Wind Loads on Rooftop Photovoltaic Panel Systems Installed Parallel to Roof Planes

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Abstract

The Solar Photovoltaic (PV) industry is experiencing rapid growth in the United States. In 2012, SEAOC published PV2-2012, a white paper titled *Wind Design for Low-Profile Solar Photovoltaic Arrays on Flat Roofs.* This white paper was well-received by the solar industry and enforcement agencies, and has gained prominence as the industry standard guidance for rooftop wind loads. Through the development process of ASCE 7-16, the SEAOC method has been incorporated – with modifications – into this referenced standard.

Another method was developed for ASCE 7-16 to calculate wind pressures for photovoltaic panel systems mounted parallel to pitched roofs, often referred to by the industry term “flush mounts.” This new section of ASCE 7 is based on rooftop components and cladding loads, with modifiers to account for array edge effects and pressure equalization between the upper and lower surfaces of the solar array. Some geometry constraints are also applied to the design of these flush-mount photovoltaic panel systems, which reflect the limitations of experimental work and ensure that these modifiers are applicable to the system.

Introduction

Solar market trends have been studied and the results published by GTM Research (a division of Greentech Media) and the Solar Energy Industries Association (SEIA). In Figure 1, the blue bars show the continued growth of the residential sector of the U.S. solar industry from 2010 through 2015, and projected through the end of 2016. With nearly 400,000 residential projects expected to be installed in 2016, and continued anticipated growth in subsequent years, the reader should recognize the importance of using appropriate design wind pressures.

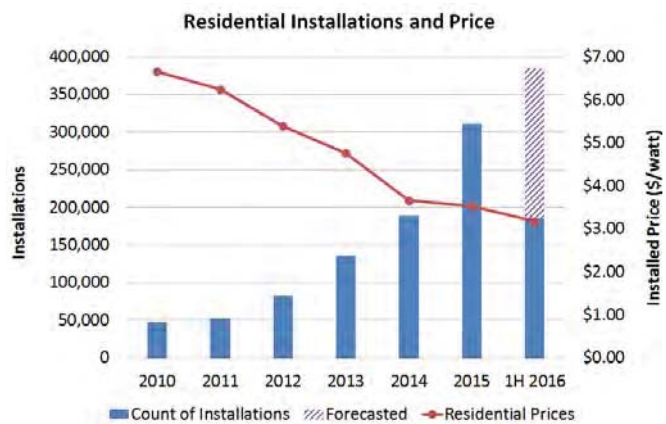

Figure 1: Residential Growth and Price Trends from 2010 through 2016

This paper provides guidance for wind loads for rooftop photovoltaic panel systems installed parallel with the roof, including layout constraints and their relationships with other codes and standards. Calculation of wind pressure begins with ASCE 7-16 rooftop components and cladding pressures, including roof corner and edge zones. The authors will discuss appropriate application of modifiers for photovoltaic array edge effects as well as a pressure equalization factor. A comparison of results derived from ASCE 7-16 and ASCE 7-10 will help readers understand the impacts of the update to this referenced standard. Some discussion of comparable and complementary procedures from the SEAOC PV2-2016 update is also provided.

As of the writing of this paper, revisions to ASCE 7-16 are mostly complete, but it is not yet in print. As final editing of the language of ASCE 7-16 was not yet disclosed at the time of this writing, the reader must understand that the final language might be different than language used in this paper.

Similarly, SEAOC PV2-2016 has not yet been formally approved for publication.

Terminology

To facilitate the reader's understanding of terminology used in this paper, we offer the following introduction. Although *module* is actually an electrical term, the rectangular and rigid, field-installable units that produce electricity from sunlight are often interchangeably referred to as *photovoltaic panels* or *modules*. Most solar modules have an extruded aluminum-alloy frame, but there are also double-laminated glass-on-glass modules that are frameless.

In the solar industry, the term *collector* is associated with *solar thermal* systems (for solar heating and cooling), and is not associated with solar photovoltaic panels. There are many different configurations of solar thermal collectors. Historically, the term *flat-plate collector* has often been used to describe solar thermal collectors that are rectangular in shape and rigid. Solar flat-plate collectors are usually much larger in all dimensions than photovoltaic panels, and fewer of them are used on a particular project. For example, a home with typical domestic-hot-water demand might have two side-by-side solar thermal collectors that are 4 feet by 8 feet in dimension. Flat-plate collectors have enough thickness to allow for glass, an air space, a collector surface, and tubing and manifolds beneath the collector surface for heat transfer fluid. These systems are out-of-scope for this paper, as these dimensional properties and single-row geometries have not been modeled in wind tunnel studies, so there is no data.

