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Wind Load Calculations for PV Arrays

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Solar America Board for Codes and Standards

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Solar American Board for Codes and Standards Report

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Executive Summary

Today's photovoltaic (PV) industry must rely on licensed structural engineers' various interpretations of building codes and standards to design PV mounting systems that will withstand wind-induced loads. This is a problem, because–although permitting agencies require assessments of the structural attachment of solar equipment to rooftops—the safety and sufficiency of these attachments are not adequately addressed in any codes or standards. The result is a multitude of code interpretations from a range of individuals and groups, often yielding different design loads for the same design specifications.

It is important to evaluate equipment and attachment methods to ensure that PV equipment will remain attached to structures during windstorm events, and that additional loads or load concentrations do not exceed the structural capacity of the building. *ASCE Standard-7-05 (American Society of Civil Engineers Standard 7-05)* is the standard for wind forces on structures, but it does not provide adequate guidance to the design professionals and code officials tasked with assessing PV installations.

This lack of guidance creates obstacles for the PV industry. The resulting problems include frustrated installers, unhappy customers, and wind-related structural failures. In addition, uncertainty about what constitutes a safe and secure installation for a given wind load can slow or even stop the approval process for PV installations and complicates the training of code officials.

In this report, we provide sample calculations for determining wind loads on PV arrays based on *ASCE Standard 7-05*. We focus on applying the existing codes and standards to the typical residential application of PV arrays mounted parallel to the roof slope and relatively close (3 to 6 inches) to the roof surface. We do not address other array configurations or building-integrated PV.

It will require much more work to gather information and develop standards specific to wind loading on rooftop PV installations. Although the information in this report does not completely solve the problem, it does provide initial guidance to designers and code officials.

In this paper, we recommend an approach for the structural design of roof-mounted PV systems based on *ASCE Standard 7-05*. We provide examples that demonstrate a step-by-step procedure for calculating wind loads on PV arrays. The approach is applicable to PV modules mounted on rooftops that are no more than 60 feet high, when the PV array is oriented parallel to the roof surface, and when the mounting structure is sufficiently rigid. The PV array should be mounted a maximum of six inches above the roof surface. This distance is measured from the bottom of the PV frame to the roof surface, and is based on assumptions about typical mounting system configurations. The building should meet all requirements listed in Section 6.4.1.1 of *ASCE Standard 7-05*.

> "*ASCE Standard-7-05. . .* does not provide adequate guidance to the design professionals and code officials tasked with assessing PV installations."

It is important that design professionals read and understand the appropriate codes and standards when designing rooftop PV systems. This report is not meant to be a substitute for existing codes and standards. It is also important for design professionals to stay current with existing codes and standards, because we expect the body of information about designing PV systems to withstand local wind loading to grow rapidly in the near future.

Recommendations

1. At present, we recommend basing the structural design of roof-mounted PV systems on the *ASCE Standard 7-05* as follows:
   a. Section 6.5.12.2, main wind-force resisting system (MWFRS), is the recommended starting point for designing the PV mounting structure, with the PV module oriented above and parallel to the roof surface.

b. Section 6.5.12.4.1 addresses wind loads on components and cladding. We recommend the use of Section 6.5.12.4.1 and supporting Figures only for the design of the PV module attachment clips and hardware to the structure, and for calculating loads on individual PV modules.

c. We do not recommend Section 6.5.15, 6.5.15.1, and Figure 6-21 for the design of PV systems.

d. This report provides basic guidance for applying *ASCE Standard 7-05* to existing codes and standards for the typical residential application of PV arrays mounted parallel to the roof slope and relatively close (3 to 6 inches) to the roof surface.

2. We recommend wind tunnel testing be conducted for the most common rooftop PV installations to verify methods and calculations. The installation types include stand-off mounting parallel to the roof, stand-off mounting at an incline relative to the roof, and ballasted installations on flat roofs.

3. We recommend that codes and standards be modified to specifically address the mounting of PV arrays to rooftops to eliminate potential barriers to market development in high wind regions.

4. We recommend that local jurisdictions and design professionals use the recommendations in this report to ensure continuity in interpreting existing codes and standards.

Author Biographies

Stephen Barkaszi

Stephen Barkaszi, P.E. is a Senior Research Engineer in the Solar Energy Division at the Florida Solar Energy Center (FSEC). Mr. Barkaszi's areas of research include photovoltaic (PV) module and system testing and certification, distributed generation, utility-interconnection issues, building-integrated PV, and roof-mounted PV arrays. He also conducts research on high performance buildings and has been involved in the Zero Energy Homes (ZEH) efforts at FSEC since 1998. The ZEH projects have led to Disaster Tolerant Structures, which incorporate super energy efficient design with on-site generation for short and long-term power outages caused by wind storms and hurricanes in Florida or other coastal areas. Mr. Barkaszi's teaching activities include various seminars and short courses on PV, building energy efficiency, and building systems design. One popular offering is the week-long course *Installing Photovoltaic Systems* that FSEC offers each month. He received his B.S. and M.S. degrees in ocean engineering from the Florida Institute of Technology. Mr. Barkaszi is a licensed civil engineer in the state of Florida and previously managed the construction materials testing division for a private civil engineering firm.

Colleen O'Brien

Colleen O'Brien, P.E. has worked in the PV industry since 1996. She managed the Testing and Reliability group at PowerLight (now SunPower) for nine years, where she was responsible for mechanical and electrical testing of photovoltaic (PV) modules and mounting hardware. In that capacity, she ensured wind and seismic code compliance of PV mounting hardware, oversaw wind tunnel test programs, monitored and analyzed data from fielded PV systems, and evaluated emerging PV technologies. Ms. O'Brien continued this work in her current position with the consulting firm BEW Engineering, where she has expanded the scope of her expertise to include PV energy forecasting and system code compliance. She earned a B.S. in mechanical engineering from the University of New Hampshire and is a registered professional mechanical engineer in the state of California.

Solar America Board for Codes and Standards

The Solar America Board for Codes and Standards (Solar ABCs) provides an effective venue for all solar stakeholders. A collaboration of experts formally gathers and prioritizes input from groups such as policy makers, manufacturers, installers, and large- and small-scale consumers to make balanced recommendations to codes and standards organizations for existing and new solar technologies. The U.S. Department of Energy funds Solar ABCs as part of its commitment to facilitate widespread adoption of safe, reliable, and cost-effective solar technologies.

