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Review

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

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A B S T R A C T

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 on an architectural level. Lastly, suggested future research paths are presented.

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, 2014b). 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. (2005) 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

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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, since 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.

In later years, the properties of snow have also been examined with specific regards to photovoltaics. Powers et al. (2010) modelled and measured the effect of snow on a photovoltaic test bed in Truckee, California. The experimental results suggest that annual production losses are directly proportional to the amount of snow received, and proportional to the square cosine of the tilt angle of the panels. Powers et al. report annual losses of 15% due to snow; then again, Truckee is one of the snowiest cities in the world. Andrews et al. (2013) measured the effects of snow on a photovoltaic array in Ontario, Canada, and introduced a methodology to analyse snow shedding patterns. The reported annual losses ranged from 1 to 3.5%.

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 concerning 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.

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 °C. 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 in 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 °C, the dew will freeze, forming frost. Frost may also form if the ambient air temperature is above 0 °C, 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 °C. 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