

Wind Loads Acting on Solar Panels in a Row by CFD Analysis

Veysel Emre Uslu¹⁾, Oguz Uzol²⁾ and *Afsin Saritas³⁾

^{1), 3)} Dept. of Civil Eng., Middle East Technical University, Ankara 06800, Turkey

²⁾ Dept. of Aerospace Eng., Middle East Technical University, Ankara 06800, Turkey

³⁾ asaritas@metu.edu.tr

ABSTRACT

Wind loads acting on ground mounted solar panels are studied by computational fluid dynamic (CFD) analysis. In order to investigate wind loads acting on these panels, steady state SST k- ω turbulence model is considered in CFD analyses undertaken in this study. 2D and 3D numerical models are considered in the verification studies to assess the accuracy of the employed methods with respect to available data in the literature. Then, 2D CFD analysis is chosen due to significant reduction in number of meshes, where this results into more robust and still reliable wind simulations with regards to assessing wind flow and its effects throughout consecutively placed ground mounted solar panels. Solar panels are placed in a row, where the influence of the forward and reverse wind flow, panel length, clear height from the ground, spacing between consecutive panels and tilt angle is parametrically studied.

1. INTRODUCTION

Wind energy is one of most promising renewable energy source that receive significant amount of research and development. These energy sources are considered to be safe and much less harmful to the environment. Once the construction of a solar farm is completed, the yearly operating costs are significantly lower compared to the other forms of energy production. With regards to the technological developments on the solar energy front, the development of cheaper and energy efficient photovoltaic (PV) panels is the main emphasis. In the last decade, attention is also rising with regards to the safety of the solar panels that are ground mounted or placed on the roofs. There are now applications of ground mounted solar panels, called as solar farms, which are expected to occupy more than 100 km² of land in only a single project. The enormous amount of land use and material use to support the safety of solar panels clearly requires attention, and researchers and engineers need to provide not

¹⁾ Former Graduate Student

^{2,3)} Associate Professor

only the safety of solar panels against potential environmental actions but also the optimal use of the supporting structures. The structural supporting systems have smaller cost percentage relative the PV panels, yet the supporting system design for the solar panels should take into account all further risks in the first design stage and the supporting structure should be strong enough to protect the PV panels, thus allowing the panels to generate electricity throughout the service life without problems.

The most important load on the PV panels is found to be caused by the wind. Although the load calculations are in advanced level with regards to the wind forces acting on several engineering structures, wind loads acting on the solar panels and their effect on analysis and design of the steel supporting structures are still inadequate due to lack of experience and knowledge. Even though it is known that private companies have different analysis approaches, accuracy and reliability of their knowledge cannot be detected since their underlying fundamental assumptions and calculations with regards to the loads acting on solar panels are kept confidential, thus not available to the outside engineers and researchers.

With regards to the research efforts on the analysis of wind loads acting on solar panels, most of the studies focused on roof solar panels. Research studies on the determination of wind loads acting on ground mounted solar panels placed on open terrains have attracted small attention by the researchers. It is known that the wind flow is mainly blocked by the first row of the panels in solar farms; therefore the wind loads acting on the following rows of solar panels exhibit completely different trends. The reason for the change is due to the variations in the direction and speed of the wind after facing not only the first row of panels but as well as the following rows. Inclination of the panels, spacing between the panel rows, and clear distance of the panels from the ground, length of the panels, and the direction of the wind altogether influence the wind loads acting on the array of panels. Currently in the design guidelines, there are no suggestions with regards to how much the wind loads would be on a row of panels placed in a solar farm.

In terms of consideration of wind loads in the design phase of a structure, ASCE 07/10 (ASCE 2010) and Eurocode-1 (Eurocode 2004) provide an estimation of wind loads acting on mono-slope free roofs and canopies. This type of a structure may represent a single ground mounted solar panel standing alone; however, there are no suggestions with regards to how the wind loads acting on consecutively placed solar panels in a solar farm can be calculated. By the way, it is worth to add that Eurocode has a very small section devoted to the multi-bay canopies, but these canopies are placed without any gap and in saw pattern. In this regards, the use of wind tunnel experiments and the use of computational fluid dynamic (CFD) analysis are the main approaches undertaken by solar energy companies. However, a general overview and outlook are not available for these experiments.

In the literature, there are increasing numbers of research studies on roof mounted solar panels, but lesser amount of studies have been undertaken on ground mounted solar panels, where these have mostly focused on single row placement. Therefore,

the reaction and the behavior of the consecutive solar panels can be safely said to be unstudied research topic.

