# Wind loads at solar and photovoltaic modules for large plants

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## 1 INTRODUCTION

Wind loads at solar and photovoltaic modules are not subject of international and national wind load codes. The reason is that the number and size of solar and photovoltaic plants have been increased in the past three to four years and that this topic was not on the agenda at the codification committees ten years before. Only some publications exist for single applications for one to four modules on a roof [1, 2]. Geurts [3] has published a proposal for some applications, which is coordinated with a proposal made in UK [4].

Large plants in the MW-range have not been considered in the literature. The authors have published two papers [5, 6], where wind tunnel results at large photovoltaic plants are presented and where the problems of the wind loads at such large plants are described. Further wind tunnel tests have been performed and some results will be presented in this paper.

## 2 THE PROBLEMS AT LARGE PHOTOVOLTAIK PLANTS

The common praxis is to install photovoltaic plants on existing large flat roofs. In most cases it is not allowed to fix the modules by screwing at the roof plane. The only way to fix the modules is by activating sufficient friction between the module support frame and the roof surface and this requires additional ballast weight on the module frame structure. Consequently the additional weight on the roof can be too large and the photovoltaic plant cannot be installed. The required ballast depends on the lift force caused by the wind. Therefore it is of eminent interest to know the real lift force on the modules and further to minimize the lift force, if possible.

A similar problem exists at photovoltaic plants mounted on the ground (free field plants). The economic purpose is here in the foreground. If the supporting system is too strong, the plant may be safe against wind action but it is too expensive. Therefore the real wind load must be known.

Numerous parameters influence the wind load:

- angle of the module to the horizontal plane
- distance of the module rows to each other
- distance to the building walls
- position of the module in the module field
- gaps between the modules respectively gap to the ground or roof surface
- closed or open side of the module rows
- wind safe deflector at the north side of the module
- supporting system
- free zones inside of the module field
- height of the building

- arrangement parallel or diagonal to the building walls
- roof with or without a parapet
- shape of the building roof corner (round or sharp)
- geometry of the module field arrangement
- slope of the ground at free field plants
- wind direction

Photovoltaic as well as solar systems are in a permanent developing stage. New ideas arise frequently and require new investigations for the wind load. The main purpose is to reduce the wind load, to reduce the weight of the support system and to avoid or to minimize the ballast at roof systems.

Photovoltaic and solar modules must be regarded as an airfoil system with aerodynamic ground effect. The aerodynamic at the modules is different from the aerodynamic at a flat or sloped roof and therefore wind load coefficients given in the wind load codes for roofs cannot be applied to the modules. The only exception is the integration of the modules into the roof, but even in such case the internal pressure must be considered carefully, because this pressure may increase the wind load at the module.

The following examples show some aerodynamic aspects at the modules at flat roofs. Figure 1 shows the wind flow at the building roof corner. The flow separates at the sharp corner and is directed down again by the suction in the wake zone which leads to the well known reattachment on the roof. If the first row of the module is more or less in the wake of the flow separation, the wind load is reduced, but if the module is in a position further downstream, the full wind pressure can act to the module and the wind load increases. This effect is influenced by the ratio of module size/building height (Fig. 2). At low buildings the ratio Δh/H is nearly 1 or something below 1 and the flow separation at the roof corner has a minor reduction effect on the wind load at the first module. At higher buildings the ratio of Δh/H is small and the first module row is more or less in the wake of the flow separation. This effect is increased, if the roof corner has a parapet. The wake zone is expanded but the wind flow curves down to the modules at the third or fourth module row which will receive an increase of wind action. This effect is shown in the sketch of Figure 3.

