Article

Wind Loads on a PV Array

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Featured Application: This study determines the wind loads for a photovoltaic (PV) array at a high angle of tilt. The data is useful for the detailed structural design of an offshore PV array.

Abstract: This study experimentally determines the wind loads on a stand-alone solar array (length-to-width ratio of 0.19; 1/10-scale commercial modules). The freestream velocity in a uniform flow is 14.5 ± 0.1 m/s, and the turbulence intensity is 0.3%. The angle of tilt ranges from 10° to 80° and the wind is incident at angle of 0°–180°. Mean surface pressure measurements on the upper and the lower surface of the inclined solar panels are used to calculate the lift coefficient. For the angle of incidence of 0°–60° for the wind, the variation in the lift coefficient with the angle of tilt is U-shaped. The formation of a strong windward corner vortex results in greater lift force on the right half of the inclined plate for the angle of incidence of 30°–45° for the wind.

Keywords: PV; tilt angle; wind incidence angle; wind load

1. Introduction

The use of solar energy has increased, due to public concerns about climate change and environmental pollution. The total respective capacity for solar photovoltaic (PV) systems was 303 GW and 402 GW in 2016 and 2017 [1]. A PV system consists of inclined panels, which are usually mounted on the rooftops of residential or commercial buildings. Floating PV on reservoirs, ponds, or lakes are another emergent solar energy system [2–5]. In nearshore areas, a PV system floats in the ocean using a buoyancy system [6].

To harness solar energy, PV panels for roof-top or ground systems are installed at an optimal tilt angle that allows the sunlight to fall perpendicular to the panels’ surface. Wind loads depend on the tilt angle, the angle of incidence of the wind, and the spacing and sheltering of the arrays [7–11]. For an inclined panel with a length-to-width ratio, L/W, of 2 that faces a uniform flow, Chung et al. [12] showed that there is a decrease in the sectional lift coefficient as the angle of tilt increases (α = 15°–25°). Corner vortices are also observed. For an inclined panel (L/W = 0.22) on flat roofs, an increase in α (= 20°–45°) produces greater suction [13]. Cao et al. [14] noted that wind-induced loads on an inclined panel are due primarily to pressure equalization at large angles of tilt and turbulence at small angles of tilt. The effect of the angle of incidence of wind, β, was investigated by Chou et al. [15]. There is greater suction on the upper surface near the windward corner for β = 15°–60°. A study by Shademan and Hangan [16] obtained similar results.

For a PV system, wind loads are significantly reduced by the presence of neighboring upwind arrays (sheltering effect) [17,18]. Therefore, this study only determines wind loads for a stand-alone PV array (nine panels, L/W = 0.19). In addition, the wind loads on the PV panels in a sea environment are not the same as those for PV panels that are located on land. The motion of a pontoon results in the
variation in $\alpha$ during a wave cycle. The safety of PV panels in environments that feature large waves is a practical issue for the system design. To ensure that the system functions properly, the effect of $\alpha$ (up to 80°) and $\beta$ is determined.

2. Experimental Setup

The experiments were performed in a closed-loop wind tunnel at the Architecture and Building Research Institute (Tainan, Taiwan). The wind tunnel has a working cross section of 2.6 m (height) \times 4 m (width) \times 36.5 m (length) and a contraction ratio of 4.71. To determine the critical wind loads, a 1/10 scale stand-alone array (nine inclined panels, P1–P9; $L = 168$ mm and $W = 900$ mm) was constructed, as shown in Figure 1. The origin of the coordinates ($x/L = 0$ and $y/W = 0$) is located at the upper left corner of the inclined panel. When the low surface faces the flow, this corresponds to $\beta$ of 0°. The lift coefficient, $C_L$, is negative in the upward direction. The model sits 10 mm above the tunnel floor and the blockage ratio is up to 1.4%.

