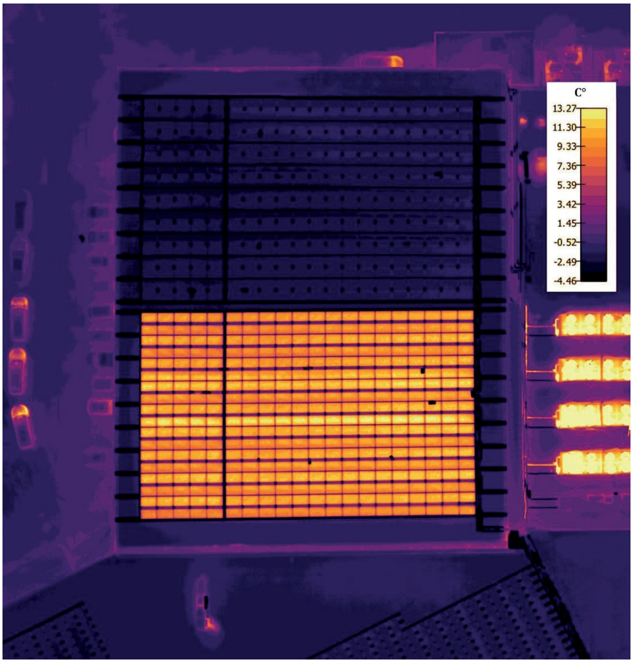

Fig. 3. Temperature map of the photovoltaic snow mitigation system; half of the system has forward bias applied

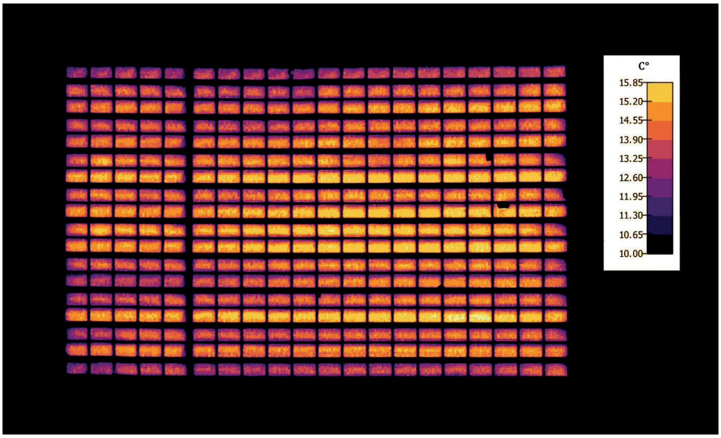

Fig. 4. Temperature map highlighting detail of the photovoltaic snow mitigation system with forward bias applied

The temperature map is created from 79 single images taken from a height of 50 m. The temperature scale is set to a wide range which includes the temperature of the surroundings. The map comprises surrounding objects such as recently used cars, smaller buildings at ground level, and the cooling system that is clearly running to the right on the map. The black dots at the modules are calibration points as described in Section 3.2.

The second map excludes the surroundings and amplifies the details of the modules emitting heat.

The temperature map is created from 68 single images taken from a height of 30 m above the roof. The temperature scale is set to a narrow range, amplifying the details and excluding the surroundings. In addition to the small temperature differences on the modules, there appears to be a pattern of equal temperatures in the strings of modules. Modules on the same string have similar temperatures, from one end to the other. The highest measured temperature on the PV-system was 15.85 °C, while the temperature of the air was approximately -4.7 °C [18].

4.2. Load reduction test of a full-scale photovoltaic snow mitigation system

Shortly after applying forward bias to the three strings, the temperature increased on the module surface. For the East-North-East rows facing the wind, the snow melted on the module surface only to be refrozen on the rim of the frame. An ice cap was created over the module, as shown in Fig. 5. Underneath the ice cap, there was liquid water, encapsulated by the module and the ice. The meltwater did not reach the heated gutters directly beneath the modules, and there was no significant load reduction. The refreezing of meltwater did not occur for the rows facing West-South-West, which were sheltered from the wind.

