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Double-layer orthogonal-offset photovoltaic platforms

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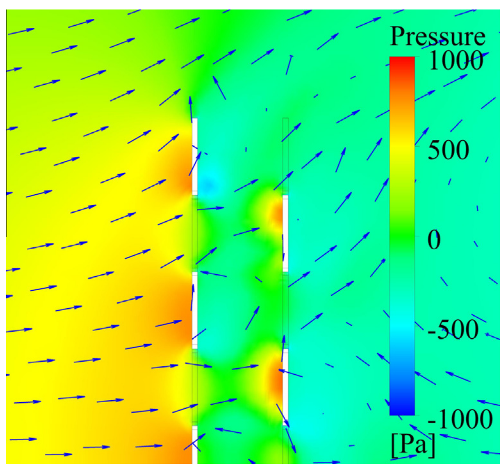
HIGHLIGHTS

- Double-layer orthogonal-offset platforms are a novel arrangement of PV or CPV modules.
- The novel arrangement offers BOS advantage by decreasing mounting system costs.
- Case study shows 30% more PV modules on novel system for the same wind loading.
- The novel system has been verified by experimental tests and computational analysis.

GRAPHICAL ABSTRACT



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ABSTRACT

Photovoltaic panels used for power generation are subject to significant wind loads of concern to mounting systems. A novel method of arranging photovoltaic surface in layers of non-overlapping panels is proposed for tracking systems to reduce wind load forces. The potential of this approach is assessed for double layer systems called DLOOP using Computational Fluid Dynamic turbulence modelling and wind tunnel tests.

A consistent pattern of wind-force reduction is found as distance between double layers is increased up to and beyond the scale of the integrated panels' side length.

A 49 panel DLOOP arrangement when tested in high winds had the potential to carry 30% more panels than a single layer arrangement of side by side panels for equivalent wind loading.

1. Introduction

The installed cost of photovoltaic (PV) systems for both residential and commercial customers has been falling for decades. In the USA it is reported that between 1998 and 2013 average annual decrease has been 6–7% [1,2]. Since 2008 the cost of PV modules in systems has been falling fastest at 35% p.a. and based on 2011 costings it now makes up less than 21% of total median installed price for systems in the USA of ⩽10 kW [3]. This shift to the cost base of PV energy systems puts the focus on Balance Of System (BOS) factors – i.e. everything other than the PV modules such as

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installer business costs, customer acquisition costs, land, insurance, finance, administration/approvals permitting/connection, labour, inverters, wiring and mounting systems – to bring total cost of PV energy systems down.

This paper reports research concerning Double-Layer Orthogonal-Offset Platform (DLOOP) technology proposed to reduce the BOS costs of mounting systems with tracking. The technology aims to achieve this by reducing the force exerted by wind on PV platforms. The additional energy output of a PV system obtained by tracking must be offset against the BOS cost of the mechanism providing the tracking function. If the economic benefit of a mounting system providing tracking falls below that of the additional fixed modules and mounts of a comparable system then it is no longer cost competitive and will disappear. Tracking systems will choose to integrate high performance modules to maximise their multiplicative advantage over fixed systems. Fixed systems have the advantage of a niche where roofs of buildings exist and are compatible with PV demands however such foundations are not arbitrarily found or replicable in the field the way mounting systems providing tracking are [4].

Costs are discussed more fully later, following presentation of DLOOP efficiency results in Section 7, but maximum wind-load force on PV panels in service significantly exceeds that of their weight and therefore the cost of tracking mounts is proportional to high wind pressure rather than panel mass (or numbers), see Table 1 figures.

The wind-load characteristics of various DLOOP configurations, relative to reference side-by-side panel arrangements, are investigated by Computation Fluid Dynamic (CFD) analysis and wind tunnel tests. Details of these investigations follow in Sections 4 and 5, and entail:

- a broad exploration of DLOOP performance with geometry and module numbers varied;
- a DLOOP case study adopting commercial modules chosen to illustrate BOS saving potential; and
- physical tests of models to underpin analysis findings.