One of the earlier research studies was carried out by Chevalier and Norton (Chevalier 1979) on the wind tunnel tests on solar panels located at the roof of the buildings. In that study Chevalier and Norton tried number of wind tunnel tests in order to find the wind effects on roof mounted panels. The vortex effects near the sides of the panels were investigated by (Kopp 2002). In those experiments, different wind angles were considered. In addition to these studies, (Chung 2008) conducted experiments to reduce the impact of severe typhoons on solar water heaters placed on the roof of buildings. Those experiments were mainly carried out to reduce the uplift forces. The influence of different angle of attacks of wind and consecutive placement of panels placed over low-rise building roofs were studied by (Kopp 2013). (Maffei 2013) provided recommendations for low-slope roofs solar panels by reporting that ASCE 07/10 is insufficient to provide guidance in calculating wind loads on solar panels placed on roofs.

With regards to ground mounted solar panels, (Shademan 2009) studied the sheltering effect and the behavior of solar panels located in open terrain under wind loads through CFD analysis. The sheltering effect was investigated by considering three consecutive rows of solar panels. In that study, different wind angle of attacks and different panel inclinations were also investigated. (Jubayer 2012) studied the effects of wind forces on ground mounted panels places in solar farms by CFD analysis, as well. An important observation stated in the paper was the lack of scientific studies on ground mounted panels placed in solar farms. Both full scale and model scale versions of a ground mounted single solar panel were considered for CFD analysis.

In a recently published journal paper, (Warsido 2014) highlighted the importance of the sheltering effect, where the authors carried out wind tunnel tests to study the consecutive placement of solar panels and the spacing effects, both horizontal and lateral. The plexi-glass plate of 0.3m by 0.045 m was used to represent 9.14m by 1.34 m solar panel with a scale of 1:30. The solar panels were placed with 25° of inclination. The tests were conducted with a wind speed of 15 m/s at the velocity inlet. Different than that of Shademan and Hangan's study, more than 15 consecutively placed solar panels were used and different lateral spacings were considered. Out of these 15 panels, the first 10 rows were instrumented with devices to record the wind effects.

The research study in this paper attempts to provide a contribution in terms of analysis of wind loads acting on not only single placed ground mounted solar panels but also on solar panels that are placed consecutively in solar farms, where the emphasis will be the widely used flat plate panels. CFD by using ANSYS FLUENT (ANSYS 2011) is employed in order to model, analyze and understand the effects of the wind forces acting on solar panels. CFD analysis and experiments available in the literature are considered for further verification of the method employed in the analyses carried out both in 2D and 3D. Steady state SST $k-\omega$ turbulence model is used in CFD analysis. 2D CFD analysis approach is undertaken in the parametric analyses performed in the later

part of the thesis, where sheltering effect is investigated with the placement of 10 consecutive panels. Parametric analyses are undertaken for both forward and reverse wind flows by considering panel length, clear height from the ground, spacing between 2 consecutive solar panels and tilt angle (inclination) as variables.

2. BACKGROUND AND EQUATIONS ON CFD ANALYSIS

Experimental wind studies on relatively large projects with complexity are hard to undertake due to the physical limitations of the research facilities. These difficulties are faced when solar panels are studied in the wind tunnels. Therefore, numerical studies are preferred rather than wind tunnel experiments. Although scaled models may be used for the experiments, using consecutive solar panels for experiments are still not reliable. Therefore, using numerical methods in order to find the wind loads on the consecutive solar panels is the best possible solution.

In this study, 2 dimensional (2D) and 3 dimensional (3D) numerical analyses will be conducted for determination of wind loads acting on solar panels. Domain dimensioning is enlightened in (COST-Action-732 2007). According to this guideline, the dimensions are specified as follows; the domain top should be at least 5H above the top of the object that is of interest, where H is stated as the height of the object. In this work, H is taken as the height from ground to the highest point on the panel. Therefore, the total height of the domain becomes 6H. With regards to the flow of wind from inlet, at least 5H distance of air domain should be provided before the wind first hits the object. After air flows around the object, it is also necessary to provide at least 15H distance of air to flow up to the outlet to permit flow to be redeveloped in the wake region. With regards to the 3D modeling, it is also necessary to provide 5H distance of air to flow in the lateral directions past the object of interest, as well. By providing 5H lateral domain, the blockage ratio of the object falls below 3% as recommended by COST Action.

The mesh of the domain is done with ANSYS Mesh generator and in order to find out the model's mesh dependency 3 different element sizes are examined; coarse, normal and fine meshes. Mesh generator of ANSYS is set to tetrahedrons with patch conforming method. Face sizing is also added to mesh variables in order to decrease the element size and to increase the element number.