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Introduction

Today's photovoltaic (PV) industry must rely on licensed structural engineers' various interpretations of building codes and standards to design PV mounting systems that will withstand wind-induced loads. Ensuring that PV installations are safe and secure can involve custom testing methods such as wind tunnel testing or computer simulations, which are acceptable if approved by a structural engineer. The result is a multitude of code interpretations from a range of individuals and groups, often yielding different design loads for the same design specifications.

Please note that Chapter 6 of the ASCE Standard 7-05 *describes the procedure for determining wind loads on buildings and structures. All figures, tables, and sections of Chapter 6 begin with the prefix "6." For example, Figure 6-10, Table 6-3, and Section 6.3 are all parts of* ASCE Standard 7-05*, Chapter 6. These conventions have been adopted in this report, therefore any references to tables and figures beginning with a "6" refer to tables and figures in* ASCE Standard 7-05*, while those that do not begin with a "6" are contained within the body of this report.*

Background

The American Society of Civil Engineers (ASCE) *Minimum Design Loads for Buildings and Other Structures* (*ASCE Standard 7-05*) is the most comprehensive wind design standard in the United States. Other building codes such as the International Building Code (IBC) contain wind design requirements that are less comprehensive than *ASCE Standard 7-05*. This is especially true for design problems with atypical building geometry such as roof-mounted PV systems.

Fortunately, the IBC and other building codes explicitly permit the use of the *ASCE Standard 7-05* for the design of buildings and structures. However, it is difficult—and in some cases inappropriate—to derive the design loads on roof-mounted PV arrays from the existing standards, because there is no specific provision for these structures. The recommended design approach for roof-mounted PV systems presented in this report is based on the most recent version of the ASCE standard, *ASCE Standard 7-05* (ASCE 2006). This work is an initial attempt to provide some guidance to design professionals and begin a dialogue in the PV community that will move this issue further toward consensus.

Existing Codes and Standards

In this report, we recommend an approach for the structural design of roof-mounted PV systems that is based on the *ASCE Standard 7-05*. We provide examples that demonstrate a step-by-step procedure for calculating wind loads on PV arrays. Our approach is applicable to PV modules mounted on rooftops that are no more than 60 feet high, when the modules are oriented parallel to the roof surface, the mounting structure is sufficiently rigid, and the PV array is mounted a maximum of six inches above the roof surface. This distance is measured from the bottom of the PV frame to the roof surface and is based on assumptions about typical mounting system configurations. The building should meet all requirements listed in Section 6.4.1.1 of *ASCE Standard 7-05*.

Existing codes and standards do not cover PV modules oriented at an angle to the roof surface, and an analysis of this configuration is beyond the scope of this report. Designing for wind loading on this type of orientation and mounting structure is significantly more complex than designing for modules parallel and close to the roof, and will require further research and possible testing. This report also does not address building-integrated PV.

> "The result is a multitude of code interpretations from a range of individuals and groups, often yielding different design loads for the same design specifications."

[1] Note: *ASCE Standard 7-05,* Section 6.2, defines rigid buildings and structures as having a fundamental frequency of at least 1 Hz. The 1 Hz limitation was developed as a worst-case value for high-rise buildings, and the application of this limitation has been the subject of some controversy in the ASCE community. PV

mounting structures are typically less than 10 feet in height and often substantially shorter, and will likely have a fundamental frequency higher than 1 Hz. *ASCE Standard 7-05* supports adopting the 1 Hz limitation for PV systems, but this should be verified as applicable by a licensed structural engineer on a case-by-case basis. Defining a maximum fundamental frequency for rigid PV structures will require further testing.

Experts in the areas of PV system design, aerodynamics, wind tunnel testing, and ASCE Standard 7-05 conducted a thorough review of the code. Based on this review, the team concluded that:

1. Unfortunately, there is no prescribed method in the standard that clearly addresses the specific geometry of roof-mounted PV systems.
2. Sections 6.5.15 and 6.5.15.1 and Figure 6-21 are not recommended for the design of PV systems.
3. Section 6.5.12.4.1 addresses wind loads on components and cladding, but the use of this section and the supporting figures are recommended only for the design of the PV module attachment clips and hardware to the structure, and for calculating loads on individual PV modules.
4. Section 6.5.12.2 (main wind-force resisting system [MWFRS]) is the recommended starting point for designing the PV mounting structure with the PV module oriented above and parallel to the roof surface.

Discussion

We studied Section 6.5.15, 6.5.15.1, Figure 6-21, and the commentary on Figure 6-21 in *ASCE Standard 7-05* to determine their potential applicability to roof-mounted PV systems. Section 6.5.15.1, "Rooftop Structures and Equipment for Buildings with h < / = 60 feet" is a new addition to this version of the standard. The text would appear to be applicable to PV systems.

However, it is the opinion of the authors that this was due to a lack of clarity in the actual text. This section of the standard was intended to be applicable to roof-mounted structures with a prismatic shape, such as chimneys, air conditioners, etc. It was not intended for rooftop installations like PV systems that have gaps between the equipment and the roof. These gaps can allow pressurization below the surface of the PV modules independent of pressure in the building interior.

Put another way, *ASCE Standard 7-05* was written for buildings, not the tops of buildings. Wind loading for installations like PV systems that leave gaps between the equipment and the roof surface is very different from wind loading for roof-mounted structures with a prismatic shape. For this reason, the authors do not recommend the use of Section 6.5.15.1 or Figure 6-21 for the design of PV systems.

"Unfortunately, there is no prescribed method in the standard that clearly addresses the specific geometry of roof-mounted PV systems.."

Section 6.5.12.4.1 addresses wind loads on components and cladding. "Components and cladding" is defined by ASCE as an "element of the building that does not qualify as the MWFRS." Many structural engineers and PV designers have considered roof-mounted PV systems to qualify as components and cladding, and not the MWFRS, due to the fact that the PV support structure is not the wind resisting structure for the building. The MWFRS is defined by ASCE as "an assemblage of structural elements assigned to provide support and stability for the overall structure. The system generally receives wind loading from more than one surface."

Components receive wind forces directly or from the cladding system. Those loads are transferred to the MWFRS, which bears the structural loads. Based on the descriptions of the differences between components and cladding and the MWFRS, we concluded that the PV modules themselves and the hardware that secures the modules to the structure could be considered components and cladding. However, the means of attachment to the roof is the MWFRS, because the PV mounting system provides support and stability for the overall structure. It is this means of attaching the modules to the structure (via the roof) that is of primary concern. Therefore, we recommend using Section 6.5.12.4.1 and the supporting figures for calculating loads on individual PV modules and attachment hardware, and Section 6.5.12.2 for the design of PV rooftop mounting structures.