There are many other types of solar thermal collectors commonly installed on rooftops that are not rigid and/or not rectangular in shape. One such example is a swimming pool solar collector that includes coils of tubing filled with heat transfer fluid lying flat on the roof surface. Further, there are photovoltaic systems that are not panel systems. Some *building integrated photovoltaic* (BIPV) modules are a direct replacement of roof covering materials, and therefore need to comply with the same requirements as the components they replace. Other BIPV products are flexible films that are adhered to a roof covering such as metal roof panels. All of these products are also out-of-scope for this paper.

There are two general categories of rooftop solar mounting systems for photovoltaic panel systems. *Rail-based mounting systems* often have pairs of rails supporting rows of photovoltaic panels, which can be installed in *portrait* or *landscape.* Photovoltaic panels are typically laid flat on the top edges of the rails and then secured to the rails with aluminum alloy *mid-clamps* and *end-clamps.*

The introduction of *rail-less mounting systems* marked a significant milestone of innovation in the residential rooftop market. Reductions of balance-of-system parts and labor costs were achieved with a decrease in the number of parts required and a corresponding increase in speed of installation. Rail-less mounting systems typically use a modified module frame as the bending member spanning between points of attachment and support. The module frame extrusions are specified to provide greater stiffness than module frames used in rail-based systems, and to provide opportunities for direct attachment of mounting hardware.

Historic Progression of Wind Calculations for Solar

There are no solar-specific provisions in ASCE 7-05 or in ASCE 7-10. Historically, designers and engineers have applied the Components & Cladding (C&C) roof wind pressures to the PV system. The design wind pressures applied to the PV system have been the roof wind pressures calculated for each roof zone beneath the system. Beginning in 2010, the design wind pressures have been decreased to account for pressure equalization, as discussed in the following section.

The topic of roof-mounted PV systems first entered the International Building Code (IBC) in the 2012 edition. Section 1509.7.1 of the 2012 IBC states: "Rooftop-mounted photovoltaic systems shall be designed for wind loads for components and cladding in accordance with Chapter 16 using an effective wind area based on the dimensions of a single unit frame." This provision was carried over to 2015 IBC Section 1510.7.1, with minor revisions to the language.

The original SEAOC PV2-2012 wind paper provided a solar-specific definition of effective wind area, based on the definition of EWA in ASCE 7-10. Revisions to ASCE 7-16 include a solar-specific definition of EWA. Therefore, Section 1510.7.1 will be deleted in the 2018 IBC.

ICC-ES Acceptance Criteria AC 428

In October of 2010, the International Code Council Evaluation Services (ICC-ES) first published Acceptance Criteria AC 428, *Acceptance Criteria for Modular Framing Systems Used to Support Photovoltaic (PV) Panels.* As of the writing of this paper, the most recent update to AC 428 is November 2012.

In ICC-ES AC 428, design wind load criteria is found in Section 3.1.3.1. Following is an excerpt from Section 3.1.3.1.1 for flush-mounted PV systems:

All elements shall be designed for Components and Cladding (C&C) pressures defined within the applicable code … except that the internal pressure coefficient, GC_{pi}, shall be equal to zero, and therefore the design wind pressure, *p,* shall be determined as follows:

Design Wind Pressure, $p = q_h(GC_p) \geq 16$ psf (770 Pa) per Section 30.2.2 of ASCE 7-10 for the 2012 IBC

where: q_h = velocity pressure determined at mean height of the row of PV panels in the array, *h,* and appropriate exposure category from ASCE 7.

The first three conditions of using the AC 428 method are constraints on system placement and geometry, which are stated as follows:

1. PV panels shall not be installed within 10 inches (254 mm) of a roof edge or ridge.
2. The distance between the roof or wall surface and the PV panel must be between 2 and 10 inches (51 and 254 mm).
3. A minimum gap of 0.25 inch (6.4 mm) must exist between PV panels and adjacent rows of panels.