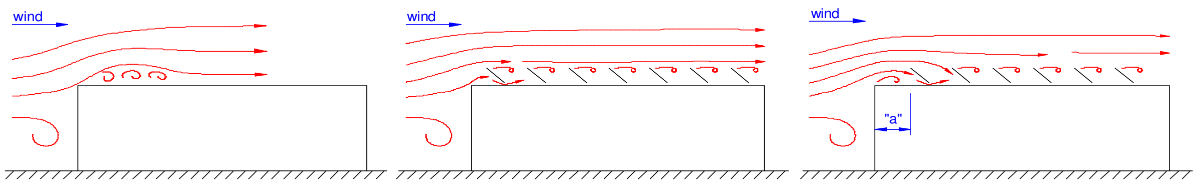


Figure 1. Flow separation at the building roof corner without and with modules on the roof

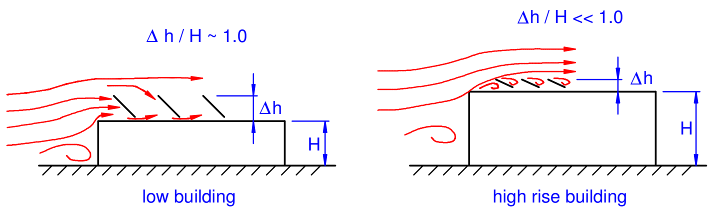


Figure 2. Influence of the height ratio Δh/H on the flow attack to the module

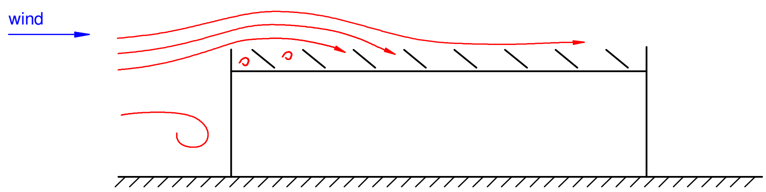


Figure 3. Effect of a parapet to the wind action at the module field

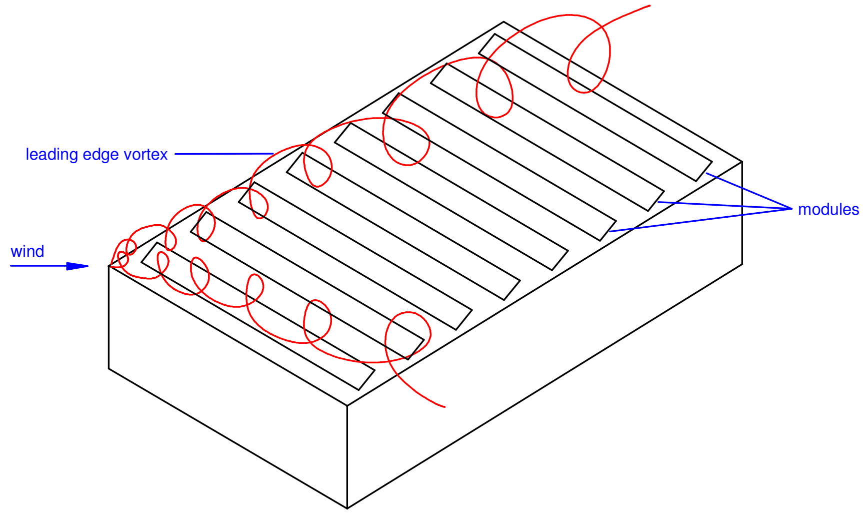


Figure 4. Leading edge vortex system at a building, wind direction towards the building corner