SST $k-\omega$ model proposed by (Menter 1994) is used to carry out the analysis, and the equations are provided below:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_i k)}{\partial x_i} = \tilde{G}_k - Y_k + S_k + \frac{\partial}{\partial x_j} \left[(\Gamma_k) \frac{\partial k}{\partial x_j} \right] \quad (1)$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \left[(\Gamma_\omega) \frac{\partial \omega}{\partial x_j} \right] + G_\omega - Y_\omega + D_\omega + S_\omega \quad (2)$$

Equation (1) represents the k-equation and Equation (2) represents the ω equation. In above equations the terms are defined as follows: ρ is the density; k is the turbulence kinetic energy; ω is the specific dissipation rate; \tilde{G}_k is the turbulence kinetic energy due to mean velocity gradients; Y_ω and Y_k represent the dissipation of ω and k due to turbulence, respectively; D_ω represents the cross-diffusion term, S_ω and S_k are user-defined source terms. ; Γ_ω and Γ_k represent the effective diffusivity of ω and k , respectively, and these are defined as follows:

$$\Gamma_k = \mu + \frac{\mu_t}{\sigma_k}; \quad \text{and} \quad \Gamma_\omega = \mu + \frac{\mu_t}{\sigma_\omega}$$

$$\sigma_k = \frac{1}{\frac{F_1}{\sigma_{k,1}} + \frac{(1-F_1)}{\sigma_{k,2}}}; \quad \text{and} \quad \sigma_\omega = \frac{1}{\frac{F_1}{\sigma_{\omega,1}} + \frac{(1-F_1)}{\sigma_{\omega,2}}}$$
(3)

where σ_ω and σ_k are the turbulent Prandl numbers for ω and k , respectively. The turbulent viscosity μ_t is computed from the following equation by the use of S strain rate magnitude:

$$\mu_t = \frac{\rho k}{\omega} \frac{1}{\max \left[\frac{1}{\alpha^*}, \frac{SF_2}{a_1 \omega} \right]}$$
(4)

and α^* is the coefficient that damps the turbulent viscosity causing a low-Reynolds number correction.

The blending function F_1 in Equation (3) is obtained from the following expression:

$$F_1 = \tanh \left\{ \left[\min \left[\max \left(\frac{\sqrt{k}}{\beta^* \omega y}, \frac{500\mu}{\rho y^2 \omega} \right), \frac{4\rho k}{\sigma_{\omega,2} D_\omega^+ y^2} \right] \right]^4 \right\}$$

$$D_\omega^+ = \max \left(2\rho \frac{1}{\sigma_{\omega,2}} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}, 10^{-10} \right)$$
(5)

where y is the distance to the nearest wall and D_ω^+ is the positive portion of the cross-diffusion term.

The second blending function F_2 in Equation (4) is written as follows:

$$F_2 = \tanh \left[\left[\max \left(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\mu}{\rho y^2 \omega} \right) \right]^2 \right] \quad (6)$$

$$D_\omega = 2(1 - F_1) \rho \frac{1}{\omega \sigma_{\omega,2}} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$$

By blending k- ϵ and k- ω models through $\alpha = \alpha_1 F + \alpha_2 (1 - F)$, the constants come out to be: $\beta^* = 0.09$, $\alpha_1 = 5/9$, $\alpha_2 = 4/9$, $\sigma_{\omega,2} = 0.856$ in above equation.

In the numerical analysis carried out in this paper, SST k- ω model is used through setting the density and viscosity of fluid (i.e. air) as 1.225 kg/m^3 and $1.7894\text{e-}05 \text{ kg/m-s}$, respectively, and by considering the parameters in ANSYS FLUENT (ANSYS 2011) as the following values: $\alpha^*_\alpha = 1$, $\alpha_\alpha = 0.52$, $\alpha_0 = \frac{1}{9}$, $\beta^*_\alpha = 0.09$, $\beta_i = 0.072$, $R_\beta = 8$, $R_k = 6$, $R_w = 2.95$, $\zeta^* = 1.5$, $M_{t0} = 0.25$, $\sigma_k = 2.0$, $\sigma_w = 2.0$.

3. VERIFICATION OF CFD ANALYSIS METHODOLOGY

3.1. Comparison with Jubayer's Study

(Jubayer 2012) conducted a numerical simulation to find out the wind loadings on a single solar panel mounted on the ground. In that study, the solar panel was designed with the supporting columns and after the simulation, the lift, drag and moment coefficients are found. In order to utilize the model, ANSYS Fluent is used and solar panel array consists of 24 solar panel cells with each $1.2 \text{ m} \times 0.6 \text{ m}$ placed with 4 rows and 6 columns without gap between them, resulting into a solar panel with dimensions of 2.4 m to 7.2 m . The panel dimensions are taken from (First-Solar 2014) panel producer specification, however the thickness is unknown and not provided by Jubayer, as well. In order to see the effect of the thickness different trials are conducted with various thicknesses and it is seen that the thickness has no effect in the loads for 7mm to 60mm thickness ranges.

The inclination angle is set to 25 degree with respect to horizontal. The clear distance from the ground is approximately 0.59 m where the mean height from the ground is 1.1 m . The analyses by Jubayer were conducted with OpenFOAM CFD program and the methods used to carry out computational fluid dynamic analyses were 3D unsteady Reynolds-Averaged Navier-Stokes (RANS) method and SST k- ω turbulence model. In Jubayer's model, there were 3 columns used to support the structure. It is worth to point out that no specific information was provided by Jubayer on the complexity and dimensions of these columns. However, in the modeling part, there appears a clear gap between the panels and supporting structures, which means the air flow is permitted between them. Also, the panel and the supporting structures are modeled as rigid bodies, which mean there will be no vibrations.