ASCE Standard 7-05 differentiates between components and cladding and the MWFRS because the small tributary area of components and cladding can result in higher instantaneous loads than the MWFRS. Components and cladding transfer loads to the MWFRS. At one instant in time, some of the components and cladding may experience extreme uplift while others experience less uplift or even a downward force. The MWFRS can distribute these varying loads, and the net effect is reduced wind loading on the structure. Section 6.5.12.4.1 provides a procedure for calculating wind loads on components and cladding, and 6.5.12.2 provides a procedure for calculating wind loads on the MWFRS. These are the recommended starting points for designing mounting structures for roof-mounted PV installations in which the PV module is oriented parallel to the roof surface.

Although the referenced figures in 6.5.12.2 have geometries that appear to be similar to tilted PV modules, we do not recommend applying this section to modules oriented at a tilt relative to the roof surface. None of the referenced figures in this section address the geometry of tilted PV, which is inherently non-aerodynamic when it is mounted on top of a building. Future work will include the consideration of analytical techniques based on fundamentals of aerodynamics, combined with publicly available wind tunnel test data as well as data in *ASCE Standard 7-05* to develop a procedure for estimating loads for tilted modules. Although wind tunnel testing would be the preferred solution, sufficient information is not currently available, and empirical data analysis is left to future studies.

When modules are oriented parallel to the roof surface—provided that they are mounted close to the roof—they are subjected to the same type of wind flow as a roof at the same pitch. Based on typical roof-mounted PV array hardware configurations and current practices, the authors recommend limiting the PV array height to six inches above the roof in order to use the approaches discussed in this report. It is unknown at this time how much internal pressurization (positive pressure below the module) will be created because of the gap distance between the roof and module frame (the opening) and the distance between the roof and the back of the module (the structural diaphragm). Although *ASCE Standard-7-05* does provide values for internal pressure coefficients, these coefficients were developed for buildings more than 15 feet tall with various types of openings around the building that are specific to common buildings—open (at least 80% of each wall is open), enclosed (walls have very few openings), or partially enclosed (walls have some openings). The geometry of the air space below the PV module could be categorized similarly. However, while analogous, it may be very different from the geometry of the walls and interior airspace of a building because of the significant scaling differences.

The problem of not having accurate internal pressure coefficients for common PV geometries is a key weakness in applying the *ASCE Standard 7-05* to roof-mounted PV systems. Of the three building classifications described in *ASCE Standard 7-05*, one could easily justify classifying the PV module as an "open building," (internal pressure coefficient GCpi = 0), which would yield the lowest wind load of the three options. Given the proximity of the PV module to the roof, and the presence of structural and electrical components between the modules and the roof, one could also consider the module as a “partially enclosed” building (internal pressure coefficient GCpi = +/- 0.55), which would yield the highest wind load of the three options.

Based on discussions with experts in the field of wind tunnel testing and the ASCE Standard, we believe that a value of +/- 0.1 to +/-0.3 is a reasonable choice for systems with limited restrictions to airflow below the module. Some authorities having jurisdiction (AHJs) or structural engineers may require designers to apply the classification of a partially enclosed building. However, we expect that most AHJs will defer the decision to a licensed engineer.

The decision about how conservative a designer should be when choosing an internal pressure coefficient may also be influenced by the potential reduction in wind loads most PV systems experience due to pressure equalization. *ASCE Standard 7-05* does not account for this reduction.

With stand-off mounted PV systems parallel to the roof, most of the uplift load on modules is due to pressure differentials above and below the module. The difference in pressure between the top and bottom surface gives the total uplift or downward pressure acting on the module. Because modules have a relatively small area compared to roofs, and because there are typically one-half to two-inch gaps between modules, pressure differentials above and below modules typically equalize in a short amount of time, on the order of fractions of seconds. *ASCE Standard 7-05* does acknowledge the phenomenon of pressure equalization in the discussion of “air permeable cladding” in Section 6.4.3, because pressure equalization is entirely dependent upon the geometry of the cladding. Properties that affect the amount of pressure equalization are the length and width of the module (smaller modules will have better equalization, larger modules will take longer to equalize), the vertical distance of the module from the roof surface (closer to the roof will reduce the volume of air to pressure equalize), the horizontal distance between modules (larger distances will create a better path for pressure transmission), and the degree of restriction to airflow below the module due to the presence of structural or electrical components (fewer restrictions will enhance pressure equalization).

Because PV modules are typically close to the roof surface and have gaps on all sides, pressure differentials between the top and back of the PV surface likely equalize quickly. This phenomenon could reduce wind loads on the module by 50% to 80% or even more, but quantifying the degree of pressure equalization that occurs in various PV systems will require wind tunnel testing on a variety of geometric configurations.

Sample Calculations

In Sample Calculation 1, we determine wind loads on a PV mounting structure based on the assumption that it is part of the MWFRS. In Sample Calculation 2, we outline how a designer should determine wind loads on PV modules and mounting hardware.

Again, this approach is limited to applications in which the PV module is oriented parallel to the roof surface and is a maximum of about six inches above the roof deck. In addition, the building must be 60 feet high or less and the mounting structure should have a fundamental frequency of 1 Hz or greater.

Sample Calculation 1

Wind Load on PV Mounting Structure (MWFRS, Section 6.5.12.2)

Location: Phoenix, Arizona

Terrain: Open desert, very few buildings.

Building height: 17’3” at the eave, 22’9” at the ridge, 20’ mean roof height

Building shape: Gable roof with a 20° pitch

Building type: Residential

Building dimensions: 60’ (along the ridge) x 30’ (perpendicular to the ridge)

Module orientation: Parallel to roof, 5” above roof surface, minimum 4’ from the roof edge.

