BRE

digest

Wind loads on roof-based photovoltaic systems

Digest 489

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There is a little information and no authoritative guidance about wind loads on roof-based photovoltaic (PV) systems available to the designer. In the UK, determining wind loading on PV systems and their component parts tends to be based on experimental data, extrapolation of wind loading data intended for other building elements, or from design guidance for PV installations in other countries where the wind loads or construction practice can be quite different. This gives rise to a wide range of design wind loads and, sometimes, potentially unsafe designs.
This Digest reviews the wind loading information appropriate for roof-based PV systems and gives recommendations and guidance for the design of roof-based PV systems for wind loads. It has been developed from work undertaken during a Partners in Innovation project funded by the DTI; a list of the partners in this project is given on page 8.

Determining wind loads

Information is required to allow you to determine wind loads on individual PV modules, arrays of modules and supporting structures and fixings. This requires knowledge of extreme wind speeds expected at the particular site and appropriate pressure coefficients. The British Standard for wind loading on building structures, BS 6399: Part 2, gives methods for determining the gust peak loads on 'buildings and components thereof'. The equivalent European standard is EN1991-1-4. As there are no wind loading standards specifically for PV systems, BS 6399: Part 2 is the most appropriate for the UK although it will eventually be superseded by EN1991-1-4.

Determining wind loads is conceptually simple although quite complex in practice. The first step is to determine the basic mean wind; the next step is to determine the dynamic wind pressure for the particular site by applying a series of factors to account for terrain, topography, building height, etc. This dynamic wind pressure should embody all of the statistical parameters which govern the probability of occurrence of wind speed and hence the wind load. The wind force on the PV module is then obtained by multiplying the dynamic wind pressure by the area over which the wind load acts and pressure (or force) coefficients.

The dynamic wind pressure can be readily determined for any PV installation in the UK from BS6399, or from the simplified approach in this Digest. However, pressure coefficients are not so readily available because the BS does not specifically include values appropriate for PV systems. Therefore, the recommended values of pressure coefficients for PV systems given here have been derived using expert judgement and data from other published sources.

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Determine the design wind load

The general equation for the wind load, F, used in the design of roof-mounted PV systems is given in equation 1.

$$F = q_s \, C_{p,net} \, C_a \, A_{ref} \qquad \ldots (1)$$

where

- q_s is the dynamic wind pressure at the reference height H for the PV installation, which can be obtained from BS6399 or the simplified method given in this Digest. Unless otherwise defined, H can normally be safely taken as the maximum height of the roof (the height to the ridge) to which the PV system is attached
- $C_{p,net}$ is the appropriate pressure coefficient for the system under consideration
- C_a is the size effect factor from BS6399-2. C_a may be safely taken as 1.0
- A_{ref} is the loaded area for the system or fixing under consideration. For overall loads on individual PV modules, A_{ref} will be the area of the module exposed to the wind.

Simplified method to determine dynamic pressure, q_s

This simplified method has been derived from the methodology given in BS6399 and is based on four wind speed zones – see Figure 1. For zones I, II and III, obtain the wind dynamic pressure, q_s from Tables 1 and 2; obtain q_s for sites in zone IV from BS6399. The values given for zones I to III assume that the site is in open country terrain and so will give conservative values for sites in towns. Table 1 gives values for sites where topography is not significant, ie sites where the ground slope is <5% or where the site is less than halfway up a hill or ridge. Table 2 gives values for hilly sites where topography is significant.

Pressure coefficients

The pressure coefficients used to determine the design wind load depend on where the PV system is installed on the roof and on the particular generic type of PV system. For the purposes of wind loading design, there are four generic PV classes.

- nominally airtight PV modules integrated into pitched roofs;
- air permeable arrays of PV tiles/slates integrated into pitched roofs;
- PV modules mounted on or above pitched roofs;
- PV stands mounted on flat roofs (free standing or mechanically fixed).