Fig. 1a Mesh view of 2D CFD Model

Fig. 1b Mesh view of 3D CFD Model without columns

Fig. 1c Mesh view of 3D CFD Model with columns

(Jubayer 2012) conducted the study with reference velocity of 17.5 m/s at 10 m height with aerodynamics roughness length of 0.03m. Although (Jubayer 2012) only conducted the analysis with 3D model, in this study both 3D model with and without columns and 2D model without column are studied. The reason is to find out if the results of these different approaches will show similarities. If they happen to be similar, using 2D analysis instead of 3D will decrease the amount of computation time and memory needed to compute for analysis significantly.

The solution method of SST k- ω is assigned with default Fluent values explained previously. The Low Reynolds correction is not forced in this analysis. The velocity is set to 17.5 m/s at the velocity inlet with turbulent intensity of 1%. Since the wind in the velocity inlet is not disturbed in the beginning, the turbulent intensity of 1% is enough. However, for the pressure outlet the turbulent intensity is increased to 5%. Also to show that the models are mesh independent, the comparison of different mesh numbers and element sizes will be shown.

Lift (C_l), drag (C_d) and moment (C_m) coefficients are calculated through the use of following equations:

$$C_l = \frac{F_l}{\frac{1}{2} \cdot \rho \cdot v^2 \cdot A}; \quad C_d = \frac{F_d}{\frac{1}{2} \cdot \rho \cdot v^2 \cdot A}; \quad C_m = \frac{M}{\frac{1}{2} \cdot \rho \cdot v^2 \cdot A \cdot s} \quad (7)$$

where F_l and F_d are the lift and drag forces (N) acting on the panel, respectively, and M is the moment acting on the panel with respect to centerline axis; ρ is the mass density of the fluid (kg/m^3); v is the speed of the fluid relative to the object (m/s); A is the reference area (m^2) and s is the chord length. Density of air ρ air is taken as of 1.225 kg/m^3 , velocity is taken as 17.5 m/s and the reference area, A , is taken as 17.28 m^2 in this study.

Table 1. Drag, Lift and Moment Coefficients Reported by (Jubayer 2012)

	Drag Coefficient	Lift Coefficient	Torque Coefficient
Model Scale	0.56	-1.2	0.12
Full Scale	0.54	-1.15	0.14

Table 2. Drag, Lift and Moment Coefficients obtained in Current Study

CFD Analysis	3D				2D	
Mesh Number	1,621,967 (w/o columns)	2,888,212 (w/o columns)	5,654,033 (w/o columns)	9,677,985 (w/ columns)	265287	86057
Drag Coefficient	0.586	0.582	0.578	0.522	0.594	0.596
Lift Coefficient	-1.193	-1.209	-1.217	-1.052	-1.218	-1.198
Moment Coefficient	0.099	0.099	0.110	0.095	0.110	0.105

As can be seen from Table 1 and

Table 2, the results of (Jubayer 2012) and the results found in this study show that the correlation with the results in the literature is good, the description of the solution domain is realistic, meshing method is enough to provide mesh independent solutions and numerical solution method employed to solve the problem is verified. Therefore, it can be concluded that 2D solution method can be used in the parametric study part.

In addition to choosing 2D solution method, it is observed that 3D CFD analysis of the model with columns causes in smaller wind loads acting on the panels compared to the case without columns. Therefore, working with panels without columns gives safe side results which are relatively higher than the one with columns. By this way, the usage of the panels without columns is safer and significantly decreases the solution time and data storage.

3.2. Comparison with Warsido's Study

(Warsido 2014) conducted a wind tunnel experiment on the scaled model of consecutively placed solar panels to find out the effects of having rows on the wind loads. In that study, both horizontal and vertical spacing influences are considered to find out the effects on the wind loads. As indicated in (Warsido 2014), the lateral spacing between the panels has minor effect on the wind loads. To start the comparison, full scale 2D model is prepared in numerical platform, namely ANSYS FLUENT. The panel length is set to 1334 mm with 25° of inclination from horizontal and clear length of 0.81 m from the ground. The wind speed is set to 15 m/s as in (Warsido 2014), and the normal force coefficient and moment coefficients were calculated by the pressure tubes. These pressure values are recorded and then calculated as peak, mean and root of mean square values. In order to compare the experimental results in (Warsido 2014) with CFD analysis results in this study, the mean values of (Warsido 2014) are chosen versus the steady state analysis results carried out in current work of this paper. As mentioned earlier, the numerical analyses are conducted in 2D and to be precise the C3 column of (Warsido 2014) are chosen. The reason is that C3 columns are located in the middle, which behaves closer to the 2D analysis. The results are compared with C3Y0x24, C3Y0x48 and C3Y0x72, which indicated the testing section of C3 with no lateral spacing and with horizontal spacing of 0.61 m, 1.22 m and 1.83 m. These horizontal spacing values represent the spacing factors close to 1, 2 and 3.

