The influence of snow and ice coverage on the energy generation from photovoltaic solar cells

Erlend Andenæs [a]*, Bjørn Petter Jelle [ab], Kristin Ramlo [a],
Tore Kolås [c], Josefine Selj [d] and Sean Erik Foss [d]

[a] Norwegian University of Science and Technology (NTNU),
Department of Civil and Environmental Engineering, NO-7491 Trondheim, Norway.

[b] SINTEF Building and Infrastructure,
Department of Materials and Structures, NO-7465 Trondheim, Norway.

[c] SINTEF Materials and Chemistry,
Department of Materials and Nanotechnology, NO-7465 Trondheim, Norway.

[d] Institute for Energy Technology (IFE),
Department of Solar Energy, NO-2027 Kjeller, Norway.

* Corresponding author: erlend.andenas@ntnu.no (e-mail).

Abstract

This literature study examines previous studies of the optical properties of snow, and attempts to tie them together with studies on the effects of shading on photovoltaic solar panels. The study presents some information on the general properties of snow, and ice including geographic extent and some conditions of snow and ice formation. General optical properties of snow are examined, such as reflectance (albedo) and spectral transmittance. Common transmittance profiles for snow covers are also examined. The study also presents some commonly understood effects of shading on photovoltaic panels, both in the form of uniform shading (weak light) and partial shading. Other snow-related aspects of operating a photovoltaic system are also brought up, such as snow loads and the risks posed by snowmelt, particularly in regards to building-integrated or building-applied photovoltaics. Common methods of addressing snow-related challenges are summarized, both on a material and an architectural level. Lastly, suggested future research paths are presented.

Keywords

Snow; Ice; Solar energy; Photovoltaic; Solar cell; Building integrated photovoltaics; BIPV; Transmission; Transparency; Building; Energy

Contents

1. Introduction

The rapid development of photovoltaic (PV) technology over the last decade has led to solar electricity generation on an unprecedented scale (IEA-PVPS, 2015). It is now becoming feasible and economically viable to cover an increasingly larger energy demand with solar energy production almost all over the world, even in the boreal and polar regions. While the solar radiation in these regions is of comparatively low intensity, and energy production will be greatly reduced during the winter, photovoltaic cells remain a viable source of energy for parts of the year. It has been demonstrated that buildings outfitted with photovoltaic panels can achieve a net surplus of energy over its lifetime, even as far as 60 degrees north (Fjeldheim et al 2015). For this reason, photovoltaic panels have become a popular feature on low-energy buildings. The concept of building-integrated photovoltaics (BIPV) has emerged with the goal of merging solar panels and building materials. A tighter integration of photovoltaics and buildings also means that issues and challenges related to both fields of study will be integrated closer. The needs of the building will influence the design of the PV system, and the needs of the PV system will influence the design of the building.

PV technology faces certain challenges in cold climates. Snow and ice may form and accumulate on the panels, obstructing light from reaching the cells, thus hampering electricity production. Full or partial obstruction will significantly reduce the electricity generation of the panels, at a rate disproportional to the area being shaded (Deline 2009). Snow and ice may linger for extended periods of time after their formation, until it melts away or is otherwise removed. Forceful or careless removal of the snow may also damage the panels (Brearley 2015). Jelle (2013) discusses other challenges of snow removal from photovoltaic solar cell roofs, summarizing roof-related issues that have to be dealt with to efficiently operate a photovoltaic system on a roof in snowy areas.

To quantify the impact of snow on photovoltaic modules, some understanding of the effects of shading is required. Obstruction of light has always been a major concern for photovoltaics, so the effects of shading and soiling have been extensively studied. Grunow et al. (2004) and Reich et al. (2004) studied how various types of photovoltaic cells behaved under weak light conditions. It has been shown that partial shading is more critical to the operation of a PV system than uniform shading (Woyte et al. 2003). While uniform shading merely reduces the output of the system, akin to clouds blocking solar radiation or the sun setting, partial shading causes complex changes to the balance of electric currents against the conductive properties of the cells. Snow and ice will under various circumstances cause both uniform and partial shading. It is necessary to examine the behaviour and influence of snow and ice on photovoltaic panels, to accurately determine and improve the long-term performance of solar power in snow-prone areas.

Studies on the optical properties of snow and ice have been performed for decades, long before solar panels became commercially viable. Most notably, a great amount of research has been conducted on the reflectance of snow, and conditions of its formation, in the fields of meteorology and hydrology. The reflectance, or albedo, of snow constitutes a major part in the energy budget of a snow cover, and thus remains perhaps the most studied optical property of snow and ice. However, studies on the transmittance of snow remain scarce. Dunkle and Bevans produced their "...approximate analysis of the solar reflectance and transmittance of a snow cover" in 1956, where mathematical models for radiation reflection and transmission were presented. Later, Giddings and LaChapelle (1961) elaborated on energy distribution and albedo of snow. Bergen (1971) studied the transparency of snow, further working on determining an extinction coefficient for light passing through a snow layer. Warren (1982) provided a more thorough analysis on its optical properties. Perovich (2007) conducted practical measurements, determining light transmission and radiation transmittance for radiation of various wavelengths within the visible spectrum. Järvinen and Leppäranta (2013) measured solar radiation transfer through snow in Antarctica, finding trends similar to Perovich (2007) but a significantly higher rate of transmission. All authors stress that the optical properties of snow is dependant on a variety of factors, which will not be explored in-depth in this study.

The objective of this study is to examine the state-of-the-art literature on snow and ice formation, on snow transparency, and on the influence of shading on photovoltaic panels. Some common issues related to snow on buildings will also be examined. Attempts will be made to tie the observations from the relevant fields together, and present further opportunities for research paths on snow and ice with regards to their effects on photovoltaic electricity generation.

2. Formation of snow and ice

2.1 Geographic extent

Snow and ice may form almost anywhere on Earth's surface in rare cases, but only in certain regions will it happen frequently enough to have any significant impact on photovoltaic electricity generation. As a rule of thumb, snow and ice will form with some regularity in regions classified as "Cold" or "Polar" (category D or E according to the revised Köppen-Geiger classification (Peel et al. 2007)). Dietz et al. (2012) mapped the mean snow cover duration for Europe between 2000 and 2011, showing that most of the continent will experience at least a few days of snow per year on average, see Fig.1. The Nordic countries in particular will experience long periods of snow cover each year, and it seems clear that some measures need to be taken against snow to keep photovoltaic cells a viable means of electricity generation. Further south and west in Europe, one might do without such measures, as the power loss from rare snowfalls may not be worth the cost of installing systems specifically to reduce the impact of snow.

In addition, snow and ice might form at high altitudes regardless of climate. Photovoltaic panels enable electricity generation in isolated high-altitude locations, such as mountain cabins, as it is very expensive to extend cables to connect them to the power grid. Thus, the concern of snow-related issues affecting the electricity production of PV systems is not limited to boreal or polar regions.

Note that certain coastal areas will remain relatively snow-free even in the polar regions. For instance, the west coast of Norway will have most of its precipitation in the form of rain for most of the year.

