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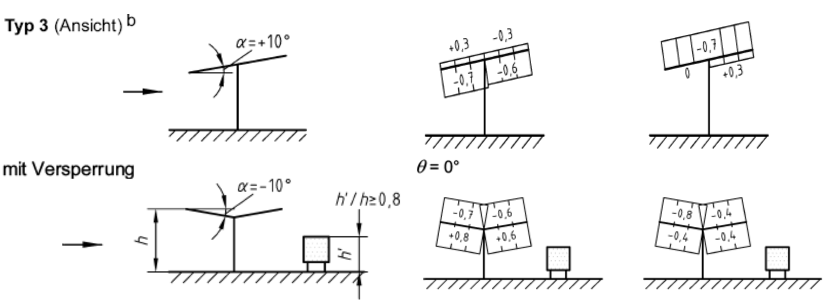
Expert statement on the wind loads impacting solar modules with different inclinations from below

In the structural analysis of inclined solar plants on roofs and in open areas, the external influences by wind, snow and temperature changes have to be considered. The safety level that is required for the construction in question is decisive in this context. Looking at the situation on the market in the area of photovoltaics, it can be observed that there are different ways of dealing with this matter. While some suppliers work strictly according to official regulations and the technical sets of rules of engineering, some other suppliers work on the basis of rather pragmatic estimations.
In this context, it has to be stated that solar plants clearly have been defined as parts of buildings or as buildings of their own in the building codes of the federal German states, and thus have to be dimensioned according to the technical sets of rules of engineering. Regarding the loads that have to be assumed, the latest version of DIN 1055 (2005-2006) has been compulsory since January 1, 2007 for the determination of wind and snow loads. Regarding the snow loads, the DIN 1055 includes clear regulations that do not leave the installer any room for interpretations. But when it comes to wind loads, things are very different! In part 4 of the DIN 1055 in the version from March 2005, wind velocities and squall velocities are clearly determined in relation to the location, the terrain category and the building height. Using the input parameter of the squall velocity pressures, the wind loads are to be determined by multiplication with pressure coefficients c_p respectively force coefficients c_f. Pressure and force coefficients for several basic construction forms are listed in this technical standard. There is no basic construction for solar plants that are impacted by wind flow from below included in the DIN 1055. Thus, many structural engineers use the regulations for free-standing roofs. In picture 1, the pre-conditions and the pressure coefficients for this basic construction form are shown. By definition, these pressure coefficients apply for inclined roofs (for example roofs of railroad platforms) with an inclination of not more than 10°.

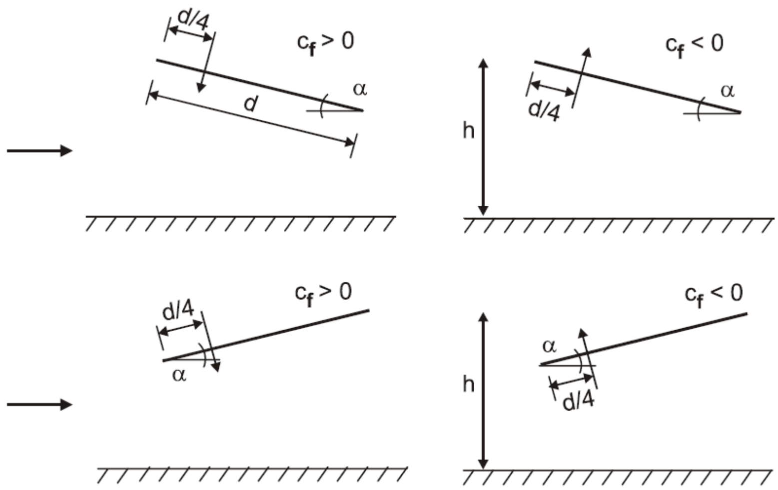


Picture 1 Pressure coefficients for free-standing roofs (DIN 1055-4 chart 8)

