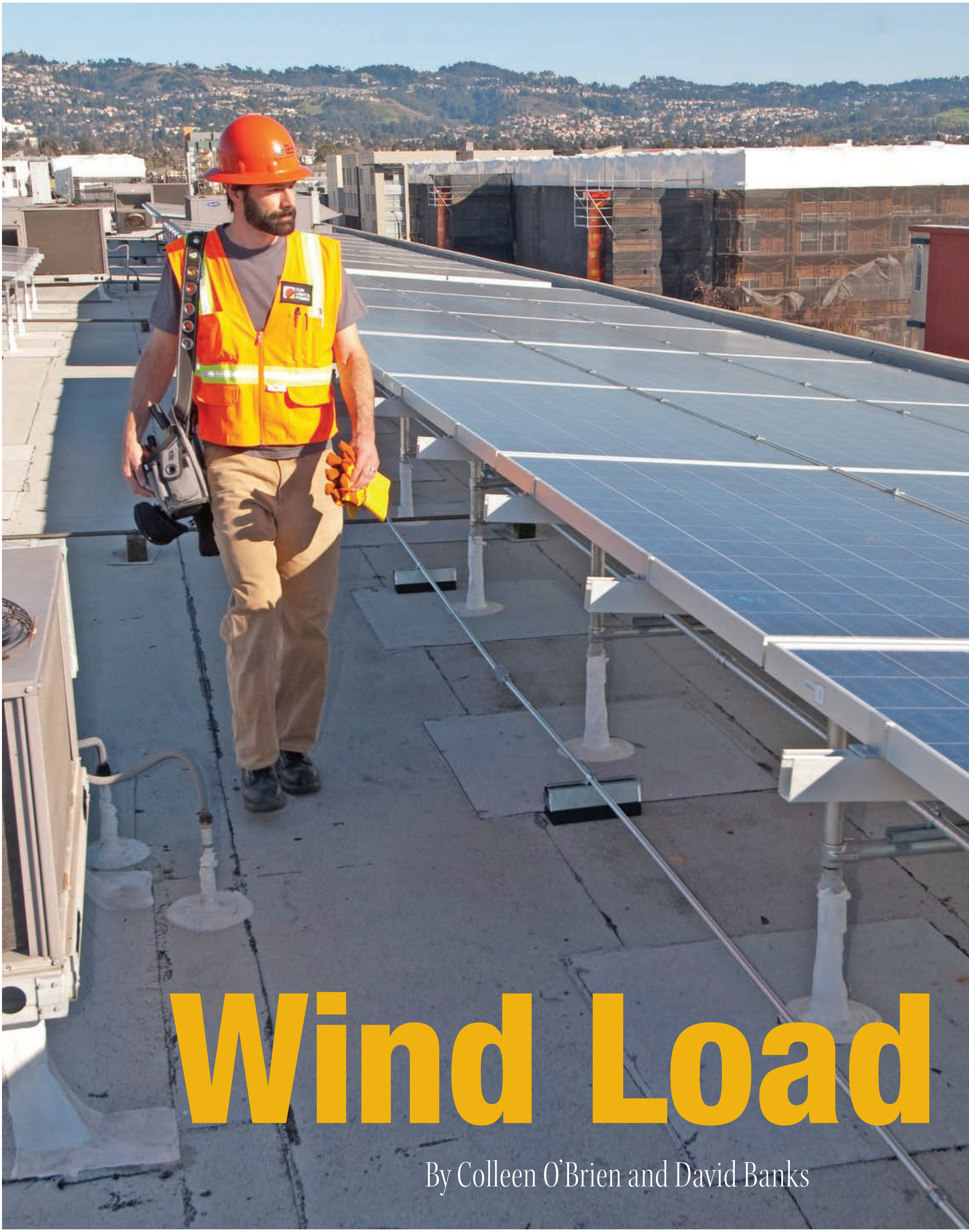

Shawn Schreiner

Wind Load

By Colleen O’Brien and David Banks

Analysis
for Commercial Roof-Mounted Arrays

PV modules mounted to racks or trackers should be designed to withstand wind forces as prescribed in the building codes, like any other important structure. However, there is a significant challenge in applying existing codes to commercial and industrial roof-mounted PV arrays.

Everyone is familiar with the potentially destructive forces that wind can exert on structures, whether from video footage or firsthand experience with structural damage from strong winds. The wind load on a structure depends on many factors, including the wind speed, the wind characteristics (turbulence and velocity profile), the geometry of the structure, the effect of surrounding objects and the height above the ground, to name just a few. A structural engineer must calculate wind forces or loads to ensure that a structure can resist wind conditions at a particular location.

The engineer should always determine wind loads on PV systems, even if local building departments do not require such an analysis. Wind-related failures of both roof- and ground-mounted systems have occurred—and more can be expected because wind loads are poorly understood. The spread of solar energy will depend on favorable public opinion, and a poor safety record is counterproductive. The long-term success of the solar industry depends on the deployment of systems that are structurally engineered to meet building codes. Unfortunately, this is not as easy as it sounds.

In this article, we discuss wind loads on sloped PV modules installed on standard open racks on a flat or low-slope roof. We also provide high-level guidance for other types of systems. We present some fundamentals of wind loading on rooftop PV systems, as well as challenges associated with applying existing building codes to this type of system. While building codes will eventually include improved guidelines for determining wind loads on PV systems, the process of developing these guidelines is likely to take years. Until then, structural engineers need strategies to reduce the guesswork in estimating wind loads, particularly for sloped PV modules on flat roofs, because building codes are least applicable to this type of system.

With support from its parent company, Det Norske Veritas (DNV), and its wind engineering partner, CPP, BEW Engineering has developed an analytical approach for determining wind loads on sloped PV systems mounted on flat and low-slope roofs. BEW analyzed the results of thousands of wind tunnel tests in the process of developing this method. While this approach is more complex than typical *ACSE 7* methods, the partnership developed a free online design tool for designers and engineers to simplify the process and expedite the analysis. Here we discuss how this tool works and how to apply the results.

The Building Code and PV

While all US building codes have sections on wind loading, it is widely accepted that the most comprehensive guide for estimating wind loads on structures is Standard No. 7 of the American Society of Civil Engineers (ASCE), *Minimum Design Loads for Building and Other Structures (ASCE 7).* All other building codes allow for the use of this ASCE standard. The latest edition of this standard is *ASCE 7-10,* the 2010 edition. However, *ASCE 7-10* has not been widely adopted, and the 2005 edition is still mainly in use. Therefore, we reference *ASCE 7-05* in this article. By the time *ASCE 7-10* is widely adopted, it is likely that a broader range of publicly available wind tunnel data will be available that will improve upon the methods described in this article. The wind loading content found in *ASCE 7* was primarily developed to calculate wind loads on buildings, though a small subset of other structures, such as billboards and chimneys, is included. As a result, building codes do not provide clear guidance on how to calculate wind loads on PV arrays, unless these are shaped like buildings—for instance, PV carports.