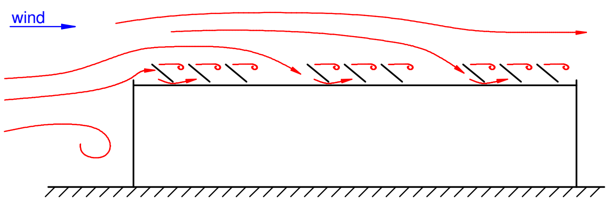


Figure 5. Wind flow in a gap between module rows

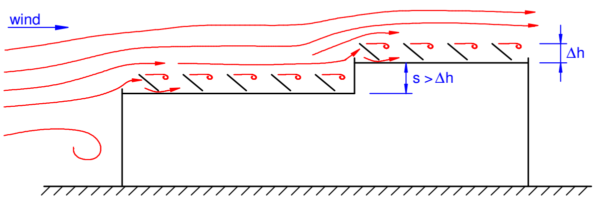


Figure 6. Wind action to the module on a roof step

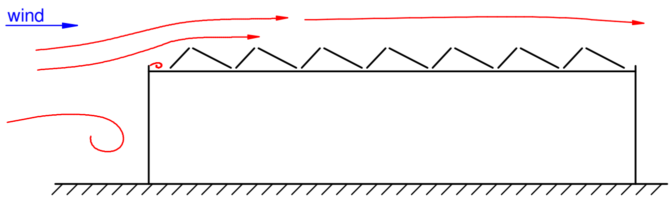


Figure 7. Module with wind safe deflector

A very complicated flow to the module occurs at wind directions towards the building corner. This flow produces the so called leading edge vortex system (Fig. 4). The rotating flow field with high speed generates suction and positive pressure on the modules with complicated pattern. The extreme suction at the modules is achieved near the corner of the building.

If one or more module rows are missing or if there is a space free of modules within the module arrangement, the wind flow is reorganized flowing down to the surface. The wind load is increased at least at the first row of the gap. Figure 5 shows the principle of the flow in the gap between module rows.

A step in the building roof has to be considered. The first rows of the module at the higher level will receive higher wind actions. If the step, s, is significantly higher than the height, $\Delta h$ of the module field, the first row has the maximum wind load. Figure 6 shows the principle.

A very successful possibility to reduce the suction load at the module is to install a wind safe deflector at the north side (Fig. 7). Depending on the design details the reduction of the wind load can be significantly, but it has to be taken into account, that the horizontal load increases by the wind load on the wind safe deflector and the structural material.

## 3 PRESSURE DISTRIBUTION AT THE MODULE

The wind pressure at the module is not homogeneously distributed. The distribution is similar to the pressure distribution at an airfoil respectively at a flat plate. The suction at the front side is larger than on the rear side. Figure 8 presents the real pressure distribution and the simplification for practical application for the suction case (north wind) and for the positive pressure case (south wind). This distribution causes an overturning moment to the supporting structure.