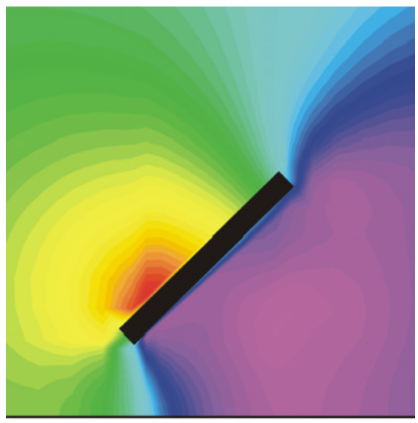
As there are no specific regulations, some structural engineers have decided to apply these pressure coefficients also for inclination angles α >10°, which corresponds to the usual range of application of solar installations. This approach is not permissible, as constructions that are designed in such a manner do not comply with the generally accepted rules and standards of technology [2]. The typical procedure to obtain reliable pressure coefficients is as follows:

- Evaluation of other sets of rules or specialized press publications
- Wind-dynamic calculations
- Tests

The purposeful reading of specialized press publications already provides comprehensive information about the given subject. In [1], a load assumption approach for inclined solar modules on the basis of the pressure and force coefficients according to Eurocode 1 is presented. This procedure is based on the research results by the University of Chemnitz. Within the framework of a research project, the problem was examined both by calculation and long-time tests, so that now there are generally accepted rules and standards of technology. In Eurocode 1, the wind loads impacting free-standing roofs with angles ranging from 0° ≤ α ≤ 30° are assumed as individual loads in the quarter points of the roof length (picture 2). In picture 3, an exemplary load distribution on the basis of a flow calculation is shown. The positions of the maximum pressures that are displayed in red show the correctness of this calculation approach.

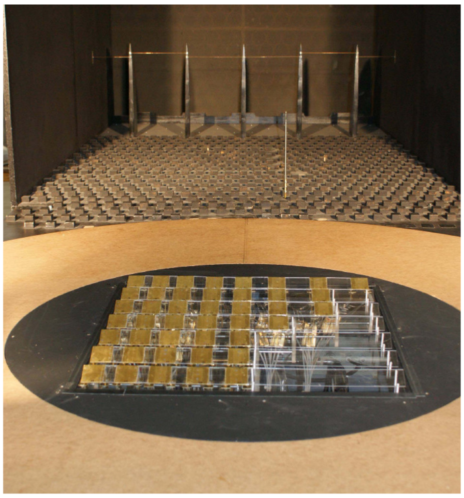


Picture 2 Load application points for wind forces (Eurocode 1)

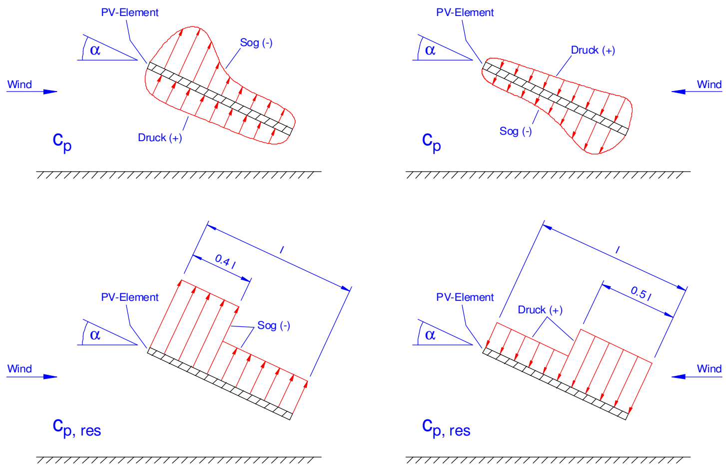


Picture 3 Pressure distribution [1]

In attachment 1, the pressure and force coefficients for inclined roofs 0°≤ α ≤ 30° according to Eurocode 1 are shown in the form of charts. The pressure coefficients apply for the module and the module beam, whereas the force coefficients have to be applied for the support and the verification of the fastening to the roof or in the soil. The comparison of the values stated for 10° shows that this order of magnitude approximately corresponds to the regulations laid down in DIN 1055. With increasing inclination, the absolute values of the pressure and force coefficients increase significantly. With an inclination of 30°, wind loads that are twice as high have to be assumed in good approximation. This comparison shows that the verification according to DIN 1055 is significantly on the unsafe side with bigger inclination angles.
The normatively regulated pressure coefficients for free-standing roofs according to Eurocode 1 quite naturally have to cover a wide range of possible constellations regarding the structural surroundings, flow directions and minimum heights. Moreover, the mutual wind protection of several rows behind one another is not explicitely stated in many cases.
According to the specific conditions for photovoltaic modules, more exact values can be determined by wind tunnel tests. This procedure is explicitely approved by DIN 1055, part 4 in chapter 6.3. For this kind of tests that serve for the evaluation of building aerodynamics, a boundary layer wind tunnel has to be used.