It is important to note that the earliest version of AC 428 required a minimum 0.75 inch gap between rows of PV panels. The minimum gap width was reduced to 0.25 inch in revisions to the Acceptance Criteria, as a minimum gap of 0.75 inch was found to exceed the gaps provided by many of the existing mounting systems already in the marketplace.

The exclusion of the internal pressure is based on the idea that the PV system is "air permeable cladding," as discussed in section C30.1.5 of ASCE 7-10. This is also the basis for the pressure equalization factor introduced in ASCE 7-16.

First Edition of SEAOC PV2 Paper for Low Profile Photovoltaic Panel Systems on Low Slope Roofs

The 2012 edition of SEAOC PV2 provides procedures for the calculation of wind loads on low-profile PV racking systems mounted on "flat" (low slope) roofs. The document permits the procedures to be used for systems with 0° tilt (i.e., flush-mounted systems). It will generally be quite conservative for such systems, as the methods are based on atmospheric boundary layer wind tunnel testing for tilted systems. Wind loads typically increase with increasing panel tilt.

The flush-mount procedures from ASCE 7-16 are more appropriate, and have been incorporated into the forthcoming 2016 update version of PV2.

Atmospheric Boundary Layer (ABL) Wind Tunnel Studies

Many manufacturers of commercial rooftop photovoltaic mounting systems have considered wind tunnel studies to be an important part of their value engineering. ASCE 7 states that ABL wind tunnel testing "may always be used for determining wind pressures for the MWFRS and/or for C&C of any building or structure. This method is considered to produce the most accurate wind pressures of any method specified in this Standard." Only full-scale testing is better.

By commissioning wind tunnel studies, manufacturers can reduce both construction cost and risk of structural failure by incorporating better understanding of wind pressures into their design practice to optimize their designs. Care does need to be taken in the interpretation of the results (Kopp and Banks, 2012).

ABL wind tunnel studies are performed using a scale model of the rack system (typically in approximately 1/40 scale) in a boundary layer wind tunnel, according to the Wind Tunnel Procedure described in ASCE 7-10 Chapter 31.

It is relatively rare for such studies to be performed on flush-mounted systems, however. One exception is the extensive testing performed by Stenabaugh (2015), which forms the basis for the new ASCE 7-16 equalization factors.

The experimental setup is shown in Figure 2. The gap between the panels and the height above the roof were varied. Results are presented as net pressure across the panels as a fraction of suction pressure on the top surface of the panels.

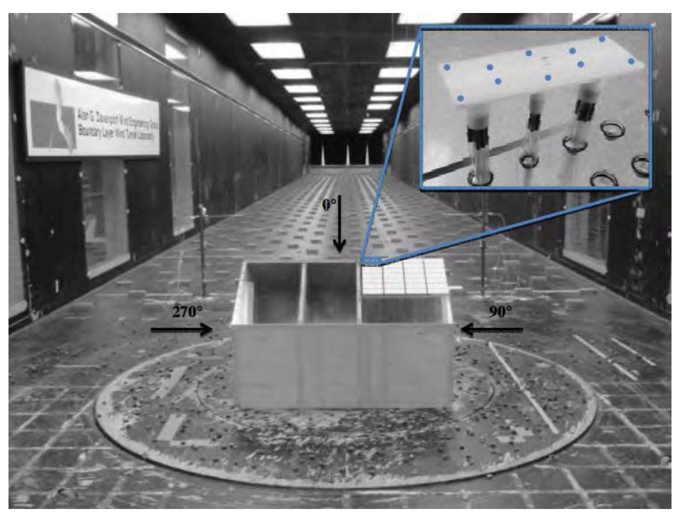

Figure 2: Scale model used by Stenabaugh (2015)

The experiments clearly showed two characteristics that enhance pressure equalization and reduce net pressure: 1) wider gaps between the panels, and 2) placement of the panels closer to the roof surface.

ASCE 7-16 New Parallel-to-Roof Method

These results form the basis for the new flush-mount method in ASCE 7-16, where the key equation is:

$$p = q_h\,(GC_p)(\gamma_E)(\gamma_a) \quad (\text{lb/ft}^2)\ (\text{N/m}^2) \qquad (1)$$

As before, the starting point is the external pressure coefficients for Components and Cladding of roofs, the GC_p values. These can be reduced by the Array Pressure Equalization Factor, γ_a, or increased by the Array Edge Factor, γ_E.