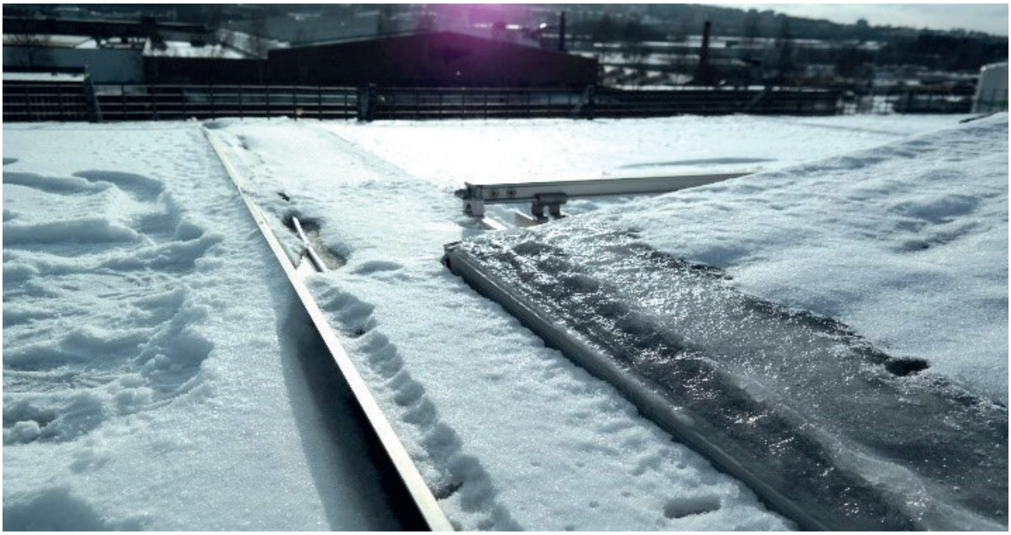

Fig. 5. An ice cap formed on the lower edge of the modules that were facing the wind. The heated gutter can be seen under the module, stretching towards the edge of the roof

4.3. Case study with single modules

The first case involved melting old wet snow in ambient temperatures above freezing. When forward bias was applied to the modules, the snow melted on the module surface and created a small layer of water-saturated snow on the module surface. The water drained efficiently despite the module not having a significant tilt. In the second case, the layer of snow on the modules was from a recent snowfall and had the light, fine structure that fresh snow often has. The temperature was below 0°C when the experiment was conducted. In this case, snow melted on the module surface and a significant amount of meltwater was sucked into the capillary pores of the dry snow. At the end of this test, a 5-cm-thick layer of slush was observed at the bottom of the module as shown in Fig. 6.

Fig. 6. A 5 cm slush layer was observed at the bottom of the snowpack at the end of the second melting test