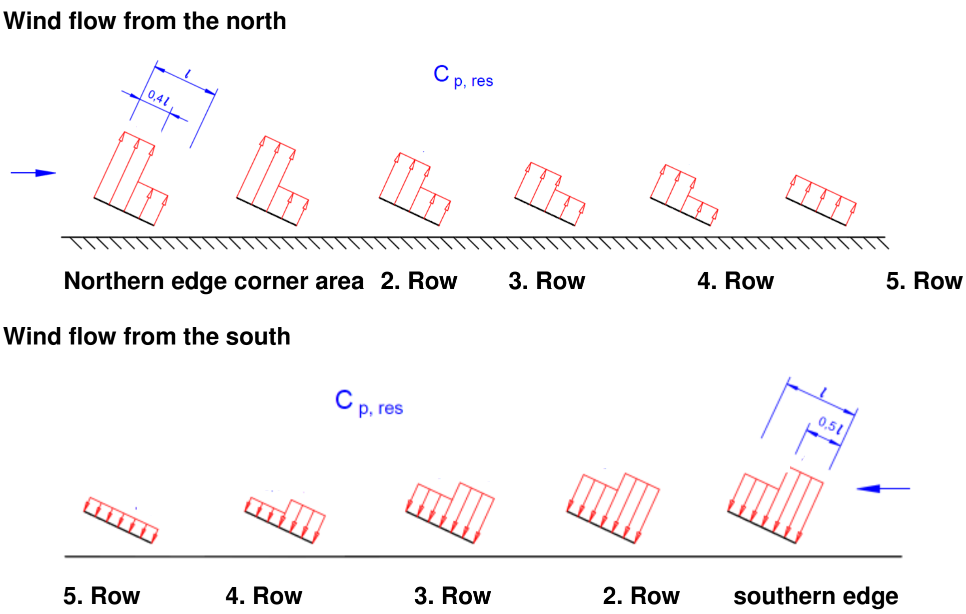


Picture 3 Boundary layer wind tunnel [3]



Picture 4 Real and idealized pressure distribution [3]

Picture 3 shows a boundary layer wind tunnel with a model of the building or construction, in this particular case several rows of a scale model of an open area solar plant are arranged on a turntable. Thus, the influence of all inflow directions is explicitly considered. In picture 4, the pressure distributions in the upper area that have been quantitatively measured for wind inflows from the front and from the back are displayed. As the non-linear suction and pressure fields can only be considered in the structural planning with a big calculation effort, they are transformed into idealized pressure and suction distributions that cause even loads and moments on the module field. The results coincide qualitatively well with the tests in [1] and Eurocode 1. However, the absolute values and the center of gravity of the load pattern allow a more economic dimensioning. In picture 5, the influence of mutual wind protection of rows behind one another is shown. If the wind impacts from behind (usually north), the elevations undergo continuously decreasing stresses from wind impact. Starting from the fifth row, there will be an approximately evenly distributed load on the complete module surface. But if there are bigger open areas within the plant, edge areas have to be taken into account again. As wind flow from north-west or north-east also leads to higher wind loads on racks on the east and west side of the solar plant, these areas have to be dimensioned as edge areas.



Picture 5 Qualitative display of the wind protecting effect of rows one behind another

A similar effect can be observed when the wind impacts from the south. In this case, concentrated pressure forces in the lower part of the module area can be observed. Also in this case, there is a homogeneous pressure field starting from the fifth row.
The qualitative display of the pressure conditions in picture 5 applies for solar mounting racks regardless of the manufacturer. Quantitatively, a certain influence of the specific solution in relation to the profile dimensions and the gap measurements between the modules is to be expected. Moreover, the pressure coefficients significantly depend on the inclination of the module area.