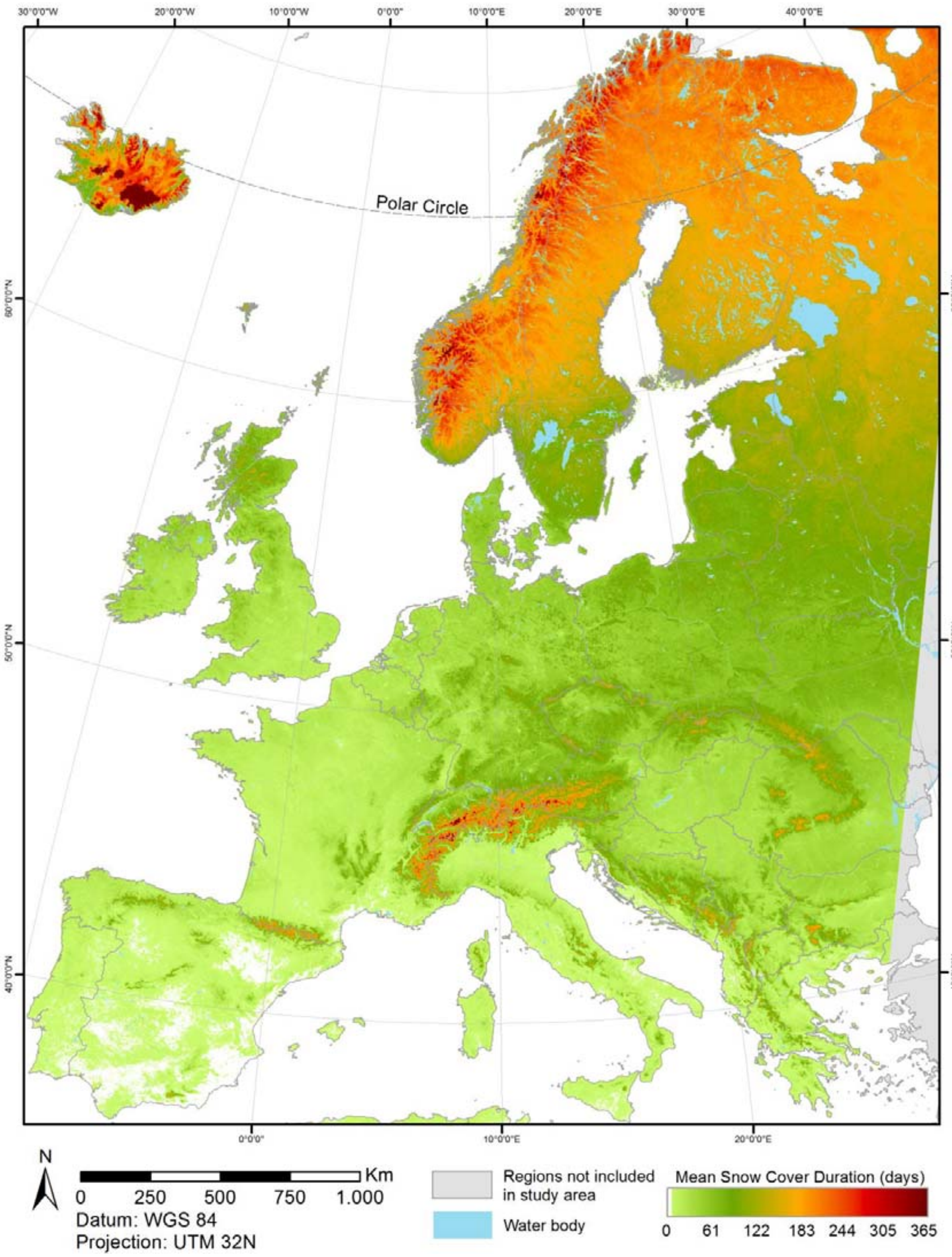

Figure 1: Mean snow cover duration from 2000 to 2011 for Europe (Dietz et al. 2012).

2.2 Conditions of snow and ice formation

Arguably, it is redundant to speak about “snow and ice”, as they technically can be considered the same substance. Snow consists of flakes of crystalline ice, formed in clouds and fallen to the ground via precipitation. However, the properties of snow are different enough from those of solid ice that, for the purposes of this study, the two terms will be used separately. Snow and ice, being the solid form of water, will form at temperatures below 0 ºC. As snow forms in clouds, high above the ground, snow may fall even when the ambient air temperature near the surface is above the freezing point. Ice, as the term is used here, is water which freezes on a surface.

Freezing precipitation is a phenomenon in which super-cooled rain droplets fall against a surface with a temperature lower than the freezing point. The individual raindrops will rapidly freeze upon contact with the surface, forming a layer of ice known as glaze (AMS 2015). The glaze layer will be visually transparent with a relatively high transmittance of solar radiation, but unless quickly melted it can compromise the effect of the solar panel's surface coating, as ice is not hydrophobic (Varanasi et al 2010). In layman's terms: “ice sticks to ice”, so once an ice layer is built up on the surface, a snow layer might easily form on top of it. In addition, glaze has a higher reflectivity than a solar panel surface, as the latter is usually coated with anti-reflective coating. Freezing precipitation is a smaller problem in some locations than others; a study of meteorological observations conducted in Finland (Makkonen and Ahti 1995) found that on average, each station experienced 0.65 freezing precipitation events per year over a period of 23 years.

Dew will form when the temperature of a surface falls below the dew point of the air. At temperatures lower than 0 ºC, the dew will freeze, forming frost. Frost may also form if the ambient air temperature is above 0 ºC, if the surface experiences excessive heat loss to the clear sky because of long-wave radiation. Frost usually forms during winter nights when temperatures drop, and melts quickly in sunlight due to its large surface-to-volume ratio.

Once gathered in sufficient amounts, snow and ice may remain in place even when the temperature increases well above the freezing point. Wet, half-melted snow may freeze again and harden when the temperature drops back below 0 ºC. Such cycles of thawing and freezing will make snow significantly more compact, eventually to the point of resembling solid ice. Water run-off from melted ice may also freeze again, expand upon freezing and possibly cause damage if it finds its way into cracks or freezes in drainage pipes. It is important to provide a photovoltaic system on a roof or façade with reliable drainage, to drain snowmelt away safely and efficiently.

3. Influence of snow and ice

3.1 Obstruction of solar radiation

The main influencing factor of snow on PV systems is the blockage of solar radiation on the photovoltaic cells. In order to quantify and assess the importance of this, some understanding of the optical properties of snow is required. While these properties vary depending on a number of factors, such as average grain size, free water content, or the formation of layers within the snowpack (Giddings and LaChapelle 1961), some broad observations can be applied for snow in general.

Arguably the most notable of the optical properties is the reflectance, defined by the ratio of reflected radiation from a surface to radiation incident on it. The term "albedo" is often used interchangeably with reflectance, but is not strictly defined and is often used to describe reflectance of solar radiation only in the visible spectrum (Coakley, 2003). The reflectance of snow is significant all across the visual spectrum, hence its white colour. For thin snow layers, albedo will be dependent on the snow depth. O'Neill and Gray (1973) show that the albedo of a snow layer will reach its ultimate value at snow depths at around 4 cm. The typical values of albedo for a snow pack a few centimetres deep is 70 to 90 %, according to most sources (Giddings and LaChapelle (1961), O'Neill and Gray (1973), Warren (1982), Perovich (2007)). Even disregarding radiation absorption in snow, it is evident that a snow cover will inherently reduce the incident solar radiation to an underlying solar cell to a fraction by virtue of reflectance alone, regardless of the depth of the snow pack. As the snow melts, the albedo will decrease, but as the snow's water content then will increase, radiation absorption will increase to make the snow even less transmissive (Perovich 2007).