With proper guidance—see "Wind Load Analysis Recommendations by PV System Type" (p. 90)—designers and engineers applying *ASCE 7-05*

Courtesy BEW Engineering

Damage control Wind damage investigators determined that the system designer did not follow the racking manufacturer's instructions. These avoidable failures are potentially disastrous to an industry that is reliant on favorable public opinion.

methods can do a reasonable job of estimating wind loads on some flat-plate PV systems. For example, ground-mounted PV systems are very much like small open buildings—meaning buildings with no walls, such as carports—closely spaced together. In addition, wind load patterns on modules mounted parallel to and close to the roof—as is common in residential applications—may be estimated by calculating the loads expected on the exterior of the building cladding. In many but not all of these cases, building codes overestimate wind loads on these types of PV systems, and designers and engineers can use these conservative results with confidence.

Applying building codes to sloped PV systems on flat roofs presents significant challenges. While some data are provided in the *ASCE 7* standard related to "rooftop equipment," these were developed for equipment with a prismatic shape, such as chimneys and HVAC units, with no gaps between the equipment and the roof. These data are not applicable to roof-mounted PV. Designers are left with nothing to do but guess which tables and figures—for example, which building shapes—in the building codes best apply to PV systems. Many of the choices designers must make depend upon the type of building classification.

Building classification. *ASCE 7-05* has three different classifications of buildings depending on the porosity of the walls (Section 6.2): *open buildings, enclosed buildings* and *partially enclosed buildings*. Most buildings are considered either enclosed or partially enclosed buildings.

The walls of open buildings must be at least 80% open. Carports are an example. Partially enclosed buildings are those in which a wall has openings that are larger than the openings on other walls. In this situation, large positive pressures can develop inside the building. Enclosed buildings are buildings that are neither open nor partially enclosed.

PV system classification. Rooftop PV arrays are like very small open buildings on top of very large enclosed or partially enclosed buildings. This is unchartered territory for building codes. Should the engineer apply the loads for a flat roof to tilted panels on a flat roof? If so, that ignores panel tilt. Should the engineer use tilted roof numbers? If so, which ones: sawtooth or monosloped? Engineers must make a judgment call on whether to use the PV tilt or roof tilt, or perhaps some combination of the two. Should they calculate net design wind pressures using the components and cladding (C&C) method or the main wind force resisting system (MWFRS) method? *ASCE 7-05* provides no guidance on these issues.

Whatever method engineers eventually choose, the resulting wind loads will likely exceed the amount of ballast that most roofs can support. Further, ballasted systems are typically engineered with custom aerodynamic features that the generic application of building codes

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cannot address. Therefore, manufacturers of ballasted systems must often rely on wind tunnel testing to verify that their systems have adequate wind resistance, particularly when they have implemented unique design features to lower the wind loads.

Wind tunnel testing. The requirements for proper wind tunnel testing are spelled out explicitly in Method 3 of *ASCE 7-05*. Additional guidelines are found in the article by Gregory Kopp and others, "Rooftop Solar Arrays and Wind Loading: A Primer on Using Wind Tunnel Testing as a Basis for Code Compliant Design per ASCE 7." (See Resources.) Unfortunately, it is all too common for wind tunnel testing to fail to comply with these guidelines.

For example, to perform a wind tunnel test correctly for a roof-mounted PV system, a model of the building must be included. The dimensions of the model building and the parapet height need to be to scale. The slope, row spacing and height above the roof of the model PV array also must be to scale. If a friction coefficient is modeled, it should match that expected on the actual roof.

Further, to model the boundary layer, most tests must be done at a small scale (1:30 to 1:50). Unless testing was done at the new Insurance Institute for Business & Home Safety wind tunnel (see Resources), it is unlikely that tests done at larger scale or at full scale properly model wind flow. Designers may wish to hire an independent expert to review wind tunnel reports from manufacturers. The independent expert should comment on the compliance with *ASCE 7-05* requirements and the similarity between the models and the full-scale systems.

When done correctly, however, using wind tunnel tests to determine wind forces removes the guesswork involved with applying building codes to PV systems. The wind tunnel data that we have analyzed suggest that some types of PV array structures are overdesigned, while others may be significantly underdesigned relative to expected wind loads—especially corners and edges of sloped PV arrays on flat roofs.

Wind loads on PV systems. Wind flowing over PV systems applies forces to PV modules, fasteners, the racking system and the roof, if an array is roof mounted. All wind forces on a roof- or ground-mounted array must ultimately be transmitted through the structure to the ground. All of the structural components in a PV system have limits on how much wind force they can withstand, so it is critical that wind loads on PV arrays be determined for every PV system; further, all structural components in the system should be verified to resist expected wind loads—not to mention the loads on the PV module itself or the loads that the entire system transmits to the roof or ground.

Note that "every PV system" means any size residential, commercial, or utility-scale system; ballasted or structurally attached; and rack mounted, flat roof mounted, sloped roof mounted or ground mounted. Similarly, "all structural components" includes all fasteners; welds; steel; aluminum, wood, concrete, plastic and other structural members; and motors, gears and drive mechanisms for tracking systems.

Shawn Schreiner

Rigidity and resonance The small size of most roof-mounted PV structures relative to the building results in *vortex shedding*—swirling gusts of wind flowing off the structure—with significant energy in the 2–3 Hz range. To avoid dynamic resonance, the PV structure should have a higher natural frequency than these vortices. If a structural engineer determines that the natural frequency of the PV racking system is less than 4 Hz, a dynamic analysis for flexible structures should be done based on *ASCE 7-05.*

Wind Load Fundamentals

The force and pressure of the wind are proportional to the velocity of the wind squared. The basic equation that converts wind velocity into pressure is shown in Equation 1:

$$\text{Wind pressure} = \tfrac{1}{2}\rho \times V^2 \times C \qquad (1)$$

where ρ is the density of air, V is the wind velocity, and C is a dimensionless coefficient that is typically measured for a specific object.

