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An optical-energy model for optimizing the geometrical layout of solar photovoltaic arrays in a constrained field

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ABSTRACT

The number of rows of photovoltaic (PV) modules in a field are limited by the area available for installation. With the objective of achieving maximum solar energy collection by the modules, determining the geometric layout becomes an optimization problem that couples the tilt angle and inter-row spacing. The existing optimization methods are simplistic as they consider tilt angle and inter-row spacing as constant values for all rows. This paper presents an optical-energy model for determining the optimal geometrical layouts of PV arrays by considering different tilt angles and row spacings for every row, given a field constraint. It is comprised of two sub-models: (i) an optical sub-model that determines mutual shading and (ii) an energy sub-model that evaluates the yearly solar energy collection. Optimization was performed by proposing random layouts for the model and using the one that yielded the maximum yearly collection. A situation in which the proposed model can be used as a powerful tool for optimization is explained via a case study conducted in Auckland, New Zealand. The effects of maintaining either a constant tilt angle or a safe row-spacing on year-round performance are investigated.

1. Introduction

Solar energy is the most abundantly available form of renewable energy on earth [1]. It is sustainable, free and can be converted directly into electricity using photovoltaic (PV) modules [2]. Depending upon the electric energy demand, more than a single PV module may be required to fulfill the requirements [3]. For industrial and commercial scale electricity production, several parallel rows of these modules may be required, known as arrays, which are installed facing north or south in fields in the southern or northern hemispheres, respectively.

The arrays are inclined at an angle to maximise solar energy collection during a given time frame. Several studies have been conducted in the past to determine the optimum value of the tilt angle. The methods generally employed include algorithms that sweep through the angles from 0º to 90º [4–8]; the Maximization Algorithm [9]; Genetic Algorithm [10,11]; Simulated Annealing [12]; Particle Swarm Optimization (PSO) [13]; Ant Direction Hybrid Differential Evolution Algorithm [14]; Harmony Search Algorithm [15]; and Artificial Neural Networks [16,17]. Frequently, the optimum tilt angle for year-round performance is equal, or close to, the latitude angle of the field [18,19]. However, the analyses in these methods assume a single module with no obstructions in its surroundings. Hence, they do not account for losses due to mutual shading (shading by preceding rows). This phenomenon is a common problem in arrays and needs to be addressed; it creates complications for module-level power electronic conversion systems, e.g. Maximum Power Point Trackers (MPPT) in efficiently extracting power from the PV array [20].

A few studies have investigated the effect of mutual shading on the design of solar collector fields. Bany and Appelbaum [21] and Jones and Burkhart [22] found that the latitude angle of the field, the modules' dimensions, length of rows, tilt angle and inter-row spacing are the key parameters contributing to the length and shape of the shadows. These factors also limit the number of rows that can be installed in any given field. However, the previous studies assumed that the tilt angle and the inter-row spacing, whether given or optimized, was constant for all rows.

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Nomenclature

A	Surface area of module (m^2)
E	Energy collected by a module (kJ)
E_{site}	Year-round energy collected by all the modules in the field (GJ)
G	Normal solar beam irradiation (kJ/m^2)
H	Horizontal dimension of module (m)
L	Length of field (m)
M	Number of modules in each row
N	Number of rows of modules in a field
n^-	All the rows before the row in observation
$\widehat{P}$	Unit vector representing normal to the module
$\widehat{S}$	Unit vector representing position of sun
V	Vertical dimension of module (m)
W	Width of field (m)
Y	Coordinate of the intersection of shadow with the module's foot (m)
b	Lit condition of module
d	Numberth of day of the year
j	Length of the projection of module on ground (m)
l	Distance of module from northern edge of field (m)
m	Numberth of module in a row
n	Numberth of module row
s	Shadow length of module (m)
t	Hour of the year (hr)
y	Coordinate of the module's foot (m)
α_s	Altitude angle of sun (degrees)
α_{so}	Altitude angle of sun on the shortest day of year during noon (degree)
β	Tilt angle (degrees)
γ_s	Azimuth angle of sun (degree)
Δ	Row-spacing (m)
δ	Declination angle (degree)
θ	Incidence angle (degree)
φ	Latitude angle of field (degree)