Like the roof cladding pressure coefficients themselves, the Array Pressure Equalization Factor, γ_a, decreases with larger tributary area, as shown in Figure 3.

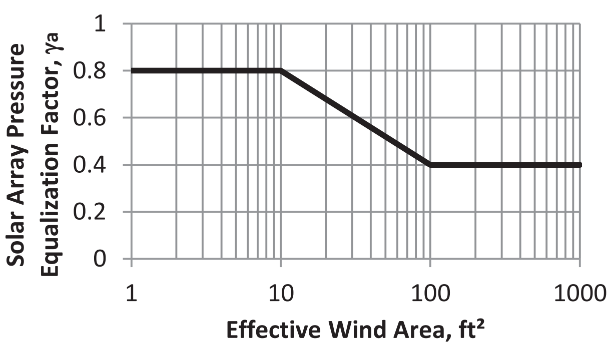

Figure 3: Array pressure equalization factor, γ_a

To use this curve, PV panels must be no more than 10 inches above the roof surface, and there must be a minimum 0.25 inch gap between panels on all sides. A maximum panel size of 6.7 ft (2 m) is also specified. The reason for this last restriction is that regular gaps are essential for equalization. This constraint illustrates why single rows (e.g., pairs) of 4 ft x 8 ft solar thermal panels are out of scope for this paper.

Another geometry restriction is imposed in this method as well: the array shall be located at least twice the array height above the roof from any roof edge, gable ridge, or hip rafter. The reason for this is to avoid having the edge of the array protrude into the accelerated flow in these regions. The effects of this accelerated flow have not been adequately characterized. It is unlikely that the loads in this situation are adequately captured by the above pressure-equalization procedure.

The array edge factor is intended to capture the fact that when the wind is flowing parallel to the roof surface, the windward edge of the array exposed to these winds will see higher loads – it's a miniature version of edge zones on a roof itself. In this case, $\gamma_E = 1.5$.

For simplicity, the array edge factor calculation procedure for flush mounts was copied from the ASCE 7-16 procedure for tilted panels on low-slope roofs. It is not based on the Stenabaugh experiments. As in the tilted-panel method most commonly applied to much larger PV arrays on commercial low-slope roofs, the edge effect – with 1.5 multiplier on wind pressure – extends a distance $1.5(L_p)$ from the end of a row, where L_p is the long dimension of a photovoltaic panel.

Owing to space constraints and locations of obstructions such as rooftop vents, most residential rooftop PV systems have arrays that range from one to three rows of panels. Some systems on larger mounting planes might have four or more rows of panels, but this is less common. As seen in Figure 4, when applying $1.5(L_p)$ from each edge, we find that arrays with one, two, or three rows are 100 percent within the area of edge effect according to ASCE 7-16, where $\gamma_E = 1.5$ multiplier. This is overly conservative.

This effect is being addressed in the update to the SEAOC PV2-2016 paper, which will recommend that the array edge effect multiplier apply only within a distance twice the height of the array above the roof. For example, if the clear height between the bottom of photovoltaic panels and the roof surface is 5 inches, then array edge effect should apply only within 10 inches of array edges.

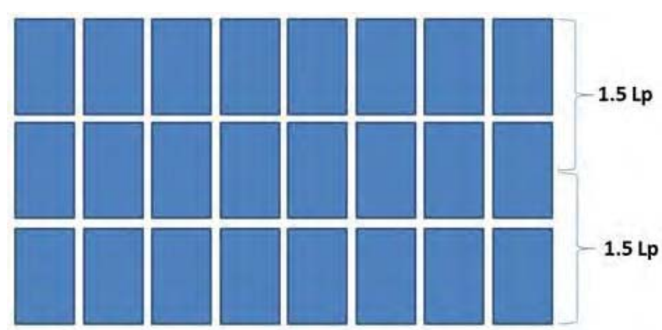

Figure 4: Example of ASCE 7-16 Array Edge Zone

Note that a panel is considered to be exposed if d_1 to the roof edge > $0.5h$, so no edge factor is applied if the array edge is close enough to the edge of the building – roof edge and array edge are not combined effects. It is also important to note that Array Edge Factor, γ_E, applies only to uplift, as it is related to suctions at the array edge; $\gamma_E = 1.0$ for downforce.