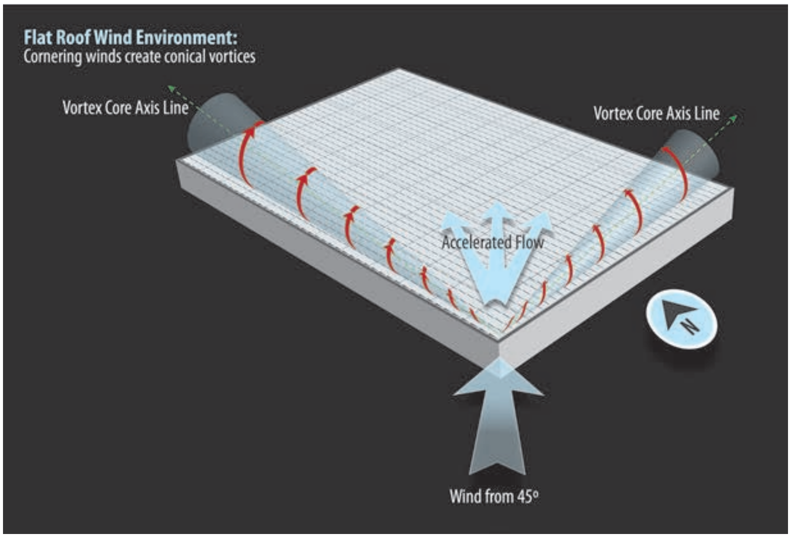
The equations found in *ASCE 7-05* are based on Equation 1 (a fundamental equation from fluid dynamics), where the coefficient C is referred to as the *pressure*

CONTINUED ON PAGE 78

coefficient. The most challenging part to estimating wind loads on any structure is finding out which of the many pressure coefficients in *ASCE 7-05* should be used. The pressure coefficient depends on many factors, including the shape of the structure and the tributary area of the structural component being analyzed.

Your firsthand experience with the force of the wind provides some understanding of what makes an object more or less aerodynamic. The evolution of the geometrical shape of cars, the curve of airplane wings, and the tuck of bicyclists and skiers has largely focused on improving aerodynamics so that these objects can move through the air with less resistance. This improvement is measured as a reduction in the pressure coefficient.

Since force is equal to pressure times the area over which the pressure is applied, wind force is determined by multiplying the wind pressure by a representative area. This area is referred to by structural engineers as a *tributary area* and by ASCE as the *effective wind area;* see the definition in Section 6.2 of *ASCE 7-05.*



Courtesy CPP

Figure 1 The conical vortices and accelerated flow region associated with oblique or cornering winds are shown here. The accelerated wind speeds between the vortices may result in actual wind pressures in excess of those calculated using typical *ASCE 7* methods.

The tributary area or effective wind area is generally understood as the area that a component structurally supports. For example, if there are four fasteners securing a 4-foot-by-8-foot sheet of plywood to a roof deck, each fastener has a tributary area equal to the total area of the plywood divided by the number of fasteners, or 8 square feet. The effective wind area can also be thought of as the area over which loads are transmitted and effectively resisted by the structural system. For PV systems, one way to think of the effective wind area is this: Suppose the PV array was placed on a surface without physically restraining the system from uplift. If one were to lift one PV module in the array, how much of the system would lift along with it without permanently damaging any of the components?

More than one effective wind area applies to most PV systems, depending upon the component under analysis. When analyzing the racking structure, the effective wind area may be relatively large—perhaps the area of 5 to 30 modules if the rack is rigid enough to support the applied loads from this many modules. However, the fasteners that secure the module to the rack have a smaller effective wind area. If one PV module is secured with four fasteners, each fastener has an effective wind area of one-quarter of the module area. The PV module itself has an effective wind area equal to the module area.

Components with smaller effective wind areas have higher wind pressures. This is because wind pressure distributions on structures vary rapidly with time and location on the structure. One PV module may be subjected to a high wind pressure while a module 4 feet away may have a much lower wind pressure. A rigid rack supporting both modules may be able to spread the load across the structural components. However, load sharing across individual PV modules is limited, and the fasteners that secure modules to the structure cannot spread loads. Similarly, a PV mounting system that is insufficiently rigid will not spread loads over a large area. It is very important to analyze wind loads on individual PV modules using the effective wind area for one PV module to ensure that wind loads do not exceed the module's rating. There are applications where wind loads in excess of module ratings are a very real possibility.

As shown in Equation 1 (p. 76), wind force and pressure on any object is proportional to the wind velocity squared. Therefore, a wind speed of 60 mph creates wind forces four times larger than a 30-mph wind. This is important to remember when considering claims that a product can withstand a 90- or 120-mph wind speed simply because it survived a 70- or 80-mph wind event.

In addition, it should be noted that the *basic wind speed* provided in the *ASCE 7-05* standard for any location in the US represents the *free-stream velocity,* which corresponds with unobstructed flow over open Exposure C terrain (as defined in *ASCE 7-05*) at 10 meters above the ground with an averaging period of 3 seconds. Further, the basic wind speed values in *ASCE 7-05* represent the expected wind speed with a 50-year recurrence interval.

When you compare *ASCE 7-05* wind speeds to measurements made in the field, be sure that you are comparing apples to apples. Wind sensors placed within an array at module height do not provide free-stream velocity measurements. In fact, a wind speed measurement taken anywhere in the vicinity of the PV modules could be significantly higher or lower than the free-stream velocity. Wind speeds averaged over any period other than 3 seconds are not *3-second gust* wind speeds, as defined in the standard. Wind speed measurements taken at different heights and over different averaging periods can be modified using equations in *ASCE 7-05* to determine the equivalent 10-meter, 3-second wind speed. However, to do this modification, the surrounding objects must not affect the measurement, and unfortunately this is almost never the case with wind sensors in PV arrays.

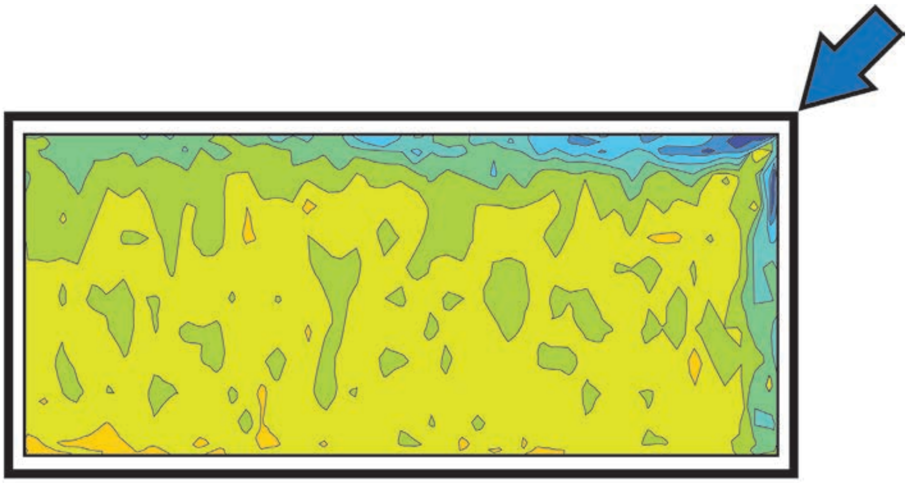
Wind Loads on Roofs and Rooftop PV

When wind flows around an object, the wind flow becomes disturbed and its qualities are changed. When wind flows over a building, this change is dramatic, and the effects of this disturbed wind flow are very different than for wind flow across the ground.

