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A method to calculate array spacing and potential system size of photovoltaic arrays in the urban environment using vector analysis

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HIGHLIGHTS

- A new methodology to calculate array spacing via vector analysis is presented.
- The methodology covers any combination of PV array and surface tilt and orientation.
- The presented methodology is confirmed against ray tracing methods.
- The presented methodology is implemented within APVI's Solar Potential Tool.

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ABSTRACT

The standard mathematical approach used to calculate photovoltaic (PV) array spacing contains a number of assumptions that limits its use to PV arrays installed on horizontal surfaces. This paper utilises vector analysis to develop a new method to calculate array spacing and potential system size for any combination of PV array and surface tilt and orientation. This approach is validated by comparing the vector results with ray-tracing shadow visualisations utilising the Ecotect software package. The vector method is presented as an approach compatible with online solar/PV mapping tools after a review of the existing online tools indicated that rack mounted array functionalities were rarely included. The methodology is further demonstrated via results from the Australian PV Institute's (APVI's) Solar Potential Tool which utilises the array spacing method presented. This paper also applies the methodology to a general analysis of array spacing and power density (installed capacity/unit area) for an optimally tilted equator facing array on roof surfaces of a variety of tilts and orientations.

1. Introduction

The availability of, and interest in web based solar (irradiance) and photovoltaic (PV) mapping tools at city and building surface scales has increased significantly over the past decade. The maps to date have primarily been developed to engage interest in PV and to educate the general public about its benefits and costs [1]. Since irradiance maps and PV output calculators for building surfaces enable remote PV site assessment, these tools have also generated a strong interest from installers within the solar community. At the city scale, irradiance and PV maps have found additional uses such as the assessment of PV deployment in network areas [2] and the integration of solar energy into cities' emergency planning strategies [3].

The increase in the prevalence and use of solar and PV mapping tools at the city and building scale highlights the need for a review of the methodologies and assumptions used to develop these maps and their associated level of accuracy for predicting irradiance, estimating potential PV system size (or capacity) and associated PV performance. Reviews of existing solar maps presented in the literature [4–6] list the methodologies used by a range of maps to estimate irradiance, categorise the performance of different roof spaces and other features available on the maps. These reviews, however, do not investigate methodologies used to estimate potential PV system size. The allowable PV system size for any site depends on the tilt and orientation of the modules, and the spacing required to avoid self-shading, at least for the hours during which the majority of solar irradiation occurs. In addition, the tilt and orientation of the underlying surface alters the extent of self-shading, and therefore array spacing and potential system size.

The solar maps listed within the current literature [4–6] were reviewed for this paper, in order to determine the methodologies

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and assumptions used for estimating the potential system size of PV arrays. The results of the review are presented in Tables A.1 and A.2 within Appendix A. While most of the existing solar maps do not provide detailed documentation of the methodologies and assumptions used, the review indicated that the majority of the existing maps either did not consider rack mounted arrays, or simplifications were employed to enable the calculation. The simplifications employed included (1) the use of rack mounted arrays only on horizontal surfaces; (2) calculations for rack mounted arrays only at fixed optimum tilt and orientation angles for the map's location; and (3) the use of a fixed percentage of useable surface area to account for the spacing required between the rows of PV modules in the rack mounted PV array (e.g. 40% for the Aachen [7] and Berlin [8] solar maps in Germany and 33.33% for the Amersfoort [9] solar map in the Netherlands). Although a subset of the maps had the functionality to adjust tilt angle and orientation of the PV array, the adjustment of these two parameters did not alter the estimated PV system size in any of the maps reviewed. The review indicated that only the New York City (NYC) Solar Map [10] accounted for variations in the estimated system size based on the tilt angle of the underlying surface, but not the impact of the underlying surface orientation or the tilt and orientation of the PV array. The most advanced maps for system size calculation were the Dusseldorf [11] and Arnhem [12] maps, which in expert mode allowed the user to define the system tilt, orientation and whether any spacing between modules and rows of modules existed. These maps however did not provide any guidance for what the spacing between the rows of PV modules should be to avoid shading and system performance losses. It appears that only flush mounted PV array configuration and simplifications for rack mounted arrays are employed by the majority of the existing solar maps due to the complexity of calculating array spacing and hence PV system size for any combination of PV array and surface tilt and orientation, and the absence of published relations for these calculations.