An Aside about Downward Wind Pressure

The magnitude of downward wind pressures on tilted systems on low-slope roofs can be comparable to the uplift. This is not the case for flush-mounted PV systems, because the starting point for loads on these systems is the external pressure on the roof itself.

As seen in Figure 5, the magnitude of the positive (downward) pressure is significantly lower than the negative (upward) pressure. The downforce values range from 15 to 55 percent of the uplift for comparable tributary areas. This is typical for residential roof wind loads. As a result, most of the discussion in this paper focuses on negative pressures, sometimes referred to as suctions.

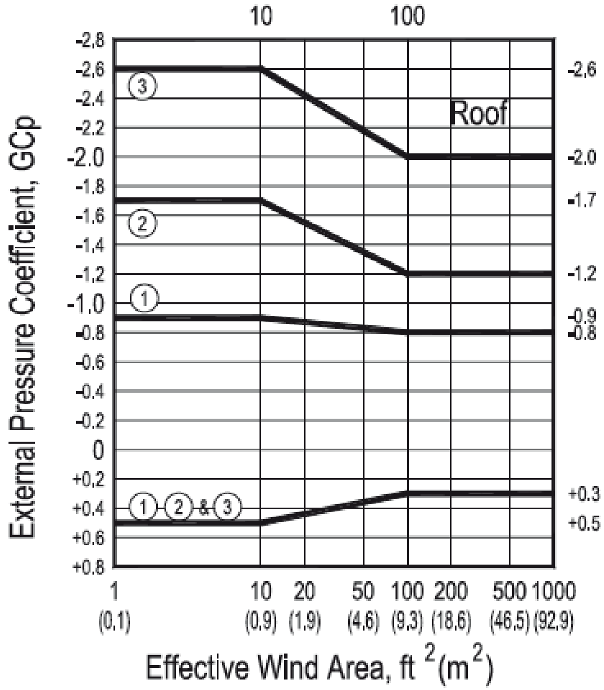

Figure 5: GC_p plot from ASCE 7-10 Figure 30.4-2B (Gable/Hip Roofs with slopes between 7° and 27°)

Supplementary Recommendations for ASCE 7-16 Procedures Expected in SEAOC PV2-2016

Extensions or modifications to the ASCE 7-16 parallel-to-roof method have been proposed for the SEAOC PV2-2016 update. First, the restriction to enclosed and partially enclosed buildings is not necessary. The procedure may be applied to PV systems parallel to any roof surface. As previously discussed, the array edge factor should only be applied within 2 array heights of the exposed edge of an array.

The pressure equalization factor should be decreased (leading to lower net loads) for arrays that are close enough to the roof (5 inches or less) and which have wide enough gaps between the panels (0.75 inches or more). Some interpolation will be permitted.

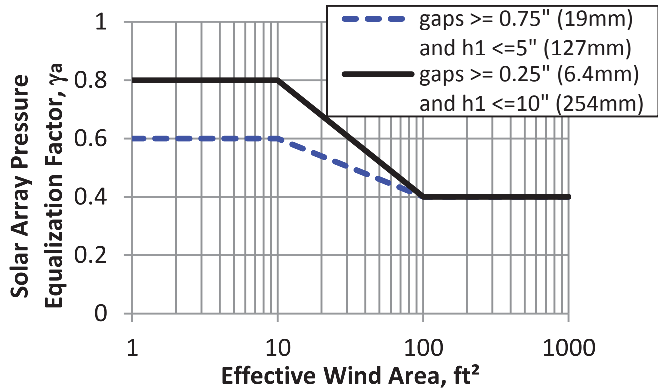

Figure 6: "Blue (dashed) line" pressure equalization curve proposed for SEAOC PV2-2016

It is important to note that the original (only) line on the ASCE 7-16 γ_a chart is for the combined worst-case condition of systems that are installed at the maximum threshold of 10 inches above the roof surface, and the minimum threshold of 0.25 inch gaps between panels. Most PV panel systems are installed at a distance of about 3 to 5 inches above the roof surface. Many systems have gaps between panels greater than 0.25 inch. This combined conservatism under-estimates pressure equalization for most residential mounting systems.