Consider a large retail building with a flat roof, classified as a *low-rise building*. A low-rise building refers to a structure of modest height and substantial girth: consumer retail stores, wholesale clubs, warehouses and distribution centers are common examples. Large flat or nearly flat (low-slope) roofs are characteristic of low-rise buildings. Decades of wind tunnel testing and field measurements have shown that worst-case wind loads on the roof occur when wind hits the corner of these types of structures. These so-called *cornering winds* also result in worst-case wind loads on roof-mounted PV modules.

Conical vortices. When wind hits a building, the flow separates at the roof edges. However, the two zones of flow separation interact as they both reattach, and the result is the generation of conical vortices above the roof. These vortices can be thought of as horizontal tornadoes that originate at the corner of the roof and radiate at angles of 10° to 20° along the leading edges of the building. The position and strength of these vortices are a function of the wind direction, and strong vortices are present for wind approach angles of 25°–65° (45° ±20°).

Figure 1 shows the vortices that form along the edges of a roof without PV modules when wind hits the corner of the building. In between the vortices near the windward corner, there is a region of accelerated flow where wind speeds along the roof surface are 20% higher than those approaching the



Courtesy CPP(3)

Figure 2 This figure shows the wind pressures measured in a wind tunnel on the roof of an enclosed low-rise building without PV modules. The arrow indicates wind direction. Color contours illustrate the effects of conical corner vortices: Dark blue indicates areas with strong suction force; orange indicates areas with negligible suction force.

building at roof height. The presence of accelerated airflow as a result of cornering winds is one reason why *ASCE 7-05* and other building codes can underpredict wind loads on PV arrays.

Wind tunnel testing has shown that the vortices along the edges of the roof during cornering winds are responsible for the highest peak pressures on the building envelope, which occur directly beneath the vortices as shown in Figure 2. While the accelerated flow associated with conical vortices does not have a big impact on the loading of the roof itself—which is what *ASCE 7-05* and other codes were designed to take into account—it does have an impact on objects that protrude above the roof.

Conical vortices are responsible for the greatest wind pressures that occur across roof-mounted PV modules. However, the manner in which vortices load rooftop PV modules fundamentally differs from how they load the roof cladding elements that codes are based on. This is illustrated in Figures 3a and 3b, which provide typical patterns measured in the wind tunnel of net pressure coefficients (GC_p values) for an array of moderately tilted (10°–15°) modules on a roof that measures 6h × 6h, where *h* is the mean building height. (Note that in many figures in *ASCE 7-05,* the pressure coefficient is given the variable name GC_p instead of C.)

It is clear from Figure 3a that on one hand the vortex that forms along the north edge of the building during northeast cornering winds is “quiet,” having little discernible effect on the modules. (Note that the term *north* and all other directions in this article are defined based solely on the array orientation, which is assumed to face to the south.) The east edge vortex at the northeast corner, on the other hand, produces significant wind loads that peak at an angle of nearly 30° from the roof edge. This indicates that it is the interaction between the swirling and reattaching wind flows and the accelerated between-vortex flows that creates peak pressures for the modules, rather than

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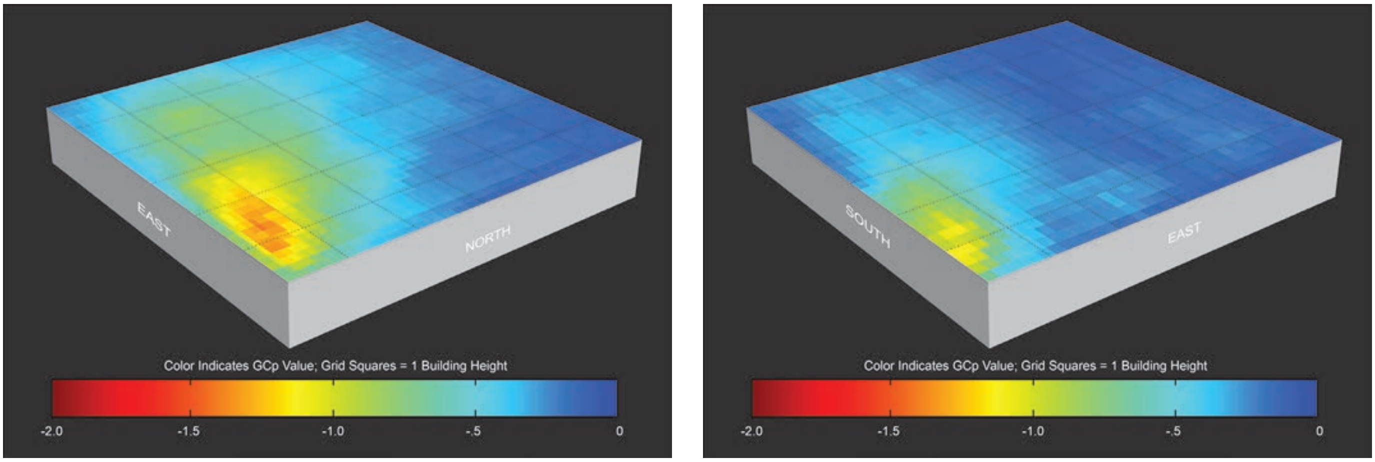
Figures 3a and 3b In these wind tunnel tests, wind pressures were measured on a PV array aligned with the edges of a low-rise building and covering most of the roof. The color red indicates areas subjected to significant uplift forces; the color blue indicates areas with negligible uplift forces. Figure 3a (left) illustrates the typical worst-case wind pressure—resulting from northeast cornering winds—on moderately tilted PV modules on a flat roof. While lower overall wind pressures result from southeast cornering winds, as shown in Figure 3b (right), the areas in yellow represent the worst-case wind loading on the mechanical components located near this corner of the roof. The structural design needs to account for the worst-case wind loads from winds in any direction.



transfer of the high pressure at the center of the vortex to the surface, as is the case for the roof itself.

Conversely, Figure 3b shows that the east edge vortex of the southeast corner vortex pair is quiet, creating little lift on the modules, while the south edge vortex creates substantial lift. In this case, the location of the lift is closer to the edge of the roof and more nearly beneath the vortex core axis.

If the modules shown in Figure 3 were rotated to face to the west, then patterns in each corner would be reversed. Any noticeable rotation of the modules relative to the building edges increases the lift associated with the two quiet vortices, and may worsen overall loads as well. More data is needed to evaluate wind loads when arrays are not aligned along the same axes as the building edges.

Impact of array layout. It is important to note that the pressure coefficients in Figures 3a and 3b are for an array that completely covers the roof, with no gaps other than typical spacing in the north-south direction between rows of sloped PV modules. In most cases, there are gaps between mechanical sections of a PV array. PV modules located along the edges of mechanical subarrays can experience increased wind pressure. (Note that while the *NEC* defines the term *subarray* as "an electrical subset of a PV array," in this article we apply the term to mechanical sections of an array that are separated from other array sections by distances larger than the standard row spacing in the north-south direction or more than a foot in the east-west direction.)

