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Thermal impact of adhesive-mounted rooftop PV on underlying roof shingles

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ABSTRACT

Adhesive mounting of residential rooftop photovoltaics (PV) is an alternative to traditional rack mounting that reduces installation costs. Adhesive mounting is fast, simple and reduces the need for skilled labor. In our novel design that further reduces the installation costs, a lightweight (glassless and frameless) PV module is directly adhered to a shingled roof using an adhesive tape, creating a < 5 mm air gap between the PV back-panel and the roof shingle surface. Although the gap is sufficient for moisture and rainwater transport under the PV panel, potential heat buildup under the module may adversely impact the long-term durability of the shingles. Heat buildup may also increase the heat flux through the roof, resulting in an overall increase in building cooling loads. This study investigates the thermal behavior of the roof under an adhered PV system. Two identical test huts with dark shingle-covered roofs were located in the hot, desert climate of Albuquerque, NM. Adhesively-mounted lightweight PV modules were installed on the south-facing roof of one of the test huts (PV hut), with the other one serving as a reference hut. During the summer season, the asphalt roof shingles under the PV modules experienced a 13 °C reduction in daytime peak temperature compared with the exposed shingles. No evidence of heat buildup under the PV module was observed. It was also found that the temperature of shingles underneath the adhesive was up to 6 °C higher than for shingles underneath the gap space at the daily peak time. Thin but ventilated air gap between the PV back-panel and the roof shingles helped remove the heat, while the adhesive pads (patches) served as thermal bridges between the PV module and the roof. Daily peak heat flow through the attic ceiling was almost 49% lower in the PV hut compared to the reference hut. These results show no evidence of an adverse thermal impact of the adhesive-mounted PV system on the roofing materials, while demonstrating a potential for a notable reduction in space conditioning energy requirements.

1. Introduction

Substantial reductions in the PV module cost in recent years has fueled a rapid rise in US residential rooftop PV installations. In 2015, the residential PV installations exceeded 2 GW (Kann et al., 2015). By comparison, the National Removable Energy Laboratory (NREL) estimates that the technical potential for residential PV in the US is approximately 731 GW (Gagnon et al., 2016). To realize this huge market potential, however, the non-hardware (soft) material and installation costs must be reduced (Ardani et al., 2013; Barbose et al., 2013; Morris et al., 2013; Morris et al., 2014). These soft costs remain higher in the US than in most other countries, due in part to a higher cost of installation and complicated code approvals (Barbose and Darghouth, 2015). Traditional rack-mounting of PV modules on the residential roofs is both time and skill intensive and involves: drilling mounting holes into the roof, attaching and flashing the mounts, attaching rails to the mounts, and securing PV modules to the rails. The complexity and cost of rail-based mounting has led to an increase in popularity of rail-less mounting methods (Harris, 2016). However, both mounting approaches require roof penetration, which increases the risk of moisture damage to the building.

In a United States Department of Energy (US DOE) funded Plug and Play project, we investigated the adhesive mounting of lightweight (glass-less, frame-less) PV modules as a mean to reduce the soft costs (Fraunhofer CSE, 2016; Honeker et al., 2016). The use of adhesives to attach lightweight PV modules directly to a residential roof has the advantages of speed, simplicity and reduction of skilled labor. By removing the frame and the glass frontsheet, the resulting lightweight module is well suited for adhesive mounting and may not require structural permitting which is both time consuming and adds to the installation cost. The design of this frame- and rack-less PV system does not include any metal component, which avoids the need for electrical

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grounding, saving on the associated materials and electrician labor cost.

To ensure the sufficient structural integrity, we studied the wind uplift, creep performance and durability of the adhesives (Honeker et al., 2016). Wind uplift tests performed in the wind-tunnel suggest that, properly installed, the adhered modules can withstand wind gusts up to 150 mph. During field exposure tests performed in Albuquerque, NM, it was found that, a slow displacement of the module over time (creep), may occur under extreme conditions of high angle, high temperature and high loads. Finally, a series of adhesive durability tests performed in climatic chambers, demonstrate that the thermoplastic adhesive bond gains strength on exposure to high temperatures as temperature facilitates the adhesive's ability to wet into the granulated shingle surface.

To examine the impact of adhesively-mounted rooftop lightweight PV on the moisture transport of the underlying roof elements, we conducted an outdoor test hut study in cold, humid climate of Boston, MA (Shukla et al., 2017). Lightweight PV modules were attached using 0.15 cm (0.6 in.) thick adhesives and covered approximately half of North and South roofs of the test hut. Moisture content data collected over two winter periods showed no adverse effect of the adhesively-mounted PV on the hygrothermal behavior of the underlying roof deck element.

A series of field experiments focused on the thermal effects of adhesive mounting on the PV module electric performance were performed in Albuquerque, NM (Beutner et al., 2017). The study compared the temperature and power output of glass/glass modules mounted at gaps of 17.78 cm (7 in.), 10.16 cm (4 in.) and 0.32 cm (0.125 in.) (adhesive) on the test huts. The recorded average annual temperature of adhesively mounted glass/glass module was found to be 3.4 °C and 4.3 °C higher than the 10.16 cm (4 in.) gap and 17.78 cm (7 in.) gap mounted modules, respectively. This temperature increase resulted in an average annual yield loss of 4% and 6.5%, respectively. To complement the above study, this study focuses on the effects of adhesive mounting on the roof temperature and building cooling loads.

