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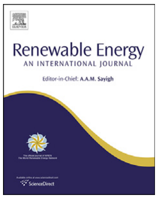

Experimental investigation of wind effects on a standalone photovoltaic (PV) module

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A B S T R A C T

The pressure field on the upper and lower surfaces of a photovoltaic (PV) module comprised of 24 individual PV panels was studied experimentally in a wind tunnel for four different wind directions. The results show that the pressure distribution on the module surface is symmetric about its mid-plane for head-on wind (0° and 180°) and asymmetric at other wind directions. The inter-panel gap (which is essential in large PV modules) is found to influence module's surface pressure field. Pressure magnitudes on the module surface were increased with the module inclination angle, as expected. It is also observed that the mean pressure magnitudes on the PV module under smooth wind exposure are higher than those under open terrain wind exposure.

1. Introduction

Photovoltaic (PV) or solar modules are becoming increasingly popular for domestic as well as industrial electricity generation. Advancements in solar energy technology continue to improve their overall efficiency and long-term reliability. These improvements are motivated by the continual depletion of other sources of energy especially fossil fuels, which are also sources of increasing environmental concerns. Among various alternative energy technologies, PV modules are the fastest growing and most popular renewable energy systems with global annual investments exceeding US$100 billion [1]. PV modules are exposed to wind all the time. Wind has two different types of impact on the PV panels; (i) The positive impact of the wind is to increase the cooling of the PV panel, which helps in reducing the cell temperature [2] that is crucial in order to maintain PV conversion efficiency. (ii) The negative impact of wind is the exertion of force on the PV panel, which could lead to a significant structural damage. At present, there is a scarcity of provisions of wind load in building standards and codes to design these PV structures.

The most common PV modules are rectangular shaped flat plates usually referred as PV panels or PV structures. Ground mounted PV modules are commonly inclined for optimal energy extraction while flat rooftop mounts are usually horizontal, driven by constraints other than the energy generation. When inclined, the latitude of the location where they are installed usually determines the inclination angle, α, of the module's plate. This is to allow the PV panel to capture maximum amount of sunlight. The common rule of thumb is $\alpha = \beta \pm 15°$, where β is the location's latitude [3].

The nature of the force induced on a structure by the wind depends, largely on the characteristics of the wind such as its direction, speed, exposure conditions and the shape of the structure. Ground mounted PV modules, which are the subject of this study, are typically low-rise structures. They are therefore immersed within the lowest region of the atmospheric boundary layer (ABL) where the flow of the wind is highly unpredictable due to the intense turbulence actions [4]. The mean velocity profile of the wind in this region is largely influenced by the ground roughness. In nature, for any particular terrain, roughness cannot be accurately determined owing to variations in the size, shape, distribution and density of the roughness elements (trees, grasses, buildings, etc.) [5]. In wind experiments, a power law is commonly used to characterize the mean wind velocity profile [6]. The exponent of the power law is dependent on the terrain (roughness) and is provided in various codes such as the National Building Code of Canada (NBCC) [7] and its American counterpart from the ASCE [8].

The wind loads on various types of solar modules had been measured in the wind tunnels and reported in the literature. Early examples include the wind load experimental tests on arrays of flat

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plate PV panels, commissioned for testing by the US Department of Energy [9]. The results of the test show that upstream flow sheltering elements such as barriers and fences can be used to reduce the wind loads on PV arrays while end plates were found most suitable in reducing the large load measured on the panels at the corners of the array.

Several studies reported the testing of scaled-models of roof-mounted PV panels in the wind tunnel. Radu et al. [10] tested an array of solar panel models, mounted on the roof of a scaled five story-building model in a boundary layer wind tunnel. Their experiments were performed on three different building models with flat roofs. Each building had different kind of attic. The results showed that the front row panels had higher pressure and force coefficients. These front row panels shelter the panels behind them from the wind action. They observed that the maximum variations in the force coefficient ranged between -1.4 and $+1.25$. In subsequent studies, the lift forces on the support structures of these panels were also investigated [11]. They concluded that appropriate building attics could reduce wind loads on PV modules installed on building rooftops. Wood et al. [12] also tested PV modules mounted on the flat rooftops of a scaled building model in a wind tunnel. The pressure on the scaled building roof was simultaneously measured which agreed well with the full-scale results of the Texas Tech experimental building. They observed fluctuations in the net pressure coefficient acting on the panels, with peak values varied between -0.2 and 0.2. Both the clearance height between the rooftop and the panel, and the lateral spacing between the panels were varied during these tests. Except for the leading edge where slight variation was recorded, the results showed no significant changes in the overall pressure on the modules from the variation of the clearance height and panel spacing. An array of six parallel slender solar modules were tested by Kopp et al. [13] in the wind tunnel at a Reynolds number of 7.6×10^4 and wind speed of 15 m/s. They determined the location of the highest system torque on the modules as well as the critical loading angle of the approach wind. A linearized model to predict the peak system torque of these modules was subsequently presented.

