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# A numerical approach to the investigation of wind loading on an array of ground mounted solar photovoltaic (PV) panels

Chowdhury Mohammad Jubayer*, Horia Hangan

*The Wind Engineering, Energy and Environment (WindEEE) Research Institute, Western University, London, Ontario, Canada N6A 5B9*

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ABSTRACT

Aerodynamic loads on, and wind flow field around, an array of ground mounted solar photovoltaic (PV) panels, immersed in the atmospheric boundary layer (ABL) for open country exposure, are investigated using the unsteady Reynolds-Averaged Navier–Stokes (RANS) approach. A full scale three-dimensional (3D) solver from OpenFOAM® (ESI Group) is employed with the Shear Stress Transport (SST) k–ω turbulence closure. Several azimuthal wind directions (South, 0°; Southwest, 45°; Northwest, 135° and North, 180°), for a Reynolds number of $3 \times 10^6$, are considered. The numerical modeling approach is validated by comparing the velocity field surrounding a ground mounted stand-alone solar panel with wind tunnel experiments. Detail analysis of wind loading on the array is provided in relation to the wind flow field surrounding the array. The results for the array configuration show that all the trailing rows are in the complete wake of the leading row for straight winds (0° and 180°), but not for oblique winds (45° and 135°). For all four wind directions studied here, the first windward row experiences the maximum wind loads in terms of drag and lift. In terms of the maximum overturning moment, the 45° and 135° wind directions are critical with similar overturning moment coefficients for each row.



## 1. Introduction

Utility scale photovoltaic (PV) power stations or solar farms are emerging as one of the significant contributors to electricity generation. As of 2014, at least 53 solar farms with a capacity more than 50 MW are operating in 13 countries (REN 21, 2014), whereas before 2009, only one solar farm had installed capacity of more than 50 MW (Olmedilla PV Park, Spain, 60 MW). Typically, solar farms are sited in a large open field and employ arrays of ground mounted solar PV panels designed to supply electricity to the commercial power grid. Optimizing PV panel support structures to withstand aerodynamic forces is one of the challenges experienced by the solar panel manufacturer and installer. Both experimental (Bechtel National Inc., 1980; Miller and Zimmerman, 1981; Radu et al., 1986; Radu and Axinte, 1989; Wood et al., 2001; Kopp et al., 2002, 2012; Chung et al., 2008, 2011; Aly and Bitsuamlak, 2013, 2014; Kopp and Banks, 2013; Pratt and Kopp, 2013; Banks, 2013; Browne et al., 2013; Cao et al., 2013; Stathopoulos et al., 2014; Warsido et al., 2014; Abiola-Ogedengbe et al., 2015) and numerical studies (Bitsuamlak et al., 2010; Meroney and Neft, 2010; Shademan et al., 2014; Jubayer and Hangan, 2014) have been performed to investigate wind loads on solar panels. As the focus of this study is on solar farms, only studies on arrays of ground mounted solar panels are discussed here.

Both studies by the Bechtel National Inc. (1980) and Miller and Zimmerman (1981) were conducted as commercial industrial projects to initiate an effort towards reducing the cost of solar panel arrays. Bechtel National Inc. (1980) reported the wind loads on ground mounted solar array using strain gages in a boundary layer wind tunnel. Aerodynamic coefficients were found to be independent of the scales used (1:24 and 1:12). In addition to the scales, solar panel height above the ground (lower edge height of 0.61 and 1.22 m), porosity (2.5%, 5% and 10%) and aspect ratio (Width/Breadth, $W/B$ of 2, 3 and 4) also did not have a significant effect on the aerodynamic coefficients of the panel. Unlike Bechtel National Inc. (1980), Miller and Zimmerman (1981) utilized pressure taps to measure wind loads on the panel and was able to provide pressure distributions on the solar panel surface. For the wind tunnel speed of 15.24 m/s, between 1:12 and 1:24 scales, the dimensionless pressure and force coefficients were independent of Reynolds number.

A wind tunnel study on a ground mounted solar panel array was performed by Kopp et al. (2012) to investigate the effect of buildings on roof mounted arrays since roof mounted arrays were the principal focus of this study. For the ground mounted array, 0° and 180° wind directions for a 20° panel inclination were tested. A total of 12 rows of panels were arranged in tandem to form the

* Corresponding author. Tel.: +1 519 661 2111x88152.
*E-mail addresses:* cjubaye@uwo.ca (C.M. Jubayer), hmhangan@uwo.ca (H. Hangan).

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**Nomenclature**

| | |
|---|---|
| $A$ | surface area of a single row of panels ($m^2$) |
| $A_i$ | surface area associated with $C_{pi}$ ($m^2$) |
| $B$ | breadth of the panel (m) |
| $B'$ | breadth of the panel in the PIV measurement plane (m) |
| $b$ | distance from the leading edge of the panel on the panel surface along the breadth of the panel (m) |
| $C_p$ | coefficient of pressure (dimensionless) |
| $C_{pi}$ | coefficient of pressure over an area $A_i$ (dimensionless) |
| $C_D$ | coefficient of drag (dimensionless) |
| $C_L$ | coefficient of lift (dimensionless) |
| $C_{Mz}$ | coefficient of moment about $Z$ axis (dimensionless) |
| $Cr$ | courant number ($=v\Delta t/\Delta l$) (dimensionless) |
| $H$ | height of the panel (m) |
| $k$ | turbulent kinetic energy ($m^2/s^2$) |
| $M_Z$ | net moment from the upper and lower surfaces of the panel about $Z$ axis (N-m) |
| $t$ | flow time (s) |
| $t^*$ | non-dimensional flow time ($=t\overline{U_H}$) (dimensionless) |
| $\overline{U_H}$ | mean stream-wise velocity at height $H$ (m/s) |
| $v$ | local mean wind speed in a cell (m/s) |
| $\overline{V_{mag}}$ | mean velocity magnitude (m/s) |
| $W$ | width of the panel (m) |
| $x'$ | distance of the row centers from the center of the first windward row (m) |
| $y_0$ | aerodynamic roughness length (m) |

