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Effect of wind on temperature patterns, electrical characteristics, and performance of building-integrated and building-applied inclined photovoltaic modules

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ABSTRACT

The influence of mounting setup on the wind flow field, temperature pattern, and electrical performance of building-integrated (BIPV) and building-applied (BAPV) photovoltaic modules was investigated using wind tunnel experiments. Tests were done with an inclined 3 × 2 module for four air gap thicknesses varying from 0 cm (BIPV) to 5.5 cm (BAPV) and five freestream approaching wind speeds from 1 to 5 m s^{-1}. Wind speed and temperature were measured along the central line of the module, on the top (illuminated) as well as on the back (shaded) side. Short-circuit current and open-circuit voltage were determined from I-V measurements, and the maximum power was calculated. The wind and temperature patterns and the electrical performance were considerably affected by the mounting setup. The BAPV configurations were always better cooled by the wind than the BIPV setup because of the additional cooling in the air gap. Although a better cooling does not automatically guarantee a higher electrical performance, the BAPV configurations showed the highest performances in the test. In addition, the development of a boundary layer above and (in the case of BAPV) below the module and the trapping of heat into it, created a surface temperature gradient that significantly affected the electrical performance of the individual solar cells in the module. This is important because in most PV modules, solar cells are connected in series. Since the operational temperature influences mainly the open-circuit voltage, the open-circuit voltage of the whole module, and hereby the power output, will be determined by the behavior of each individual solar cell. In the tests reported here, the BAPV module with the thickest air gap (5.5 cm in this study) was the best performing configuration.

1. Introduction

It is well known that the maximum power output and electrical efficiency achievable by a PV module is strongly dependent on the temperature of the cells (Skoplaki and Palyvos, 2009; Wilson and Paul, 2011). The efficiency of photovoltaic *c*-Si cells is approximately inversely proportional to the cell temperature (Gan 2009; Mirzaei and Carmeliet 2015). Various correlations have been proposed for estimating the efficiency drop, varying between 0.40 and 0.65 rel% per K (Hasan and Sumathy, 2010); Kumar and Rosen, 2011; Mattei et al., 2005).

Most solar energy yield prediction models assume a uniform temperature over a PV module. However, previous studies (Mirzaei et al. 2014; Mirzaei and Carmeliet 2015; Goverde et al. 2015; Carmeliet et al. 2015; Goverde et al., 2017) have reported significant differences in temperature within PV modules that are caused by local variations in wind speed and the trapping of heat in the boundary layer developing over the module's surface. These local temperature differences affect the solar cells of the module, causing local differences in cell performance even when the cells are uniformly illuminated (Goverde et al., 2015).

Nowadays, two different applications of photovoltaics exist in urban architecture but the performance of PV modules may strongly differ between these two cases. In building-integrated photovoltaics (BIPV), where PV panels are integrated in the roof or façade of a building, only the front side of the panel is directly cooled by the wind. In the case of building-applied photovoltaics (BAPV), on the other hand, PV panels are not directly integrated in the roof or façade but mounted on a

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supporting frame attached to the building. Apart from wind-induced cooling on the front side, these panels are also cooled by wind flowing over their back side because of the open space between the roof (or façade) and the panel.

Back-ventilation is a simple cooling technique to avoid high surface temperatures (Ritzen et al., 2017). Its performance has been widely studied in BAPV using numerical techniques such as computational fluid dynamics (Corbin and Zhai, 2010; Yoo and Manz, 2011; Gan, 2009; Wilson and Paul, 2011; Xing et al., 2014; Zhang et al., 2017). However, the simultaneous effect of airflow above and below the panel, and the associated heat convection, are rarely considered (Mei et al., 2009; Naewngerndee et al., 2011) although in reality both flows are equally important (Mirzaei et al., 2014). Wind tunnel studies in which wind and temperature were measured on both sides of a BAPV surface attached to a scale model of a building have been performed by Mirzaei et al. 2014; Mirzaei and Carmeliet 2015, and Carmeliet et al. 2015. These studies focused specifically on wind and temperature and only worked with low to very low wind speeds, from 0.5 to 2.0 m s^{-1} (freestream wind velocity upwind of the building model). Other limitations were that only BAPV was tested (there was always an air gap between the PV modules and the building), and that no measurements were performed of the electrical output of the solar cells on the scale model.

In this study we report wind, temperature and electrical measurements performed on an inclined 3 × 2 PV module installed on a building in a wind tunnel. Experiments were done for wind speeds between 1 and 5 m s^{-1}, for three different air gaps underneath the module (BAPV) and also for a module directly integrated in the building (BIPV). The aim of this study is not only to verify previously published results for a different geometric configuration, but also to collect information for a wider range of wind speeds, to directly study and quantify the effects of above-module and below-module winds on the electrical performance of a PV module, and to compare BIPV to BAPV. In addition, information on wind, temperature, cooling, and electrical characteristics has been collected all over the module to quantify and explain the spatial differences in electrical output that occur within inclined PV panels.

