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Wind loads on solar panels mounted on flat rooftops: Progress and limitations

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ABSTRACT

Published literature regarding wind loads on solar panels mounted on flat rooftops is reviewed, and findings regarding critical wind directions, mean and peak wind loads, and sensitive parameters are summarized. For solar arrays mounted on rectangular rooftops, the dominating wind directions for the edge panels are most probably oblique to the building walls. Wind load coefficients vary significantly among different studies, perhaps due to factors such as building shapes, setbacks, array distances, tilt angles, turbulence, model scales and the like. Some problematic issues regarding building height, tributary area and tilt angle are analyzed and discussed. It is shown that the parapet's influence could be related to the non-dimensionalization of its height; the influence of building height may be attributed to a combination of the 'step' and 'end' effects; and the effects of tributary area involve the similarity criterion that has not yet received enough attention. Overall limitations and problems that need further investigation are presented and discussed, including the torsional wind loading, irregular rooftops, and panels installed oblique to building edges.

1. INTRODUCTION

Challenges on issues of energy and environmental protection have resulted in rapid applications of photovoltaic solar panels throughout the world. Solar panels are commonly installed on building rooftops or just on the ground. Wind loading is one of the main factors dominating the design of such panels and their racking systems. Damages due to inadequate wind design have occurred to both roof- and ground-mounted solar panels. These have attracted attention of wind engineers worldwide, and significant amounts of literature have surfaced in recent years. Most of these wind load studies have been conducted by means of model tests in wind tunnels.

Previous studies include those by Rada and Axinte (1989), who investigated the lifting forces developed on solar arrays mounted on flat roofs; Geurts and Van Bentum (2007), who argued that the wind loading standards are inadequate to address the most

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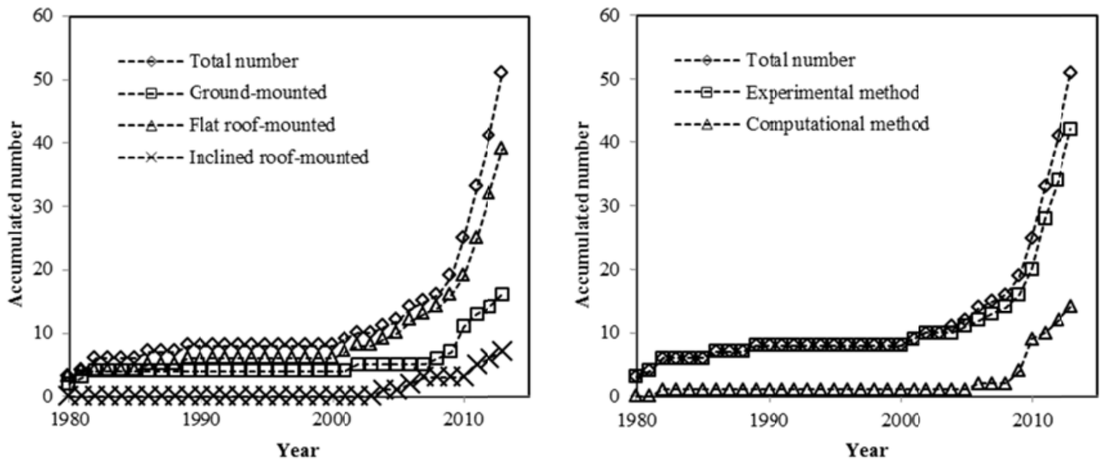
common types of roofs equipped with solar energy products; Chung et al. (2008); Bienkiewicz and Endo (2009); Chung et al. (2011), who tested a single solar panel model mounted on a flat roof; Ruscheweyh and Windhövel (2011), who discussed some basic properties regarding the wind loads developed on roof-mounted solar arrays; Kopp et al. (2012), who tested the loads on solar arrays placed separately on the ground and a rooftop; Pratt and Kopp (2013), who aimed exclusively at winds perpendicular to building walls and investigated the Reynolds stress distribution, tilt angle effects etc; Banks (2013), who concentrated on the role of corner vortices in determining the peak wind loads; Cao et al. (2013), who investigated the wind loads on a single panel and multi arrays mounted on a rooftop; Browne et al. (2013), who investigated the parapet effects on the wind loads; Geurts and Blackmore (2013), who investigated the effect of distance between the panel and the roof; Stathopoulos et al. (2014), who tested the local and overall wind pressure for a single solar array mounted on different locations on a flat rooftop; Maffei et al. (2014), who made recommendations, including categorizing of support-systems, applicable to pressure coefficients.