Interestingly, this assumption has continued in all subsequent studies, where regardless of other variables, tilt angles and inter-row spacings were held constant for all rows. For example, Appelbaum and Bany [23] developed an approach for obtaining the optimum number of rows by observing the changes in energy collection after varying the inter-row spacing. However, the tilt angle was used as an input to the model rather than a variable to be optimized. Similarly, Weinstock and Appelbaum [24] investigated maximising energy collection and sets of constraints coupling the number of rows. Later, Sadineni et al. [25] evaluated minimum inter-row spacing, which was again kept constant for all rows in an inclined solar field with a fixed tilt angle, with the objective of maximising solar energy collection. Copper et al. [26] presented a vector-based method to calculate an optimized inter-row spacing and system electrical size for any surface tilt and orientation, which was validated by comparing the results with ray-tracing shadow visualizations in the Ecotect software package. d'Alessandro et al. [27] presented an automated tool for quickly evaluating the yield of a PV plant accounting for mutual shading loses. Martín-Chivelet [28] proposed a method for maximising the yield based on the optimizing the packing factor, defined as the ratio between the area of PV array and the installation area. The optimum value of the tilt angle was estimated using a correlation based on the latitude angle of the site, while the inter-row spacing was minimized by setting the shading losses as the primary criteria. Appelbaum [29] concluded that the vertical bifacial modules facing east-west in a field, separated by a fixed inter-row spacing, receive maximum solar radiation. Horoufiany and Ghandehari [30] presented a scheme for enhancing the power output of an array considering the mutual shading conditions. However, it was assumed that all the rows were facing nearly south, with the same tilt angle and inter-row spacing. Alsadi and Nassar [31] developed an approach for evaluating the solar irradiance received by a field having PV modules separated by constant spacing. The tilt angle was held constant while simulations were performed to assess the influence of electrical and geometrical design parameters on the performance and profitability of the solar field. Sánchez-Carbajal and Rodrigo [32] optimized inter-row spacing, normalized over the field's length, to

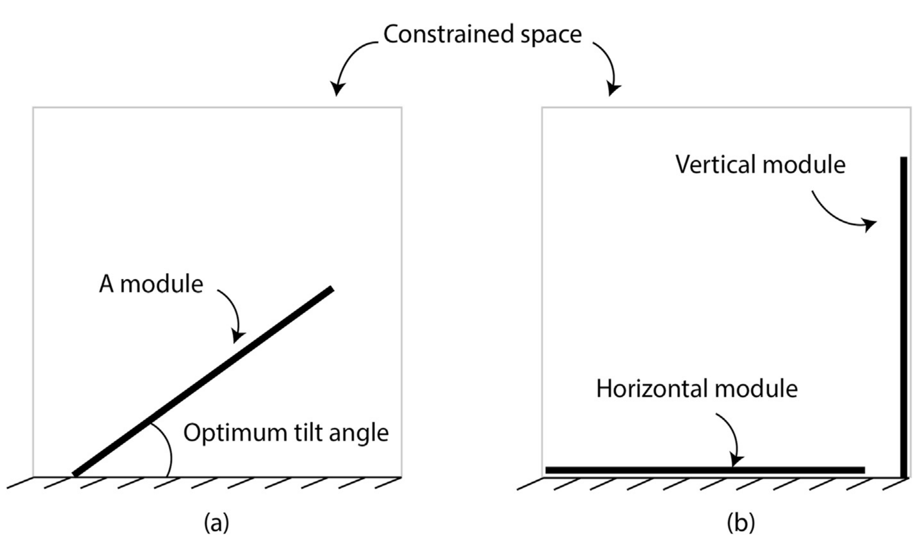

Fig. 1. (a) A single module can fit in a constrained space when tilted at an optimum angle; (b) Two modules can fit in the same constrained space (one vertical and one horizontal) without causing mutual shadowing issues.