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How to Calculate Wind Loads on Roof Mounted Solar Panels in the US

By Dr. David Banks, PEng.

This paper addresses some of the frequently asked questions that we have encountered while consulting on wind loads for dozens of solar energy designs over the past 5 years.

In the US, there are two approved methods for calculating wind loads on structures like solar panels:

1. Use tables provided by the American Society of Civil Engineers, in ASCE 7, “Minimum Design Loads for Buildings & Structures”
2. Conduct a suitable wind tunnel test, as described in ASCE Manuals and Reports on Engineering Practice No. 67, Wind Tunnel Studies of Buildings and Structures.

This paper will describe the manner in which both of these methods can be performed correctly, and will also address some other tools useful for design, such as full scale testing or computational fluid dynamics simulations.

Using the Tables in ASCE 7

As any engineer who has been charged with interpreting ASCE 7 knows, there are no tables explicitly intended for use with roof mounted solar collectors. However, depending on the geometry of your collectors, one of two methods is most applicable:

A. For flat or flush-mounted collectors, the external gust pressure coefficients (GCp) for the roof itself can be used. These values can be found in Figure 6-11 and will yield conservative loads, even if the internal pressure, GCpi, is assumed to be zero.

   The reason is that the air plenum underneath such panels tracks the pressure above the panels. How well the plenum tracks the panels depends on how many panels are linked together (i.e. the size of the plenum), and more importantly, the size and spacing of the gaps around the panels relative to the size of the plenum.

Note that in this situation, mechanically attached flush-mounted solar panels will not increase the wind load on the roof structure itself. The roof load remains roughly the same, with some fraction acting on the panels.

B. For panels tilted above 10 degrees with no wind protection on the north side, the CN values from Table 6-18 for monosloped free roofs can be used along with equation 6-25. (The gust effect factor, G, is considered separately for this method, and we recommend that G be taken as 1 for solar panels). Using this table assumes that 3-second-gust wind speeds along the roof surface are comparable to those in the approach flow.

This is generally reasonable, with the notable exception of the roof corner and edge regions. The net effect is that:

i. Wind speeds near the surface can exceed the approach flow wind speed by over 20% during cornering winds. As a result, for any location within 2 building heights of a roof corner, GCN should be multiplied by Kcorner = 1.5.

ii. There is additional uncertainty related to how the twisting flow patterns near the roof edges will interact with any given panel geometry. In the absence of testing, we advise the use of an uncertainty factor of 1.4 within 2 building heights of a roof corner or a roof edge.

iii. Finally, tilted panels should never be placed closer than 2 panels heights from the roof edge (or 2 panels heights + the parapet height if there is a parapet), to avoid having the panels exposed to the very high wind acceleration right above the roof edge.

There is an additional complication here for tilted ballasted panels, regardless of where they are on the roof. Since these panels can slide, the GCp or GCN values (which represent forces normal to the panel surface) should be multiplied by

$$K_{sliding} = \cos(\alpha) + \sin(\alpha)/\mu,$$

where α is the tilt angle, and μ is the friction coefficient between the panel and the roof. This takes into account the combination of lift and drag. When the panels are slightly lifted, they are more prone to sliding.

For both calculations A and B, the velocity pressure qz is calculated at roof height, with the same factors for wind directionality, exposure, topography and importance as would be used for the building itself. While we do not believe that it is necessary to design the solar panels to a higher standard than the building upon which they sit, we also believe that it is important that the panels not be the weakest link when the building experiences a design wind storm. For this reason, the load combination factors of Chapter 2 of ASCE 7 (sometimes referred to as "safety factors"), must be applied. This will result in a wind load safety factor or roughly 1.7.

Note that this safety factor has the effect of increasing the recurrence interval from 50 years to roughly 700 years. In the upcoming ASCE 7-10, these safety factors will be removed, but the recurrence interval will be increased. As a result, the design load will not change significantly in most regions of the country.

