Weighing the costs

Ascertaining whether ballast design calculations provided by mounting system manufacturers are performed correctly is not an easy task for the untrained eye. Thorsten Kray, Head of Building Aerodynamics at Institute for Industrial Aerodynamics Aachen (IFI) , has created a checklist for review of ballast calculations which can be used by owners, EPCs, and others involved in designing and realizing projects.

Most flat roof mounting systems are susceptible to two failure mechanisms due to wind: 'uplift' and 'sliding'. In order to avoid these, ballasting is required – which needs to be calculated separately for each of the two effects.

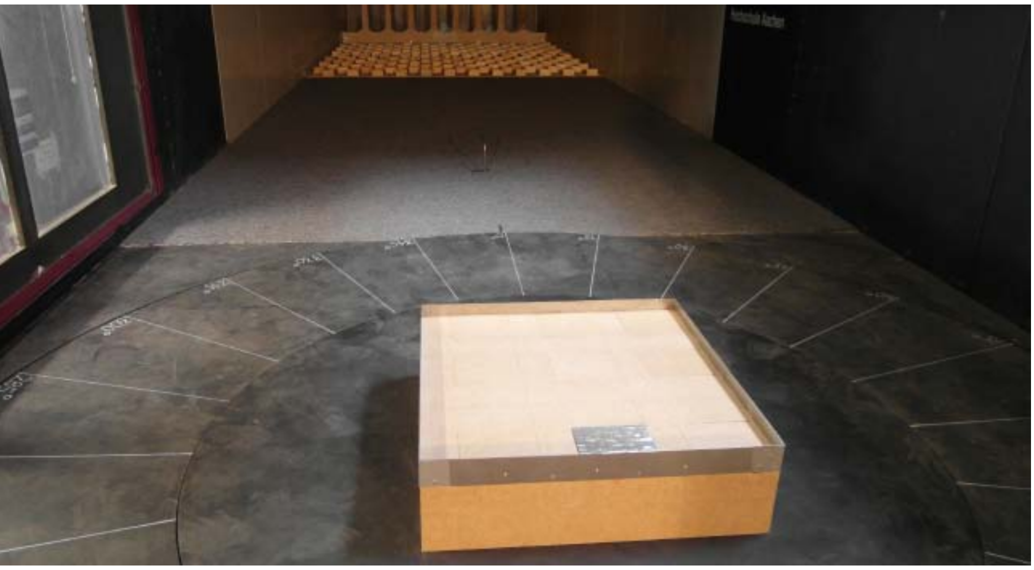
Structural interconnection is crucial to increase load sharing. If horizontal wind forces can be shared by the interconnected substructure, the solar array can only slide as a whole, an ability which justifies redistribution of ballast within an array.

However, the vertical system stiffness and the ability to share vertically by adjacent modules is much smaller than in the horizontal direction. Therefore, ballast to prevent uplift should generally not be redistributed within solar arrays.

To prevent sliding, friction needs to be taken into account. The larger the static friction, the more horizontal force is needed to make a body move.

Polished ballast calculations

There is consensus among experts thatballast weight needs to be based on equations of static equilibrium considering uplift and sliding forces.



Wind tunnel model of a flat-roofed building with parapet and an array of a solar ballasted roof mount system on a scale of 1:100 in the large I.F.I. boundary layer wind tunnel.

Major players in the solar industry usually consult with wind and structural engineers to ensure that ballast weights are designed correctly. However, some ignore these insights. What follows is an example of a mounting system manufacturer tweaking ballast calculations to increase the likelihood of winning a project, but simultaneously increasing the risk of wind-related failure.

Analysis of around ten ballast calculations provided by this particular manufacturer gives evidence that this is done consciously. In each calculation, there was evidence of ballast being underestimated.

Initially, the manufacturer (1) only provided ballast needed to prevent uplift of the solar array, though it was not clear if the structural interconnection was properly taken into account: It turned out that standalone rows were designed for ballast in the same way as interior rows.

Nevertheless, the calculated ballast seemed too much for the load bearing capacity of the roof. Calculations for sliding ballast were completely ignored. A check of the calculated ballast revealed major implausibility (see table on p.61).

Although ballast was reduced, the roof's load bearing capacity was exceeded. The manufacturer then provided an updated ballast layout, which gave lower values. This time, weights to prevent sliding were provided, and uplift was omitted. Additionally, the calculated sliding ballast included a load sharing effect, termed 'group effect'. This was believed valid for solar arrays consisting of structurally interconnected rows, but was regardless also applied to standalone rows.

Once again, a ballast check conducted by IFI. revealed implausibility (see table on p. 62). Sliding ballast calculated by (1) represented a 25% underestimation of the true ballast in the yellow zone and 62% in the grey zone. In conclusion, (1) had reduced the ballast result on purpose to have an advantage securing the business with the building owner.