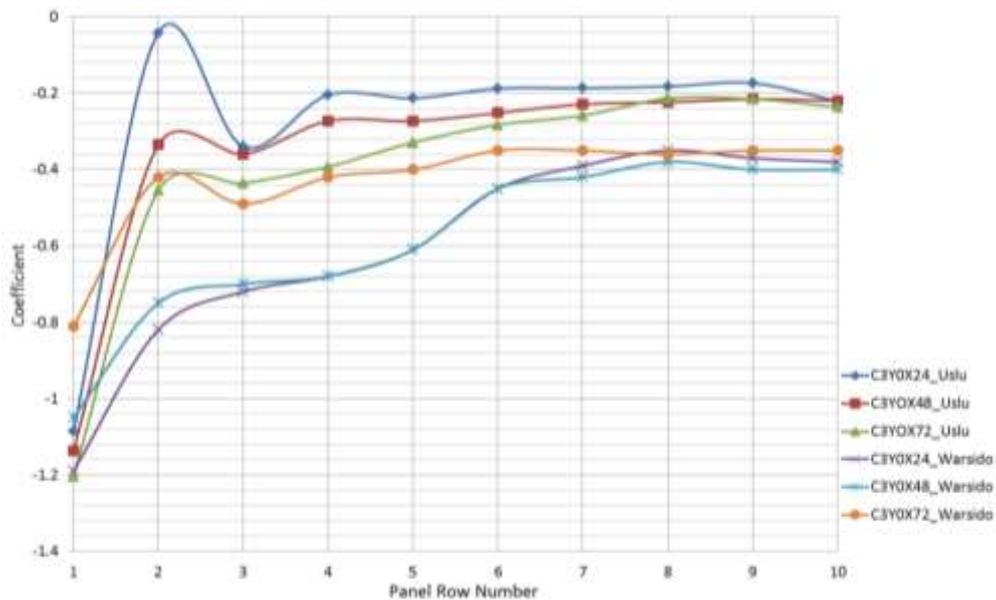


Fig. 2 Warsido’s Mean Normal Force Coefficients vs. Uslu’s Normalized Force Coefficients by CFD

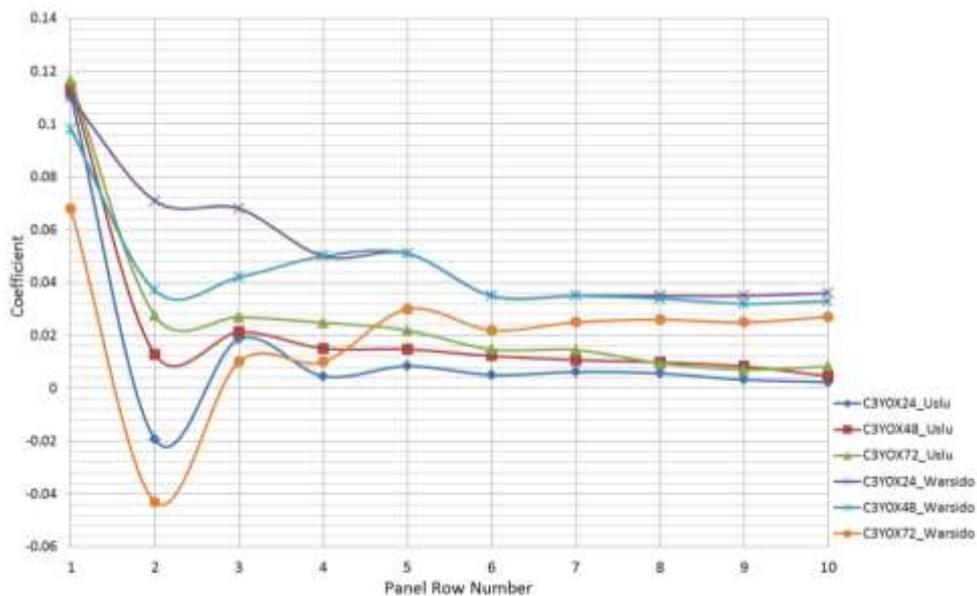


Fig. 3 Warsido’s Moment Coefficients vs. Uslu’s Moment Coefficients by CFD

The comparison of (Warsido 2014)’s scaled model experience results and the result of this paper are compared and can be seen in Figure 2. This comparison shows that the results of both studies demonstrate similar trends in term of values in addition to capturing sheltering effect through 10 consecutive solar panels. In both the experiment and CFD analysis, the normal force coefficients are observed to be converging to the same value at the last (10th) panel. Moreover, the comparison of moment coefficients in Figure 3 reveals better match between the experimental and numerical results. The minor differences might be resulting due to the experimental conditions available in

wind tunnel and usage of 2D numerical analysis, and more importantly on the dependency CFD models to reflect the conditions of wind tunnel testing. Since the general trends and results are very similar to each other, it can be concluded that both experimental and numerical results provides confidence on the CFD analysis employed in this paper.