PV array area: 100 square foot array (10’ x 10’)

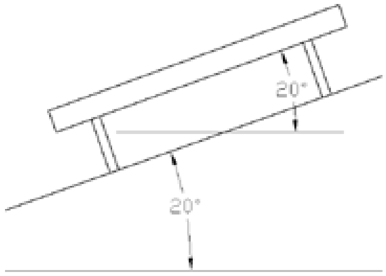


Figure 1. Array mounted parallel to the roof slope

Steps:

1. Reference Figure 6-1 to determine the basic wind speed for the Phoenix, Arizona, location. From this Figure, the wind speed is V = 90 mph.
2. Reference Section 6.5.6.3 to determine the surface roughness category. Do a physical site inspection or review photographs of the surrounding terrain in all directions to properly classify the surrounding terrain using the definitions in this section. If the terrain varies in the upwind direction or if the location is in a transitional zone, use the worst-case wind loads. For this sample problem, we assumed that Exposure C applies for this open desert location.
3. Determine the occupancy category using Table 1-1. In this case, it is Type II for a residential building.
4. Determine the importance factor using Table 6-1. In this case, I = 1.00 for a Type II building.
5. Reference Section 6.5.7.1 to determine the topographic factor, K_{zt}. For this sample calculation, we will assume that the site is on level terrain, so K_{zt} = 1.0.
6. Determine a velocity pressure exposure coefficient using Table 6-3. As discussed in the definition of the height (h) in Section 6.3, use the mean roof height (note that eave height is used for a roof pitch < 10°). The mean height in this case is 20 feet. For an exposure terrain classification of C, and a roof height of 20, we obtain a velocity pressure exposure coefficient of K_z = 0.90.
7. Determine enclosure classification and internal pressure coefficients (GCpi). Section 6.2 provides definitions of enclosure types (open, partially enclosed, and enclosed buildings), and the designer must identify the enclosure classification in order to determine the internal pressure coefficients. Many racking systems create very little obstruction below the PV module, which may lead the designer to choose an “open building” classification. However, the typically small vertical space (on the order of 3 to 6 inches), as well as the PV frame, wiring, conduit, and structural components below the module will cause a restriction in airflow. For this reason, the PV array could also be considered to be a “partially enclosed building.” Sections 6.5.3, 6.5.11.1, and ultimately Figure 5 provide internal pressure coefficients for the various enclosure classifications. In actuality, most PV systems likely have internal pressure coefficients somewhere between those given for an open building (GCPi = 0) and a partially enclosed building (GCpi+/-0.55). Based on consultations with numerous wind loading experts and engineers, we recommend a range of +/-0.1 to +/-0.3. Because the ASCE Standard is not clear, a designer could justify classifying the PV array as an open building (GCpi=0), but our recommendation provides an added margin of safety.

Some AHJs or structural engineers may require a more conservative value of GCpi = +/0.55. In this sample calculation, we used a value of GCpi = +/- 0.3.

8. Determine external pressure coefficient. To select the correct data from Figure 6-6 for buildings more than 60 feet high or Figure 6-10 for buildings less than 60 feet high, the designer must consider the geometry of the roof. However, Figure 6-18A through 6-18D should be used in place of Figures 6-6 or 6-10 for buildings with no walls (see the definition in Section 6.2 for Free Roofs). In our example, the building is a residence, which we assume is an enclosed or partially enclosed building with a roof that has a 20-degree pitch. We took the external pressure coefficients from Figure 6-10 for this sample building.

   Figure 6-10 shows eight basic load combinations, illustrated in the eight building images and the "reference corners" on the first page of Figure 6-10. For buildings more than 30 feet high, there are two torsional load cases to consider. To calculate wind loads on the 10-foot by 10-foot PV array on the roof of our sample 20-foot tall building, the application of Figure 6-10 can be greatly simplified to one load case, although the result will be slightly conservative. We present a simplified process in this section of this report (see Figure 3), but first we propose a more rigorous application of Figure 6-10.

   Figure 1 A, B, C, and D and Figure 2 A, B, C, and D show how we applied ASCE Figure 6-10 to the sample rooftop PV array. Each of the eight images corresponds to the load cases shown in the images on the first page of Figure 6-10. The first four images are used for the design of the PV mounting structure when analyzing loads on components in a transverse direction (the "Direction of MWFRS Being Designed" arrows in ASCE Figure 6-10 and the red arrows in Figure 1 A-D and Figure 2 A-D). The second four images are used for designing the structure when analyzing loads in a longitudinal direction.

   Note that each image has a "reference corner." When wind hits the corner of a building, wind loads on the roof reach a peak. Rather than require that the building be designed under the assumption that each corner is subjected to a "corner wind load" at the same moment in time, which is not possible, *ASCE Standard 7-05* allows designers to analyze loads on the building one corner at a time. The same can be done for the PV mounting structure, although the analysis can be simplified as we discuss later in this section. The reference corners in each of the images represent the upwind corner of the building at one moment in time.

   The zones that are applicable to the sample rooftop PV system on a 20-foot tall building are 2, 3, 2E, and 3E. The other zones in Figure 6-10 are applicable only to walls. The "E" in these zone categories stands for "edge." The differentiation between edge and interior regions is important, because upwind edge locations on a roof are known to have higher wind loads than interior regions. For this reason, it is wise to place PV arrays as far from the edges of buildings as possible. As shown in Figure 1 A-D and Figure 2 A-D, various parts of the sample PV array are situated in each of these zones, depending on the direction of the structural component being analyzed (transverse or longitudinal) and the upwind reference corner.

   In order to define the boundaries zones 2, 3, 2E, and 3E, the designer must determine the dimension noted as 'a' in Figure 6-10. Figure 6-10 defines 'a' as "10% of the least horizontal dimension or 0.4h, whichever is smaller, but not less than 4% of the least horizontal dimension or 3 feet." We determined the value for 'a' for this building follows:

1. 10% of the least horizontal dimension for this building is 0.10 times the smallest horizontal building dimension of 30' = 3'.

2. 0.4 times the building height (h, defined in Section 6.3) for this building is 0.4 times the mean roof height. The mean roof height is 20'; 0.4 x 20' = 8'.

3. 4% of the least horizontal dimension is 0.04 x 30' = 1.2'.

4. Applying the definition of 'a' in the previous paragraph and calculations 1, 2, and 3, we obtain a = 3'.

Figure 6-10 shows edge and interior roof zones, defined as the area within a distance of two times a, or six feet from the upwind edge. The edge regions are shown in Figure 1 A-D and Figure 2 A-D as dark shaded areas on our sample rooftop system.

The second page of Figure 6-10 is used to identify the applicable external pressure coefficients for the sample building. For a 20-degree pitched roof, these values are shown below in Table 1.