In summary, it can be stated:

Calculation approaches for wind loads on the basis of established technical standards in the area of application specified are generally permissible for the verification of structural safety. Conclusions by analogy on the basis of other types of construction like mono-slope roofs, roofs of station platforms or billboards are insufficient and do not comply with the generally accepted rules and standards of technology. Specific wind tunnel tests in a boundary layer wind tunnel also comply with the generally accepted rules and standards of technology and bring about economic optimization options for homogeneous module fields without significant empty spaces, especially reduced wind loads in the interior zone. If the aerodynamic coefficients are applied correctly in the structural planning, structural safety is safeguarded without restrictions.

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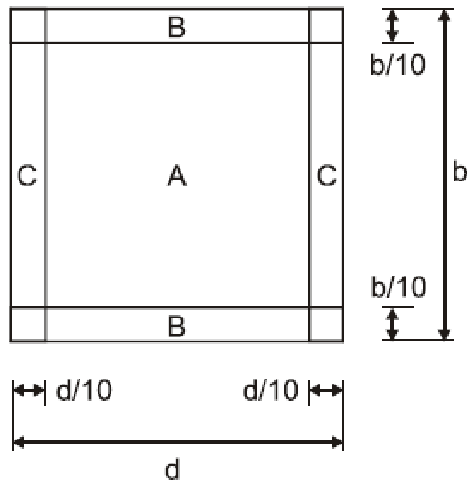
[1] Erfuth/Bahner: Support structures for solar plants, Planning manual for elevations of solar collectors, Solarpraxis Supernova AG, 2001. ISBN 3-934595-11-1
[2] Univ. Prof. Dr.-Ing. Jens Schneider: Expert statement on the assumption of wind loads with (open area) solar plants that are impacted by wind from below. Darmstadt, April 2010
[3] Ruscheweyh Consult GmbH: Wind tunnel tests regarding the wind loads impacting open area solar plants for the company Schletter GmbH, Aachen, Juni 2010

Attachment 1: Pressure and force coefficient for inclined roofs 0° ≤ α ≤ 30° (DIN EN 1991-1-4; Eurocode 1)

Net Pressure coefficients $c_{p,net}$

Key plan



Roof angle α	Blockage φ	Overall Force *Coefficients* c_f	Zone A	Zone B	Zone C
0°	Maximum all φ	+ 0,2	+ 0,5	+ 1,8	+ 1,1
	Minimumφ = 0	- 0,5	- 0,6	- 1,3	- 1,4
	Minimum φ = 1	- 1,3	- 1,5	- 1,8	- 2,2
5°	Maximum all φ	+ 0,4	+ 0,8	+ 2,1	+ 1,3
	Minimum φ = 0	- 0,7	- 1,1	- 1,7	- 1,8
	Minimum φ = 1	- 1,4	- 1,6	- 2,2	- 2,5
10°	Maximum all φ	+ 0,5	+ 1,2	+ 2,4	+ 1,6
	Minimum φ = 0	- 0,9	- 1,5	- 2,0	- 2,1
	Minimum φ = 1	- 1,4	-1.6	- 2,6	- 2,7
15°	Maximum all φ	+ 0,7	+ 1,4	+ 2,7	+ 1,8
	Minimum φ = 0	- 1,1	- 1,8	- 2,4	- 2,5
	Minimum φ = 1	- 1,4	- 1,6	- 2,9	- 3,0
20°	Maximum all φ	+ 0,8	+ 1,7	+ 2,9	+ 2,1
	Minimum φ = 0	- 1,3	- 2,2	- 2,8	- 2,9
	Minimum φ = 1	- 1,4	- 1,6	- 2,9	- 3,0
25°	Maximum all φ	+ 1,0	+ 2,0	+ 3,1	+ 2,3
	Minimum φ = 0	- 1,6	- 2,6	- 3,2	- 3,2
	Minimum φ = 1	- 1,4	- 1,5	- 2,5	- 2,8
30°	Maximum all φ	+ 1,2	+ 2,2	+ 3,2	+ 2,4
	Minimum φ = 0	- 1,8	- 3,0	- 3,8	- 3,6
	Minimum φ = 1	- 1,4	- 1,5	- 2,2	- 2,7

NOTE + values indicate a net downward acting wind action

- values represent a net upward acting wind action