Factoring in radiation absorption in snow to find the final value of radiation transmission, it is clear that even a relatively modest snow cover will reduce PV electricity generation to almost nothing. According to Perovich (2007), a 10 cm thick snow layer might reduce the transmission of visible light by about 95 %, and infrared transmission by more than 99 %. Even as little as 2 cm of snow will reduce the transmission by nearly 90 %. Other studies have contested these results, for instance Järvinen and Leppäranta (2013) who determined the snow depth necessary to block 99 % of the downwelling irradiance to be in the range of 47-74 cm.

Snow is not a homogeneous substance. O'Neill and Gray (1973) showed that the "active layer" – the top few centimetres of the snow cover – has somewhat different optical properties than the snow deeper into the snowpack. This is because the surface snow is not compressed by the weight of more snow above it, making it lighter and "fluffier". At snow depths lower than the thickness of the active layer, the optical properties of the snow pack will be influenced by its underlying surface. This active layer has a higher extinction coefficient than the deeper snow, resulting in a more rapid extinction of solar radiation passing through it. Järvinen and Leppäranta (2013) agree with these findings, stating that a "diffuse regime" begins at snow depths between 1 cm and 10 cm.

It is shown by Perovich (2007) that the extinction coefficient of a typical snowpack, within the visible spectrum, is greatest for long-wave radiation. As such, the solar radiation penetrating the snow layer is of comparatively low wavelengths, with the highest transmittance occurring at wavelengths between 450-550 nm. The extinction coefficient of snow appears to be the lowest between 400 and 700 nm, increasing sharply for wavelengths above 700 nm. The extinction coefficient is somewhat lower for older snow than for new fluffy snow, and significantly higher for very wet, melting snow. This is in agreement with the findings of O'Neill and Gray (1973). The findings of Perovich have been reproduced in Fig. 2.

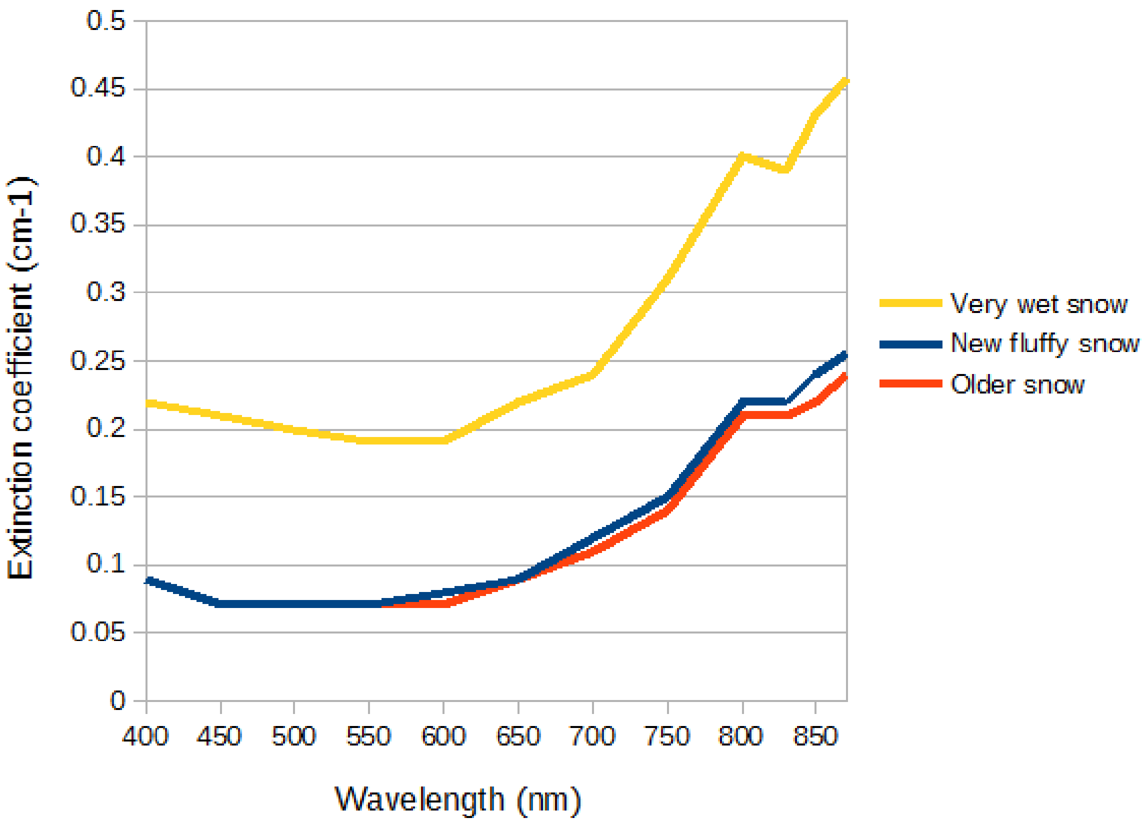

Figure 2: Spectral extinction coefficient as a function of wavelength for various types of snow. Redrawn from Perovich (2007).

The extinction coefficients presented here will not be utilized further in this study, as proper calculations of snow transmittance are dependent on many other factors. Regardless, Fig. 2 provides a useful illustration of the significant variance of the optical properties of snow across the visual spectrum. It also shows how wet snow will have a much higher rate of absorption, and thus transmit less radiation than dry snow despite its comparatively low albedo.

The transmittance measurements by Perovich (2007) are summarized in Fig. 3. It shows how transmittance is rapidly decreasing with increasing snow depth, significantly more so for radiation of high wavelengths.