4. PARAMETRIC STUDY ON CONSECUTIVE PANELS

The wind loads and effects are known for the single solar panel thanks to the previous literature studies; however the changes and trends are not very clear for consecutive solar panels compared to the single placed solar panels. A parametric study is undertaken in this section in order to find the effects of different parameters on the wind loads acting on consecutively placed solar panels. For this purpose 6 different parameters are used, namely, normal and reverse wind flow, panel length (L), the distance between 2 consecutive solar panels (D), the clear distance from the ground (H), tilt angle-inclination (θ).

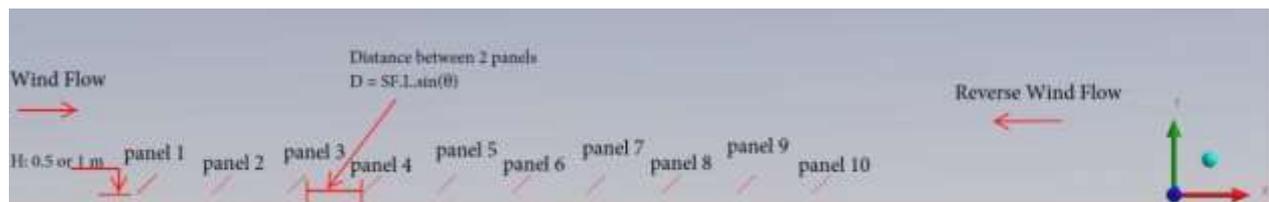


Fig. 4 CFD Panel Set up in ANSYS FLUENT

Horizontal distance D between the panels is taken as the shortest distance from the end projection of a panel to the nearest edge of the next panel. This distance is related to the panel length L, inclination angle θ and a spacing factor SF as given in the next equation.

$$D = SF \cdot L \cdot \sin(\theta) \quad (8)$$

where spacing factor (SF) is calculated in practice by companies through an optimization process so that shadowing of panels within a time range of target during daytime is eliminated in order to increase energy production; horizontal distance (D) is the distance between front most panel's end and posterior panel's start; L is the length of the panel; θ is the inclination angle of the panel is determined in order to maximize energy production. CFD panel set up is presented in Figure 4.

In this study, 2 different clear front heights from the ground, 3 different panel lengths, 5 different spacing factors between the panels, 6 different inclination of panels (IoP) and lastly normal and reverse wind flows are considered resulting in 360 CFD analysis cases in total, where the results are all documented in the thesis of (Uslu, 2014). These parameters are selected as shown in Table 3.

Table 3. Considered Parametric Study Values

	Parametric Values
H, Clear Front Height (m)	0.5 - 1.0
L, Panel Length (mm)	1000 - 2500 - 5000
SF, Spacing Factor	1 - 2 - 3 - 4 - 5
θ Inclination of Panel – IoP (°)	7.5 - 15 - 22.5 - 30 - 37.5 - 45
Wind Flow Direction	Forward - Reverse

The wind speed of 40 m/s is chosen, since this value practically provides the target design wind speed for most regions in USA as specified by ASCE 07/10. The reason for the choice of 2D analysis is due to the nature of computation power needed to carry out 3D analysis for consecutively placed panels for 360 different cases of CFD analysis, and furthermore the reliability of results for angle of wind attacks in normal and reverse wind flow directions for a solar farm.

In these simulations, inclination of panels has been observed to have the largest effect on the wind loads acting on solar panels, where panel inclination is actually chosen according to the latitude of solar farm to be constructed. Small changes in panel inclination are observed to result in significant changes in wind loads. Using lower inclination angle usually decreases the drag, lift and moment coefficients. However, designer should be careful when using an inclination angle less than 15° for which sheltering effect is observed to be reducing. Spacing factor has also a major impact on wind loads, but this parameter is also mostly a fixed value chosen as a result of the latitude of the solar farm, in order to avoid shadowing of the panels.

In this paper, the panel length that appears to be the only independent parameter with regards to the latitude location of the solar farm will be discussed in detail, while the rest of the influence of other parameters is available in (Uslu, 2014). By the way, clear distance from the ground is also an independent parameter, but it has minor effect on the wind loads compared to the level of influence of the rest of the parameters considered in this study.

Discussion on the influence of panel length will be presented for the following case: clear height from ground H is taken as 0.5 m, spacing factor SF is set to 3.0, and inclination of panel IoP is considered as 22.5°. For the normal flow direction, the normal force coefficient on the first panels under varying panel lengths is very close to each other (Figure 5). Furthermore, it is also observed that increasing the panel length from 1.0 m to 2.5 m or 1.0 m to 5.0 m results almost the same level of slight increase on normal force. A similar observation also holds for the normal force experienced by the succeeding panels. The normal force coefficients at 9th panel are observed to be very close to each other under varying panel lengths, except than a slight increase for 1.0 m panel length. Physical reason behind these changes is due to the sheltering effect provided by longer panels onto the succeeding panels.