Calculations for tipping should also be performed for both tilted and flush panels. The latter is perhaps less obvious. However, around the perimeter of such an array, depending on the stiffness of the connections between panels, the panels may lift, or "peel". As peeling starts, the panel tilt increases, the panels can become much more susceptible to the oncoming wind. ASCE 7 does not provide any guidance regarding how to estimate these moments for flush mounted panels. Our experience suggests that the entire load should be applied to the outside edge of the panel.

Many panel designs fall between the two examples cited above. For example, what about panels at a 5º to 10° tilt with a protective wind spoiler on the north side? It is difficult to predict how effective a wind deflector will be, or at what tilt the panels will begin interacting with the flow. It is recommended in such cases that calculations following both methods A and B be used, and that the method providing the highest loads be applied.

We are often asked about the potential sheltering effect of parapets. It is true that in some situations, particularly immediately behind the parapets, some wind protection is afforded to the panels. However, 2 or 3 parapet heights from the roof corners, the magnitude and extent of the wind acceleration a short distance above the roof is increased by the parapet, and can result in wind loads that are 50% greater than in the absence of a parapet, particularly for unprotected tilted panels.

We are also commonly asked about the 10 psf minimum in §6.1.4.1 of ASCE 7, which states that the loads should not be less than 10 psf multiplied by the area of the structure projected onto a vertical plane normal to the assumed wind direction. Using the methods above, it is highly unlikely that loads below 10 psf will be calculated. However, we do not believe that this limit was intended to be applied to solar panels, and with proper wind tunnel testing, we believe that values below the 10 psf limit can be justified.

Wind tunnel testing

Three key things to remember when commissioning a test are:

1. The flow patterns on the roof are very complex, so the panels need to be testing in a flow regime like that on the roof – with big vortices, flow separation and reattachment, and local acceleration.
2. You need to measure peak loads, not mean loads.
3. The wind is turbulent. For the peaks to be accurate, the simulation must include the right proportion of wind gusts of all sizes.

Three things you should expect to get from the tests (and which are not addressed in ASCE 7) include:

1. How are the wind loads reduced as the array gets larger? Roof mounted solar racks are typically rigid, so that panels cannot slide or move individually.
2. How well do the panels shelter each other? Wind loads on the edge row panels are typically much higher (2-3 times) than on the interior panels.
3. How does location on the roof affect loads? Loads will be different on the north edge, south edge, east edge, corner, and middle of the roof.

Other tools

In some situations, modeling considerations such as Reynolds number independence can prevent testing using scaled models, and outdoor full-scale or near-full-scale testing is required. As with the scaled model in the wind tunnel, the panels must be placed in a range of positions on the roof of a building, and the approach flow velocities and turbulence must be well understood. Full scale testing provides a wide range of significant challenges, both technical and logistical: fidelity of pressure sensors after rains, temperature drifting in the instrumentation, and interactions with animals, to name a few.

Computational Fluid Dynamics (CFD) can also be used to simulate flow over the panels (and, as always, the building). However, there are currently no accepted procedures for ensuring that peak loads are adequately measured, so this type of analysis is not approved by ASCE 7 or any US building codes. Nonetheless, CFD can be a valuable design tool, providing insight into whether design changes improve performance or not.

What should a roof-rack designer do?

It is clear that using the ASCE formulas near the roof corners brings with it considerable uncertainty. The methods described above may not be conservative in this region. In our experience, the wind loads calculated with the ASCE 7 methods described above are not a significant challenge for roof-mounted building integrated PV racks which are mechanically fastened to the building structure. However, few buildings are likely to be able handle the ballast weight that these calculations imply. It is therefore likely that if ASCE 7 methods are used, panels near the roof corners will need to be mechanically fastened.

A well designed system can achieve significantly lower wind loads than the above calculation procedures dictate, permitting ballasted systems to be used in many situations, including near the corners. However, the author knows of no way to acceptably demonstrate that these wind loads reductions without physical testing.

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