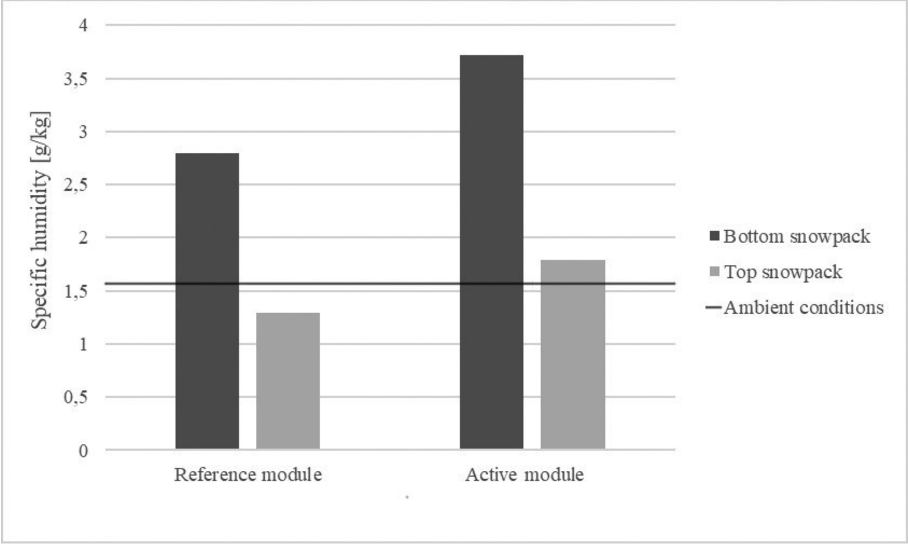

Fig. 7. Graph showing the average logged specific humidity of the reference and active module at the top and bottom of the snowpack in relation to the ambient conditions

The third case involved sublimating snow in cold conditions. At the end of the test, a clear dent in the snowpack was visible on the active modules, indicating a change in the snowpack. The temperature and humidity loggers document the change in specific humidity for the active and reference modules providing information indicative of the change in mass. Figure 7 illustrates the average specific humidity at the top and bottom of the snowpack based on the logged temperature and humidity.

The temperature and humidity loggers shows an increase in temperature on the module surface towards 0°C when forward bias is applied, and a corresponding increase in humidity in the snowpack. The partial pressure of vapour was highest at the bottom of the snowpack where heat was applied, and decreased towards the top of the snowpack. The partial pressure of water vapour for the modules applied forward bias was generally higher at the top of the snowpack than in the air, implying the transport of moisture from the snowpack to the air. For the reference module, the partial pressure of water vapour was higher for the air than the top of the snowpack, indicating condensation. This corresponds with measured changes in weight where the active module lost weight and the reference module gained a small amount of weight. The weight reduction was calculated by comparing the density and the snow depth measurements before and after the test. The average weight reduction for the active module was measured at 0.86 kg/m^2 per day. The total energy applied to the modules was 2299.2 kJ per kg of sublimated snow. At the end of the experiment, an ice sheet was uncovered on the surface of the active modules, although the loggers show that temperatures did not exceed zero. The ice sheet was thin and porous and covered the entire module surface.

5. Discussion

The results from the experiments highlight the importance and possible difficulties of transporting meltwater away from the roof due the risk of refreezing and water saturation of the snow. This is illustrated in the load reduction test at the warehouse, which resulted in meltwater freezing directly at the module. The refreezing of meltwater obviously contributes to insufficient load reduction, but it can also cause an unfavourable redistribution of load if water accumulates on the roof surface before refreezing.

However, the test at the warehouse is not entirely representative of a real snow load reduction scenario. Melting with the intent of reducing the snow load is only required for larger snow depths imposing a high load. The insulating effect of snow will increase the temperature on the module surface and will also provide shelter from the wind. Melting snow in cold conditions is therefore likely to be more easily performed for thick than for thin snowpacks.

The case study with single modules showed that the snow's capacity for being saturated with water is highly dependent on the microstructure of the snow, and is an important factor for the drainage conditions on the roof. The snow's ability to suck up meltwater on the module and roof surface inhibits the drainage of water and the subsequent load reduction. A slush layer on the module or roof surface will continue to delay the drainage until the snow is fully saturated and cannot hold more water. The case study showed that if the snow is fresh and dry, it has a larger buffer capacity for holding water than older and more grainy snow. Draining meltwater from old and grainy snow, typically present in spring, is therefore likely to be less problematic than for snow with a fine microstructure that is typical of mid-winter conditions. Water saturation of the snow also increases the consequence for freezing of meltwater if the weather conditions change. If such a slush layer was to freeze, it could result in an ice sheet on the roof surface, further preventing drainage.

Poorly insulated roofs are subject to significant heat loss through the roof surface, increasing the temperature under a thick snowpack, favourable for drainage with respect to the refreezing of meltwater and the water saturation of snow. For roofs with significant insulation, heated gutters are recommended to improve the drainage conditions. Either way, a heat supply preventing the refreezing of meltwater in an unobstructed pitched flow path is crucial for the transportation of meltwater away from the roof when melting snow in cold conditions.