Table 1 Dynamic wind pressure, q_s (Pa) for sites where topography is not significant

Zone	Building height (m)	Site Altitude, A metres above mean sea level: A <100m	100m ≤ A < 200m	200m ≤ A < 300m
I	5	891	1060	1244
	10	1036	1233	1448
	15	1120	1332	1564
II	5	1068	1271	1492
	10	1243	1480	1736
	15	1343	1598	1876
III	5	1262	1502	1763
	10	1469	1748	2051
	15	1587	1888	2216

Table 2 Dynamic wind pressure, q_s (Pa) for sites where topography is significant

Zone	Building height (m)	Site Altitude, A metres above mean sea level: A <100m	100m ≤ A < 200m	200m ≤ A < 300m
I	5	1569	1791	2028
	10	1826	2084	2360
	15	1972	2252	2550
II	5	1882	2148	2433
	10	2190	2500	2831
	15	2366	2701	3058
III	5	2223	2538	2874
	10	2588	2954	3345
	15	2795	3191	3613

Notes to Tables 1 and 2

❒ Interpolation may be used between building heights
❒ For every 100 m increase in site altitude above 300 m, multiply the values by 1.2
❒ For building heights greater than 15 m, use BS6399
❒ The values given in the tables do not include any factors of safety; these would normally be applied to the fixing resistance of the supplied PV systems. Since these are proprietary products, the manufacturers advice should be sought.

BS EN 61215 gives test methods to determine the electrical, thermal and mechanical characteristics of PV modules. This Standard specifies a mechanical load test of 2400 Pa applied for one hour to each side of the PV module. In some cases, the design wind pressure on PV modules in the UK will exceed this value. However, the duration of the design wind pressure is typically one second. It is likely that a PV module tested to 2400 Pa for one hour will be able to resist a greater short-duration wind pressure, although the extent of this additional load capacity will depend on the particular module design.