Table 1: External Pressure Coefficients for Sample Calculation 1

Zone	GCpf
2	-0.69
3	-0.48
2E	-1.07
3E	-0.69

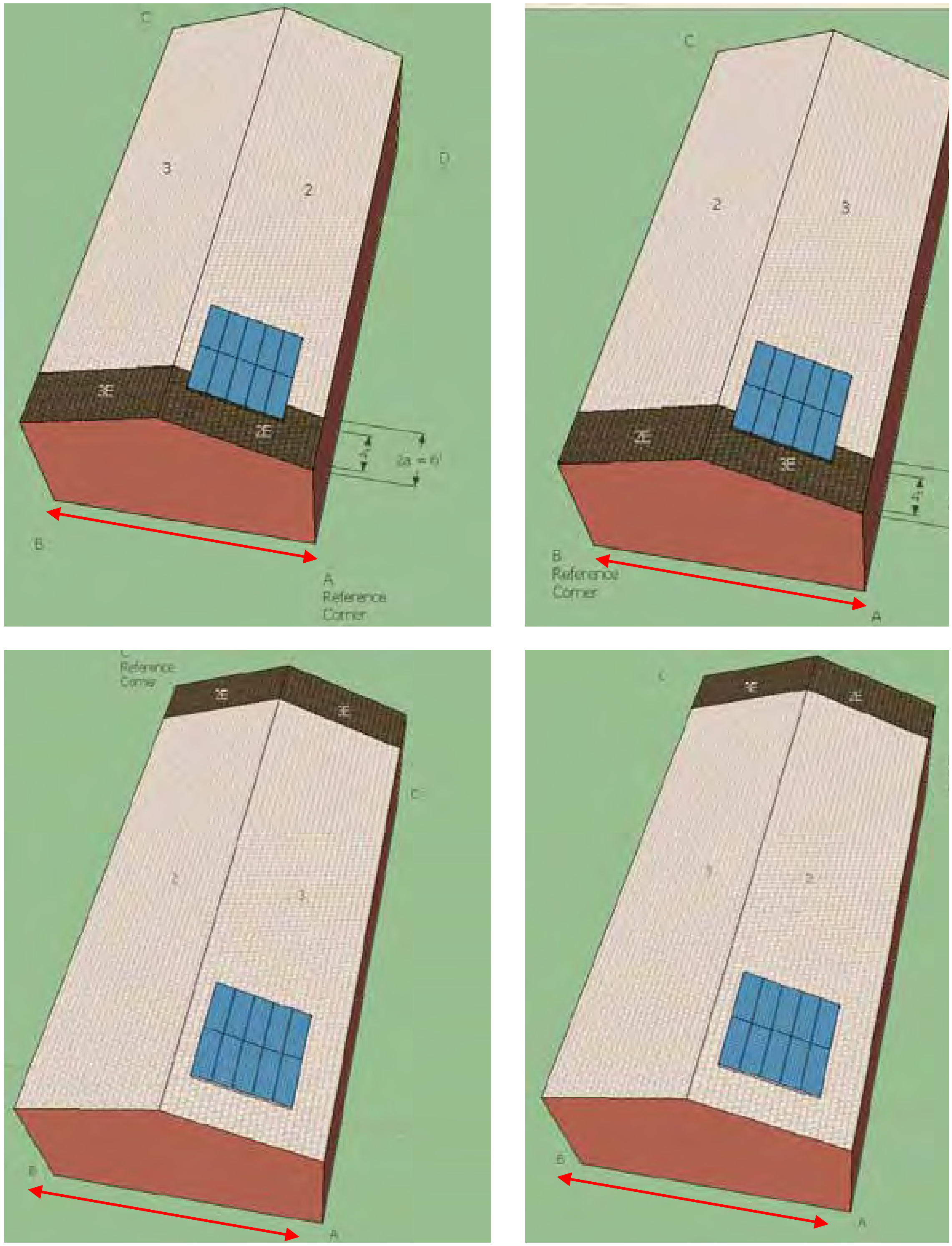


Figure 1-A, B, C, and D: Roof zones for Sample Calculation 1, based on ASCE Figure 6-10 and the geometry of the sample building. Red arrows indicate the direction of the structural members being designed (transverse direction).

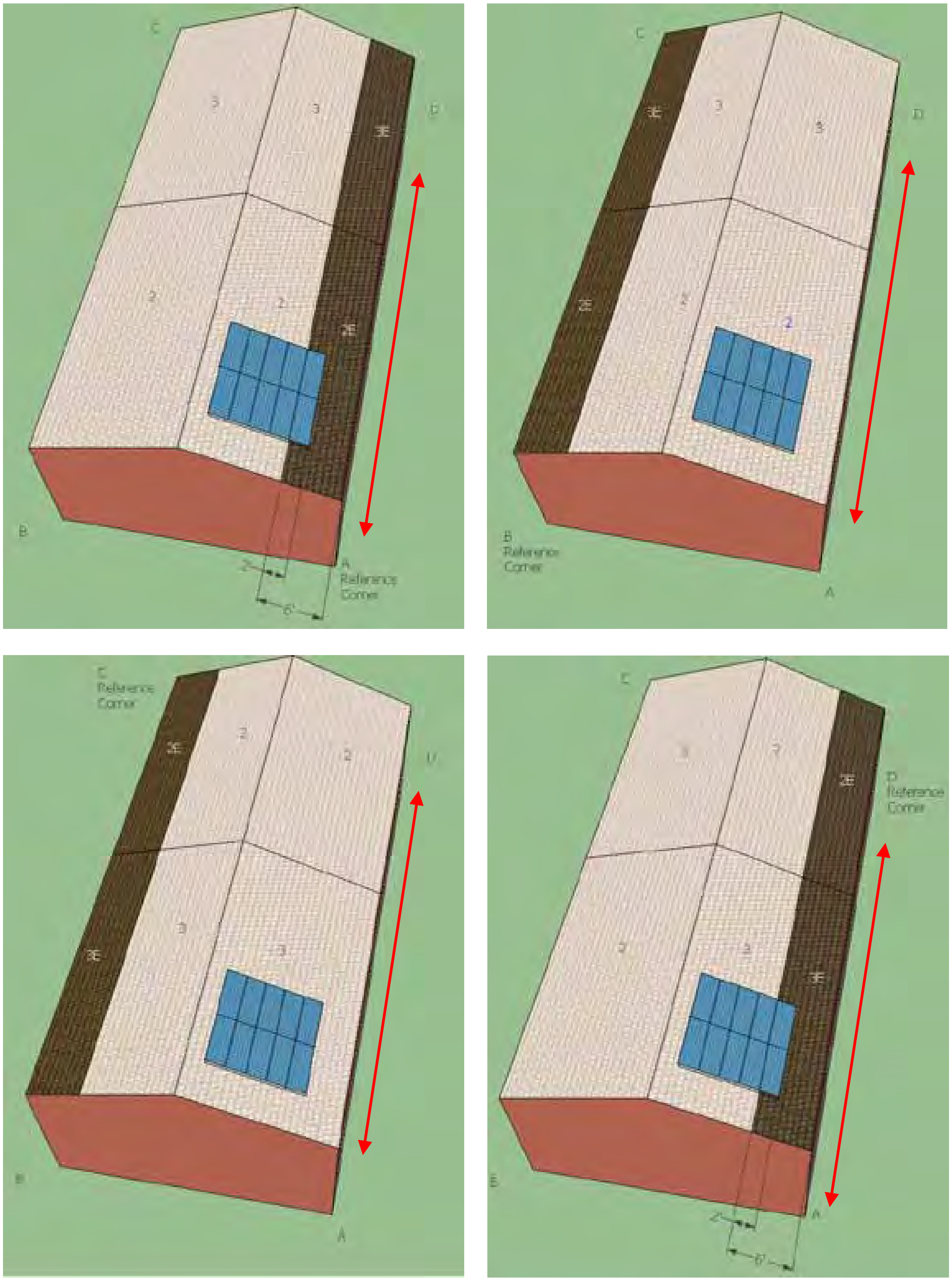


Figure 2 A, B, C, and D: Roof zones for Sample Calculation 1, based on ASCE Figure 6-10 and the geometry of the sample building. Red arrows indicate the direction of the structural members being designed (longitudinal direction).