Attention to aerodynamic properties has also been paid by some other authors. Aly and Bitsuamlak (2013) designed 5 solar models of different scales and investigated the model scale effect. However, insufficient attention has been paid to the similarity of the turbulence structure among different scales. Schellenberg et al. (2013) set up a finite element model for the dynamic responses of a solar panel system and tried determining the dynamic effects.

The academic attention can be reflected by the papers released over the recent three decades, as shown in Fig. 1, where it can be noticed that a rapid growth of the amount of papers in this field has occurred since 2008. It is also noticed that, in spite of the rapid application of computational technologies, model testing is still the principal research methodology. Also, most of the released literature is concerned with solar panels mounted on flat rooftops. The objective of this paper is to provide a concise summary of most recent research studies, in regard to their common findings, comparisons of the main results, as well as general limitations.



(a) (b)

Fig. 1 Accumulated (approximate) articles regarding wind loading on solar panels

2. MAIN PROGRESS

2.1. Critical wind directions

Solar panels installed in the northern hemisphere are all tilted toward the south. Hence the wind loads acting on them distinguish between north and south wind directions. Quite a lot of investigations have suggested, however, that the wind direction corresponding to the largest wind load is not exactly northern or southern. Kopp et al. (2012) showed that, for the ground-mount arrays, the critical wind directions for most areas are northern (0° to 10°, see Fig. 2), except along the eastern (or western) edges of the array field where the northern cornering winds (40°~50°) are critical. In contrast, for the same array mounted on a flat rooftop, the critical wind directions are northern (0°~10°), northern cornering (40°~50°), and southern(170°~180°).

The study of Browne et al. (2013) indicates that the critical wind directions for the northeast corner are from 30° to 70°, and for the south leading row are from 140° to 170°. Banks (2013) stated that, for most cases tested, the cornering vortices induced by oblique wind directions could dictate the maximum uplift on the solar arrays. Although the exact critical directions differ among investigations, the parameters involved are quite distinct as well (see Table 1). Therefore, it could be claimed that some differences come quite natural simply because different parameters mean different configurations and aerodynamic features. However, a qualitative conclusion that could be drawn that the dominant wind directions for the edge panels are most probably oblique to the building walls.

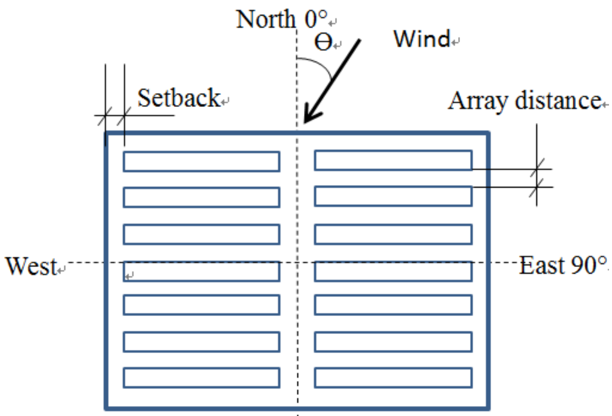


Fig. 2 Schematic diagram of solar arrays and the wind direction

Table 1 Comparison of the critical wind directions and main parameters

Author	Critical wind directions (°)	Building size *W*×*L*×*H* (m)	Module size *c*×*l* (m)	Setback (m)	Tilt angle(°)	Array dist. (m)	Scale
Kopp et al. (2012)	0~10; 40~50; 170~180	22.5×23.5×7.3	1×1.65	1.22/2.93	20	1.68	1:30
Browne et al. (2013)	30~70; 140~170	30×36×10	1.05×1.35	2.0	10	0.51	1:25
Cao et al. (2013)	300~310	25×25×20	2.0×1.0	2.5	15	unknown	1:50

2.2. Mean and peak wind loads

For a given tributary area, the force (or force coefficient) in this paper are defined as

$$Cp = \frac{\iint (p_u - p_l) dA}{q_H \iint dA} \tag{1}$$

where p_u denotes the wind pressure in the upper side of the panel; p_l the wind pressure in the lower side of the panel; q_H the reference wind pressure at the building height; dA the area element.