Meteorological data from nearshore buoys in Taiwan (Qigu, Longdong and Hsinchu) were collected [19] to determine the test conditions. The most common values of $\beta$ for Qigu (23°05′42″ N) were 210°–225° and 315°–360° for the period of 2013–2017. In Longdong (25°05′48″ N) and Hsinchu (24°45′19″ N), the respective values for $\beta$ were 0° and 30°–45°. The variation in $\alpha$ for PV panels with respect to wind was ±45°. In this study, the value of $\alpha$ was between 10° and 80° (in increments of 10°) and the value of $\beta$ ranged from 0° to 180° (in increments of 15°). Note that the angle between the PV arrays and the surface of the sea is fixed for an offshore-type PV system. This is not the case for the wind tunnel tests. However, the experimental results of this study can be used for preliminary structural designs of an offshore PV array and to validate the numerical simulation.

For an inclined panel for which $L/W = 2$, Chung et al. [12] showed that there is a small increase in wind load when there is an increase in the intensity of the freestream turbulence. Therefore, the experiments for this study used a uniform flow. The freestream velocity was $14.5 \pm 0.1$ m/s, and the turbulence intensity was 0.3%. A Pitot-static tube was positioned at the same height as the front edge of the inclined panels to determine the static, $p_{\infty}$, and the dynamic pressure, $q$, for the incoming flow. The Reynolds number, which is based on the length of the inclined panels, was $1.64 \times 10^5$. Note that there is Reynolds number independence for an inclined panel [20]. A total of 434 pressure taps were drilled on the upper and lower surfaces of the model. Flexible polyvinyl chloride tubes of 1.1 mm in diameter and 60 cm in length were connected to SCANIVALVE multichannel modules (Model ZOC 33/64Px 64-port; Model RAD3200 pressure transducer, Scanivalve Co., Liberty Lake, WA, USA) to measure the mean surface pressure. The full-scale range of the sensors was ±2490 Pa, and the accuracy was ±0.15% of the full scale. The sampling rate was 250 Hz, and each record had 32,768 data points. The mean pressure coefficient, $C_p = (p - p_{\infty})/q$, and $C_L = \frac{1}{2} \int_A \Delta C_p \cos (\alpha) dA$ were calculated. The differential pressure coefficient, $\Delta C_p = (C_{p,up} - C_{p,low})$ was determined using the value of $C_p$ for the upper and lower surfaces.

![Figure 1. Test configuration for a stand-alone array.](image-url)
3. Results and Discussion

3.1. Longitudinal Pressure Distributions

Examples of the pressure distribution in the longitudinal direction, $C_{pl}$, ($\alpha = 20^\circ$–$80^\circ$) for $\beta = 0^\circ$ at $y/W = 0.5$ are shown in Figure 2. Negative values for $C_{pl}$ (or suction) were observed on the upper surface for all test cases. For $\alpha = 20^\circ$ and $40^\circ$, the value of $C_{pl}$ decreased along the longitudinal direction. The location with the lowest $C_{pl}$ value moved upstream for $\alpha = 60^\circ$ and $80^\circ$. The variation in $C_{pl}$ ranged from 4.6% ($\alpha = 20^\circ$) to 10.9% ($\alpha = 60^\circ$). For an inclined panel with $L/W = 2$, Chou et al. [21] showed that there is a significant change in the value of $C_{pl}$ for $\alpha \leq 30^\circ$. This is due to the formation of intense side-edge vortices. On the lower surface, the value of $\alpha$ had a significant effect on the $C_{pl}$ distribution. For $\alpha = 20^\circ$ and $40^\circ$, the value of $C_{pl}$ decreased initially, and then the distributions flattened. The values of $C_{pl}$ for $\alpha = 60^\circ$ and $80^\circ$ were greater for the first half of the inclined array. This demonstrates that the localized load was most significant near the front edge for greater values of $\alpha$. The value of $C_{pl}$ for $L/W = 0.19$ (an array) was less than that for $L/W = 2$ (a panel).