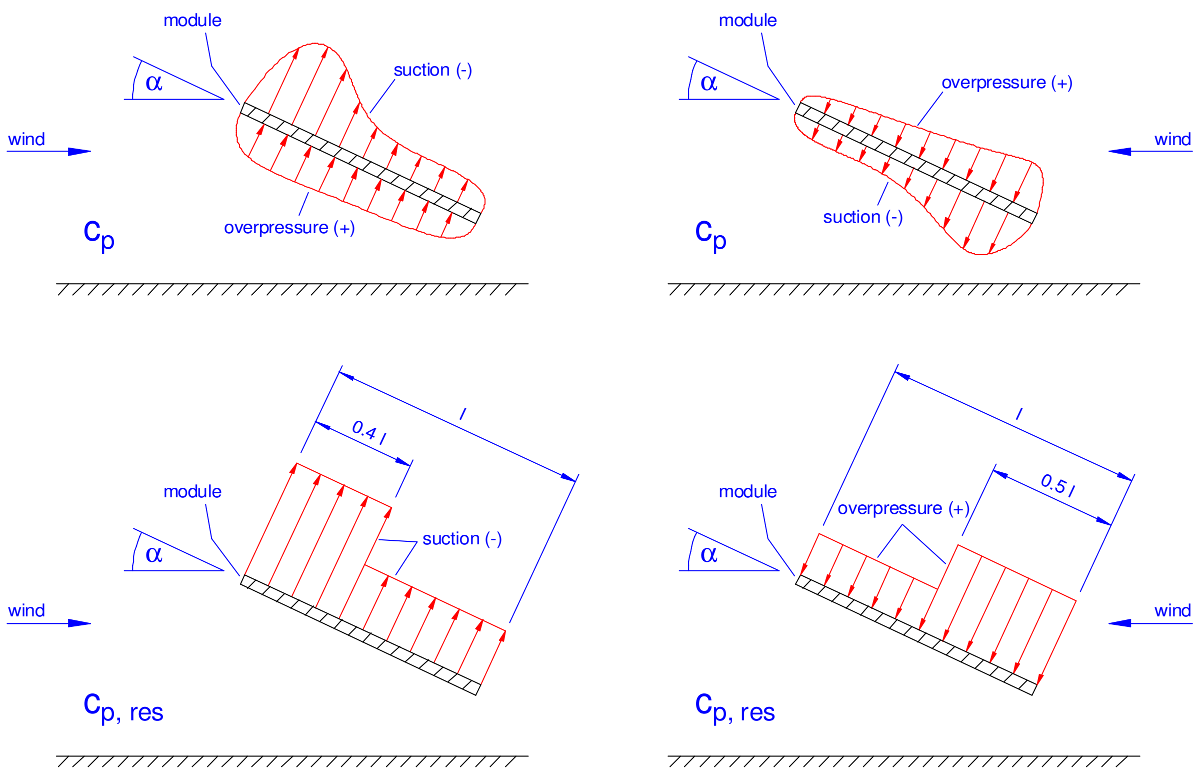


Figure 8. Pressure distribution at the module for wind directions from north and south, real distribution and simplification for practical application

## 4 WIND TUNNEL TEST

Several photovoltaic plants of different size and design have been investigated in the boundary layer wind tunnel of the Ruscheweyh Consult GmbH in Aachen, Germany. Figure 9 presents the test arrangement. The wind profile is generated by the Counihan method [7]. The model test has been performed with a boundary layer for a free field, presented in Equation 1:

$$\frac{v}{v_{ref}} = \left(\frac{z}{z_{ref}}\right)^{0,16} \qquad (1)$$

The longitudinal turbulence is shown in Figure 10.

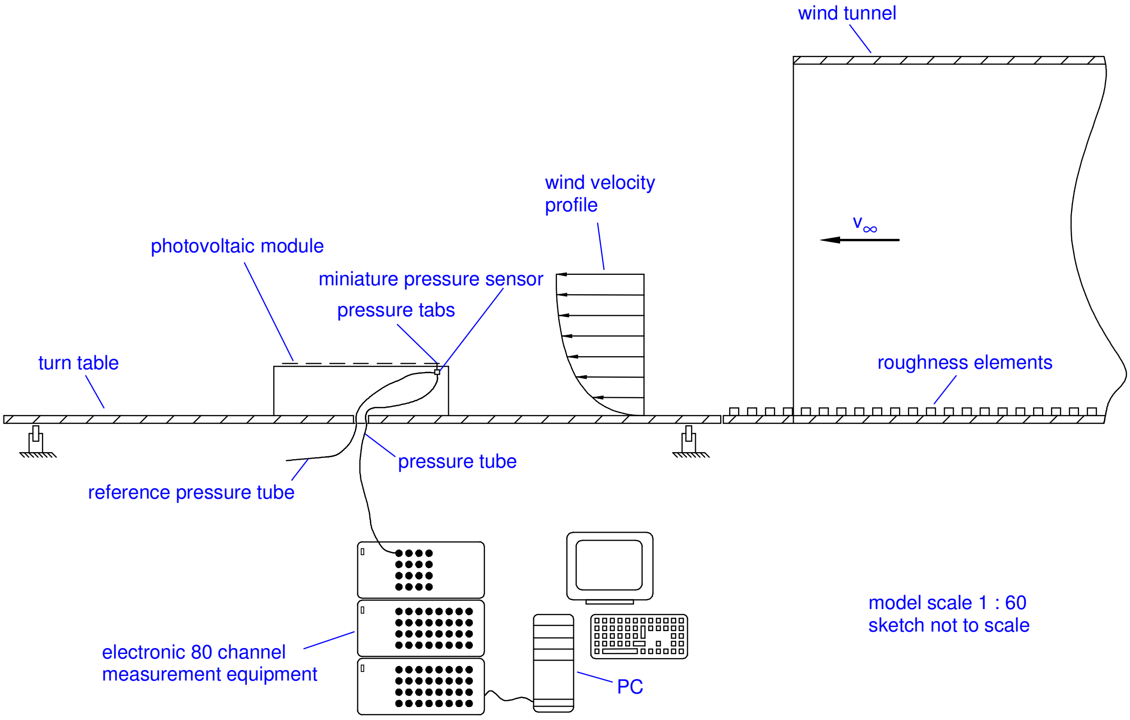


Figure 9. Test arrangement in the boundary layer wind tunnel of the Ruscheweyh Consult GmbH