*Greek symbols*

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|---|---|
| $\alpha$ | wind direction (deg) |
| $\varepsilon$ | dissipation rate of turbulence ($m^2/s^3$) |
| $\rho$ | density of air ($kg/m^3$) |
| $\theta$ | panel inclination angle (deg) |
| $\omega$ | specific dissipation rate of turbulence ($s^{-1}$) |
| $\Delta l$ | dimension of a grid cell in flow direction (m) |
| $\Delta t$ | time step (s) |
| $\Delta t^*$ | non-dimensional time step ($=\Delta t\overline{U_H}$) (dimensionless) |

*Abbreviations*

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| ASCE | American Society of Civil Engineers |
| ABL | Atmospheric Boundary Layer |
| BLWT | Boundary Layer Wind Tunnel |
| CFD | Computational Fluid Dynamics |
| ESDU | Engineering Sciences Data Unit |
| GCI | Grid Convergence Index |
| LES | Large Eddy Simulation |
| NMSE | Normalized Mean Square Error |
| PIV | Particle Image Velocimetry |
| PISO | Pressure Implicit with Splitting of Operators |
| PV | Photovoltaic |
| RANS | Reynolds-Averaged Navier–Stokes |
| SEAOC | Structural Engineers Association of California |
| SHARCNET | Shared Hierarchical Academic Research Computing Network |
| SST | Shear Stress Transport |
| TI | Turbulence Intensity |

array. For both wind directions (0° and 180°), wind load was maximum for the first windward row then it decreased to the minimum at around the third or fourth row, followed by load increasing on further downstream rows. Wind tunnel tests were also conducted by Warsido et al. (2014) to investigate the effect of row spacing on wind loads for a solar panel array mounted on the flat roof of a building and also on the ground. Minimal influence of lateral spacing between panels was found on the inner panel columns of the ground mounted system. However, increasing longitudinal spacing between panels increased wind loads on the panels.

In the study by Bitsuamlak et al. (2010), one case of arrayed ground mounted solar panel was studied using numerical simulations. Three stand-alone systems were arranged in tandem for the arrayed configuration and only one wind direction (180°) was considered. It was found that the sheltering effect from the upwind panel reduced wind loading on the downstream panels significantly. However, the Large Eddy Simulation (LES) modeling approach used was rather challenging for the domain size employing a grid size limited to $1.68 \times 10^6$ cells for a Reynolds number of $2.5 \times 10^6$. According to Spalart et al. (1997), for Reynolds numbers of the order of $10^7$, a computational grid consisting of a minimum of $10^{11}$ cells has to be used to fully resolve the surface layer and obtain a fully developed aerodynamic solution for LES. Shademan et al. (2014) investigated the effect of row spacing for a ground mounted solar panel array for 45° inclination angle and 0° wind direction. Steady Reynolds-Averaged Navier–Stokes (RANS) approach was used with the Shear Stress Transport (SST) k–ω turbulence model. It was observed that the row spacing did not have an effect on wind loading of the first windward row of panels. However, for the rest of the rows, drag increased and lift decreased with the increase of row spacing.

North American building standards (ASCE 7-10, 2010 and National Building Code of Canada, 2010) do not cover any information regarding minimum design wind load for solar panel arrays, either ground mounted or roof mounted. However, Australia (AS/NZS 1170.2, 2011) and California (SEOAC, 2012) have some standards for roof mounted solar panels but not for ground mounted installations. Clearly, published literatures and building standards lack information for designing wind loads on ground mounted solar panels in an array configuration as in solar farms.

The present study is performed to investigate not only the wind load but also the underlying aerodynamic mechanism responsible for wind loads on a ground mounted solar panel array. Four wind directions, South (0°), Southwest (45°), Northwest (135°) and North (180°), are considered here. Computational Fluid Dynamics (CFD) approach with the 3D unsteady Reynolds-Averaged Navier–Stokes (RANS) simulation is undertaken to satisfy the objective of this study. The CFD methodology used here is similar to the study by Jubayer and Hangan (2014) in which the wind loading on a stand-alone ground mounted solar panel has been estimated. However, configurations of a stand-alone system and an array of panels are different with an expected difference in the wind flow field around the solar panels and thus the wind loads. In this study, the critical wind directions are clearly identified based on drag, lift and overturning moment acting on the individual row of panels in the array. Also, the surface pressure distributions are analyzed in relation to the wind flow field around the solar panel. This current study extends the work of Jubayer and Hangan (2014) from a stand-alone system to arrays of ground mounted solar panel with application to utility scale PV power stations.