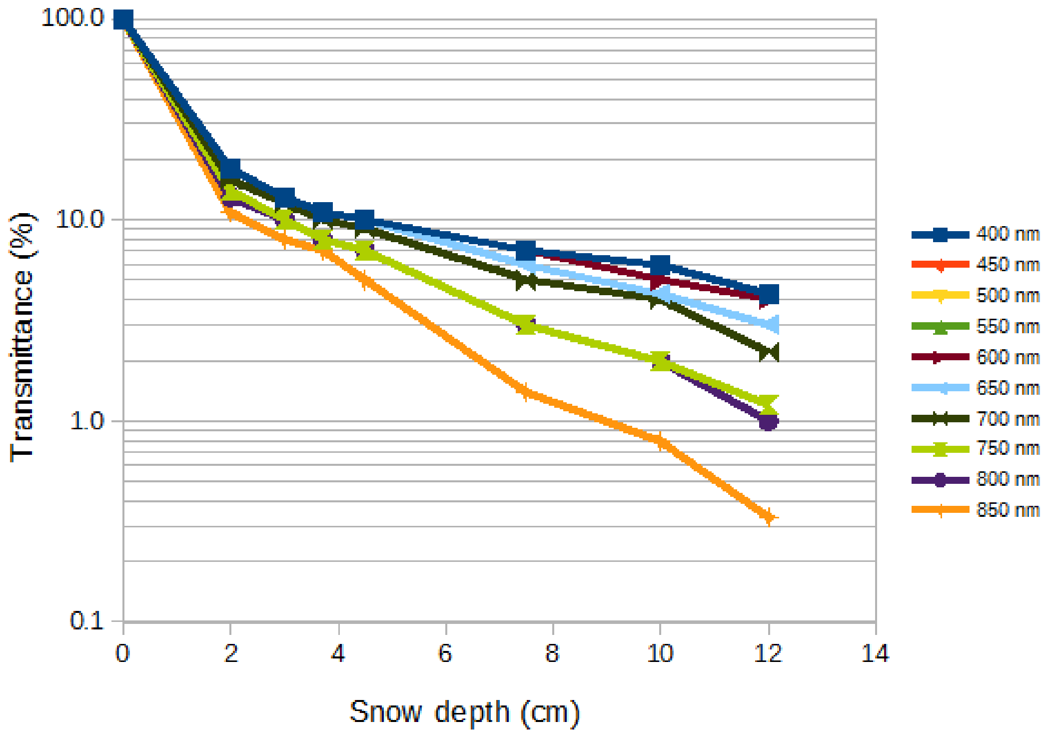

Figure 3: Transmittance vs. snow depth for various wavelengths. Note that the data points for wavelengths 400-550 nm were indistinguishable in the original figure and have been assumed to be identical in this reproduction. Redrawn from Perovich (2007).

One minor deficiency in Perovich's data is the lack of transmittance measurements for shallow snow covers. The ”active layer”, as described by O'Neill and Gray (1973), will have great influence on the transmittance of a snow cover shallower than 2 cm. While the figure is drawn with a linear development of transmission rates for snow depths of 0-2 cm, this is not likely to reflect the actual transmission rate for such snow layers.

Perovich did, however, measure the albedo of a shallow snow layer. His data are presented in Fig. 4. While this figure does not provide a complete picture of how much light penetrates the snow layer, it illustrates well how severely transmission rates are reduced by even a light sprinkle of snow. For the purpose of estimating solar cell efficiency, the practical implication of a thin snow layer is clear even without factoring in radiation absorption: The impact of reflection losses alone is great enough to severely hamper the electricity production, even for very thin snow layers. Note that it takes only a centimetre of snow to reduce the potential radiation transmission by two thirds, even without factoring in absorption.

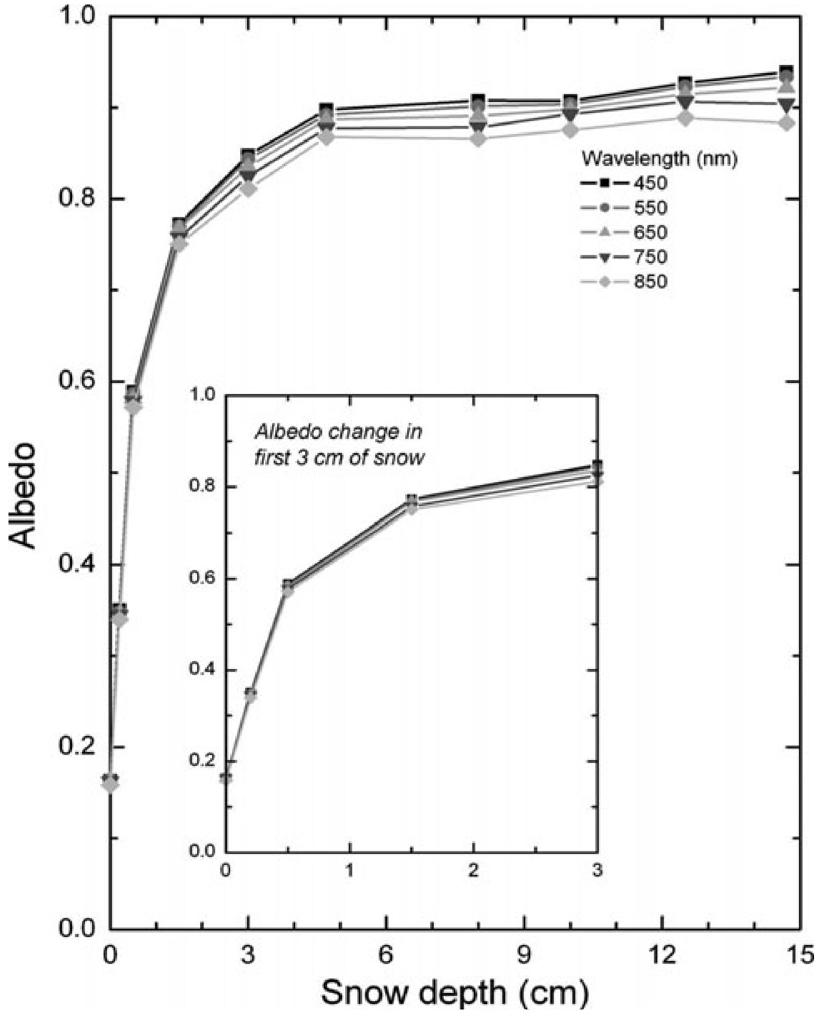

Figure 4: Albedo vs. snow depth for a shallow snow layer. The measurements were undertaken as snow fell, hence the snow studied is very fresh (Perovich 2007).

3.2 Solar cell efficiency

3.2.1. Reduction of efficiency in weak light

Knowing that snow will drastically reduce the amount of incident light on photovoltaic modules, it is possible to assess the impact on the performance of a photovoltaic system. To simplify calculations, a ”cut-off point” should be established, a point where electricity production can be considered negligible due to lack of light. Measurements done by Reich et al. (2004) seem to indicate that the relation between light intensity and solar cell efficiency remains close to directly proportional for light levels down to 20 % relative to standard test conditions (STC). Under standard test conditions, a radiation intensity of 1000 W/m^2 is applied.

Grunow et al. (2004) found that the power output of crystalline silicon photovoltaic modules is reduced in weak light, at a rate disproportional to light intensity. It was shown that the efficiency of the cells is reduced in low light conditions, but that cells with a high shunt resistance will perform better in weak light than those with low shunt resistance. Their measurements seem to indicate a drop in solar cell efficiency at light intensities below 400 to 600 W/m^2. Grunow et al. measured efficiency for incident radiation levels as low as 100 W/m^2, at which point the cell efficiency was reduced by 10-25 % relative to the efficiency at 1000 W/m^2, depending on cell type.

Reich et al. (2004) mapped solar cell efficiency for radiation levels as low as 2.9 W/m^2, indicating a further collapse in efficiency at radiation intensities below 100 W/m^2. The results seem to indicate a logarithmic correlation between radiation intensity and efficiency for crystalline silicon cells, whereas the efficiency of amorphous silicon and gallium arsenide cells are less affected by weak light. Note, however, that these effects seem to make a difference only at very low light levels. See Fig. 5.