Full-scale outdoor experiments were carried out on roof-mounted PV modules by Geurts and Steenbergen [14] to investigate lift forces on the panels. The PV modules were mounted parallel to a pitched roof. The wind speed and wind direction were measured using a cup anemometer and directional vane position at a height of 10 m above the ground. The pressure difference at the top and underside of the panel were measured to determine the wind load. The maximum lift force on the solar panel, which is dependent on the wind direction, corresponded to a pressure coefficient, C_p, value of -0.55. A differential pressure coefficient, ΔC_p, value of -0.3 for the upward and 0.2 for the downward acting force was recommended for a single solar panel on such rooftops. A 1/3rd scaled model of a sun-tracking PV modules [15] were tested by Velicu et al. [16] in an open circuit wind tunnel. The drag and lift forces on the PV modules were measured using force transducers. The results showed that the force coefficients on the PV panel increased as the panel tilt angle increased from 0° to 90°.The force coefficients also increased as the wind velocity increased, as expected.

Very limited studies investigated the wind loading on ground mounted PV panels. Bitsuamlak et al. [17] studied the aerodynamic effects on full-scale ground mounted PV panels using Computational Fluid Dynamics (CFD). Experimental measurements were also conducted on a full-scale model for validation. The results showed pressure distribution on the windward and leeward sides of the panel for two wind directions. The velocity data clearly depicted the flow separation and wake patterns. Shademan et al. [18] conducted wind load investigations on standalone and array PV modules using CFD. Various configurations of the standalone solar panel were considered at different wind angles. Their results showed that the maximum wind loading was produced at wind directions of 0° and 180° and on the panels at the bottom row of a standalone system. They also investigated the effects of the lateral gap spacing between sub-panels as well as the ground clearance and the wind direction on the wind loading of the full panel as well as array effects. They observed that gap spacing between the panels changed the flow structure in the wake region and produces regions which can experience large wind loading while increased ground clearance causes larger mean wind loading on the panels.

Meroney [19] used different turbulence models to simulate the flow around PV modules. Their study estimated the drag, lift and overturning moments on the solar panel support systems. Static pressure results on the panels at 0° and 180° wind angles showed higher pressures at the front rows of panels, consistent with the observations of Radu et al. [10] and Shademan et al. [18].

The wind effects on other types of solar collectors are also reported in the literature. For example, Wu et al. [20] investigated the effect of the gaps between panels on the surface of a heliostat through CFD and experimental testing on scaled-model. Heliostats have similar geometrical configurations as PV panels. Both the experimental and numerical results showed that the overall wind load slightly increased with an increase in the gap size. The CFD results showed that this increase was due to the flow acceleration through the gap, which caused a decrease in the static pressure at the gap's outlet. Therefore the overall drag force increased due to the resultant decrease in the leeward pressure coefficient. Gong et al. [21] experimentally studied the dynamic response of heliostat due to wind loading. They observed maximum displacement of the heliostat structure at the upper corners due to the fluctuating wind pressure. They also developed a finite element model to predict the dynamic response of the heliostat. Zemler et al. [22] numerically studied the wind effects on parabolic-shaped solar collectors. They considered different aperture sizes of the paraboloid and orientations, and suggested a parametric model to estimate forces exerted by wind on the collector based on the wind speed and the aperture.

As the above literature review shows, several studies have investigated the wind effects on PV panels. However, a significant number of these studies were focused on roof-mounted panels and the studies focused on the investigation of wind effects on ground-mounted PV panels are relatively few, which are mainly computational in nature. Furthermore, the literature is still lacking a detailed characterization of wind loading on ground-mounted PV panels exposed to atmospheric boundary layer. Existing building codes in North America (ASCE 7-10, 2010 and National Building Code of Canada, 2010) do not provide information on design wind loads for ground mounted or roof mounted solar panels. The only structure, that resembles a stand-alone ground mounted solar panel, is the mono-slope free roof for which design loads for 0° and 180° wind directions are reported in ASCE 7-10. The present work is therefore important in order to determine to what extent the design loads for mono-slope free roofs are applicable to ground mounted stand-alone solar panels.

As the growth of large-scale PV solar farms is exponential, it is becoming more critical to review the wind effects on ground-mounted PV panels. This improved knowledge is vital to the growing solar farm industry to mitigate the risk of damage caused by wind effects.

The present study is focused on an experimental investigation of the wind load on a ground-mounted PV module. It includes a detailed characterization of pressure distribution on the panel surfaces as well as a parametric study to determine the effect of varying parameters such as wind exposure and panel inclination. A comparison between the load on the model and its flat plate