Uplift ballast

	zone			
	yellow	**blue**	**red**	**grey**
γ_q (partial safety factor)	1.5	1.5	1.5	1.5
γ_g (partial safety factor)	0.9	0.9	0.9	0.9
dead load in kg	37.51	37.51	37.51	37.51
cp, vi (pressure coefficient)	-0.5	-0.42	-0.35	-0.25
cp, vs (pressure coefficient)	-0.45	-0.3	-0.2	-0.1
module tilt angle in °	15	15	15	15
qp (peak velocity pressure) in kN/m^2	0.58	0.58	0.58	0.58
module area in m^2	1.64	1.64	1.64	1.64
ballast calculated by I.F.I. in kg	**110.8**	**74.9**	**48.3**	**17.1**
ballast calc. by manufacturer (1) in kg	**102.6**	**57.2**	**26.9**	**0**
difference between (1) and I.F.I. in %	**-7.4**	**-23.6**	**-44.4**	**-100.0**

Ballast needed to prevent Uplift based on parameters provided by mounting system manufacturer (1) compared with a check conducted by I.F.I. (Roof zones are attributed to colors in calculations conducted by mounting system manufacturer (1) and range from the most exposed yellow zone to the less exposed blue and red zones, and finally to the least exposed grey zone)

“The mounting system manufacturer reduced ballast results on purpose to have an advantage.”

Do it yourself checks

The majority of manufacturer's ballast calculations lack parameters to conduct plausibility checks. A checklist for ballast calculations should include the following considerations:

1. Have all parameters been provided by the mounting system manufacturer? Crucial are partial (safety) factors for wind load and permanent load (dead load), dead load of modules and mounting structure, pressure or force coefficients, module tilt angle, rear deflector tilt angle, peak velocity pressure, module and deflector areas, and the static coefficient of friction.

Close shot of the examined PV array, with the parapet in the background.

Sliding ballast

	zone			
	yellow	blue	red	grey
γ_q (partial safety factor)	1.5	1.5	1.5	1.5
γ_g (partial safety factor)	0.9	0.9	0.9	0.9
dead load in kg	37.51	37.51	37.51	37.51
ca, dyn (force coefficient)	-0.28	-0.22	-0.18	-0.13
cw, dyn (force coefficient)	0.021	0.02	0.02	0.02
module tilt angle in °	15	15	15	15
qp (peak velocity pressure) in kN/m²	0.58	0.58	0.58	0.58
module area in m²	1.65	1.65	1.65	1.65
static friction coefficient	0.51	0.51	0.51	0.51
ballast calculated by I.F.I. in kg	**66.9**	**46.8**	**33.8**	**17.5**
ballast calc. by manufacturer (1) in kg	**50.2**	**32.4**	**20.9**	**6.6**
difference between (1) and I.F.I. in %	**-25.0**	**-30.7**	**-38.1**	**-62.3**

Ballast needed to prevent "Sliding" based on parameters provided by mounting system manufacturer (1) compared with a check conducted by I.F.I. (See Table 1 for explanation on zoning.)

2. Separate equations for uplift and sliding ballast are needed. On pitched roofs, the component of the weight which is parallel to the sloped surface needs to be taken into account.
3. Are partial factors for wind load and dead load in line with governing codes? The basis of structural design is given in EN 1990:2002 and corresponding National Annexes.
4. What is the origin of pressure or force coefficients used for ballast design? For solar ballasted roof mount systems these should be an outcome of wind tunnel testing compliant with national guidelines and standards. If no wind tunnel study was conducted, pressure coefficients need to be in compliance with EN 1991-1-4:2005 and corresponding National Annexes.
5. What is the tributary area that was used for calculation of pressure or force coefficients? It should reflect the structural interconnection of the system. If uplift is of concern, only small tributary areas may be applied. A rule of thumb is that corner modules have less load sharing than edge modules, and edge modules have less load sharing than interior modules.
6. If a wind tunnel study is available, checks need to be conducted whether the study is in compliance with the governing wind tunnel testing guideline of the specific country. Checking whether such standards were met is no trivial task to do for non-experts. However, it is possible to check whether the atmospheric boundary layer was modeled in the wind tunnel.
7. Testing in automotive wind tunnels and use of Computational Fluid Dynamics (CFD) are non-code-compliant. Testing on full-scale PV modules is not appropriate because of cross sections generally only being large enough to accommodate few modules without building underneath.
8. Has the peak velocity pressure at the site been determined correctly? Often terrain category III (which in most National Annexes corresponds to suburban terrain) is assumed, whereas terrain category II (open terrain) would be appropriate. The use of an overly favorable terrain category typically results in an underestimation of the peak velocity pressure by about 10%. Topography may also be of relevance.
9. Does the assumption of the static coefficient of friction make sense? For bituminous roof membranes, assuming a value of 0.5 is often appropriate. For foil roofs, measured values are often lower than 0.4. Only in special some cases the static coefficient of friction is larger than 0.6.
10. Consultation of a specialized wind engineer is recommended if after having checked items one through nine, there remain doubts as to the accuracy of a ballast layout. pv

Thorsten Kray

About the author

Having led the Institute of Industrial Aerodynamics Solar Group for 8 years, **Thorsten Kray** has recently been promoted to Head of Building Aerodynamics. He has overseen wind tunnel studies on hundreds of different solar roof and ground mount systems and has been involved in solar projects all over the world. His key skills are wind tunnel data based ballast layouts for solar arrays mounted on flat roofs, but also static and dynamic loads on ground mount solar fixed tilt and tracking systems.