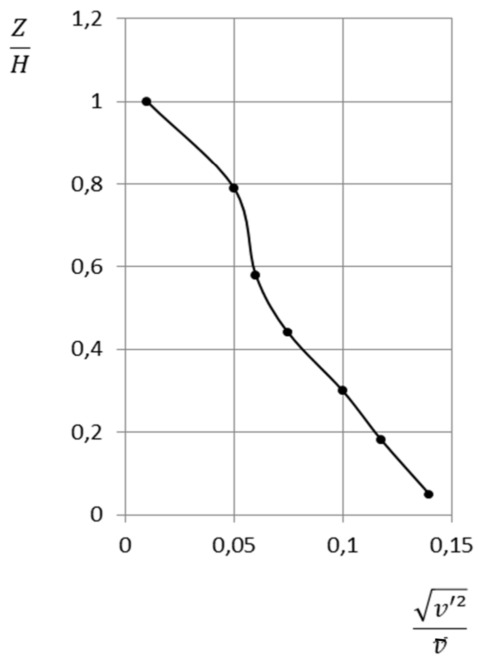


Figure 10. Longitudinal turbulence profile

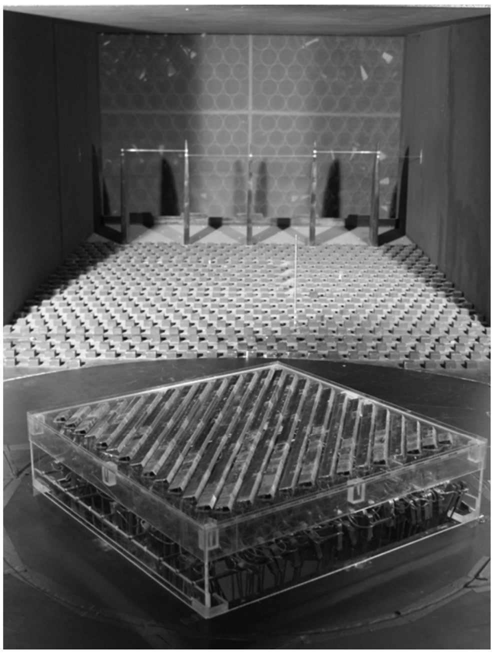

Figure 11. Model of a PV-plant in the boundary layer wind tunnel

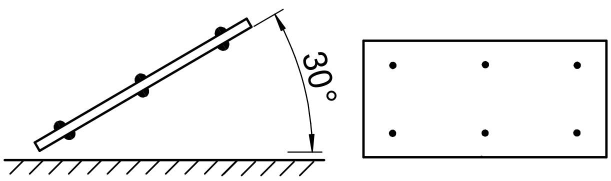


Figure 12. PV-measuring element with the pressure taps

A model of the PV–plant is fabricated in a scale of 1:50. Figure 11 shows the model in the boundary layer wind tunnel. In the background can be seen the elements for simulating the natural wind profile. The PV modules are simulated by brass and plexiglass elements. For measuring the wind pressure these measuring elements have pressure taps at the upper and lower side (Fig. 12).

The model is mounted on a turn table in order to simulate all wind directions. Pressure transducers are placed in a short distance below the modules. The pressure signals are transformed into electrical signals, which are sampled with a frequency of 10 kHz and stored as parallel time series in a computer. A number of 80 measuring values can be measured at the same time.