9. Calculate velocity pressure as described in Section 6.5.10:

$$q_h = 0.00256*K_z*K_{zt}*K_d*V^2*I \text{ (in pouns per square foot [psf])}$$

$$q_h = 0.00256*0.90*1*1*90^2*1 = 19 \text{ psf}$$

10. Determine the design wind pressure as described in Section 6.5.12.2.1:

$$p = q*(GC_{pf} - GC_{pi})$$

In Step 9, we quantified q as 19 psf, in Step 7, we determined GCpi to be +/-0.3, and in Step 8, we determined four values for GCpf for four possible roof zones. Table 3 shows the resulting pressures for uplift and downward pressures in each of the roof zones. We calculated uplift using the equation in Step 10 above, and the lowest exterior pressure coefficient (GCpf) provided in the Figures in *ASCE Standard 7-05* for a given roof zone, which is typically a negative number, and the positive interior pressure coefficient (GCpi) from Step 7, above. The negative exterior pressure coefficient represents uplift pressure on the top surface of the PV, and the positive interior pressure coefficient represents pressurization under the module. The combined action of each of these pressure coefficients is to exert an uplift force normal to the PV structure, away from the roof.

Downward pressure is calculated by using the highest exterior pressure coefficient provided in the Figures in *ASCE Standard 7-05* for a given roof zone, and the negative interior pressure coefficient from Step 7. In some cases, the highest exterior pressure coefficient may be a negative number.

Figure 6-10 provides only one exterior pressure coefficient for each roof zone, so the same exterior pressure coefficient is used to calculate the worst-case uplift and downward pressure at each roof location. This is not always the case, so designers should use appropriate Figures in Chapter 6 of the *ASCE Standard 7-05*, applied carefully on a case-by-case basis.

The recommended exterior and interior pressure coefficients and resulting uplift and downward pressures are shown in Table 2.

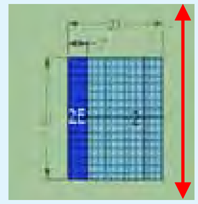
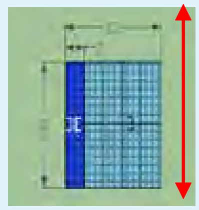
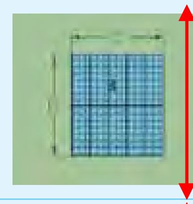
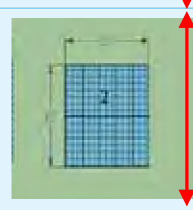
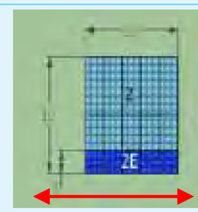
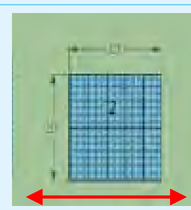
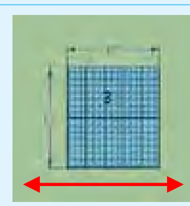
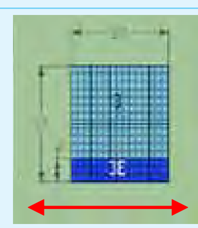
Table 2: Uplift and Downward Pressures for All Roof Locations

Roof Zone	Positive Interior Pressure Coefficient, $+GC_{pi}$ (to calculate uplift pressure)	Negative Interior Pressure Coefficient, $-GC_{pi}$ (to calculate downward pressure)	Exterior Pressure Coefficient, GC_{pf}	Design Wind Uplift Pressure, $p=q*(GC_{pf} - GC_{pi})$	Design Wind Downward Pressure, $p=q*(GC_{pf} - GC_{pi})$
2	0.3	-0.3	-0.69	-18.81	-7.41
3	0.3	-0.3	-0.48	-14.82	-3.42
2E	0.3	-0.3	-1.07	-26.03	-14.63
3E	0.3	-0.3	-0.69	-18.81	-7.41

The results show that downward pressure need not be considered in this case, because all values in the right-most column are negative, indicative of uplift pressures that are lower in magnitude than the design wind uplift pressures in the second to last column. This may not always be the case, so the designer should check for each system design. In this example, we need only consider the design wind uplift pressure values for each of the zones.

A structural engineer would need to consider the uplift and downward loads shown in Table 2 on various sections of the array, depending on the location of the array relative to the four roof zones in each load case. The load cases are summarized in Table 3, below. These load cases should be used to evaluate loads on the PV mounting structure as well as loads on the building resulting from the installation of the PV system.

Table 3: Load Cases for PV Structure, Based on ASCE Figure 6-10

Load Case	Direction of MWFRS[1]	Ref. Corner	Ref. Figure	Array Loading Diagram
1	Transverse	A	Figure 1 A	
2	Transverse	B	Figure 1 B	
3	Transverse	C	Figure 1 C	
4	Transverse	D	Figure 1 D	
5	Longitudinal	A	Figure 2 A	
6	Longitudinal	B	Figure 2 B	
7	Longitudinal	C	Figure 2 C	
8	Longitudinal	D	Figure 2 D	

[2] Reference ASCE Figure 6-10 and the red arrows in the Table 3 column labeled "Array Loading Diagram."