Relevant Non-Solar-Specific Changes to ASCE 7-16

Equation (1) for flush-mount PV systems starts with the basic wind velocity pressure (q_h) and the external roof pressure coefficients (GC_p). Both of these values are expected to change in ASCE 7-16.

Figure 7 shows a map of wind speeds in the contiguous United States for Risk Category II (two), as submitted in Proposal S56-16 for the ICC Group B development process for the future 2018 International Building Code (IBC). In comparing this version of the RC II wind speed map to ASCE 7-10, the reader can see that in all non-hurricane regions in the continental U.S., the basic wind speeds are being reduced. This is particularly true in California. As velocity pressure includes the square of the wind speed, reductions in design wind speed are very significant. The other major improvement is that wind speed contours are established for the remainder of the U.S., in contrast with the previous map that had design wind speed transitions at state boundaries.

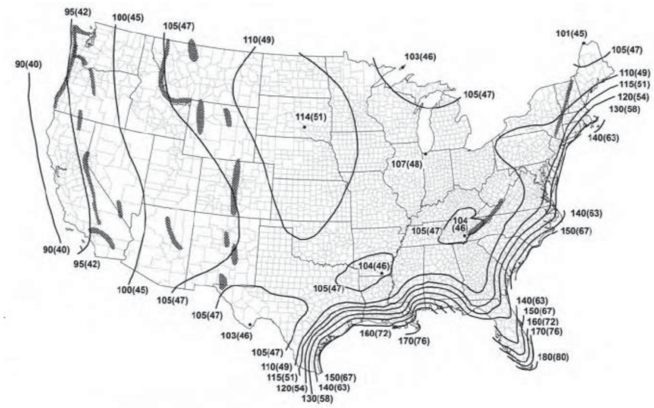

Figure 7: Risk Category II Basic Wind Speed Map

Conversely, the GC_p values for the Components & Cladding (C&C) method for gable and hip roof wind pressures are increasing. The values in ASCE 7-10 are based on studies conducted at the University of Western Ontario (Davenport et al. 1977, 1978), and at the James Cook University of North Queensland (Best and Holmes 1978). The values in ASCE 7-16 also come from work at Western (Gavansky et al, 2013, Vickery et al, 2011).

In some cases, particularly for smaller tributary areas, C&C pressure coefficients have increased significantly. An example is shown in Figure 8 for roof zone 1, where most solar is placed.

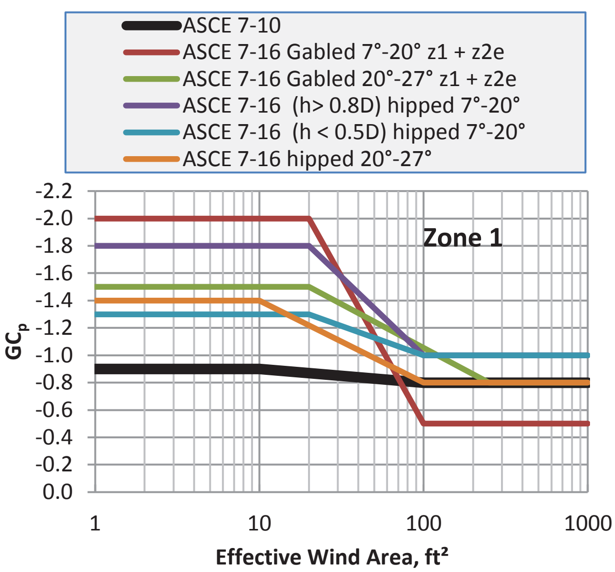

Figure 8: Comparison of ASCE 7-10 and ASCE 7-16 external C&C pressure coefficients for roof zone 1

With the equalization factor and the reduced wind speeds for California, the resulting net pressure coefficients for flush-mount PV on these same roofs is largely reduced (in the absence of edge factors) as shown in Figure 9. They would be further reduced below the ASCE 7-10 cladding values if the lower equalization factor from SEAOC PV2-2016 (the dashed blue line) was used.

The changes in the coefficients are only part of the story. There are more roof types (all five of the colored lines in Figure 8 and Figure 9 were covered by the single black line in ASCE 7-10), more roof zones (for example, corner ridge vs. corner eave), and in the case of the low-slope roof, the roof zone sizes are different.