The analysis presents the non-dimensional pressure coefficient, cp which is calculated by Equations 2-3:

$$c_p = \frac{\Delta p}{q(h)} \tag{2}$$

where $\Delta p = (p_o - p_u)$ = pressure difference between the upper (o) and lower (u) side of the module; and q(h) = reference mean dynamic wind pressure at the upper level of the roof and

$$q(h) = \frac{\rho}{2} v(h)^2 \tag{3}$$

where $\rho$ = air density; v(h) = mean wind speed in the height, h, of the building roof; and h = height of the roof above ground.

## 5 WIND LOAD CONCEPT

### *5.1 The quasi-static Wind Load Concept*

The quasi-static wind load concept is applied. The concept is included in the german wind load code DIN 1055-4 as well as in the Eurocode EN 1991-1-4. The wind load is calculated by Equation 4:

$$w = c_{p,res} \cdot q_b \tag{4}$$

where w = wind load per m²; $c_{p,res}$ = resulting wind load coefficient; and $q_b$ = gust wind pressure.

The wind force, $F_i$, at a PV-module is calculated by Equation 5:

$$F_i = w \cdot A_i$$

(5)

where $A_i$ = effective wind load area of the module. It is identical with the module area, because the action of the wind load is always perpendicular to the module area.

The resulting wind load coefficient, $c_{p,res}$, consists of the pressure coefficients at the upper and lower surface of the module (Fig. 12) as it can be seen in Equation 6:

$$c_{p,res} = c_{po} - c_{pu} \tag{6}$$

*5.2 The stochastic Wind Load Concept*

The stochastic wind load concept is used for the local maximum wind loads, which are required for the fixing and supporting system of the modules. The extreme wind load is calculated by Equation 7:

$$(\max / \min w) = (\max / \min c_p) \cdot q_{m(h)} \tag{7}$$

where $(\max / \min c_p)$ = resulting extreme wind load coefficient from the wind tunnel test; and $q_{m(h)}$ = reference wind pressure from the mean wind speed in the height of the roof above ground.

In order to perform the calculation with the same gust wind pressure, $q_b$, as for the stationary loads, the extreme (instationary) coefficients from Equation 6 are transferred as follows in Equation 8:

$$(\max / \min c_p)_b = (\max / \min c_p) \cdot \left(\frac{q_m}{q_b}\right) \tag{8}$$

The analysis of the instationary load coefficients is based on a time sequence of 0.5 sec in full-scale.