A phenomenon involving the formation of snow bridges over the PV-modules as melting is initiated was not observed in the load reduction tests, but it is a common occurrence in applications involving the melting of snow with heat cables in, for example, gutters and drains. If snow is melted from the PV-surface and the snow cover above does not collapse as the snow is melted away, a cavity can form between the PV-surface and the snow, forming a bridge of snow over the modules. The formation of such snow bridges can be reinforced by evaporating water from the roof or PV-surface condensation and freezing onto the snow. A cavity might also result in enhanced air infiltration, increasing the risk of freezing melt water. Such a phenomenon is dependent upon snowpack characteristics, weather conditions and the density of PV-modules on the roof surface.

As cold conditions can cause phenomena preventing the drainage of melt water; as revealed in the load reduction tests, the system is likely to be more suitable for warm climates occasionally experiencing heavy snow loads than for climates with long and cold winters.

The test of load reduction through sublimation indicates the potential for drainage free snow mitigation. Sublimation is conducive under cold and windy conditions, which is typically when melting is unfavourable. An amount of 0.86 kg/m^2 per day was sublimated in the case study with single modules. Although this is not much compared to the loads posing danger to roofs, the method can be improved with further knowledge of the phenomena and better control of the system, potentially resulting in more effective load reduction. Sublimation occurs naturally in snow and applying low magnitude forward bias to modules can simply amplify the sublimation if the conditions are right. This enables load reduction through cooperation with the ambient forces of nature. The amount of energy used for sublimation in the case study was calculated to be 19% lower than the latent heat of sublimation presented in Table 1, indicating a contribution of the ambient conditions. The ice sheet uncovered at the end of the experiment raises the question of whether induced sublimation on PV-modules is possible in the long term. The ice sheet indicates some sort of snow metamorphism which may prevent further load reduction. The sublimated snowpack was of a relatively shallow depth, contributing to a steep vapour pressure gradient between the snow and the air. A thicker snowpack results in a more gentle gradient and it is possible that the snow will be sublimated on the module surface only to be deposited further up in the snowpack, never reaching the outside air. The question of whether it is possible to reduce the load by induced sublimation for thicker snow packs with photovoltaic snow mitigation systems has been poorly documented and should be further researched.

The results from the aerial thermography of the PV system with forward bias applied show that the relative temperature differences between modules and strings are of low magnitude. Temperature differences between string and modules do occur, but the relative temperature differences do not indicate any deficiencies in the system. Although highly dependent on the resolution of the map, typical infrared patterns from defects [9, 26] cannot be observed in the pictures, indicating a well-functioning system.

Reducing the snow load on under-designed roofs by applying electrical power to PV systems raises the question of how much energy is required to keep the roof safe, and whether the system is a sustainable and cost efficient solution to increase snow load robustness. The amount of energy required to keep the roof safe depends on the amount of energy used in a single load reduction, and how often it is necessary to reduce the load. The frequency of load reduction depends on what the building is designed for, hence the magnitude of under-design. The magnitude of the snow load imposed on buildings varies from one year to another, making load reduction unnecessary every year. This is one of the reasons why it is not necessary, with respect to safety, to melt the snow away as it accumulates. The long-term energy balance of reducing load and producing energy is little researched and should be investigated further. The potential for increasing the yield of PV systems through melting snow during the seasonal snowpack should be taken into account in this evaluation.