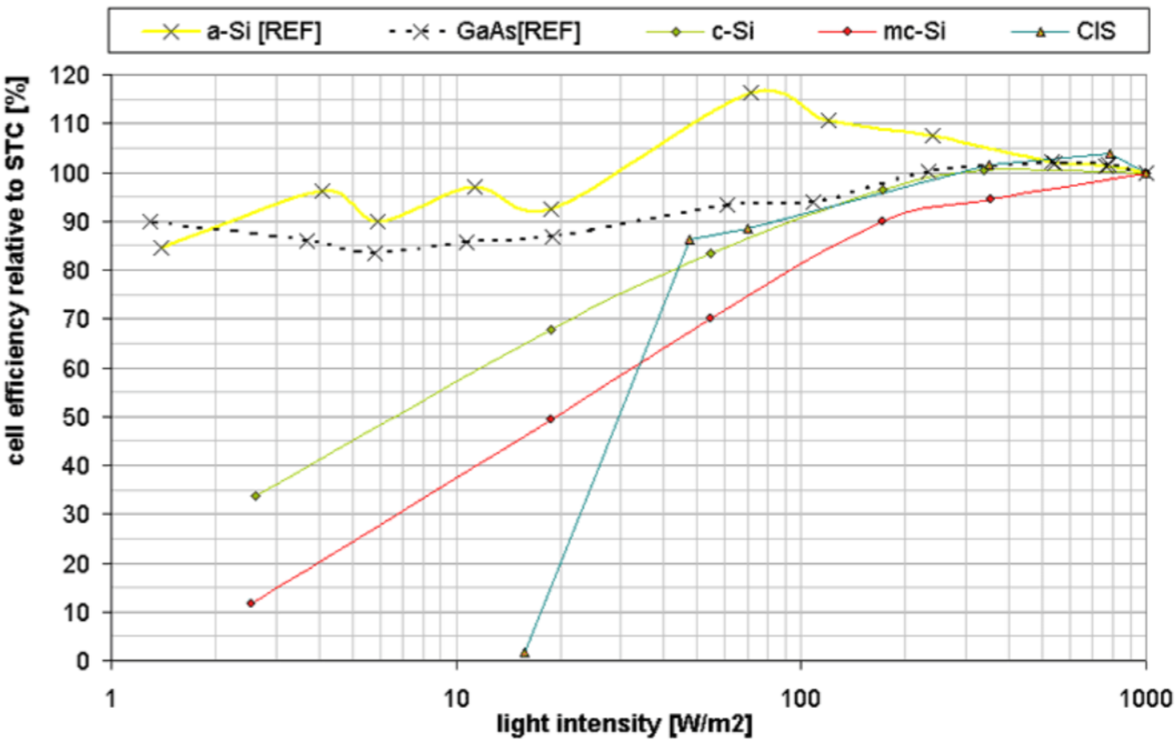

Figure 5: Comparison of efficiencies relative to standard test conditions (1000 W/m2). mc-Si, c-Si and CIS solar cell performance measured by Reich et al. (2004); a-Si PIN-PIN and GaAs cells measured by Kan and Brezet (2004). Reich et al (2004).

The data from Reich et al. may be utilized further to find the relation between light intensity and photovoltaic electricity generation. In Fig. 6, the data in Fig. 5 is transcribed, and cell efficiency is multiplied with light intensity to show that the relation is close to directly proportional for every cell type.

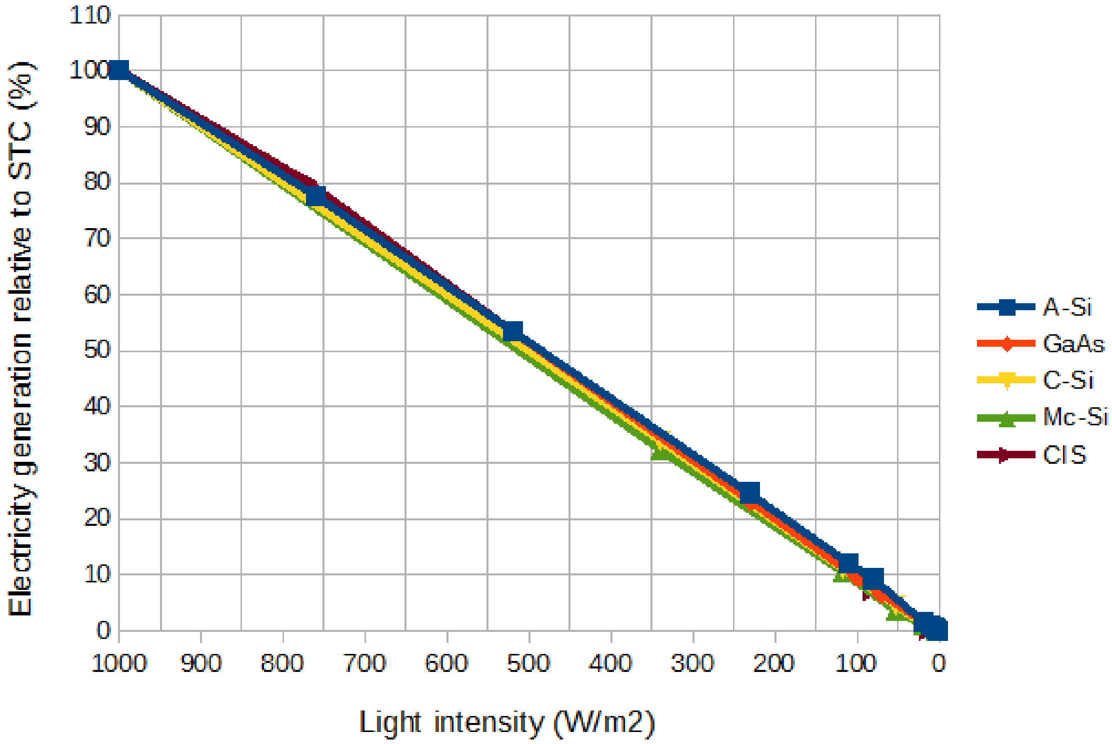

Figure 6: Electricity generation vs. light intensity for various solar cell types. The deviation from a linear relation is small enough that a linear relation can be assumed with satisfying accuracy for radiation intensities above 50 W/m^2. Figure modification based on Reich et al. (2004).

It can be seen from Fig. 5 that electricity generation begins to deviate significantly from solar radiation intensity at radiation levels below 200 W/m^2. Assuming the incident solar radiation intensity under a clear sky to be 1000 W/m^2, and the transmittance of snow as demonstrated by Perovich (2007), it can be seen from Figures 3 and 4 that approximately two centimetres of snow is required to reach this point. Shunt effects as described by Grunow et al. begin to appear at approximately half a centimetre of snow.

A DC-to-AC inverter is required to operate a complete photovoltaic system. PV panels output DC electricity, which must be converted to AC before it can be utilized. To function properly, the inverters require a minimum voltage and current. Such inverters have a nominal efficiency of 96 to 99 % (ABB 2015), meaning that they will require 1-4 % of the PV system's nominal power output to work. At production levels lower than this, the PV system will not output any AC electricity. As the solar cell efficiency is reduced at low light levels, it is difficult to predict exactly when this limit is reached, but Fig. 6 seems to indicate radiation intensity levels below 50 W/m^2 is required. This corresponds to a blockage of solar radiation of 95 % or more relative to STC, which would require roughly 10 cm of snow, as per Fig. 3.

Note that the assumption of an initial incident solar radiation flux of 1000 W/m^2 is rarely applicable in real life, as this figure is applicable for radiation incident directly onto a flat surface under a clear sky during summer. During winter, the sun is at a lower angle, which increases the path length of sunrays through the atmosphere, reducing their intensity. The estimate of a ten-centimetre cover reducing the electricity generation to negligible levels can therefore be considered a best-case scenario, the likely case is that any snow cover beyond a light sprinkle will reduce the electricity production of the PV system to near-zero levels on a cloudy winter day. On the flip side, it can be concluded that if there is more than ten centimetres of snow on the panels, there will be no electricity production regardless of the solar radiation upon the snow's surface.