![Figure 2. Mean longitudinal pressure distributions for $y/W = 0.5$ and $\beta = 0^\circ$.](image)

The $C_{pl}$ distributions for $\beta = 30^\circ$ at $y/W = 0.5$ are shown in Figure 3. On the upper surface, the distributions were flat for $\alpha = 40^\circ$, $60^\circ$, and $80^\circ$ but not for $\alpha = 20^\circ$. The value of $C_{pl}$ decreased significantly for the second half of the inclined array. On the lower surface, the $C_{pl}$ distributions were similar to those for $\beta = 0^\circ$. The values for $C_{pl}$ were lower for $\beta = 30^\circ$. For $\beta = 45^\circ$, Kopp et al. [22] observed the peak system torque at angles for approaching wind that are close to the angle of the diagonal axes of an inclined panel. Figure 4 shows that the variation in $C_{pl}$ on the upper surface was more significant at lower values of $\alpha$. The lowest value of $C_{pl}$ was observed at $x/L = 0.5$–0.7 for $\alpha = 20^\circ$, $40^\circ$, and $60^\circ$. This corresponds to the formation of the windward corner vortex. An increase in the value of $\beta$ resulted in a decrease in the value of $C_{pl}$ on the lower surface. For $\beta = 135^\circ$, Figure 5 shows that the flow decelerated along the longitudinal direction on the upper surface. An increase in $\alpha$ produced a more positive value for $C_{pl}$ on the upper surface and a more negative value for $C_{pl}$ on the lower surface.
on the lower surface. The sectional lift coefficient increased as $\alpha$ increased; hence, there is a greater downward force.

![Figure 3](image-url-3.png)  
**Figure 3.** Mean longitudinal pressure distributions for $y/W = 0.5$ and $\beta = 30^\circ$.

![Figure 4](image-url-4.png)  
**Figure 4.** Mean longitudinal pressure distributions for $y/W = 0.5$ and $\beta = 45^\circ$.
The location of the maximum force increased from the left to the right edges.

For the right half, the opposite was true. Expansion and compression were observed for the upper surface decreased slightly toward the right side and increased as the value of \( \alpha \) increased from the left to the right sides as the value of \( \alpha \) increased. For \( \beta = 30^\circ \), the \( C_{ps} \) distributions were similar to those for \( \beta = 30^\circ \). However, there was a greater pressure gradient on the upper surface. For \( \alpha = 20^\circ \), a larger windward corner vortex was formed, and the location of the lowest value of \( C_{ps} \) moved to the left. For \( \beta = 135^\circ \), wind blew over the lower surface of the inclined panels. The \( C_{ps} \) distributions on the lower surface showed similar patterns to those on the upper surface for \( \beta = 45^\circ \), as shown in Figure 9. This shows the downward force increased from the left to the right edges.

3.2. Spanwise Pressure Distributions

For \( x/L = 0.5 \), the spanwise pressure, \( C_{ps} \), distributions for \( \beta = 0^\circ \) are shown in Figure 6. On the upper and lower surfaces, there was an inverted U-shape for \( \alpha = 20^\circ, 40^\circ, \) and \( 60^\circ \), which corresponds to side-edge vortices. This agrees with the results for an inclined panel for which \( L/W = 2 \) [21]. Therefore, the side panels (P1 and P9) experienced greater suction on the upper surface and less lift force on the lower surface. For \( \alpha = 80^\circ \), the distributions were quite flat. The difference in the pressure between the upper (highly separated flow with lower value in \( C_{ps} \)) and lower surfaces (near stagnation region with greater value in \( C_{ps} \)) was greater than that for \( \alpha = 20^\circ, 40^\circ, \) and \( 60^\circ \).