Photovoltaic snow mitigation systems are designed with the intent of reducing the snow load on flat roofs, but installing PV systems on roofs changes how snow accumulates and is distributed on the roof surface. In the design standards, different roof shapes have different shape factors determining the distribution of snow on the roof due to wind erosion and the sliding of snow [10]. A shape factor for PV systems on flat roofs is nevertheless still premature for most design standards. Research indicates that PV systems influence the friction velocity on the roof important for snow erosion, depending on the angle, height and distance between the rows of the panels [5]. The layout of the system, in combination with the prevailing wind direction on the site, can potentially result in an inhomogeneous snow load distribution compared to flat roofs without PV systems. In addition to this, having PV systems on flat roofs results in a bulk of snow laying on the module surface rather than on the surface of the roof itself. This decreases the effect of melting snow due to heat loss through the roof and increases the snow load compared to roofs without PV systems. This is especially significant for poorly insulated roofs. How PV systems change the distribution and magnitude of snow loads on flat roofs should be taken into account when assessing PV snow mitigation systems as a measure of increasing robustness to snow loads. Hopefully, future design standards will provide accurate calculation methods for how PV systems affect the snow load on roofs.

As mentioned in Section 2, Annex F in ISO 4355 presents a framework enabling a reduction in the design snow load for a reliable control device or method which slide or melt snow [10]. In order for the design snow load to be reduced, documentation guaranteeing load reduction must be provided. Such documentation is highly dependent on the climate where load reduction is performed. The results from this study uncover phenomena important for snow load reduction that are applicable to similar climates. However, areas with very long and cold winters might experience additional problems that are not documented in this study. In general, it is necessary to conduct further studies of load reduction under varying climatic conditions before it can be used as a geographically widespread solution for snow load reduction.

Implementing a photovoltaic snow mitigation system on an under-designed roof and being dependent on a controlled snow load reduction severely influences the reliability of the roof. Building reliability is calculated to satisfy a predefined reliability level in the design standard, corresponding to the consequence of building failure. The variables used for dimensioning the structural components (e.g. resistance variables, permanent actions and climatic loads) have a certain statistical probability for occurring. When a PV snow mitigation system is installed on a roof, the dead load on the roof increases and the dependence of the controlled snow load reduction is added. The snow mitigation system itself has a certain probability for providing sufficient load reduction in a heavy snow load scenario, which must be taken into account in the reliability calculation. The probability of sufficiently reducing the load depends on the temporal efficiency of load reduction, and possible events interrupting the reduction (technical malfunctions, power outages, climatic conditions). Such risk factors must be identified and implemented in a reliability model for the structural safety of the building before the system can become a widespread solution for under-designed roofs.

6. Conclusion

The state of the existing building stock and the expected change in the future climate calls for new measures for under-designed roofs. Photovoltaic snow mitigation systems combine power production with snow removal by applying forward bias to the system. The results from this study show that reducing the snow load on flat roofs with photovoltaic snow mitigation systems is possible. The feasibility of load reduction is, however, highly dependent on the climatic conditions during system operation. The possible refreezing of meltwater and water saturation of snow are possible outcomes which can prevent sufficient load reduction and possibly result in an unfavourable load distribution. Melting in ambient temperatures above freezing is less problematic with respect to drainage of meltwater and it is naturally less energy consuming than melting in cold conditions. Melting a thicker snowpack in cold conditions is yet to be tested on a full-scale PV system. Reducing the snow load in ambient temperatures above freezing is therefore likely to be effective, while melting in cold conditions provides more risk due to the possible refreezing of meltwater and the water saturation of snow. For this reason, the system is likely to be more suitable for warm climates occasionally experiencing heavy snow loads, than for climates with long and cold winters. Tests of load reduction through sublimation indicates a potential new strategy for snow removal when conditions are cold and windy, typically unfavourable for melting. It is, however, unknown whether load reduction through induced sublimation is possible for thicker snow packs and if it will function in the long term due to the metamorphism of snow at the bottom of the snowpack. The load reduction tests nonetheless highlight the importance of cooperating with the weather conditions to perform sufficient and energy-efficient snow removal. Before the photovoltaic snow mitigation system can become a widespread solution for under-designed roofs, it is crucial to investigate the long-term effect of applying forward bias to PV modules and provide documentation for the system's load reduction capabilities to be used in structural design standards. In addition to this, the long-term energy balance of reducing snow loads and producing energy should be researched in order to determine the system's sustainability as a measure to increase snow load robustness.

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