2. Instruments and methods

2.1. Solar cells and wind tunnel

A custom-made 3 × 2 PV panel (54.5 cm × 34.8 cm) was used for this study. A schematic overview of the panel, the numbering of the cells and the wind direction is shown in Fig. 1. Standard

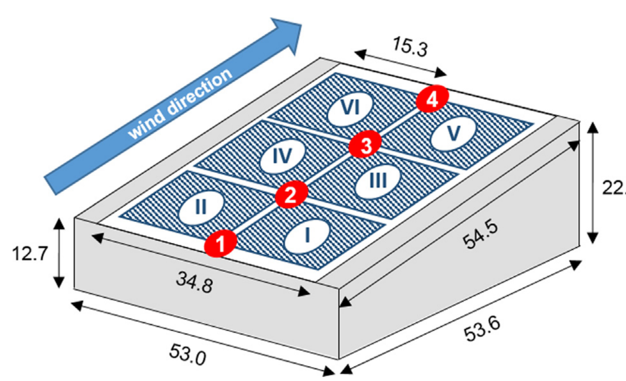

Fig. 1. Schematic overview of the mounting setup used in this study. The PV module consisted of 6 industrial full Al-BSF *c*-Si solar cells (I–VI in the figure). Arrow shows the direction of the wind. Numbers in red circles indicate the position of the sensors for wind and module temperature measurements. All numbers are in cm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

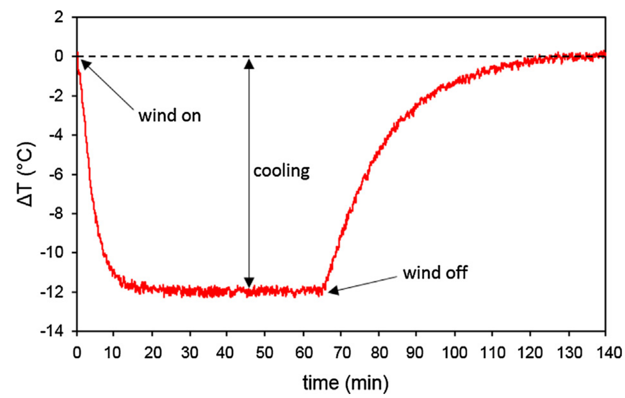

Fig. 2. Example of temperature response to wind of the tested PV module. ΔT is the difference between the module temperature with wind and the module temperature without wind, under conditions of equal ambient temperature and illumination.

156 mm × 156 mm *p*-type multi-crystalline silicon solar cells (TSEC TSS62TN) with an average efficiency of 18.6% were used in the panel. A 3-mm glass plate was used as a front plate, followed by a 300-µm thick EVA adhesive layer. The module was finished by a standard black back sheet, which has a thickness of 200 µm. The interspace between the solar cells was 5 mm in the longitudinal direction and 4 mm in the lateral direction. Each solar cell had its connection wires outside the module to be able to measure each cell individually.

All wind tunnel experiments were conducted in the closed-return wind tunnel of the Geography and Tourism Research group, KU Leuven, Belgium. This is a subsonic wind tunnel with two test sections. All experiments were conducted in the largest section, which is 7.6 m long, 1.2 m wide and 0.6 m high. For a technical diagram of the tunnel, see the study by Goossens (1989).

2.2. Experimental setup

The PV module was installed on the roof of a building model constructed from insulated polystyrene foam. In contrast to the symmetric building investigated by Mirzaei et al. (2014), Mirzaei and Carmeliet (2015) and Carmeliet et al. (2015), which intends to mimic a classic residential house, we opted for testing an asymmetric configuration, which is more typical for many agricultural and industrial constructions (Fig. 1). The leading edge of the module (and the building) was at 500 cm from the entrance of the wind tunnel's test section. An inclination of 10° (or 18%) was selected for the roof slope; the building height from the floor to the highest point of the roof was 12.7 cm at the upwind side and 22.5 cm at the downwind side. The inclination of 10° was selected based on the maximum angle that could be installed without creating too much blockage in the wind tunnel. Four thicknesses of air gap between the roof and the PV module were tested: 0 cm (no air gap), 2.1 cm, 3.5 cm, and 5.5 cm. It is important to leave a minimum air gap of 1–2 cm underneath the module to allow for heat dissipation, but too large air gaps will increase the outside temperatures of the building (Trinuruk et al., 2007).

The fetch in the wind tunnel was not prepared in any special way, and given these conditions, the depth of the boundary layer in the tunnel is of the order of 5–7 cm (Goossens, 2010). This means that the PV module itself was located in the free-stream region of the tunnel.

Five free-stream wind velocities were selected during the tests: 1, 2, 3, 4 and 5 m s^{-1}. This adequately spans the range of annual average wind speeds that are recorded near the Earth's continental surfaces, which generally vary between 1 and approximately 6 m s^{-1} (Climate-Charts, 2007). Wind velocity was measured with a standard pitot tube connected to a digital Furness FC016 manometer (Furness Controls, Bexhill, UK). Wind speeds were measured with a precision of