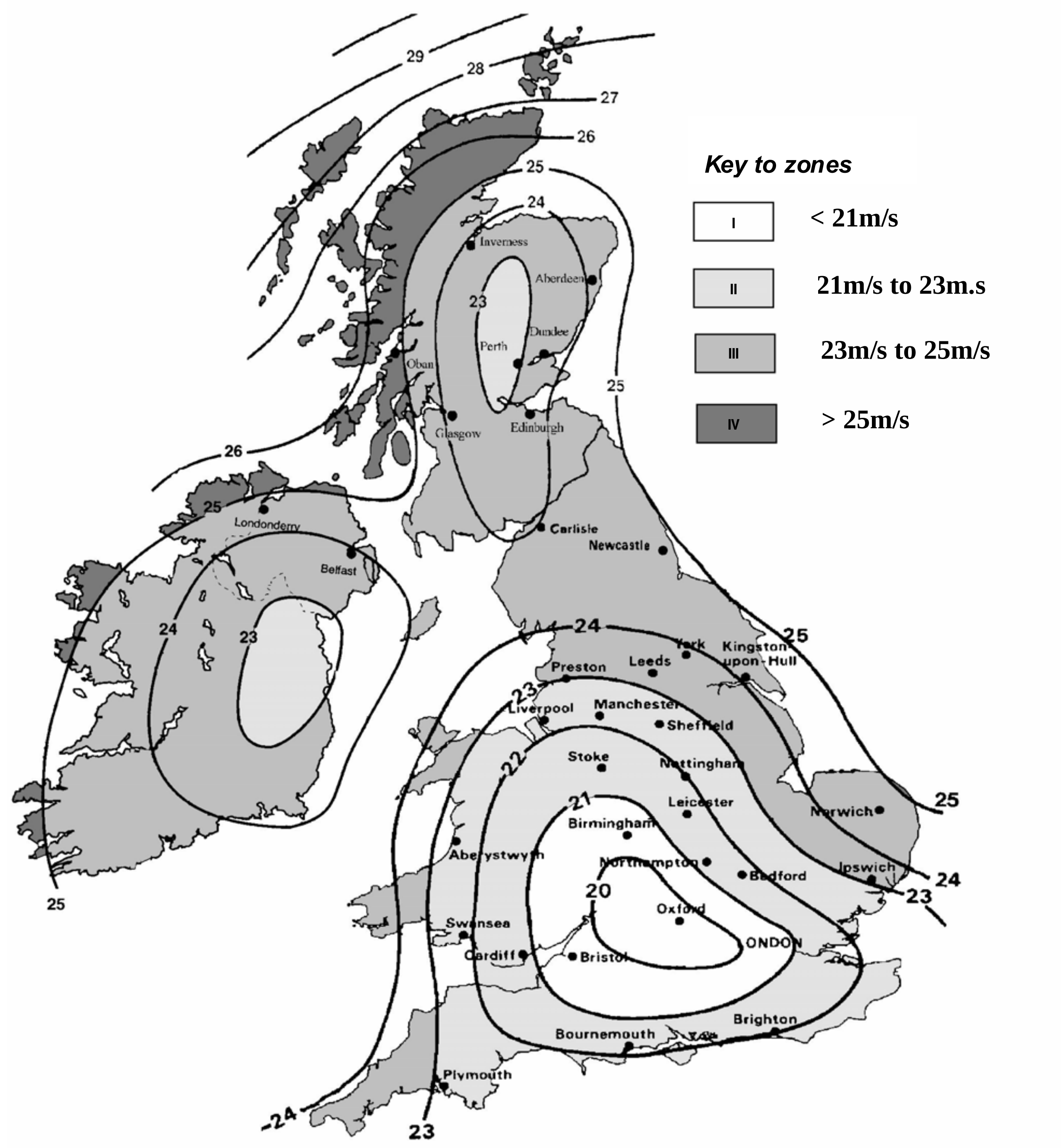


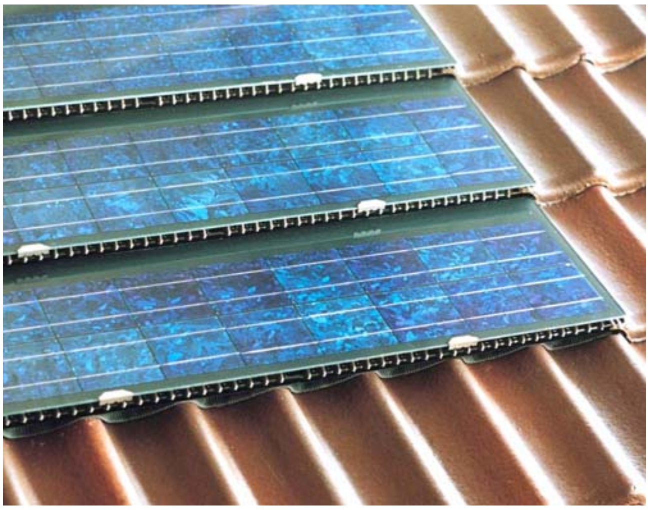
Figure 1 Map of UK wind speed zones for determining q_s from the simplified method

Nominally airtight PV modules integrated into pitched roofs

An array of PV modules that is nominally airtight and integrated into the roof so that it does not protrude significantly above the surrounding roof surface, can be treated as a normal part of the roof envelope. The internal and external pressure coefficients acting on the PV modules are determined from BS 6399 for the particular roof type (duopitch, hipped roof, etc) and the position on the roof (in the central or edge areas of the roof). Equation (1) is used to determine the wind loads.

Air permeable arrays of PV tiles or slates integrated into pitched roofs

Small format PV tiles or slates are intended to be integrated into a tiled or slated roof array; for the purposes of wind loading design, use BS 5534, provided the area of the individual PV units is no more than six times the area of the surrounding individual roof tiles (see box below). If the unit is more than six times the area of a tile in the surrounding roof, treat it as a nominally airtight system and use the procedure given for *nominally airtight systems* or seek advice from the manufacturer.