The purpose of wind tunnel tests is for the design of either a specific or a class of similar cases. Many factors could be involved and systematic experiments are still needed to obtain a codification for practical design. Table 2 tabulates the worst mean and peak uplift on panel models tested respectively by Kopp et al. (2012), Browne et al. (2013), Cao et al. (2013) in together with the main parameters involved. It can be noticed that the critical wind directions are basically in accord with one another (due to symmetry, 50° also means 310°). However, significant differences can be found among the values. The most critical mean uplift coefficients vary from -0.42 to -0.75 while the most critical peaks range from -1.9 to -3.1. These differences themselves can be justified due to the differences in a large number of parameters and the number of modules. Hence, difficulties come from determining which situation-combined data are more reasonable for practical design, and this apparently involves other issues as to the racking system used, the rigidity of the panels in response to the wind excitation, the connections between adjacent racks, etc.

Fig.3 plots out the peak uplift coefficients against the applicable tributary area. Although the data shown in Fig. 3 may differ in their origin, they are most critical values with respect to specific situations and specific parameters; therefore, the magnitude of the uncertainties of the peak uplift is reflected indirectly.

In spite of the above mentioned contradictions, some qualitative, common findings regarding the wind loads on solar panels are concluded as follows: It has been realized that for roof mounted solar panels, using zones intended for the roof itself (as per ASCE 7 provisions for components and cladding zones) may not be appropriate (Banks, 2013; Kopp, 2013). Experiments have shown that wind loads on solar arrays can be substantially different from those on bare roofs. Also, it is found that the building height variation changes not only the area-averaged coefficients but also the critical wind directions for these coefficients.

However, there are only two sources concurring with these limited commonalities. Scrutiny of additional studies shows additional differences leading to a great degree of uncertainties regarding the magnitude of pressure coefficients on solar panels.

Table 2 Critical mean and peak uplift coefficients (roofs without parapet)

	Item	1. Kopp et al. (2012)	11. Browne et al. (2013)	10. Cao et al. (2013)
Mean uplift Cp_{mean}	Most critical	-0.7 (3 modules)	-0.42 (12 modules)	-0.75 (1 module)
	Position	Northeast corner	Western edge, middle of north-south direction	0.3*L* from the north edge
	Θ (°)	50°	310°	310°
Peak uplift *GCp*	Most critical	-1.9 (3 modules)	-2.15 (1 modules)	-3.1 (1 module)
	Position	Easternmost, 1st and 7th row from the north	The 2nd row of the 2nd column from west.	0.1*L* from the north edge
	Θ (°)	50°	290°	300°
Building size *W*×*L*×*H*		22.5 m×23.5 m×7.3 m	30 m×36 m×10 m	25 m×25 m×20 m
Module size *c*×*l*		1.0 m×1.65 m	1.05 m×1.35 m	2.0 m×1.0 m
Pressure taps/module		Upper: 3; lower:1	Upper: 4; lower: 4	Upper: 8; lower: 8
Height above the roof		unknown	unknown	0.5 m
Setback from the edge		1.22 m /2.93 m	2.0 m	2.5 m
Array distance		1.68 m	0.51 m	Unknown
Tilt angle (°)		20.0°	10.0°	15°
Deflector installed		no	the northernmost row	no
Turbulence intensity		I_u: 27.5%	I_u: 16%	I_u: 20%
Integral length		unknown	unknown	unknown
Model scale		1:30	1:25	1:50
Filtered frequency		200 Hz	135 Hz	300 Hz
Duration of sampling		160 s	36 s	36 s