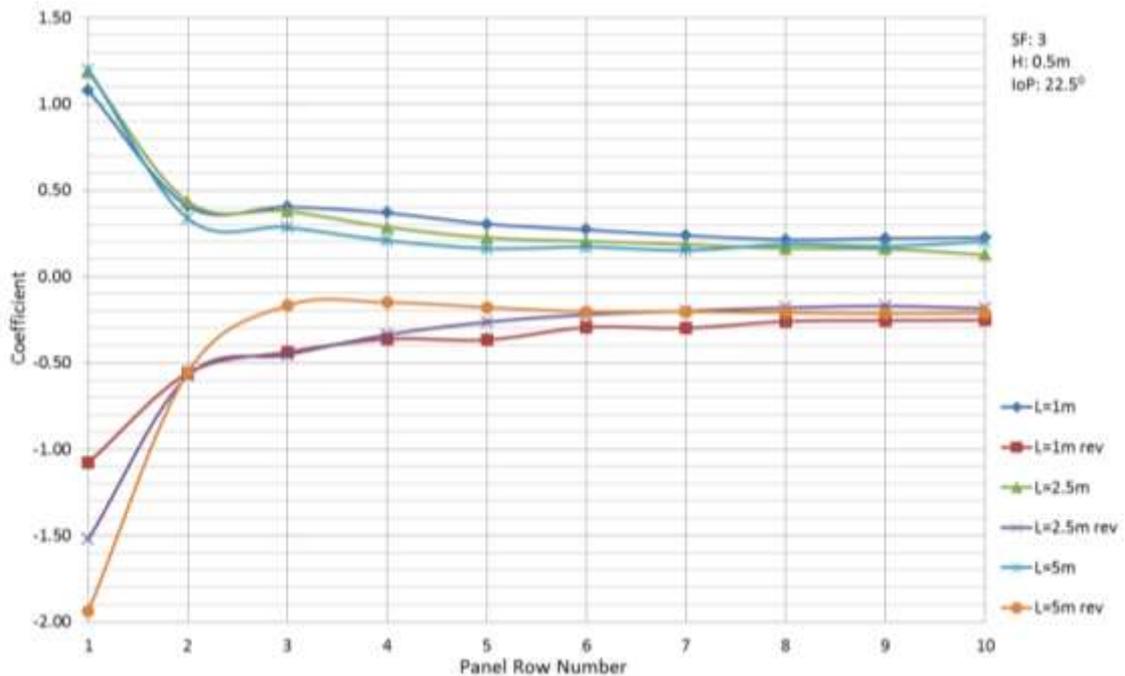


Fig. 5 Normal Force Coefficients on Panels for Panel Lengths 1 m, 2.5 m, 5 m

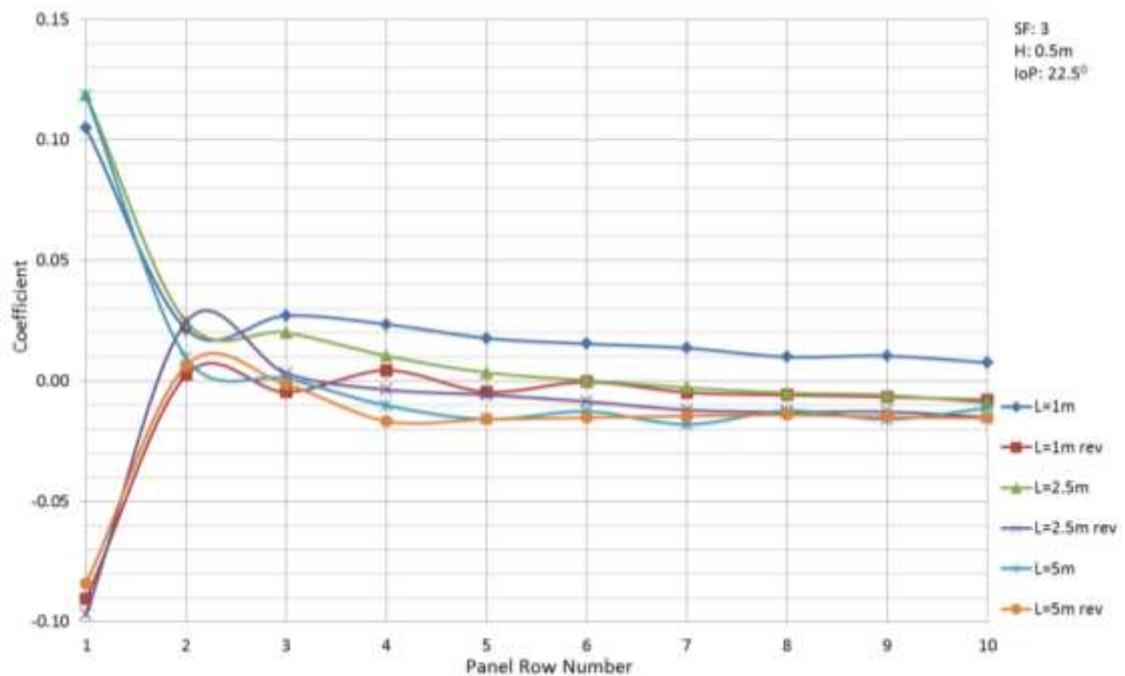


Fig. 6 Moment Coefficients on Panels for Panel Lengths 1 m, 2.5 m, 5 m

For the case of reverse wind flow, a totally different picture arises for the first panels in 오류! 참조 원본을 찾을 수 없습니다.6. It is observed that as the panel length increases from 1.0 m to 2.5 m, normal force increases close to 50%, and as panel length increases from 1.0 m to 5.0 m, drag coefficient almost doubles. As the panel

length increases, the reverse wind flow finds a much larger obstruction surface, thus a larger volume of wind has to pass underneath the panel through a fixed clear front height of 0.5 m. As the panel length reduces, the amount volume in this regards finds it easier to pass underneath the panel through 0.5 m gap. This physical action completely reverses trend right after the second panel. It is also important to see that the normal force on the second panel is the same for all panel lengths. The normal force on the 9th panel for all panel lengths also get very close to each other. The sheltering effect for 5 m panel length is the largest and for 1 m panel length is the lowest. With regards to the discussion on moment coefficients, for both cases of wind flow directions, it is observed that only the very first panel facing the wind experiences the largest moment actions, and the succeeding panels experience diminishing moment actions that may very well be ignored.

3. CONCLUSIONS

Inclination of panels and then the spacing factor between the panels are the most influential parameters in designing a solar farm, where both of these parameters are solely determined from the latitude location of the solar farm, and thus they are in most cases not free parameters to choose. In this paper, only the influence of panel length is presented due to this restriction.

It is observed that panel length has major impact on the wind loads acting on solar panels. Although the drag, lift and moment coefficients are nearly the same for the normal wind flow direction for 1 m and 5 m panel lengths, in the reverse wind flow direction, the drag and lift coefficients almost double for the first row panels, when panel length increases from 1 m to 5 m; thus, special attention is needed with regards to the design of especially first row panels when panel length increases.