To determine the wind loads on PV tiles or slates, take account of the permeability of the PV array and the depth of the air space beneath the PV tiles. BS 5534 Annex L gives a test procedure for determining the air permeability factor D for a tile array. This method is also appropriate for small format PV tiles. BS 5534 gives a default value for D of 4.7 where no test data is available; use this value also for small format PV tiles where no test data is available. The BS also includes a substrate-shielding factor, S, to account for the depth of the air gap between the underside of the tiles and the underlay or board sarking. For PV tiles laid on battens over underlay, take the value of S as 1.0 and for systems laid on counter battens take S as the lesser of $1 + (d/200)$, or 1.25, where d is the depth of the counter-batten in mm.

BS 5534 uses modified pressure coefficients (called pressure difference coefficients) which take account of the combined effect of external and internal pressure coefficients and batten space flows. These coefficients are much smaller than those normally appropriate for non-air permeable roof coverings and should be used only when designing to BS 5534. Pressure difference coefficients are given in BS 5534 for common roof forms including duopitch, monopitch and hip roofs, and for central and local roof areas. Pressure difference coefficients vary with roof pitch but for convenience it is suggested that for PV tiles the following values of pressure difference coefficient, C_{pt}, are used:

The wind loading provisions in BS 5534 include a pressure reduction factor to account for partial pressure equalisation across the tile array. If the PV units are significantly larger than the surrounding roof tiles, the pressure reduction factor will become less applicable and the design could be unsafe. BS 5534 does not specify a maximum tile size; a maximum PV unit size of no more than six times the area of the surrounding roof tiles is assumed here.

- For PV tiles in all central roof areas, $C_{pt} = -0.14$
- For PV tiles in all local roof areas, $C_{pt} = -0.21$ (the width of local roof areas may be taken as 10% of the largest plan dimension of the roof).

There are no positive (downward acting) pressure coefficients specified in BS 5534 because it is assumed that these pressures are resisted by the roof structure (battens and rafters). If the PV tiles are significantly heavier than the roof tiles, assess the adequacy of the roof structure in combination with downwards acting wind pressures in accordance with BS 6399-1 procedures for dead and imposed loads. Equation (1) is not appropriate for this class of PV system; instead use a modified form as shown in equation (2).

$$F = q_s C_{pt} A_{ref} D S \qquad \ldots (2)$$

where D and S are the permeability factor and substrate shielding factor, defined above.

PV modules mounted on or above pitched roofs

These are a very common form of retro-fit installation in the UK. In principle it might be expected that PV modules mounted above a roof would be subjected to a relatively small wind load because they present a small frontal area to the wind; if the wind is parallel to the roof (which is a reasonable assumption in the central regions of the roof) the wind speed and hence the wind load should be similar on the top and bottom surfaces. This tends to cancel out to give a small net load. In practice, though, there is likely to be considerable resistance to wind flow beneath the modules due to the small gap between the underside of the module and the roof and additional blockage caused by the supporting brackets, fixings and electrical installations which will lead to larger net loads.

A series of wind tunnel and full-scale experiments were carried out [1] in the late 1970s to measure wind loads on solar collectors mounted above pitched roofs; Table 3 shows results. No information is given regarding the degree of blockage beneath the solar collectors.

The closest analogy to a roof-based PV system in BS 6399 is the flat canopy roof where the data are intended for free-standing canopies mounted on the ground. With PV systems, the gap between the roof and underside of the panels is likely to be of the order of 50 mm to 200 mm; it is unclear what effect this small gap will have on the wind loads. Table 3 gives the canopy roof data from BS 6399. The measurements

Table 3 Net pressures coefficients for PV panels based above pitched roofs

	Wind tunnel study	Full-scale study	BS6399-2 flat canopy roof data		
			Zone Ab[1]	Zone Bb[1]	Zone Cb[1]
Positive pressure	+0.83[2]	+0.97[2]	+0.5	+1.8	+1.1
Negative pressure	-0.94[2]	-0.73[2]	-0.6/-1.3[3]	-1.3/-1.8[3]	-1.4/-2.2[3]