Simplified Approach

A slightly conservative but simpler approach can be used to design the array by simply designing for the worst-case wind loads in any section. From Table 2, it is clear that downward pressure can be neglected, that zone 2 has the highest uplift for interior sections of the array, and zone 2E has the highest uplift for any edge location. This gives the following loading diagram for the sample array, which could be applied to structural members in both the transverse and longitudinal directions:

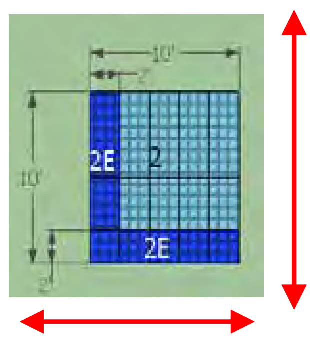


Figure 3. Simplified Conservative loading for the PV mounting structure

Sample Calculation 2

Wind Loads on PV Module, Mounting Clips and Hardware
(Components and Cladding, Section 6.5.12.4)

Location: Phoenix, Arizona
Terrain: Open desert, very few buildings.
Building height: 17'3" at the eave, 22'9" at the ridge
Building shape: Gable roof with a 20° pitch
Building type: Residential
Building dimensions: 60' (along the ridge) x 30' (perpendicular to the ridge)
Module orientation: Parallel to roof, 5" above roof surface, 4 ft from the roof edge.
PV module area: 2' x 5'

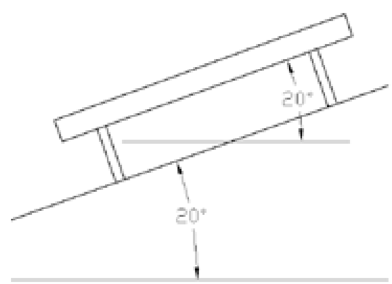


Figure 4. Array mounted parallel to the roof slope

Steps:

1. Reference Figure 6-1 to determine the basic wind speed for the Phoenix, Arizona, location. From this Figure, the wind speed is **V = 90 mph**.
2. Reference Section 6.5.6.3 to determine the surface roughness category. Do a physical site inspection or review photographs of the surrounding terrain in all directions to properly classify the surrounding terrain using the definitions in this section. If the terrain varies in the upwind direction or if the location is in a transitional zone, use the worst-case wind loads. For this sample problem, we assumed that Exposure C applies for this open desert location.
3. Determine the occupancy category using Table 1-1. In this case, it is **Type II** for a residential building.

4. Determine the importance factor using Table 6-1. In this case, **I = 1.00** for a Type II building.

5. Reference Section 6.5.7.1 to determine the topographic factor, K_{zt}. For this sample calculation, we will assume that the site is on level terrain, so $\mathbf{K_{zt} = 1.0.}$

6. Determine a velocity pressure exposure coefficient using Table 6-3. As discussed in the definition of the height (h) in Section 6.3, use the mean roof height (note that eave height is used for a roof pitch < 10°). The mean height in this case is 20 feet. For an exposure terrain classification of C, and a roof height of 20, we obtain a velocity pressure exposure coefficient of $\mathbf{K_z = 0.90.}$

7. Determine enclosure classification and internal pressure coefficients. As we discussed in the preceding Sample Calculation 1, Step 7, the recommended value for GCpi is +/- 0.1 to +/- 0.3. In this example, we used +/- 0.3.

8. Determine the external pressure coefficient. Compare the building height and shape to those shown in Figures 6-11B – D, 6-12, 6-13, 6-14A-B, 6-15, 6-16, 6-17, 6-18A-D, and 6-19A-C in *ASCE Standard 7-05*. Note that Figures 6-18 and higher are for “free roofs,” or buildings without walls (see formal definition in Section 6.2). In this example, the building has a gable roof with a 20-degree slope, and the left side of Figure 6-11C is a good match. Figure 6-11C shows three roof zones, representing interior (zone 1), edge (zone 2), and corner (zone 3) locations on the roof.

   Section 6.2 defines the effective wind area, but it is slightly ambiguous. We recommend that the designer use the area of the PV module to calculate wind loads on the PV itself. However, for determining loads on fasteners, the effective wind area should be the fraction of the PV module that is secured by the fastener.

   For example, in many arrays, fasteners are placed at third points (points one-third of the way in from either end) along the long sides of a module, as shown in Figure 5. This figure shows that fasteners in interior regions of the array are used to secure adjacent modules, so that modules are sharing fasteners. The result of this configuration is that fasteners along the perimeter of the array, such as Fastener 1 in the figure, are supporting an effective wind area equivalent to one-quarter of the module area (Area 1 in the figure). Fasteners in interior regions, such as Fastener 2, are supporting an effective wind area equivalent to one-half of the module area (Area 2 in the Figure). In most cases, the same fasteners and clips are used in all locations, so we chose the worst-case configuration. Pressure coefficients become more extreme as the effective wind area becomes smaller.

   To select the worst-case pressure coefficients for fastener design in this example, the designer should use the smallest effective wind area per fastener, equal to one-quarter of the module area of 10 square feet. In this case, the pressure coefficients are the same for an effective wind area between 1 and 10 square feet, so the same pressure coefficients would be used for all fasteners and PV modules. Note that this may not always be the case, depending on the PV module size as well as the roof geometry, which may require that the designer use a figure other than Figure 6-11C. From Figure 6-11C (left-hand of the figure for a gable roof), we obtained following coefficients:

Table 4: Exterior Pressure Coefficients for Sample Calculation 2

Roof Zone	+GCp	-GCp
1	0.5	-0.9
2	0.5	-1.7
3	0.5	-2.6

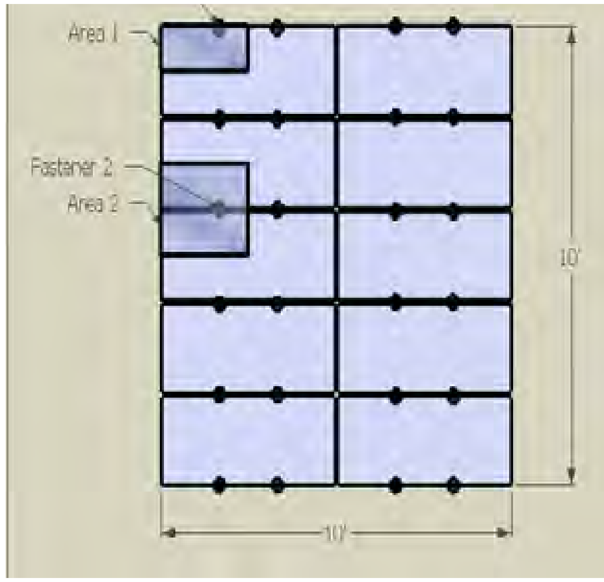


Figure 5. Array layout showing fastener locations and areas tributary to perimeter fasteners versus interior fasteners.