In a conventional rail-based rack-mounted PV system, a $>$ 10 cm gap between the roof surface and the module back surface enables significant air convection under the panel, minimizing heat build-up (Brinkworth and Sandberg, 2006; Gan, 2009a, 2009b; Hirunlabh et al., 2001). In addition, conventional rack-mounted PV modules act as roof sunshades by blocking the incident sunlight. In contrast, adhesive-mounting leaves a $<$ 0.5 cm gap between module back-surface and roof shingles. From building physics viewpoint, there is a concern that this small gap limits the air-flow below the PV module, which will result in heating of the roof surface i.e. roof shingles. Increased temperatures are known to accelerate the degradation and reduce service life of common types of shingle materials used today such as asphalt shingles. Although adhesive-mounting of PV systems on flat commercial membrane roofs and sloped metal roofs is well-known (Uni-Solar, 2015), few data exists on the thermal effects of the adhesively-mounted PVs on residential roofs.

2. Technology background

Compared with conventionally rack-mounted framed PV modules, the adhesively-mounted lightweight (frameless, glassless) PV modules are expected to alter the heat transport through the roof because of the following reasons:

(a) reduced air gap thickness between the PV and shingles in the adhesive-mounted modules compared to the rack-mounted approach may reduce the convective heat transfer underneath the PV module
(b) different surface radiative characteristics (emissivity and reflectivity) of the polymeric frontsheet of the lightweight PV module, compared with the glass frontsheet of the conventional framed module
(c) local thermal bridging caused by the adhesive pads

These heat transfer mechanisms may increase the temperature of the roof under the adhered PV module. Please note that the excessive shingle temperatures may accelerate their degradation by increasing oil migration and asphalt oxidation (ARMA, 1996; Berdahl, et al., 2008; Cash, 2000; Terrenzio et al., 1998). In addition, since a typical roof accounts for about 14% of the total cooling loads in a residential building (Buildings Energy Databook, 2010), the potential for heat build-up caused by adhesive-mounted rooftop PV may increase the cooling demand of the building. A further PV performance-affecting factor is the conversion of a portion of the solar radiation to electricity (PV effect). Since an increase in temperature reduces PV cell efficiency (Dubey et al., 2013), many studies have investigated the thermal effects of PV system design parameters (including gap spacing, aspect ratio, radiation properties etc.) on the rooftop PV module performance (Beutner et al., 2017; Hirunlabh et al., 2001; Gan, 2009a; Moshfegh and Sandberg, 1998; Sandberg and Moshfegh, 1998; Wilson and Paul, 2011). In contrast, fewer studies are available on the thermal impacts of rooftop PV systems on underlying roof elements. Generally, the literature shows that rack-mounted PV systems shade the building envelope, resulting in reduced building cooling loads.

Yang et al. (2001) have simulated the effect of gap spacing on the temperature and performance of rooftop PV systems. Natural ventilation was found to remove a large amount of heat, reducing the building cooling demand. The roof thermal load decreased by almost 35% with the application of rooftop PV. Tian et al. (2007) modeled the effect of PV systems on the microclimate of the urban canopy layer. Simulations for Tianjin, China showed that PV systems with ventilating gaps significantly reduce roof surface temperature and heat flux density through the roof envelope compared to roofs without PV during the daytime; night differences were found to be small.

Kośny et al. (2012) performed a field study to investigate the thermal performance of a novel roofing technology utilizing amorphous silicon PV laminates integrated with the metal roof panels. The system featured phase change material (PCM), a ventilated channel over the roof deck and thermal insulation with an integrated reflective layer to suppress thermal bridging and reduce thermal loads through the roof. The test results showed an approximately 90% reduction in peak daytime roof heat flux and a 55% reduction in roof-generated cooling loads compared to a shingle roof control. However, no attempts were made to isolate the impact of PV laminates on the thermal performance.

Trinuruk et al. (2007) investigated the effect of a completely enclosed gap below a PV panel, which represents a worst-case condition from the standpoint of PV performance, on the heat flux through the underlying building envelope component. At 15° tilt (latitude in Thailand) and low wind speed, results indicated that air gaps larger than 4 cm were needed to reduce the heat transfer from the back of the PV modules to the envelope component. It was concluded that an appropriate air gap could reduce the heat load of the building by at least 1.85 kWh/m^2 per year. Bigot et al. (2009) investigated the effect of PV rooftop panels on the roof-generated heat loads of a building in tropical and humid climate of La Reunion Island. Ceiling temperature was reduced by up to 6 °C and roof thermal loads were decreased by $\sim$51% under a PV-covered roof compared with a non-covered roof.

Samady (2011) used small-scale building models to compare the thermal behavior of roofs with different PV designs. Two designs are of particular interest: (1) a flush-mounted system with no air gap and (2) a rail-mounted system with a 7.6 cm gap. The roof temperature of the flush-mounted system was significantly higher than the system with the gap. In fact, the roof temperature of flush-mounted system was found to be even higher than the exposed (uncovered) roof temperature. The temperature differences between the roof surface and the ceiling were higher for the flush roof compared to the roof with gap, indicating higher thermal loads in the flush roof case. Further analysis showed that the flush mounting yielded about 60% higher cooling load than the design with the 7.6 cm gap.

Dominguez et al. (2011) demonstrated the behavior of rooftop PV