Wind loads on PV arrays are sensitive to the physical array layout. This is one of the most critical differences between results obtained by applying the *ASCE 7-05* standard to sloped PV arrays on flat roofs and actual wind loads. Figure 4 demonstrates this point. The colored blocks in the figure represent six subarrays, shown in blue with some yellow and red regions, installed on a roof surface, shown in white. The color gradients found in the subarrays represent pressure coefficients measured in a wind tunnel, with blue representing relatively low-pressure coefficients and red higher-pressure coefficients. This figure shows how the edges of mechanical subarrays experience much higher wind loads than the interior sections.

The *ASCE 7-05* standard, which only considers corner and edge zones for the roof and not for individual subarrays, would not address these higher wind loads. The red lines in Figure 4 show the corner and edge zones as defined by *ASCE 7-05.* It is clear from this figure that peak pressures on the subarrays can occur in what *ASCE 7-05* considers to be interior roof zones.

Any building code requires us to design a structure to withstand wind loads from all directions. So even though Figure 4 shows that the north rows have the highest coefficients from a northeast cornering wind, other wind directions can cause relatively high-pressure coefficients in the south, east or west edges of mechanical subarrays.

Effects not captured by ASCE methods. Capturing the effects of subarray spacing, parapets and rooftop objects in an analytical process inherently forces the process to become more complicated than the typical application of *ASCE 7-05.* It is clear from available wind tunnel data that peak wind loads occur at locations that are more than one building height, *h,* from the roof edges. The edge and corner roof zones prescribed

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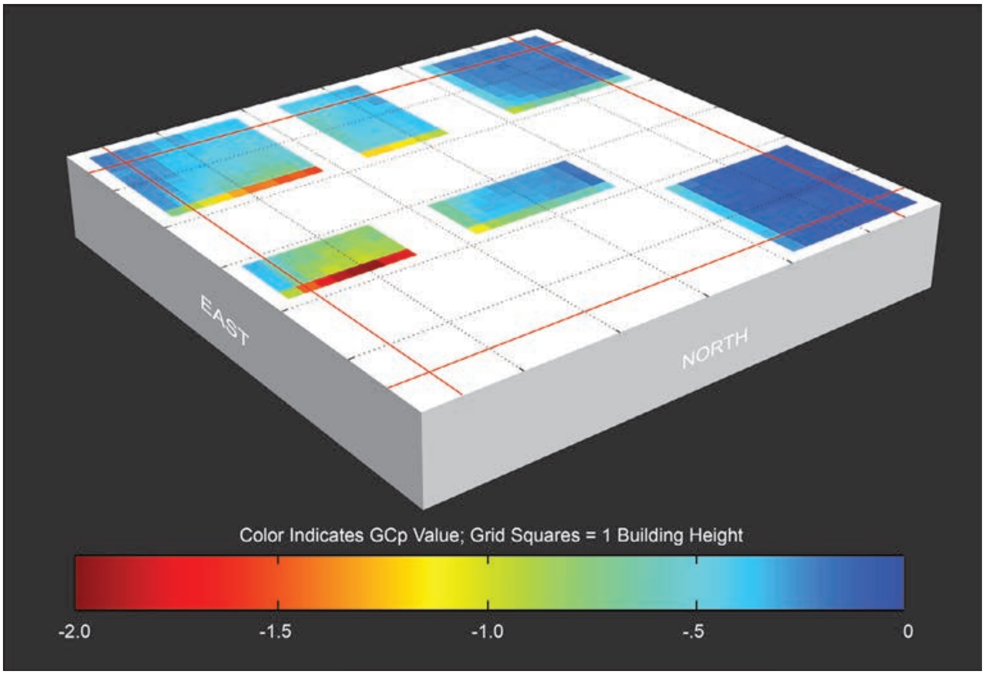
Figure 4 Most PV arrays do not cover an entire roof but are broken into mechanical subarrays, like the colored blocks in this figure. Wind tunnel test results reveal that these subarrays are subjected to higher pressures than a simple analysis based on *ASCE 7-05* roof zones would indicate. The red lines in this figure identify the corner, edge and interior roof zones according to *ACSE 7-05.* The areas in red identify subarray sections located within the interior roof zone that are subjected to significant uplift forces as a result of northeast cornering winds.



Courtesy CPP

> "Based on our testing and research, [treating arrays] as components and cladding on a monosloped roof provides a safe and generally conservative estimation of the actual loads on an array, particularly when one considers the loads over larger areas. However, when smaller tributary areas are considered, the code values appear to be less conservative and may, in certain cases, be unconservative."
>
> —Gregory Kopp, Joe Maffei and Christopher Tilley, "Rooftop Solar Arrays and Wind Loading"

in *ASCE 7-05* typically extend only 0.4h from the roof edges, while wind tunnel data suggests that the corner and roof zones should extend 2h from the roof edges.

The effects of parapet walls on PV arrays are not characterized in *ASCE 7-05* wind loads. While parapets reduce the peak wind loads at extreme corners and edges of the roof, they increase wind loads in interior areas. Modules that are very close to the parapet wall do receive some shielding benefit, provided that the parapet is close to or taller than the maximum height of the PV array.

Objects on the roof that are taller than the PV array, such as penthouses and HVAC units, can also provide some shielding benefit; however, in certain wind directions, the objects can generate vortices that increase wind loads in the vicinity of the object. This possibility is not captured in the *ASCE 7-05* standard.

The alternative to complexity is to simplify the process by making conservative assumptions. However, making overconservative assumptions tends to drive up structural costs—perhaps making a viable project uneconomical—and may rule out other viable sites due to structural loading limitations.

Recommended Practice for Estimating Wind Loads

Capturing the effects of subarray spacing, parapets and rooftop objects in a recommended analytical process inherently forces the process to become more complicated than the typical application of *ASCE 7-05.* The other alternative is to simplify the process by making conservative assumptions. To avoid being overconservative,

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the approach that we present takes all of the above impacts into account. The bad news is that the approach is more complicated than applying *ASCE 7-05*. However, there are two pieces of good news: One, the results will be more reflective of actual wind loads on the array; two, a free online design tool called the *DNV Wind Load Calculator for Sloped PV Arrays on Flat Roofs* (www.dnv.com/industry/energy/segments/solar_energy/index.asp) will perform the complicated steps for you.

The DNV Wind Load Calculator uses an alternative method of calculating wind loads that was developed by determining which parts of *ASCE 7-05* match available wind tunnel data. Thousands of wind tunnel tests have been conducted on roof-mounted PV systems. While much of the data is confidential, the results provide insights into how to best apply existing data in *ASCE 7-05* to the problem of estimating wind loads on sloped PV modules on flat roofs. The DNV Wind Load Calculator's method is completely ad hoc; there is little justification for it on the basis of physics or the intent of the code. It just fits the data.