3.2.2. Spectral comparisons

While a couple of centimetres of uniform snow coverage will effectively prevent electricity generation, the response to a shallower snow layer may be more complex. This sub-chapter discusses the optical properties of snow across the visual spectrum, and compares them to the ”band gap” of a photovoltaic cell, which describes which part of the electromagnetic radiation spectrum that is utilized by the cell.

The term “quantum efficiency” describes the percentage of incident photons on a photovoltaic cell that contribute to to electricity generation by exciting electrons. Ideally, a solar cell will excite one electron for every incident photon, but in practise, the quantum efficiency will be somewhat lower. A distinction is usually made between “internal quantum efficiency”, which is the percentage of photons *absorbed by* the cell that are converted to electric current; and “external quantum efficiency”, which is the percentage of photons shining on the panels that are converted. In short, the external quantum efficiency takes reflection and glass absorption losses into account, whereas the internal quantum efficiency does not (PVEducation 2015).

“Spectral response” is a property very closely tied to quantum efficiency; it can be described as quantum efficiency adjusted for photon energy, which is proportional to the photons' wavelength. The spectral response is defined by the ratio of generated current to the amount of power radiant upon the cell. At low wavelengths, the glass of a solar module will absorb most of the energy, while photons of higher wavelengths have too little energy to be utilized by the cell, resulting in no generated power. The resultant graph is triangular, with its peak at wavelengths near the cell's band gap (PVEducation 2015).

While the quantum efficiency varies between solar cells, for the purposes of this study, the quantum efficiency and spectral response of a monocrystalline silicon solar cell mapped by Chander et al (2015) can be assumed representative for silicon solar cells. Combining their spectral response graph with the transmittance graphs for snow by Perovich (2007), it can be illustrated how snow affects the electricity generation of solar cells.

As seen in Fig. 7, the band gap of a silicon solar cell is wider than the spectral range examined by Perovich (2007). Nevertheless, the figure illustrates how snow will vastly reduce the incident solar radiation in certain parts of the electromagnetic spectrum. Notably, infrared radiation (heat) is almost completely blocked. There is a clear bias in transmittance around the

450 nm-region, which is why light passing through snow appears blue. Note that the least transmitted wavelengths are the ones that generate the highest current in a solar cell per Watt of incident radiation.

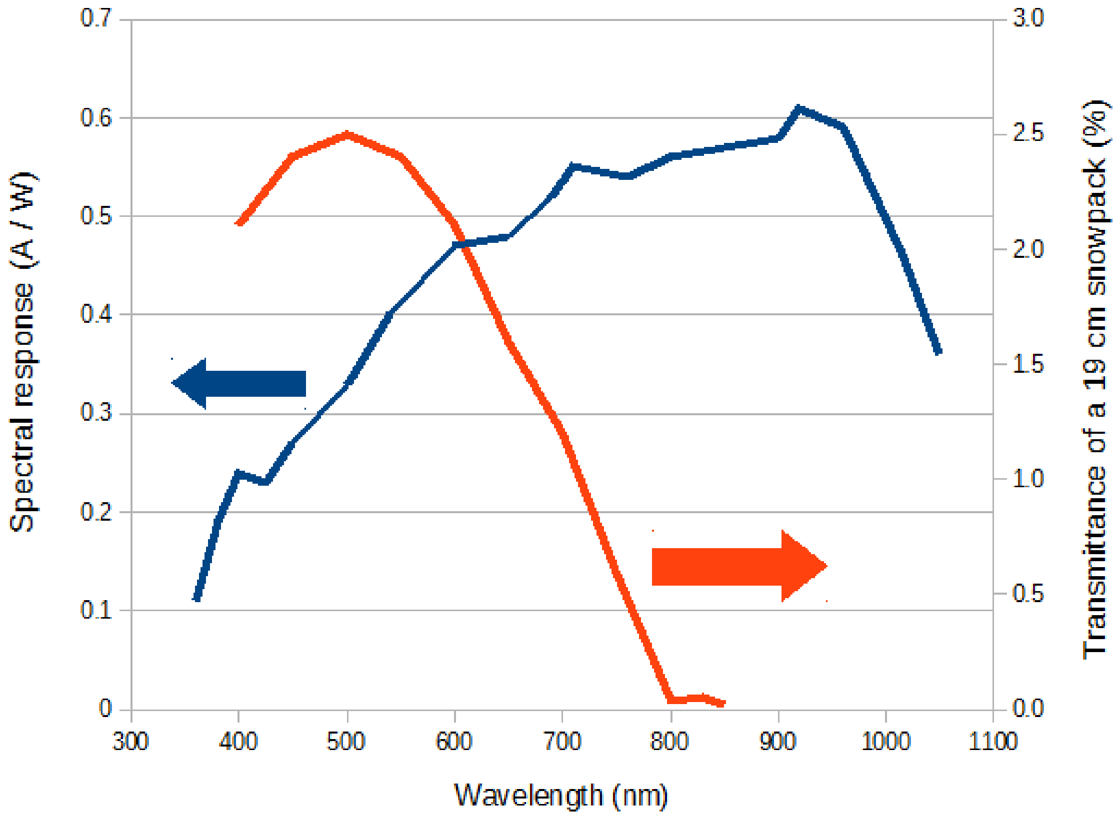

Figure 7: Spectral response graph of a mono-crystalline silicon solar cell, overlaid with the spectral transmittance profile of a 19 cm snowpack (Perovich 2007, Chander et al. 2010).

3.3. Partial obstruction

Electric current in a cable is not unlike the flow of water through a pipe; the smallest bottleneck is what limits the size of the flow. A shaded photovoltaic cell will not conduct electricity as well as a well-illuminated one, “strangling” the current through it. A partially shaded solar cell, module or system will experience a difference in conductivity and electricity generation, essentially producing more electricity than what can be comfortably conducted through the shaded area. This extra strain on the cells will cause them to heat up, which may damage the cells. On the other hand, it helps melting snow, but this effect should not be relied on for snow removal as heat will severely damage the cells in the long run. The generation of heat consumes electricity, vastly reducing the total power output of the module.

The damaging effects of partial shading of single cells is overcome to some degree by bypass diodes. Bypass diodes are installed along the cells in a solar panel, and lead the electric current around a group of cells (called a ”string”) if their electrical resistance rises too high. This could happen because of shading, in which case the entire string will be bypassed, regardless of the amount of cells actually afflicted in the string. Woyte et al. (2003) found that bypass diodes should be applied per 18 to 20 cells in a crystalline silicon solar module, since the breakdown voltage of a cell is around 10 V and each cell generates roughly 0,5 V. In such a case, casting shade over one cell would disconnect all 18-20 cells, with a corresponding reduction of power output. Consequently, the diodes have to be placed carefully so that the right sections of the module can be bypassed. If snow is expected to slide towards the bottom of an inclined module, the cells on the lower end should all belong to the same string. That way, the lowest number of cells possible will be disconnected, should snow accumulate on the panel's lower end.

Dolara et al. (2013) reports a potential reduction in module power output by more than 30 %, when 50 % of a single cell is shaded. Deline (2009) states that a shadow over a PV panel ”...can represent a reduction in power over 30 times its physical size”. That is, a shade may under certain conditions negate the electricity production of a solar cell area 30 times larger than the area of the shade. This is largely dependant on the number and placement of the bypass diodes across the module.