Although not presented in this paper, with regards to the influence of panel inclination and spacing factor, the changes in these parameters have also significant influence on the sheltering provided through the solar farm as documented by (Uslu, 2014). For spacing factor parameter, influence on first row is small, but the rest of the couple of panel rows experience significant variations. For panel inclination parameter, not just the first panel row, but the first couple of panel rows should be carefully designed for both forward and reverse wind flow directions.

REFERENCES

- ANSYS. (2011). ANSYS FLUENT Theory Guide.
- ASCE. (2010). ASCE 07/10 Minimum Design Loads for Buildings and Other Structures.
- Chevalier, H. L., & Norton, D. J. (1979). Wind loads on solar collector panels and support structure: Aerospace Engineering Department, Texas A&M University.
- Chung, K., Chang, K., & Liu, Y. (2008). Reduction of wind uplift of a solar collector model. *Journal of Wind Engineering and Industrial Aerodynamics*, 96, 1294–1306.

- COST-Action-732. (2007). Best Practice Guideline for the CFD Simulation of Flows in the Urban Environment In J. Franke, A. Hellsten, H. Schlünzen & B. Carissimo (Eds.), *Quality Assurance and Improvement of Microscale Meteorological Models*.
- Eurocode. (2004). Eurocode 1: Actions on structures — General actions — Part 1-4 : Wind actions Contents, 4 Communities 1–148 CEN
- First-Solar. (2014). First Solar FS Series 3 Black PV Module
- Jubayer, C. M., & Hangan, H. (2012). *Numerical Simulation of Wind Loading on Photovoltaic Panels*. Paper presented at the Structures Congress, Chicago, Illinois, USA.
- Kopp, G. A. (2013). Wind loads on low profile, tilted, solar arrays placed on large, flat, low-rise building roofs. *Journal of Structural Engineering*, 140(2), 04013057.
- Kopp, G. A., Surry, D., & Chen, K. (2002). Wind loads on solar array. *Wind and Structures*, 5, 393-406.
- Maffei, J., Telleen, K., Ward, R., Kopp, G. A., & Schellenberg, A. (2013). Wind Design Practice and Recommendations for Solar Arrays on Low-Slope Roofs. *Journal of Structural Engineering*, 140(2), 04013040.
- Menter, F. R. (1994). Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications. *AIAA Journal*, 32(8), 1598-1605.
- Shademan, M., & Hangan, H. (2009). *Wind Loading on Solar Panels at Different Inclination Angles*. Paper presented at the 11th Americas Conference on Wind Engineering, San Juan, Puerto Rico.
- Warsido, W. P., Bitsuamlak, G. T., Barata, J., & Chowdhury, A. G. (2014). Influence of spacing parameters on the wind loading of solararray. *Journal of Fluids and Structures*, 48, 295-315.