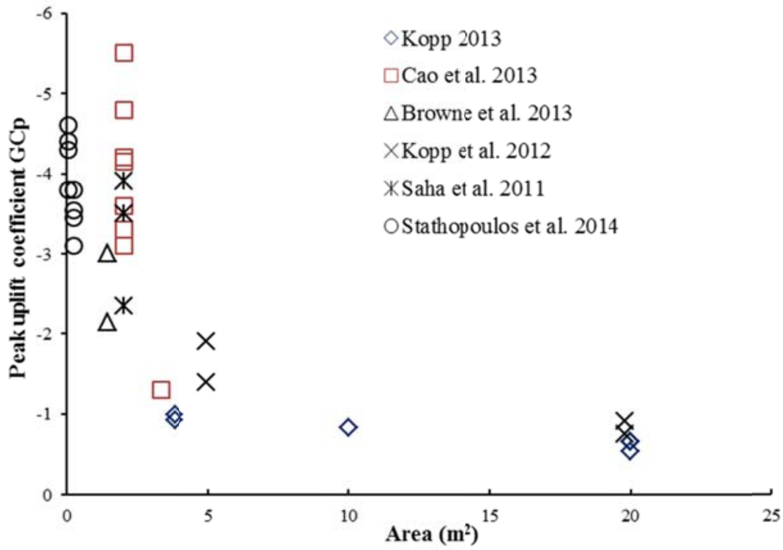


Fig. 3 Peak uplift coefficients vs tributary area

2.3. The geometric scale problem

An important issue arisen from the tributary area in Fig.3 and the geometric scale in Table 1 and Table 2, is the tributary area and the geometric scale. The relation between the peak uplift coefficient and the tributary area is influenced by two types of turbulence structures: the oncoming turbulence and the signature turbulence formed around the building model. To reflect correctly the contribution of the oncoming turbulence, the wind profile and a variety of turbulence scales should be carefully modeled and be similar to the target wind field according to the designed geometric scale. In this sense, there is an explicit geometric scale between the wind profile in wind tunnel and the target wind profile but this profile should be understood in a more general sense, namely not only the mean wind profile, but also a variety of turbulence scales. However, it is these turbulence scales that are most difficult to be modeled in most wind tunnels and hence prone to be neglected.

For the part regarding the signature turbulence, however, the connection depends on the relative area of a tested panel to the model size and is irrelevant to the specific geometric scale since the signature turbulence structure relative to a specific bluff model depends very weakly on the geometric scale. In this sense, one does not need to know the specific geometric scale (or, put it another way, any scale can be claimed) and, for specific solar arrays mounted on a specific building model, the relation between the uplift and the tributary area would depend uniquely on the non-dimensional area normalized by certain characteristic area of the building model.

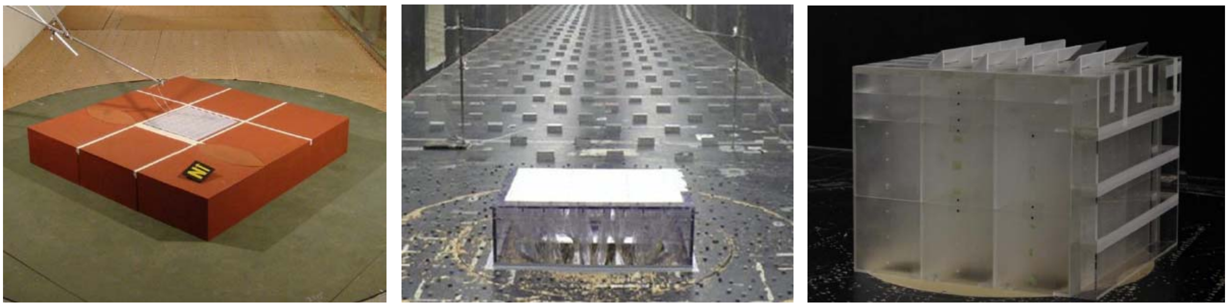
Hence, regardless of whether the oncoming wind field is properly modeled, the tributary area involved in this kind of connection cannot be separated from the specific configuration. However, this has been overlooked in the published literature.

2.4. Sensitive parameters

With a glimpse on Table 2, one can find immediately that many factors can contribute to the wind loading of solar panels. There are still other factors not being covered in Table 2, for example, the plan shape of the rooftop, the spatial correlations of the oncoming turbulence to just name a few. In this paper, two parameters, i.e. building height and tilt angle are selected for discussion.

2.4.1. The influence of building height

Kopp et al. (2006; 2012) found that the size of the building or, more specifically, the size of the wall can affect significantly the wind loads on roof-mounted arrays. Banks (2013) showed that, keeping the building height H fixed and decreasing the width and depth from $6H\times6H$ to $2H\times2H$, the worst panel uplift loads could reduce by a factor of 2 on the smaller roof. In contrast, tests conducted by Cao et al. (2013) indicate that another parameter, the building depth (along-wind direction), does not affect the wind loads on solar arrays in terms of largest mean and peak coefficients for all wind directions. Notwithstanding these inconsistent conclusions, one should realize that the configurations of the models employed by these authors are different from each other, varying from a very flat to a quite towering shape (see Fig. 4). Clearly, the wind field over a very flat building could exhibit more 'step-effects' than over a towering building, and the latter displays more 'end-effects' than does the former. The intuitive difference between these two effects is that, while the 'step-effect' varies with the step height, the 'end-effect' displays more or less independence on the building height. The real situation should be complex and be a combination of these two effects with two limits, namely pure 'step-effect' on very flat buildings and pure 'end-effect' on very slender structures. Refined investigations are still needed in regard to this issue for practical applications. Also, this could be related to the issue as to what is the reasonable way of non-dimensionalization of the parapet height.



(a) (b) (c)

Fig. 4 Building models from published literature: (a) Banks 2013; (b) Kopp et al. 2012; (c) Cao et al. 2013.