3.4 Temperature

By definition, snow and ice only exist at temperatures below the freeing point of water, 0 ºC. Once heated past this point, water will no longer be solid. The practical implication of this is that a snow- or ice-covered solar panel will not be significantly warmer than 0 ºC. This cooling effect might somewhat compensate for the effect loss caused by snow obstruction, as photovoltaic cells become less efficient at elevated temperatures (Virtuani et al. 2010), although there is clearly no net benefit of a snow cover.

For building-integrated photovoltaics (BIPV), temperature control remains a great concern. The modules are mounted as part of the building envelope, potentially ”trapping” heat due to the tight wall integration. To provide a passive means of cooling, a ventilated air gap is left open behind or underneath the panels. This allows an air flow to remove excess heat via convection. However, snow and ice might accumulate and block the air flow through the air gap, preventing the necessary ventilation. While the build-up of hot air will accelerate the melting of snow, it might also be harmful to the panels. Further research is required to get an understanding of this phenomenon, and to determine what risk it poses.

3.5 Surface wear and tear

The most critical failure modes for solar panels are glass cracking and delamination (IEA, 2014). Cracking of the surface cover might break the cells themselves or their connectors, but will have adverse effects even if the cells are unharmed. In addition to the light refraction changes resulting from these phenomena, moisture might finds its way to the electric circuits of the panels, and cause short-circuiting or corrosion. Cracking is mainly caused by global or local mechanical loads, while delamination is the result of long-term exposure to moisture. Snow and ice, unfortunately, may provide ample amounts of both.

At times, snow removal can cause more problems than the snow itself. Trying to forcibly remove ice from panels can cause abrasion damage, glass cracking, or even break the panel in its entirety (Brearley 2015), see Fig. 8.

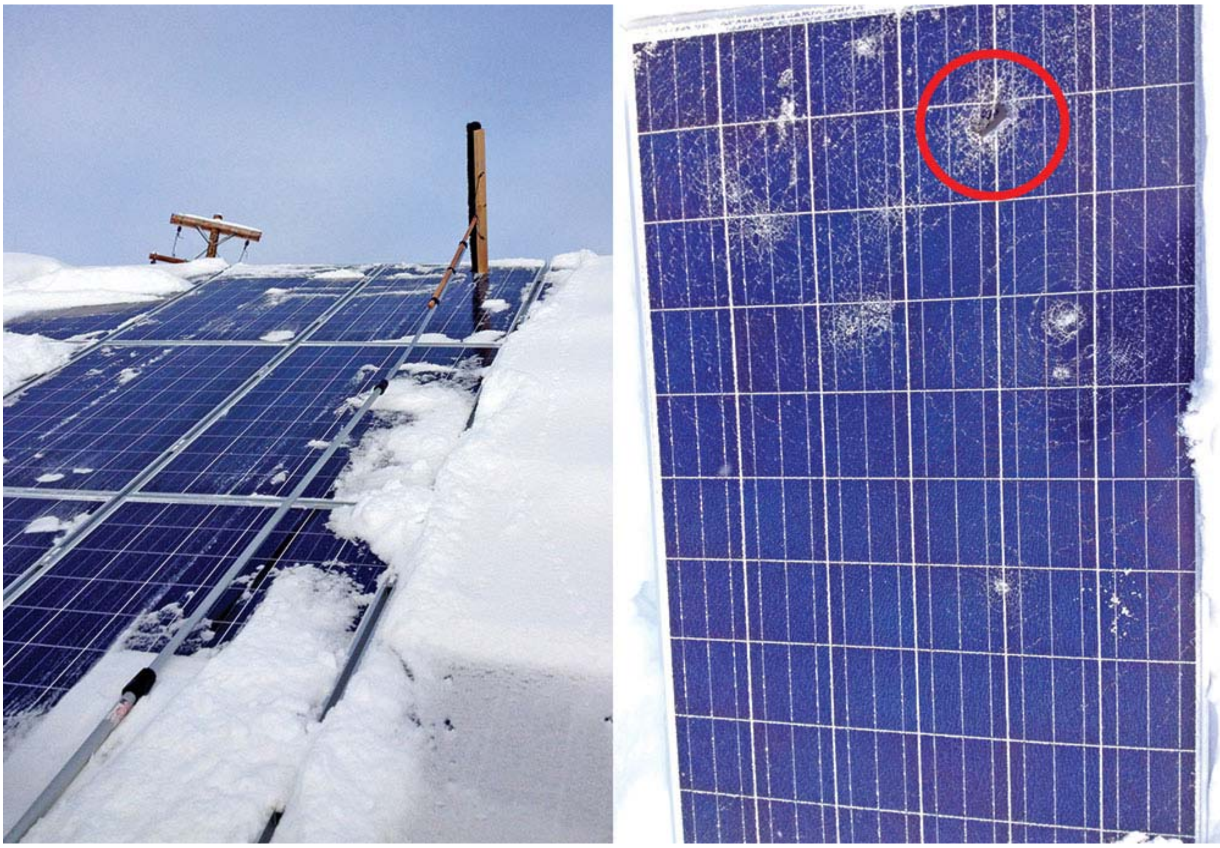

Figure 8: Illustration of how careless snow removal with a broom may cause scratch marks, cracks and even punctures of a solar panel surface. The red ring shows the result of a particularly hard impact (Brearley 2015).

Some surface coatings utilize micro- and nano-structures to roughen the surface and achieve repellency of water and ice. These surfaces are especially vulnerable against snow and ice, as the tiny structures are quite easily torn away by abrasion. Ramlo et al. (2015) provide a literature study on repellent surfaces and their interaction with snow and ice.

3.6 Snow loads

In the test regimes of IEC 61215 and IEC 61646, the international certification standards for photovoltaic modules, mechanical load tests are conducted up to 2.4 kPa. For certification of withstanding heavy accumulations of snow and ice, loads up to 5.4 kPa are applied (Arndt and Puto 2010). The load is uniformly distributed and only applied for one hour, while snow load might be more inhomogeneous and be applied for months on end. Certain locations will also have design snow loads far exceeding the requirements of the IEC test regimes, see Annex C of EN 1991-1-3. Such loads may deform or break solar panels or their fastening systems.

Experiences from the American photovoltaic industry seems to indicate that heavy snow loads tend to bend the frames of photovoltaic systems before any glass breakage occurs (Brearley, 2015). A module may survive a "fatal" snow load by itself, but the risk of micro-fractures might ruin the panel even without the glass taking any visual damage. Once a module is forced out of its fastening rails, it is advised to thoroughly inspect it before putting it back to use.

3.7 Influence on other system components or buildings

A solar power system consists of much more than a string of photovoltaic panels. There are many cables, connections, junction boxes, power trackers and panel mountings that also need to be considered. A major snow-related risk here is once again moisture, in the form of water leaking into electrical equipment (IEA PVPS 2014).

EN 1991-1-3:2003 determine the weight density of snow to vary between 1 and 4 kPa per metre of snow depth, depending on water content and the snow settling over time. This equals 100-400 litres of water per cubic meter of snow, most of which will eventually leave the roof as liquid run-off as it melts. If not properly managed, this water might cause problems in the electrical components of the PV system, or in other ways throughout the building.