How it works. Recall that Equation 1 defined wind pressure as ½ρ x V^2 x C. This fundamental equation from fluid dynamics is the basis of the method for calculating wind pressures on roofs described in *ASCE 7-05*. DNV's method relies on this equation as applied by *ASCE 7-05* as well, but provides values for the pressure coefficient, *C*, that are not part of the *ASCE 7-05* standard.

Sections 6.5.3 through 6.5.10 of *ASCE 7-05* provide detailed guidelines on estimating what is essentially the first part of this equation (½ρ x V^2), which ASCE calls the *velocity pressure*. As detailed in the standard, the *ASCE 7-05* value for velocity pressure includes some additional terms beyond air density (ρ) and wind speed (V). *ASCE 7-05* also provides values for pressure coefficients, *C*, which are a function of the building size and shape, as well as the effective wind area or tributary area of the structural component under investigation.

While the *ASCE 7-05* pressure coefficients are commonly applied to sloped PV arrays on flat roofs, wind tunnel data has shown that these coefficients are not generally applicable to this configuration. The DNV Wind Load Calculator provides alternate values for the pressure coefficient on PV arrays that take into account the PV tilt, row spacing, height above the roof and sheltering from wind due to nearby objects such as nearby subarrays or parapet walls.

For example, a parapet wall shelters nearby modules, but can increase pressures in the middle

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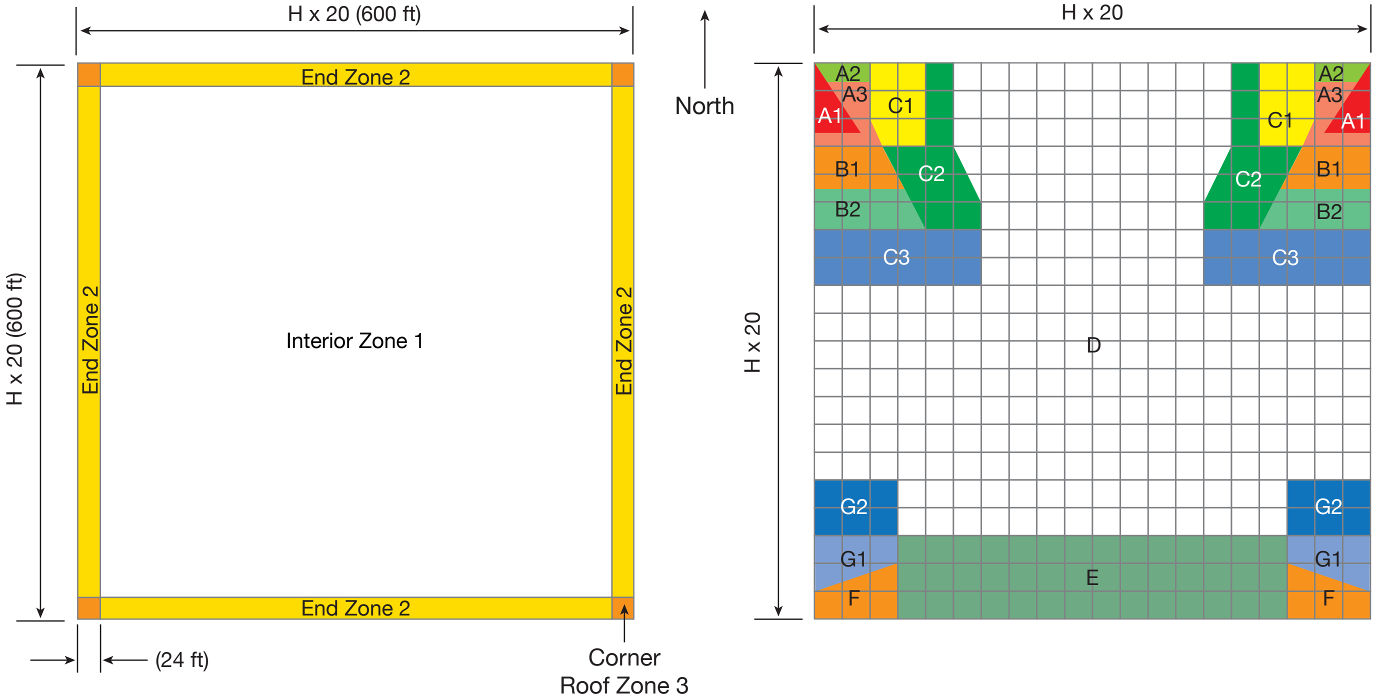
Simplified procedure vs. wind tunnel Applying the simplified procedure of determining design wind pressures, as described in *ASCE 7-05,* to a square building that is 600 feet wide and 30 feet tall grossly oversimplifies the wind zone map on the left and the expected design wind forces. By comparison, 13 distinct wind zones are identified in the map on the right, based on wind tunnel tests performed by Renusol America for its CS60 ballasted mounting system. The roof areas in red, orange and yellow indicate where significant wind forces are expected; the roof areas in white indicate where the least wind forces are expected.



Courtesy Renusol America

of the roof. The calculator incorporates the potential increase in wind pressure in interior regions of the roof when a parapet wall is present, as well as the accelerated flow around rooftop objects such as HVAC units. The velocity pressure determined in the calculator is exactly as prescribed by *ASCE 7-05,* but the coefficients are based on actual wind tunnel data.

USING THE DNV CALCULATOR

The DNV Wind Load Calculator is posted on DNV's website (see Resources) along with a user manual. The first step is to enter a series of inputs that are defined in *ASCE 7-05:* mean roof height, basic wind speed, directionality factor, importance factor, topographic factor, velocity pressure exposure coefficient and effective wind area. These inputs, which structural engineers are used to working with, are used to determine the velocity pressure according to *ASCE 7-05* .

A second set of inputs to the DNV Wind Load Calculator defines the PV array geometry. These parameters include effective wind area or tributary area, PV tilt, row spacing, height above the roof and the location of the array section being considered. Several factors are used to describe the array location, including the location within a subarray (north row, south row, eastern or western perimeter or interior), the roof location (corner, edge or middle) and the distances to nearby objects. The calculator also asks for the parapet height(s) on the building and the dimensions of rooftop objects that are taller than the array.

For each mechanical subarray section—for example, a north row in the corner of the roof—the calculator provides a wind pressure in pounds per square foot (psf). This result is the estimated pressure that should be applied analytically in the upward and downward direction perpendicular to the PV module. The calculator also provides recommended offset distances from rooftop objects, such as HVAC units, which can create regions of accelerated flow around them.