2.4.2.The influence of tilt angle.

The tilt angle is the most common parameter that has been investigated extensively by researchers. Cao et al. (2013) determined with their model that both the most critical negative mean and peak pressure coefficients increase with the tilt angle, and concluded that the larger the tilt angle, the higher the uplift wind loads on the panels. Kopp (2013) commented that for low tilt angles, the net loads are primarily due to pressure equalization of building-generated pressures, whereas for higher tilt angles, the array induced local flow fields can increase the wind loads. According to the literature, the influence of tilt angle on the wind loads developed on solar arrays can be significant. However, any single test of the wind loads under a given tilt angle should not be representative simply because there are many other factors involved in the experiment. Probably in view of this, Kopp and Banks (2013) suggested that wind loads be provided in together with specific tilt angle, wind direction, tributary area, and building height. Unfortunately, such an approach goes contrary to the generalization necessary for codification purposes.

3. OVERALL LIMITATIONS

3.1 Torsional wind loads

Most attention of published literature has been paid to the mean and peak uplift normal to the panel plane; little interest has been attracted by the overall aerodynamic torque on panels. Based on the development of a possible damage on a solar panel structure, no matter how complex the mechanism is, and no matter whether involved is strength failure, fatigue failure, or just insufficient ballast, the aerodynamic torque should always be as important as the uplift unless extensive investigations are conducted to show that the torque is negligibly small. In practical applications for the design of solar panel systems, the contribution of the aerodynamic torques (one-way or two-way) could be embodied either in separate wind loads or just in certain coefficients modifying the uplift and hence taking into account these effects.

3.2 Irregular rooftops and oblique cases

To date, for roof-mounted solar arrays, most attention has been paid to cases when solar panels are mounted on regular rooftops being characteristic of four 90° corners. Although wind load properties of solar arrays in this relatively simper situation have not been fully recognized, the task would be more complicated if buildings with L-shaped, T-shaped, and U-shaped rooftops were involved. The most distinctive feature of these kinds of buildings is that they have one or more 270° corners (see Fig. 5). For large flat-roofed buildings, investigation of the local wind load characteristics around a typical 270° corner might well be a favorable method that could be assumed independent of exact building shapes. Still, another issue worthy of investigation is whether there are significant differences with regard to the worst loads, critical wind directions, and zone dividing when the solar arrays are not arranged parallel/perpendicular to the wall lines (see Fig. 6). This could be of practical significance because many buildings are not positioned exactly on the north-south or east-west direction, and in these cases the solar arrays have to be arranged oblique to the walls if best energy absorbing is wanted.

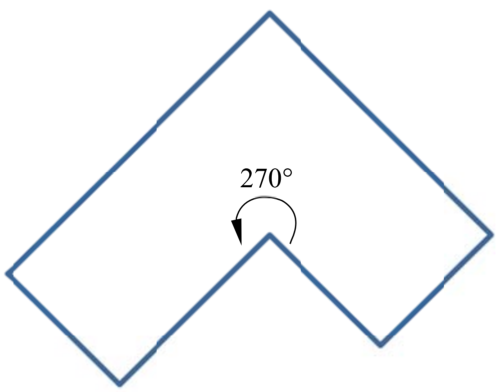


Fig. 5 A L-shaped building with a 270° corner

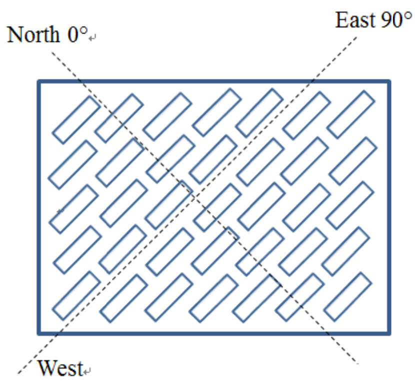


Fig. 6 Arrays oblique to walls

4 CONCLUSIONS

Recognizing the wind load characteristics of solar arrays has been a hotspot in wind engineering in the last few years. Since studies in this regard are targeted to a class of similar cases, instead of an isolated specific case, experiments must be conducted with many factors involved. Researchers have acquired substantial recognition regarding wind loads on solar panels in recent years. However, these achievements are still inadequate for engineering design practice. Inadequacies exhibit in several aspects. The relation between uplift and tributary area is not fully recognized; the variations of the 'step effect' and 'end effect' with the building height are not currently recognized; On the other hand, systematic experiments are still needed to investigate the torsional wind loads, and loading characteristics when cases of irregular rooftops and panels being arranged oblique to building edges are involved.

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