For \( \beta = 30^\circ \), the \( C_{ps} \) distributions are shown in Figure 7. For the left half (P1–P4), the value of \( C_{ps} \) on the upper surface decreased slightly toward the right side and increased as the value of \( \alpha \) increased. For the right half, the opposite was true. Expansion and compression were observed for \( \alpha = 20^\circ \), due to the formation of a strong windward corner vortex and a greater lift force on P6–P8. On the lower surface, the value of \( C_{ps} \) increased from the left to the right sides as the value of \( \alpha \) increased. The location of the maximum \( C_{ps} \) moved to the right side when \( \alpha \) increased.

For \( \beta = 45^\circ \), Figure 8 shows that the \( C_{ps} \) distributions were similar to those for \( \beta = 30^\circ \). However, there was a greater pressure gradient on the upper surface. For \( \alpha = 20^\circ \), a larger windward corner vortex was formed, and the location of the lowest value of \( C_{ps} \) moved to the left. For \( \beta = 135^\circ \), wind blew over the lower surface of the inclined panels. The \( C_{ps} \) distributions on the lower surface showed similar patterns to those on the upper surface for \( \beta = 45^\circ \), as shown in Figure 9. This shows the downward force increased from the left to the right edges.

Figure 5. Mean longitudinal pressure distributions for \( y/W = 0.5 \) and \( \beta = 135^\circ \).
Figure 6. Mean spanwise pressure distributions for $x/L = 0.5$ and $\beta = 0^\circ$.

Figure 7. Mean spanwise pressure distributions for $x/L = 0.5$ and $\beta = 30^\circ$. 

$C_{p,s}$ -0.6 -0.5 -0.4
20
40
60
80
$\alpha$
$\beta = 0^\circ$, $x/L = 0.5$

$C_{p,s}$ -2.0 -1.5 -1.0 -0.5 0.0
20
40
60
80
$\alpha$
$\beta = 30^\circ$, $x/L = 0.5$

$C_{p,s}$ -0.2 0.0 0.2 0.4 0.6 0.8
0.0 0.2 0.4 0.6 0.8 1.0
(a) upper surface
(b) lower surface

$C_{p,s}$ -2.0 -1.5 -1.0 -0.5 0.0
20
40
60
80
$\alpha$
$\beta = 30^\circ$, $x/L = 0.5$

$C_{p,s}$ -0.2 0.0 0.2 0.4 0.6 0.8 1.0
0.0 0.2 0.4 0.6 0.8 1.0
(a) upper surface
(b) lower surface
Figure 8. Mean spanwise pressure distributions for $x/L = 0.5$ and $\beta = 45^\circ$.

Figure 9. Mean spanwise pressure distributions for $x/L = 0.5$ and $\beta = 135^\circ$. 
3.3. The Lift Coefficient

$C_L$ was calculated by integrating $\Delta C_p$ (differential pressure between upper and lower surface). The variation in $C_L$ with $\alpha$ and $\beta$ is shown in Figure 10. The value of $C_L$ was negative for $\beta \leq 75^\circ$. The lowest value for $C_L$ was observed for $\alpha = 30^\circ$ and $\beta = 45^\circ$. This is similar to the results of Chou et al. [21] for an inclined panel, for which $L/W = 2$. The value of $C_L$ was relatively small for $\beta = 90^\circ$, and it was positive for $\beta \geq 105^\circ$, which represents a downward force. The critical wind loads on the inclined panels occurred for lower values of $\beta$; hence, the effect of $\alpha$ on $C_L$ is only shown for $\beta = 0^\circ$–60$^\circ$ in Figure 11. For an inclined panel, for which $L/W = 2$, the value of $C_L$ for $\beta \leq 75^\circ$ decreased linearly with $\alpha (\leq 30^\circ)$, following an increase for $\alpha = 50^\circ$. At high values of $\alpha (= 60^\circ–80^\circ)$, $C_L$ remained approximately constant for $\alpha = 30^\circ$ and $40^\circ$ [21]. For $\beta$ of $0^\circ$, $30^\circ$, $45^\circ$, and $60^\circ$, for which $L/W = 0.19$, the variation of $C_L$ with $\alpha$ was U-shaped. The lowest value of $C_L$ for $\beta = 0^\circ$ and $30^\circ$ was observed at $\alpha = 20^\circ$. For $\beta = 45^\circ$ and $60^\circ$, it respectively corresponded to $\alpha = 30^\circ$ and $40^\circ$. For high values of $\alpha (\geq 60^\circ–80^\circ)$, $\beta$ had a less significant effect on the amplitude of $C_L$. Therefore, for an inclined array at lower values of $\alpha (\leq 30^\circ)$ and $\beta (\leq 45^\circ)$, there were lower values in $C_L$, which was critical to the safe design of the system.