The loads on other roof shapes, such as the monoslope free roof often used for solar parking lot canopy structures, have not changed in ASCE 7-16, because only gable and hip roofs were examined in the new wind tunnel testing.

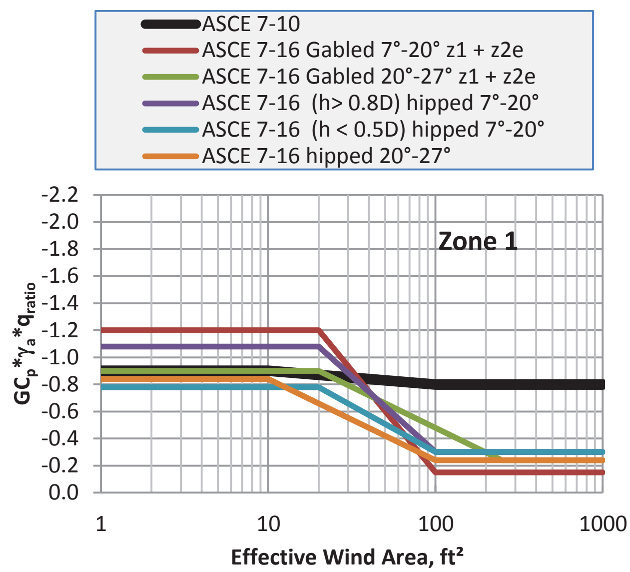

Figure 9: Comparison of ASCE 7-16 net pressure coefficients for solar in roof zone 1 with external C&C pressure roof coefficient from ASCE 7-10

How to Design PV Systems to Reduce Wind Loads

Keeping the PV system close to the roof surface will reduce the width of the array edge zone and improve pressure equalization. Wider gaps between the panels in both directions will also improve equalization.

There are some corners of the roof where the new loads are very high, particularly for very small tributary areas. The pressure coefficient at Zone 3e in Figure 10, at the low end of a high-slope gable roof, is over 2.5 times higher than in ASCE 7-10. It is likely best to be aware of, and avoid, a small (typically 3 ft by 3 ft) high-suction region like this one.

Figure 10 also shows how the zones have in some cases been effectively re-arranged for different roof types. The ridge and eave edge zones have the same value as the interior zone, effectively combining them. If the width of the gable-end edge zone had been increased (as was done for the flat roof), then the interior values would likely have decreased further.

The wind loads will be significantly reduced from ASCE 7-10 if a large effective wind area can be justified by the structural engineer. Rail-based mounting systems tend to have greater stiffness and load-sharing capability, so might be able to use multiple panels as part of the EWA. Rail-less mounting systems are more likely to have single-panel EWA.

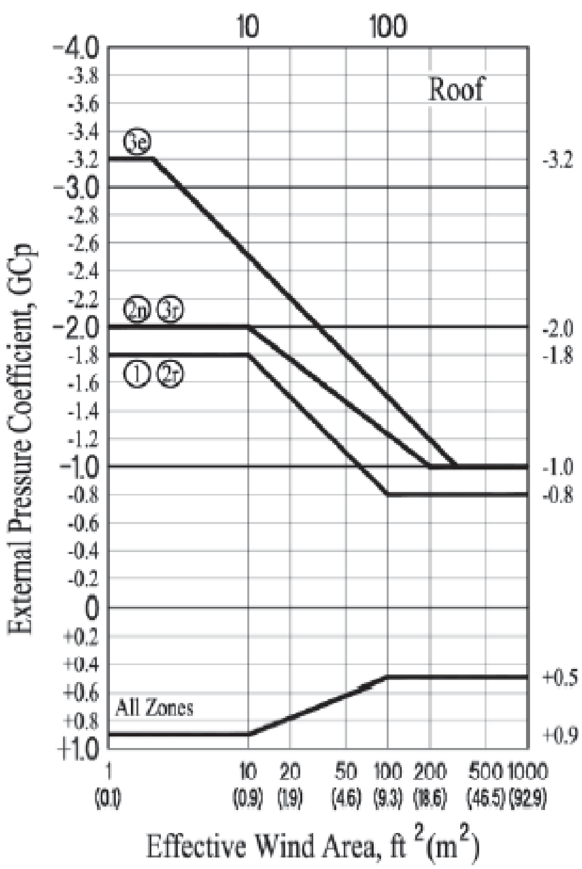

Figure 10: From ASCE 7-16 Figure 30-4.2D, high slope (27° to 45°) gable roof. Zone 3e is the eave corner, 3r is the ridge corner zone, 2n is the gable-end edge zone, 2r is the ridge and eave edge zone.