This paper presents a methodology to estimate the required array spacing for rack mounted PV arrays via vector analysis. This approach is validated by comparing the vector results with ray-tracing shadow visualisations utilising the Ecotect software package. In addition this paper details how the presented methodology can be implemented within a GIS solar map to estimate potential system size for rack mounted PV arrays.

2. Standard PV array spacing calculations

Within the existing literature, the simplest mathematical approach to calculate array spacing for a rack mounted PV array uses Eqs. (1)–(3) [13,14] for PV systems orientated towards the equator (see Fig. 1). The required equations are

$$S = H/\tan(VSA) \tag{1}$$

$$\tan(VSA) = \tan\alpha_s/\cos\gamma_s \tag{2}$$

$$H = W_p \sin\beta_a \tag{3}$$

where S is the array spacing, VSA is the vertical shading angle between the sun and the array, H is the height of the tilted module, W_p is the array row width, γ_s and α_s are the azimuth (0–360° from North) and altitude angles of the sun and β_a is the tilt angle of the PV array relative to the horizontal frame of reference. Typically the sun's position, in terms of azimuth and altitude, at 10 am or 2 pm on the Winter Solstice are used for the calculation of array spacing [13]. These times are typically chosen to ensure that no self-shading of the PV array occurs between these hours on the winter solstice (generally a worst case scenario for PV systems orientated towards the equator, as self-shading is increased due to the low altitude angle of the sun). These equations can however be utilised to calculate the array spacing required to avoid shading at any specific time of the year and sun position.

Eq. (2) is used to calculate VSA, but it only holds true when the PV array faces the equator and is mounted on a horizontal surface. However, Eq. (2) is easily modified to allow for the calculation of the array spacing for a PV array of any orientation when mounted on a horizontal surface as per Eq. (4) [14–17],

$$\tan(VSA) = \tan\alpha_s/\cos(\gamma_s - \gamma_a). \tag{4}$$

where γ_a is the orientation of the array (0–360° from North). Typically, Eqs. (1), (3) and (4) are often utilised together in a slightly different form for the calculation of shadow lengths and heights in fixed, single and double axis tracking PV field optimisations [18–21]. Other studies have also investigated the optimal array spacing using a variety of methods [22–24] from the utilisation of the PV modelling package PVsyst [24] to implementing the algorithms across various time horizons [22]. Similarly, several articles have

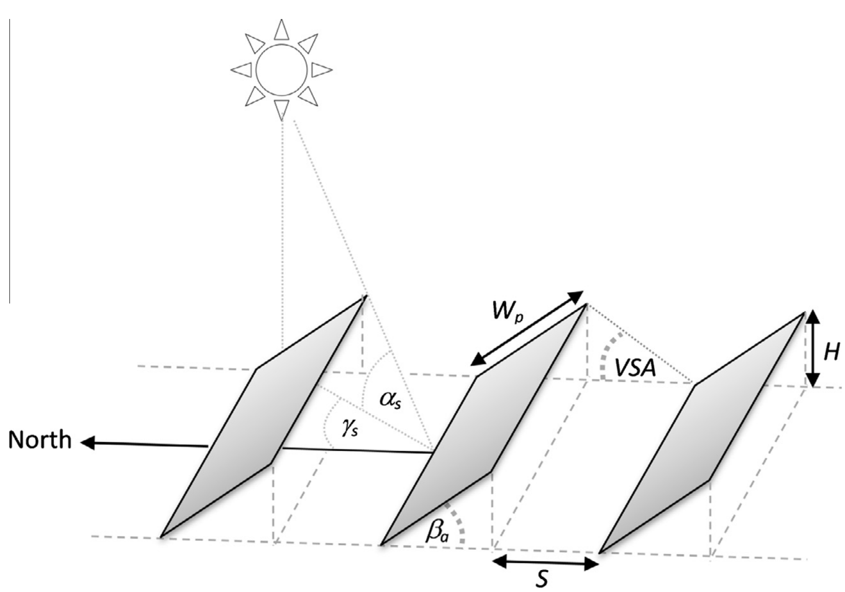

Fig. 1. North facing (Southern hemisphere) tilted PV array consisting of three rows on a horizontal surface.