![Figure 10. Lift coefficient.](image)

Figure 10. Lift coefficient.

![Figure 11. Lift coefficient. $\beta$: 0°, 30°, 45°, 60°.](image)

Figure 11. Lift coefficient. $\beta$: 0°, 30°, 45°, 60°.

Figure 12 shows the effect of $\beta$ on $C_L$ for $\alpha$ of $0^\circ$–80$^\circ$. For $\beta \leq 30^\circ$, the value of $C_L$ decreased as $\alpha$ increased ($\geq 20^\circ$). For $\beta = 75^\circ–105^\circ$, the value of $\alpha$ had a less significant effect. This agrees with the results of Chou et al. [21]. The value of $C_L$ for $\beta \geq 120^\circ$ decreased as $\alpha (\geq 40^\circ–80^\circ)$ increased, and the opposite was true for $\alpha = 10^\circ–30^\circ$. 

![Figure 12](image)
There was a significant localized load near the front edge at greater angles of tilt but less than for the variation in $L$ at lower angles of incidence for the wind are a cause for concern in the design of a system.

Conclusions

Wind loading on inclined solar panels is a key factor in the proper functioning of the system during its lifetime. This study determined the effect of the angle of tilt and the angle of the incidence of the wind on the mean surface pressure, as well as the lift coefficient for an inclined array ($L/W = 0.19$). There was a significant localized load near the front edge at greater angles of tilt but less than for

Figure 12. Lift coefficient. $\alpha$: 0°–80°.

Figure 13. Lift coefficient for P1–P9 for $\alpha = 30°$.

4. Conclusions

Wind loading on inclined solar panels is a key factor in the proper functioning of the system during its lifetime. This study determined the effect of the angle of tilt and the angle of the incidence of the wind on the mean surface pressure, as well as the lift coefficient for an inclined array ($L/W = 0.19$). There was a significant localized load near the front edge at greater angles of tilt but less than for
$L/W = 2$. For $\beta$ of $0^\circ$–$60^\circ$, the variation in $C_L$ with the angle of tilt was U-shaped. The formation of a strong windward corner vortex induced a greater lift force on the right half of the inclined plate for $\beta = 30^\circ$–$45^\circ$. Unsymmetrical wind loads on the inclined array at lower angles of incidence for the wind ($\leq 60^\circ$) in the spanwise direction induced a greater bending moment. Wind loads on an inclined array at lower angles of tilt and angles of incidence for the wind are a cause for concern in the design of a system.

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**Conflicts of Interest:** The authors declare no conflict of interest.

**Nomenclature**

- $C_L$: lift coefficient
- $C_p$: pressure coefficient in the longitudinal direction, $(p-p_\infty)/q$
- $C_{p,\text{low}}$: pressure coefficient on the lower surface
- $C_{p,\text{up}}$: pressure coefficient on the upper surface
- $L$: length of tilted panel
- $p_\infty$: freestream static pressure
- $q$: dynamic pressure
- $W$: width of tilted panel
- $x$: coordinate in the longitudinal direction
- $y$: coordinate in the spanwise direction
- $\alpha$: angle of tilt
- $\beta$: wind incidence angle
- $\Delta C_p$: differential pressure, $C_{p,\text{up}} - C_{p,\text{low}}$

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