Comparison to results from *ASCE 7-05.* Comparing DNV Wind Load Calculator results to those determined using *ASCE 7-05* is complicated because there is no one correct way to apply the standard to sloped PV modules on a flat roof. However, we have compared DNV Wind Load Calculator results to those achieved using several interpretations of the *ASCE 7-05* standard commonly used by structural engineers. These comparisons indicate that the DNV Wind Load Calculator predicts wind loads higher than *ASCE 7-05* methods in some cases and lower in others.

In general, interior PV array sections that are close to the roof, tightly spaced and that can spread loads to adjacent areas—sections with a relatively large effective wind area, in other words—will have lower wind loads than predicted by *ASCE 7-05.* Exposed array sections, particularly the north row in the corner and edge zones of the roof, may have higher wind loads.

If wind loads are found to be higher than expected or desired, the designer may iterate through many of the inputs to identify design characteristics that reduce wind loads. For example, placing the array closer to the roof, reducing row spacing or PV tilt, or increasing the effective wind area all reduce wind loads. If wind loads are still too high, a pre-engineered aerodynamic product that has undergone wind tunnel testing in accordance with

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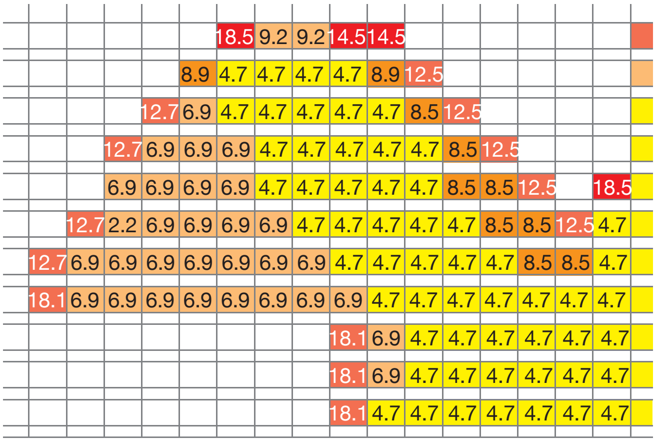
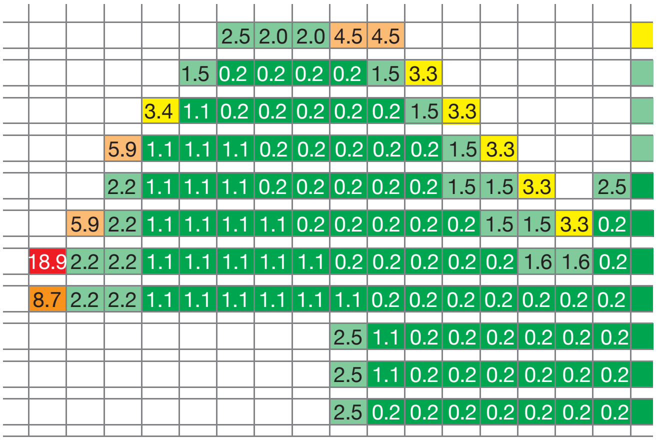
Ballast study Linking components together increases the effective wind area and reduces wind loads, as illustrated in the ballast study details below provided by Renusol America. The study on the left shows the pounds of ballast required per Renusol CS60 base in the northwest corner of a large PV array that does not use strut connections in the north-south direction. The study on the right shows the pounds of ballast required per base if strut connections are used in the north-south direction.



					18.5	9.2	9.2	14.5	14.5						
				8.9	4.7	4.7	4.7	4.7	8.9	12.5					
			12.7	6.9	4.7	4.7	4.7	4.7	4.7	8.5	12.5				
		12.7	6.9	6.9	6.9	4.7	4.7	4.7	4.7	4.7	8.5	12.5			
		6.9	6.9	6.9	6.9	4.7	4.7	4.7	4.7	4.7	8.5	8.5	12.5		18.5
	12.7	2.2	6.9	6.9	6.9	6.9	4.7	4.7	4.7	4.7	4.7	8.5	8.5	12.5	4.7
12.7	6.9	6.9	6.9	6.9	6.9	6.9	6.9	4.7	4.7	4.7	4.7	4.7	8.5	8.5	4.7
18.1	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	4.7	4.7	4.7	4.7	4.7	4.7	4.7
								18.1	6.9	4.7	4.7	4.7	4.7	4.7	4.7
								18.1	6.9	4.7	4.7	4.7	4.7	4.7	4.7
								18.1	4.7	4.7	4.7	4.7	4.7	4.7	4.7

Ballast study before N–S strut connections



					2.5	2.0	2.0	4.5	4.5						
				1.5	0.2	0.2	0.2	0.2	1.5	3.3					
			3.4	1.1	0.2	0.2	0.2	0.2	0.2	1.5	3.3				
		5.9	1.1	1.1	1.1	0.2	0.2	0.2	0.2	0.2	1.5	3.3			
		2.2	1.1	1.1	1.1	0.2	0.2	0.2	0.2	0.2	1.5	1.5	3.3		2.5
	5.9	2.2	1.1	1.1	1.1	1.1	0.2	0.2	0.2	0.2	0.2	1.5	1.5	3.3	0.2
18.9	2.2	2.2	1.1	1.1	1.1	1.1	1.1	0.2	0.2	0.2	0.2	0.2	1.6	1.6	0.2
8.7	2.2	2.2	1.1	1.1	1.1	1.1	1.1	1.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
								2.5	1.1	0.2	0.2	0.2	0.2	0.2	0.2
								2.5	1.1	0.2	0.2	0.2	0.2	0.2	0.2
								2.5	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Ballast study after N–S strut connections

Courtesy Renusol America

ASCE 7-05, such as a ballasted system with wind deflecting shields, may be a viable option.

How are the results applied? The DNV Wind Load Calculator yields a wind pressure for any array location on the roof. As with *ASCE 7-05,* it is up to the designer and structural engineer to ensure that representative sections of the array are evaluated to determine worst-case conditions, considering both uplift and downward forces. Whereas *ASCE 7-05* typically results in different values for uplift and downward pressure, the DNV Wind Load Calculator provides one result that should be applied in both directions in two separate analyses.

It is important that designers and engineers determine loads on modules, fasteners, all components within the racking system and the applied loads to the roof. Loads must ultimately be transferred from the modules to the fasteners and racking system, and ultimately through the roof deck and building structure to the ground. This is common knowledge for most structural engineers. Remember that this likely involves the use of different effective wind areas based on the load-sharing capability of the component under analysis. The wind load rating of the module should not be exceeded.

Once wind loads are determined, structural engineers must apply appropriate safety factors and combine loads as required in *ASCE 7-05* Section 2. In addition to wind loads, other loads such as snow, seismic and gravity (dead load) must be taken into account. Structural engineers must consider each of these loads separately and in combination to identify the worst-case loading situation.