9. Calculate velocity pressure as described in Section 6.5.10:

   q = 0.00256*Kz*Kzt*Kd*V2*I (in psf)

   q = 0.00256*0.92*1*1*902*1 = 19 psf

10. Determine the design wind pressure as described in Section 6.5.12.2.1:

    p = q*GCp – Gcpi

Table 5 summarizes the resulting design uplift and downward wind pressures for each of the three wind zones:

Table 5. Design Wind Uplift and Downward Pressures for Sample Calculation 2

Roof Zone	Positive Interior Pressure Coefficient, $+GC_{pi}$ (to calculate uplift pressure)	Negative Interior Pressure Coefficient, $-GC_{pi}$ (to calculate downward pressure)	$+GC_p$	$-GC_{pi}$	Design Wind Uplift Pressure, p= $q*(GC_{pf} -GC_{pi})$	Design Wind Downward Pressure, p= $q*(GC_{pf} -GC_{pi})$
2	0.3	-0.3	0.5	-0.9	-22.8	15.2
3	0.3	-0.3	0.5	-1.7	-38	15.2
2E	0.3	-0.3	0.5	-2.6	-55.1	15.2

Note that in ASCE Figure 6-11 C, a dimension 'a' defines the boundaries of the various roof zones, exactly as it was in Sample Calculation 1, in which we used Figure 6-10. The definition of 'a' in both figures is the same, so the prior result of a = 3 is valid for this calculation. Note that the edge zones in Figure 6-10 were defined by a dimension of 2*a, but in ASCE Figure 6-11 C, a dimension of 1*a defines the edge and corner zones. Zone 2 occupies the parts of the roof between the edges and three feet to the interior, with the exception of the corners. Zone 3 is the corner region, defined as three feet from two adjacent edges of the building. Figure 1 A-D and Figure 2 A-D show that the array is located four feet from the building edge, so Zone 1 is the only loading case that need be considered when calculating wind loads on PV modules or mounting fasteners. This is fortunate, because some modules are not approved for Zone 3's expected wind uplift pressure of 55 psf. This serves as an important reminder to designers to place PV systems as far from the building edge as possible. For the design of the modules and fasteners in this sample PV system, the designer should use an uplift pressure of about 23 psf and downward pressure of about 15 psf.

Conclusions

Although permitting agencies require assessments of the structural attachment of solar equipment to rooftops, the safety and sufficiency of these attachments are not adequately addressed in any codes or standards. It is important to evaluate equipment and attachment methods to ensure that PV equipment will remain attached to structures during windstorm events, and that additional loads or load concentrations do not exceed the structural capacity of the building. *ASCE Standard-7.05* is the standard for wind forces on structures, but it does not provide adequate guidance to the design professionals and code officials tasked with assessing PV installations.

This lack of guidance creates obstacles for the PV industry. The resulting problems include frustrated installers, unhappy customers, and wind-related structural failures. In addition, uncertainty about what constitutes a safe and secure installation for a given wind load can slow or even stop the approval process for PV installations and complicates the training of code officials.

PV modules and arrays present a unique design challenge in high wind regions. Eventually, codes and standards will specifically address the mounting of PV arrays to rooftops to eliminate potential barriers to market development in high wind regions.

In the meantime, this report provides design guidance, including sample calculations for determining the wind loads on PV arrays based on the recognized *ASCE Standard 7-05*. Although this does not specifically address the problem, it is the best option available at this time. The basic guidance for applying the existing codes and standards provided in this report is for the typical residential application of PV arrays mounted parallel to the roof slope and relatively close (3 to 6 inches) to the roof surface. We do not address other array configurations.

It will require much more work to gather information and develop standards specific to wind loading on rooftop PV installations. Although the information in this report does not completely solve the problem, it does provide initial guidance to designers and code officials.

It is important that design professionals read and understand the appropriate codes and standards when designing rooftop PV systems. The guidance presented here is not meant to be a substitute for following the codes and standards. It is also important to for design professionals to stay current with these publications, because we expect the body of information about designing PV systems to withstand local wind loading to grow rapidly in the near future

Recommendations

1. At present, we recommend basing the structural design of roof-mounted PV systems on the *ASCE Standard 7-05* as follows:
   a. Section 6.5.12.2, MWFRS, is the recommended starting point for designing the PV mounting structure, with the PV module oriented above and parallel to the roof surface.
   b. Section 6.5.12.4.1 addresses wind loads on components and cladding. We recommend the use of Section 6.5.12.4.1 and supporting figures only for the design of the PV module attachment clips and hardware to the structure, and for calculating loads on individual PV modules.
   c. We do not recommend Section 6.5.15, 6.5.15.1, and Figure 6-21 for the design of PV systems.
   d. This report provides basic guidance for applying *ASCE Standard 7-05* to existing codes and standards for the typical residential application of PV arrays mounted parallel to the roof slope and relatively close (3 to 6 inches) to the roof surface.

2. Wind tunnel testing for the most common rooftop PV installations should be conducted to verify methods and calculations. The installation types include stand-off mounting parallel to the roof, stand-off mounting at an incline relative to the roof, and ballasted installations on flat roofs. Wind tunnel testing is an important and critical tool that is required to gain a true understanding of pressure equalization, dynamic loads on the modules, interactions with airflow around the building, and transmission of loads to the structure. As we discussed in this report, wind tunnel testing would likely demonstrate significantly lower wind loads for stand-off mounted PV systems parallel to the roof than those predicted by the ASCE standard. When we have a fundamental understanding of the wind forces for basic configurations, we can develop more sophisticated numeric models to evaluate other geometries. These models can simplify and add confidence to the design process. When we have a more complete understanding of the fluid mechanics involved, we can accurately determine the forces on the equipment and structural attachments. With more confidence in the actual wind forces on roof-mounted PV arrays, the codes and standards can be updated to provide accurate design guidelines.

3. We recommend that codes and standards be modified to specifically address the mounting of PV arrays to rooftops to eliminate potential barriers to market development in high wind regions. Recommended changes should be based on the wind tunnel testing in Recommendation 2.

4. We recommend that local jurisdictions and design professionals use the recommendations in this report to ensure continuity in interpreting existing codes and standards.

References

American Society of Civil Engineers (ASCE) (2006), *Minimum Design Loads for Buildings and Other Structures* (7-05).

Acronyms

AHJ	authority having jurisdiction
ASCE	American Society of Civil Engineers
IBC	International Building Code
MWFRS	main wind-force resisting system
PV	photovoltaics

Glossary

Components and cladding— element of the building that does not qualify as the MWFRS. (ASCE definition)

MWFRS—an assemblage of structural elements assigned to provide support and stability for the overall structure. The system generally receives wind loading from more than one surface. (ASCE definition)