Unlike rain, which normally is a periodical event of short duration, runoff from snowmelt might happen continuously over several days or even weeks. Also note that wind might cause snow to accumulate in crevices not normally afflicted by rain water, which is discharged all at once when the temperature rises above the melting point. While not a problem specific to photovoltaic systems, it is still important to consider the build-up of snow in crevices. Snow clogging the air gap behind solar panels could form patches of ice, which reduce ventilation and bring a risk of damaging electric equipment.

It should be noted that just removing snow from roof-mounted or roof-integrated photovoltaic panels will not provide a complete solution to all snow-related problems. Jelle (2013) discusses the two main philosophies of snow removal from photovoltaic panels: leaving the snow on the roof or removing it from the roof. Leaving it on the roof may give certain issues with snow loads, as discussed in section 3.6, which are amplified if snow is left in asymmetric heaps (for instance, removing snow from PV panels covering the south side of the roof, but leaving it on the north side). On the other hand, removing snow requires a suitable depot, or a substantial amount of energy to melt it so that it can be drained away. Just dumping snow off the roof is rarely an accepted solution, especially in urban areas.

4. Managing snow and ice

4.1 Material level

Snow and ice challenges can be addressed on a material level. It has been attempted to make materials with special surface properties, so that snow and ice will slide off, or not form at all on the material's surface. So-called icephobic materials prevent or slow the formation of ice on the surface, or makes ice slide off more easily. Traditionally, photovoltaic panels have only been coated with an anti-reflective layer, but improvements in technology have made it possible to use coatings that are also self-cleaning or water-repellent. Attempts are also being made to create *icephobic* surface coatings, which repel ice or inhibit ice formation.

A superhydrophobic surface repels water by forming it into small water beads, which ”roll” off the surface. Superhydrophobicity is achieved by creating a rough surface on a scale lower than 273 µm, which is the capillary length of water. ”Ribs” and ”pillars” are common surface patterns for superhydrophobic surfaces. As the micro- and nano-scale structures are very small, they are vulnerable to breakage by mechanical loads (Ramlo et al. 2015).

Superhydrophilic surfaces take the opposite approach, spreading water as thinly across the surface as possible. Rather than forming droplets, water molecules spread out to form a thin sheet which runs off the surface (Pilkington 2015). Hydrophilic surfaces are made to be as smooth as possible, without any microstructures.

While water-repellent surfaces have achieved a significant level of success, so-called icephobic surfaces are somewhat behind in development. A clear definition of icephobicity has yet to be determined (Ramlo et al. 2015). Icephobicity is related to superhydrophobicity, but superhydrophobic sufaces are not necessarily icephobic (Hejazi et al. 2013). Certain materials and coatings have achieved degrees of icephobicity, but they are currently unfit for photovoltaic applications as they are not transparent (Ramlo et al 2015).

4.2 Architectural level

Snow and ice accumulating on vertical surfaces is considerably less common than on horizontal ones. Mounting solar panels on a steep incline or even vertically will drastically reduce accumulation of snow under most circumstances, although wet snow may still stick to and accumulate on inclined and vertical surfaces (Jelle 2013). The disadvantage of such mounting is related to the solar radiation's angle of incidence. Solar cells have to be angled towards the sun to generate electricity with full efficiency. However, most regions prone to heavy snowfall are located far north or south of the Equator, where the sun is low in the sky. Therefore, the panels should be mounted on an incline anyway. PV systems integrated in building façades (BIPV) might be less influenced by ice and snow than roof-mounted systems, but they usually have a lower efficiency unless the building is designed with optimal solar irradiance angles in mind.

Snow should be allowed to fall *away* from the panels as well, rather than clumping up at the foot of the panel. Because it leads to partial shading, snow build-up along the lower edge could reduce electricity production to an even greater degree than a uniform snow cover over the panel would have.

Panels mounted on pitched roofs below other pitched roofs also run a risk of impact damages caused by snow (Brearley 2015). While it is desirable to utilize all available roof space, it should be considered that snow sliding off one roof will fall down on the roof below. Snow and ice may slide off in large pieces, hitting the roof below (or the panels mounted on it) with significant force. As documented in Brearley's article, this effect broke a number of photovoltaic panels in at least one case in New England, USA. Steep roof pitches seem to help in these situations, since less snow will build up before sliding off, reducing the mass of impact on the panels below. An example of such mounting of panels is seen in Fig. 9.

Figure 9: Snow on photovoltaic modules mounted on pitched roofs. Note that snow might slide off one roof and fall onto the other, possibly damaging the panels mounted on it (NIST 2014).

5. Future research paths

As has been shown, a solar panel becomes functionally useless when covered by a snow cover deeper than a few centimetres. However, shallow snow covers will let some light through and might still allow electricity generation in appreciable amounts. Future studies on solar panels and snow coverage should examine the effect on such shallow layers, to determine the exact influence on the panels' electricity production.

In polar regions, snow cover will usually coincide with short winter days or even polar nights. The influence of a snow cover on solar panels will be diminished significantly as the period of snow coverage correlates with periods of low incident radiation. While the snow cover might reduce electricity production, it might not have been significant to begin with, due to the lack of solar radiation even on uncovered surfaces. A study examining the relation between expected electricity generation with or without a snow cover at extreme latitudes could determine whether there is any economic or energy-related benefit to snow-removal or -prevention measures at all, or whether one might save the cost by leaving the snow be.

As have been brought up briefly, less snow will accumulate if the panels are tilted up from the horizontal plane. It should be determined exactly how much the panels need to be tilted for snow to slide off, for various types of PV surfaces and snow parameters. In most cases, the angle of the tilt is determined from the optimal solar angle, but taking snow and ice into account, the system might benefit overall from a slightly different angle.

6. Conclusions

It has been shown that a variety of meteorological phenomena will lead to various types of water and ice deposits on the surface of PV panels in many parts of the world, snow being the most notable among them. Snow is a highly reflective medium, which means even a thin snow layer will reduce incident radiation to the underlying surface by a significant amount. The relation between incident radiation intensity and electricity generation from solar cells stays linear until the intensity falls below approximately 200 W/m^2, at which point the solar cell efficiency will drop steadily as light becomes weaker. Even under a clear summer sky, two centimetres of snow is sufficient to reduce transmitted solar radiation to this level; in realistic winter conditions, the required snow thickness is likely to be significantly lower since incident radiation is weaker. Electricity generation is completely halted once the DC output of the system drops below 1 % of nominal power, since the inverter requires that much power to work. In conclusion, it can be assumed that any snow cover will reduce the already-low wintertime electricity generation to almost negligible levels. A cover of ten centimetres or more means there will be no electricity generation regardless of solar conditions on the snow surface.

In order to repel or inhibit the formation of snow and ice on surfaces, various surface coatings are being developed. A coating that works perfectly for PV panel surfaces has yet to be made, as they tend not to be transparent. There is also uncertainty as to whether a water-repellent surface will achieve ice repellency as well. In addition, micro- and nano-structures used on these surfaces are vulnerable against mechanical loads and abrasion.

Other issues related to snow and ice will also affect the operation and design of building-integrated or -applied photovoltaic systems. The issues are mostly related to snow loads, drainage of snowmelt, and safe removal and deposit of snow from PV panels.

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