The use of these results assumes that the structure is sufficiently rigid so that it is not considered CONTINUED ON PAGE 92

Wind Load Analysis Recommendations by PV System Type

For PV system types not covered in this article, we provide the following general wind loading analysis guidelines as a starting place for system designers and engineers.

Ground-mounted systems:

- Following the definitions found in *ASCE 7-05,* treat the rows of PV modules as *open buildings* with *monosloped roofs* and use the slope of the PV modules as the roof slope to apply the standard.
- Do not use *ASCE 7-05* tables for billboards and signs.
- For trackers, check all possible tilts and forces on the drive system (gears, struts, motors and so forth).
- Results will be conservative for interior rows, but conducting wind tunnel tests in compliance with *ASCE 7-05* guidelines can reduce this conservatism.

Sloped-roof systems:

- When PV modules are incorporated directly into the roof surface, they can be analyzed using *ASCE 7-05* in the same way that a roof would be analyzed.
- If PV modules are parallel to the roof surface and offset no more than 6 inches, a method developed by the Solar ABCs and described in the report “Wind Load Calculations for PV Arrays” may be applied (see Resources).
- Any application of *ASCE 7-05* will likely be conservative for arrays that have gaps on the order of 1 inch or more between modules.
- For PV modules sloped relative to a sloped roof, there is no known publicly available data; wind tunnel testing in compliance with *ASCE 7-05* guidelines is recommended, or consider placing the modules flush to the roof.

Ballasted roof-mounted systems:

- *ASCE 7-05* and the DNV Wind Load Calculator will likely result in wind loads that cannot feasibly be resisted by ballast alone since most roofs cannot support more than an additional 5–10 pounds per square foot, which means that ballasted systems must incorporate aerodynamic features such as wind-deflecting shields and must be tested in a wind tunnel, as no other method exists for estimating wind loads.
- ASCE does not allow the use of computational fluid dynamics (CFD) in lieu of wind tunnel testing; any CFD results must be validated against wind tunnel measurements.

Designers specifying ballasted systems should ensure that:

- Wind tunnel testing was done in accordance with *ASCE 7-05* guidelines.
- Worst-case conditions—such as wet and icy—are used to determine the friction coefficient for specific roofs, since the system relies on friction between the roof and the array.
- The system will not cause a safety hazard as a result of an earthquake.
- The roof membrane is not subject to fluttering that could damage the roof or ballasted system.
- Ballasted systems installed on ballasted membrane roofs comply with established roofing industry guidelines, such as ANSI/SPRI RP-4, “Wind Design Standard for Ballasted Single-ply Roofing Systems.” ●

a flexible structure. It is recommended that PV mounting systems have a natural frequency above 4 Hz to be considered rigid enough to prevent resonance. This is higher than the 1 Hz limit prescribed in the *ASCE 7-05* standard, because the 1 Hz limit is intended for large structures not likely to shed vortices that can create an excitation (resonance) in smaller structures. Wind tunnel testing has shown that PV systems shed vortices with frequencies in the 2–3 Hz range, so structures should be designed with natural frequencies in the 4–5 Hz range.

Limitations of use. The DNV Wind Load Calculator can be applied to your project only if it meets the following conditions:

- Flat or low-slope roof (less than 7°)
- Low-rise building (less than 60 feet high and wider and longer than it is tall)
- Modules are tilted between 1° and 35° from roof surface
- Modules are flat plate
- Modules are solid (not porous)
- Modules are mounted close to roof surface (gap under lowest part is less than 18 inches)
- Top of module sits less than 4 feet above roof surface
- Modules are placed more than 5 feet from roof edge with no parapet or with parapet shorter than top of modules
- No wind deflector on perimeter of array
- Modules are aligned with building edges
- No significantly taller structures are located near roof in question
- Structure is significantly rigid (natural frequency greater than approximately 4 Hz)

Apply the results of the DNV Wind Load Calculator with caution. Due to limitations in available data and the broad range of possible sloped PV geometries, the tool cannot possibly cover all types of sloped PV systems on flat and low-slope roofs. Rather, it covers standard rack-mounted PV systems that do not have aerodynamic enhancements such as wind-deflecting shields on the edges of modules.

Ballasted systems rely on a wide variety of aerodynamic features to withstand wind loads. These features are product specific and in many cases are protected by patents. The wind tunnel data that does exist for these products belong to individual manufacturers, so it is not possible to present generic results for ballasted systems. (Recommended guidelines for using ballasted systems are included in "Wind Load Analysis Recommendations by PV System Type," p. 90.)

Local building departments may not accept the results from the DNV Wind Load Calculator. For example, the local AHJ may require the use of the analytical methods described in *ASCE 7-05* if these result in higher loads. If so, we recommend that designers and engineers use the more conservative results unless wind tunnel testing done in accordance with *ASCE 7-05* demonstrates lower loads.

Winding Up

There is no ideally suited method for calculating wind loads on roof-mounted solar modules in *ASCE 7-05.* Many methods have been suggested by subject matter experts and analyzed by industry stakeholders. However, every one of these introduces significant shortcomings when comparing the results to the real pressure patterns that have been measured in the wind tunnel.

Several efforts are currently under way that may provide new insights into the problem of estimating wind loads on PV arrays. For example, the Structural Engineers Association of California is expected to publish relevant recommendations soon. The Solar America Board for Codes and Standards has published suggested practices for estimating wind loads on flush-mounted, sloped-roof applications, and has set priorities for follow-up studies and reports.

It is likely that in the next 3–8 years, new tables or figures will be introduced to *ASCE 7* that directly address roof-mounted solar modules tilted up off the roof. Until then, the DNV Wind Load Calculator allows for the estimation of wind uplift forces on commercial and industrial rooftop PV arrays using values currently in *ASCE 7-05.*

» CONTACT

Colleen O'Brien / BEW Engineering (a subsidiary of Det Norske Veritas) / San Ramon, CA / colleen.obrien@dnv.com / dnv.com

David Banks / CPP / Fort Collins, CO / dbanks@cppwind.com / cppwind.com

Resources

American Society of Civil Engineers / asce.org
DNV Wind Load Calculator / www.dnv.com/industry/energy/segments/solar_energy/index.asp
Insurance Institute for Business & Home Safety / disastersafety.org
Solar America Board for Codes and Standards / solarabcs.org
Structural Engineers Association of California / seaoc.org

Publications

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

Kopp, Gregory, Maffei, Joe, and Tilley, Christopher, "Rooftop Solar Arrays and Wind Loading: A Primer on Using Wind Tunnel Testing as a Basis for Code Compliant Design per ASCE 7," SunLink, sunlink.com, 2011

Barkaszi, Stephen, and O'Brien, Colleen, "Wind Load Calculations for PV Arrays," Solar America Board for Codes and Standards, solarabcs.org, 2010