Before going into the specifics of the novel mounting system the emergence of commercially produced higher performance Concentrator-PV (CPV) modules [5] is likely to have a growing impact on future tracking. The CPV modules are about 4× smaller, 1.5× as efficient and 1.5× heavier than ubiquitous glass, Tedlar encapsulated high efficiency mono-crystalline (Single-Si) PV modules [6,7]. They are heavier because of integrated optics which also require them to constantly track the sun atop precise dual-axis mounting systems. For these next generation CPV modules, whose Shockley–Queisser theoretical efficiency limit doubles other technologies at 63% [8], there is a strong incentive to consider tracking the sun all the way to the horizon. In return such tracking systems will increase insolation during morning and evening daylight shoulders and increase overall yield, for example that of polar Single-Si tracking installations by a further 60% [9–11]. Therefore, producing a lighter accurate tracking system is key for the development of CPV systems.

2. Wind forces on plates

The force (F) of a fluid on a body is given by:

$$F = \frac{1}{2} C_R \rho A u^2 \quad (1)$$

where: C_R is the resultant-force coefficient, ρ is the density of the fluid (air), A is the body area and u its relative velocity. Resultant force coefficients are determined experimentally by measuring body forces in relevant conditions but may be otherwise estimated by computation.

Table 1
PV module standard mounting pressures.

Module reference	Mass (kg)	Weight/face area	Wind pressure[a]
Semprius SM-1	7.3	236 Pa	545 Pa
Soitec CX-M500	210	235 Pa	545 Pa
Suncore DDM-1090X[b]	56.4	294 Pa	545 Pa
Sunpower 327[c]	18.6	112 Pa	545 Pa

[a] Wind speed 27.8 m/s [60 mph] within 45° of face normal.
[b] Similar to Emcore G3-1090X modules.
[c] A high performance (non-C) PV module.

This paper aims to determine whether wind-load on contiguous side-by-side PV modules can be reduced by separating and distributing the modules across two layers with the constraint that no part of any plate be allowed to overlap another – the latter is important to avoid shade on solar modules when tracking.

The resultant-force coefficient of a square plate with its normal parallel to flows has a well established value just below 1.2 [12–15] and increases a few percent with flow turbulence [16]. While the magnitude of a fluid's force on most asymmetric objects varies greatly with orientation, for an obstructing flat plate the fluid-force remains normal and of constant magnitude over a very considerable angular range. This unusual feature of plate aerodynamics is shown in Fig. 1 [13,15,17] where:

- angle-of-attack (α) is measured between the flow direction and the plate's surface, i.e. $\alpha = 90^\circ$ when perpendicular (or parallel to its normal), and
- the normal force coefficient (C_N) is equal to the resultant-force coefficient (C_R) in the sector of high wind-force levels, i.e. $45^\circ < \alpha < 90^\circ$.

Of great significance to PV mounting structures this aerodynamic behaviour of plates means, for example when discounting the influence of neighbouring objects, that all side-by-side platforms facing south with any elevation angle greater than 45° will experience the same magnitude wind-force in northerly winds.

Plate wind-forces may also depend on side-length or aspect ratios, e.g. $C_R = 1.98$ for an infinitely wide rectangular plate. In the reduced aspect ratio range of commercial PV panels however C_R is relatively constant and reaches only 1.4 with aspect ratios near 1/10 [14, Fig. 3–28].

However, if two disks are placed one behind the other the resultant-force coefficient has a minimum as reported by Eiffel [12], and Hoerner [14]. As the distance between two disks increases, the shielding effect of the front plate causes the drag of the second one to become negative at separations of 1–2 times the disk diameter, as shown by Hoerner's graph reproduced in Fig. 2.

DLOOP technology seeks to extend this two disk shielding effect to double layer PV platforms and thereby achieve a lower C_R than a contiguous PV surface of equivalent area. It is conjectured that:

- if a plate is subdivided into smaller rectilinear elements (tiles) – *like the grid of a chessboard* – that are then moved to complementary overlaying layers a distance (d) apart – *light tiles in one layer and dark on other*; then
- the C_R of this arrangement can be significantly lower than that of the original plate of the same surface area.

The principle is illustrated by tile arrangements in Fig. 3 where $d = 0$ between the blue and grey tile layers in a side-by-side platform and $d > 0$ in the 3 × 3 DLOOP arrangements.

The C_R of DLOOP depends on the distance between layers amongst other features. If $d = 0$ then C_R of a contiguous plate is