Other Considerations for Setbacks from Roof Edges

In earlier sections of this paper, we have discussed constraints on PV system layout and geometry required by ASCE 7-16. PV arrays must be set back from roof edges a minimum of twice the clear height of the array above the roof surface. As the allowable height range is 2 to 10 inches, the result is a minimum setback ranging from 4 to 20 inches, with a common range of about 6 to 10 inches. In some cases, this might make the difference between fitting another row of panels on a mounting plane. However, it could also provide a small margin of worker safety near roof edges, especially on frosty or otherwise slippery roofs, so could become recognized as a best practice.

International Fire Code (IFC) Section 605.11 and NFPA 1 Fire Code Section 11.12 require access pathways to ridges and clear setbacks from ridges to allow fire fighters access for vertical ventilation. In many cases, exceptions can be granted by the fire code official if rooftop operations are not employed. The designer should have already considered these requirements by the time structural engineering is considered.

A designer could also consider the minimum setback required to keep the PV system out of the roof corner and edge zones with highest wind pressures. In many cases, this could also keep the PV system off of some gable-end roof overhangs that could be soft owing to large cantilever length.

Are Geometric Constraints of ASCE 7-16 Absolute?

In addition to questions about the wind pressure calculations, there are certain to be questions about the new constraints on geometry in ASCE 7-16. While it is not the intent of the ASCE 7-16 provisions to limit what systems can be built, systems which do not fit the description may suffer for lack of a wind load calculation method to justify them.

For example, important questions are expected to arise about the minimum 0.25 inch gaps required between all panels for pressure equalization. Some rail-based mounting systems have a gap between panels greater than 0.25 inch in one direction (along a row) but no gap in the other direction (between rows). This is likely to be the case for some shared-rail mounting systems, where one rail supports two panel edges. Rail-less mounting systems are likely to have no gap along a row, where mechanical splices between panels are necessary. If not within the prescriptive constraints of ASCE 7-16, should these mounting systems be prohibited? No.

Another very rational question is whether it is acceptable to have no gaps between panels as long as the γ_a reduction is not used in the calculations.

These questions of course can be answered with additional research, for example to derive an equivalent porosity for use with γ_a. We can all wish for more funding of research projects that can answer these questions across a range of industry concerns in the coming years.

In the meantime, one option that is always allowed is an ABL wind tunnel study. Individual manufacturers of residential mounting systems have so far been reluctant to embrace that option, in addition to all other required laboratory testing.

Discussion and Conclusions

ASCE and SEAOC are introducing significant new provisions for the calculations of wind loads on flush-mount systems commonly used for residential solar. In combination with changes to wind speed maps and pressure coefficients for roof cladding, the complexity of calculating wind loads on flush-mount PV systems may increase noticeably, and the loads themselves may change significantly.

These methods may inadvertently favor some mounting systems and restrict others, leaving some to wonder if the new methods are necessary. The simplicity of previous wind load provisions was to some extent a reflection of the limited knowledge, a short timeframe, and an absence of any existing regulations.

Having a reliable wind load calculation method for flush-mounted PV systems is a matter of life safety. In high winds, all components of solar photovoltaic systems should remain attached to a home. It is our hope that the new provisions will help well-designed mounting systems proliferate, without imposing arbitrary restrictions with marginal benefits.

The forthcoming provisions allow wind loads on flush-mounted solar to be calculated with greater accuracy than ever before. This information can be used both to improve design (by reducing wind loads) and to help select the best roof locations for solar.

We close this paper with one more question that should be discussed by wind experts and civil/structural engineers. Historically, when we have large uncertainties about the accuracy of design loads, we use large factors of safety and/or large load factors in load combinations. If wind engineers are in agreement that ASCE 7-16 design wind speeds and pressure coefficients are substantially improved – and with the absence of widespread failures of residential or other parallel-to-roof PV systems – is it time to reassess appropriate factors of safety and load factors?

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