(1) Zone A is the central roof area, Zone B is the side edge areas (parallel to the wind), Zone C is the windward and leeward edge area.
The width of the edge areas is taken as 10% of the largest plan dimension of the roof.
(2) These measurements were given as peak pressure coefficients; to be compatible with BS6399-2 they have been converted to mean pressure coefficients.
(3) The first value is for the case with the canopy fully open beneath; the second value is for the canopy fully blocked.

in Ref [1] were for solar collectors in the centre of a roof so they should be compared with the Zone A values from BS 6399. The measurements give higher suctions than BS 6399 for the fully open canopy but lower suctions when the canopy is fully blocked. Wind loads increase significantly near the edges of the roof.

Based on the data in Table 3, use the following net pressure coefficients for modules in the central roof areas for the design of PV modules mounted above and parallel to pitched roofs:

- Where the module is > 300 mm from the roof surface:

  $C_{p,net}$ for wind uplift = -0.7

  $C_{p,net}$ for downward pressure = 1.0

- Where the module is < 300 mm from the roof surface or where the space between the roof and underside of the module is blocked or there is any possibility of it becoming blocked by leaves or other debris:

  $C_{p,net}$ for wind uplift = -1.3

  $C_{p,net}$ for wind pressure = 1.0

These pressure coefficients are for modules mounted in the central regions of a pitched roof. If the module is close to the roof periphery (eaves, ridge or gable), the wind loads are likely to be significantly higher. There is no experimental data for this case, so use the pressure coefficients for Zones B and C in Table 3.

If the module is not parallel to the roof surface, determine the relative difference in angle between the roof and the module and obtain the pressure coefficients from the monopitch canopy data in BS 6399 for the appropriate difference in pitch between the roof surface and the PV module.

Use equation (1) to determine the wind loads on this class of PV system.

PV stands mounted on flat roofs

Flat roof-mounted PV stands can be either mechanically fixed to the roof, or free-standing relying on self weight and ballast to resist wind action. The wind pressure coefficients giving rise to wind uplift will be the same in both cases but for free-standing PV stands additional checks will have to be made for overturning and sliding.

PV stands on flat roofs can be classified as 'open' which have the top and bottom surfaces of the PV units exposed to the wind, or 'enclosed' that have side walls so that only the top surface of the PV modules are exposed to the wind. Such PV stands are not explicitly included in BS 6399 although it is possible that the canopy roof data might be appropriate for open stands and the fully clad building data might be appropriate for enclosed stands. However, pressure coefficients on this form of PV stand have received much more attention than other forms of installation and some reliable data is available. The most recent and probably the most appropriate is the study at TNO [2] in which pressure coefficients are given for PV modules mounted on 'open' and 'enclosed' supporting

Table 4 Pressure coefficients $C_{p,net}$ for PV modules based on open support structures

Roof zone	No parapet Negative C_p	No parapet Positive C_p	With edge parapet ≥ 200mm high Negative C_p	With edge parapet ≥ 200mm high Positive C_p
Corner	-1.8	1.2	-1.5	1.0
Edge	-1.6	1.2	-1.2	1.0
Central	-0.6	0.6	-0.6	0.6

Table 5 Pressure coefficients $C_{p,net}$ for PV modules based on fully enclosed support structures

Roof zone	No parapet Negative C_p	No parapet Positive C_p	With edge parapet ≥ 200mm high Negative C_p	With edge parapet ≥ 200mm high Positive C_p
A	-1.7	0.5	-1.7	0.5
B	-1.6	0.5	-1.2	0.5
C	-1.0	0.5	-1.0	0.5

Positive C_p values include an additional coefficient of -0.3 to account for the internal pressure within the supporting structure.

structures. Pressure coefficients are given for PV modules located in corner, edge and central roof zones, where the edge zones have a width of $L/10$ and the corner zone is where the edge zones overlap at the corner.

The worst case pressure coefficients measured on the PV modules in the TNO study for each zone and all wind directions are shown in Tables 4 and 5. Coefficients are also given for the case where there is a roof edge parapet 200 mm high. The TNO tests were all performed on PV units inclined at 35° but they should be generally applicable for pitch angles between 25° and 45°; outside this range they should be used with caution. Use equation (1) to determine the wind loads on this class of PV system.