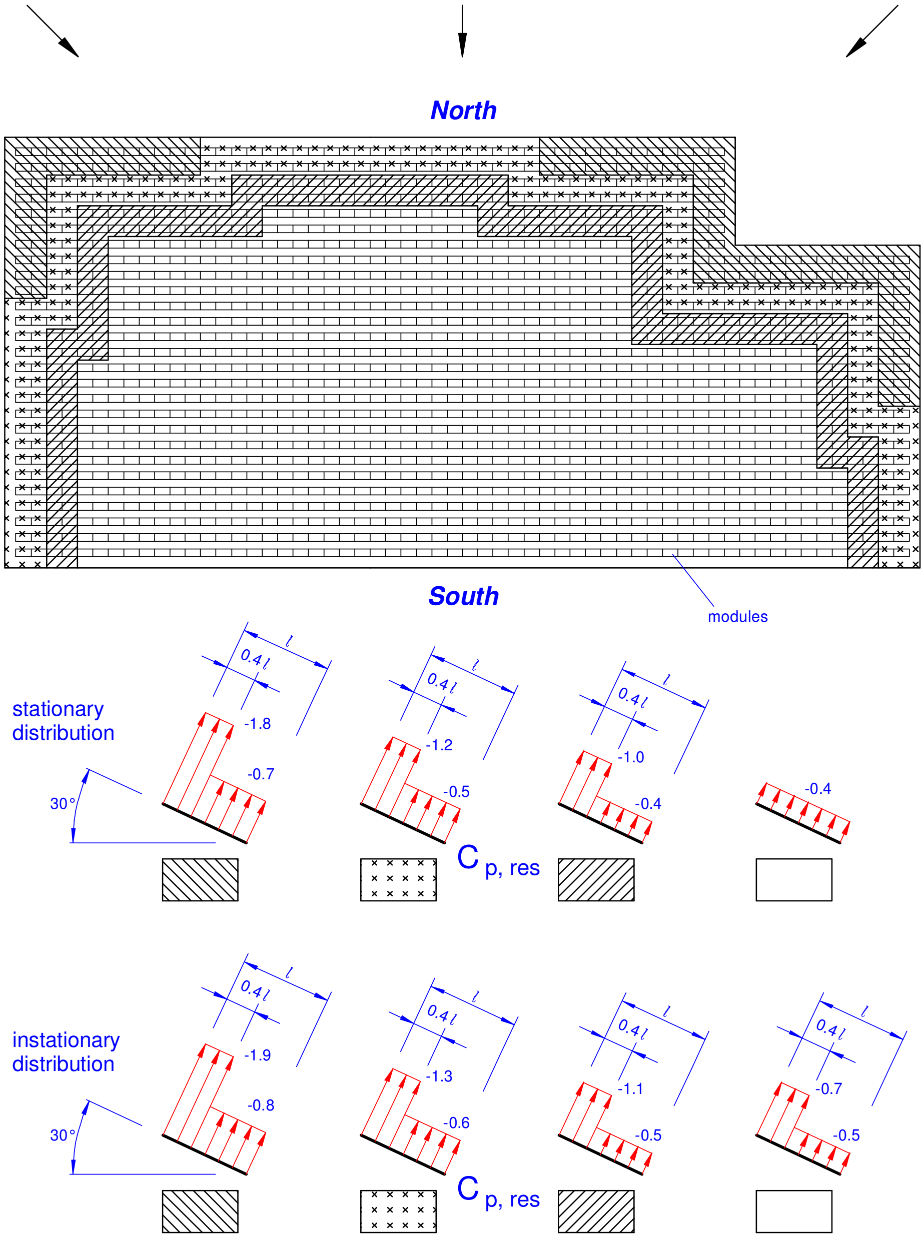


Figure 13. Wind load zones and wind load schemata, $c_{p,res}$ , of a large photovoltaic plant on a flat roof. No wind safe deflector installed at the north side.

# 6 RESULTS

All results have the same tendency: the modules at the rim of the module field, especially at the northern corner, have the maximum wind load. The wind load is reduced step by step because of the wind shadow effect and the whole rear field has a significantly reduced load. This fact enables the user to install large plants on sensible roof structures. Figure 13 presents a typical example of a photovoltaic plant on a flat roof. The module angle is $\alpha = 30°$. There is no wind safe deflector. The pressure coefficients, $c_{p,res}$, are given for the stationary case as well as for the instationary case. The stationary load is handled by Equation 4.

The instationary load is caused by gusts which may flow down locally and cause higher local load. They can act at every module. However, the correlation between the elements shows that the load peaks do not appear at the same time. The influence field is restricted to approximately 3 m x 3 m. If the supporting system of the modules has an extension larger than 3 m x 3 m, the neighbour region may be loaded with the stationary values.

# 7 SUMMARY

Because wind loads for solar and photovoltaic modules are not included in the national and international wind load codes, wind tunnel tests must be performed in order to define realistic wind load for these plants. The test show, that only the modules at the rim of the module field have higher wind loads while at the following modules the wind load decreases caused by the wind shadow effect. Numerous influence parameters have an effect on the aerodynamic load coefficients. An example of a photovoltaic plant on a flat roof is given for modules with a tilt angle of $\alpha = 30°$ and without wind safe deflector.

In the present time many innovative designs of support systems and module arrangements arise. This is a new and quickly developing market. The aim is to reduce the wind load in order to decrease or to avoid the ballast weight and to decrease the costs, which is very important for the future application of solar and photovoltaic systems. Therefore codification of the wind load is not appropriate, because fixed wind loads will stop or slow down the innovation of the development of new systems. Codification can be taken into consideration, if standard systems have been accepted by the majority of the user.

# 8 REFERENCES


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