For free standing PV stands, check for sliding and/or overturning of the PV support structure. Overturning forces will be resisted by the self-weight of the system and any ballast, see equation (3). Sliding will be resisted by the coefficient of friction between the base of the PV stand and the roof, see equation (6).

Design against overturning

For the PV stand to resist overturning, the restoring moment M_r due to self-weight and ballast must be greater than the wind overturning moment M_w, as shown in equation (3).

$$M_r > M_w \qquad \dots (3)$$

where the wind overturning moment is given by equation (4) and the restoring moment by equation (5).

$$M_w = (F_{upwards} \cdot L_U) + (F_{horizontal} \cdot L_H) \qquad \dots (4)$$

where

$F_{upwards}$ is the upwards acting wind force in Figure 2
L_U is the lever arm for $F_{upwards}$ in Figure 2
$F_{horizontal}$ is the horizontal wind force in Figure 2
L_H is the lever arm for $F_{horizontal}$ in Figure 2

$$M_r = W_{ballast} \cdot L_{ballast} + \Sigma(W_{self} \cdot L_{self}) \qquad \dots (5)$$

where

$W_{ballast}$ is the weight of the ballast
$L_{ballast}$ is the lever arm to the centroid of the ballast
W_{self} is the weight of the PV stand including the modules, frame and supporting structure
L_{self} is the lever arm to the centroid of the PV system from the point of rotation

It is recommended that a reduction factor of 0.9 is applied to the self-weight of the PV stand and the ballast.

Design against sliding

For the PV stand to resist sliding, the static resistance F_r due to self-weight and ballast must be greater than the wind force F_{wind}, given by equation (6).

$$F_r > F_{wind} \qquad \dots (6)$$

where the static resistance F_r is given by equation (7) and the wind force F_{wind} by equation (8).

$$F_r = \{(W_{ballast} + W_{self}) - (\cos\theta\, F_{upwards})\} \cdot \mu \qquad \dots (7)$$

where

μ is the coefficient of static friction (where no other information is available it is suggested that μ is taken as 0.3)
$\cos\theta$ is the pitch angle of the PV module

$$F_{wind} = \sin\theta\, F_{upwards} + F_{horizontal} \qquad \dots (8)$$

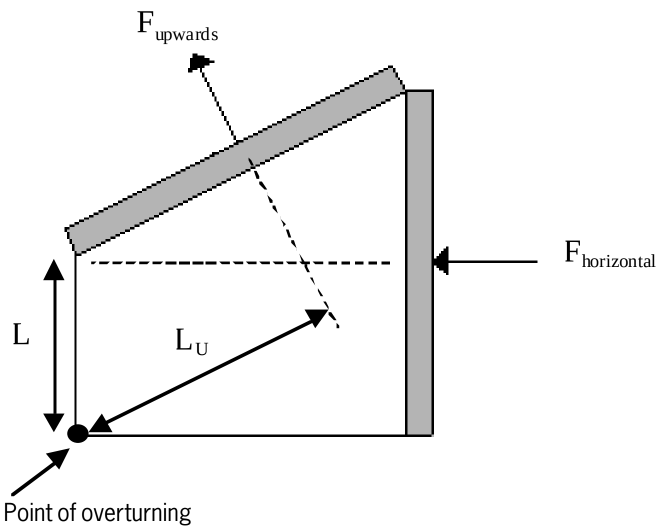


Figure 2 Definition of forces and lever arms for overturning moments

Performance requirements

There are four basic requirements for the performance of PV installations under wind loads:

- *Safety and serviceability of the exposed laminates.* Exposed laminates and their fixings should not fracture or otherwise fail under wind loads.
- *Safety of individual PV modules.* Individual PV modules should not fail or tear loose under wind action.
- *Safety of PV module supports.* The PV module support system, substructure and fixings should not collapse or pull-out under wind loads.
- *Safety and serviceability of the underlying roof structure.* Roof elements (rafters, battens, etc) which support the PV modules should be sufficiently robust to withstand the additional dead and imposed loading applied from the PV system

Susceptibility to fatigue may also need to be considered for free-standing PV stands although this is unlikely to be a problem for roof integrated PV modules.

These should all be considered when designing roof-based PV systems.

Example calculation: a PV array mounted above a pitched roof

The PV array is mounted150 mm above the roof surface in the central roof area
PV array size 2 m x 2 m
The site is in Brighton (Zone II in Figure 1)
Building ridge height = 10 m
Site is on level ground
Site altitude is 50 m above mean sea level

Determine the wind force from equation 1

$F = q_s\ C_{p,net}\ C_a\ A_{ref}$

The dynamic wind pressure q_s = 1243 Pa
(From Table 1 for a building 10 m high in zone II at an altitude ≤ 100m)

$C_{p,net}$ = -1.3 (uplift) and 1.0 (pressure) (using recommended values)

C_a = 1.0
A_{ref} = 2 m x 2 m = 4 m^2
F = 1243 x -1.3 x 1.0 x 4.0 = -6,464 N (upwards acting)
F = 1243 x 1.0 x 1.0 x 4.0 = 4,972 N (downwards acting)

The PV module and its fixings should be designed to withstand an uplift force of 6464 N and a downwards acting force of 4972 N. If the panel is supported by (say) four hooks, each hook, its fixings and the supporting roof structure should be designed to resist a quarter of the wind force.

Example calculation: a small-format, loose-laid PV tile integrated into a pitched roof

The PV tiles are 1000 mm x 325 mm installed in the central area of the roof
The site is in Carlisle (Zone III in Figure 1)
Building ridge height = 7 m
Site is on level ground
Site altitude is 150 m above mean sea level

Determine the wind force from equation 2

$F = q_s\ C_{pt}\ A_{ref}\ D\ S$

The dynamic wind pressure q_s = 1600 Pa
(Interpolated from Table 1 for a building 7 m high in zone III at an altitude ≤ 200m)

C_{pt} = -0.14 (using recommended values)
D = 4.7 (using recommended value)
S = 1.0 (no counter battens)

A_{ref} = 1000 mm x 250 mm = 0.25 m^2 (assuming 75 mm headlap)

F = 1600 x -0.14 x 4.7 x 1.0 x 0.25 = -263 N

Each PV tile and its fixings should be designed to resist an uplift force of 263 N. Because each PV tile is interlocked with surrounding PV tiles or roof tiles, failure under wind action will not be straightforward uplift: they will tend to rotate about the batten. To determine the required strength of the fixings, equate the overturning moments (due to wind action) to the restoring moments due to the self-weight of the PV tiles plus the resistance provided by the fixings (nails, screws or clips). Clips attached to the tail end of the PV tiles will provide much more resistance to wind action than head fixings, such as nails and screws. BS 5534 (Annex G and Annex I) gives procedures for calculating the resistance to wind uplift of clips and nails.

References and further reading

[1] Cattaneo L, Harris J, Reinhold T, Simiu E, Yancey C. *Wind, Earthquake, Snow, and Hail Loads on Solar Collectors.* Centre for Building Technology, National Engineering Laboratory US Dept Commerce, NBS, NBSIR 81-2199, 1981.

[2] *Windbelasting op zonnecollectoren en zonnepanelen op plat-dak opstellingen, Deelrapport: Experimentele bepaling van de ontwerp-windbelasting.*
TNO Report 2002-BS-R0061, 2002. (in Dutch).

British Standards Institution

BS 5534: 2003 Code of practice for slating and tiling (including shingles)

BS 6399 Loading for buildings. Part 2: 2002 Code of practice for wind loads

EN1991-1-4 Eurocode 1: Actions on structures – Part 1.4 General actions – Wind actions.

EN 61215 Crystalline silicon terrestrial photo voltaic (PV) modules - design qualification and type approval

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