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Optimal solar dish field layouts for maximum collection and shading efficiencies

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ABSTRACT

We derive the limit for collection and shading efficiencies and describe an optimization methodology of solar dish field layouts based on a general 2D Bravais lattice using local irradiation data and as a function of latitude, ground coverage ratio, dish perimeter shape, and sun-tracking system.

1. Introduction

Two-axis tracking solar dish systems can deliver highly concentrated solar radiation for advanced solar thermal and photovoltaic applications (Schiel and Keck, 2012; Buljan et al., 2014). At low solar altitudes, the positioning of multiple sun-tracking dishes in a field inherently leads to shading from and to the neighboring dishes. Finding an optimal layout that minimizes losses due to shading poses an optimization problem based on the shaded radiant energy (Groumpos and Khouzam, 1987; Stephens and Angel, 2012), power output (Narvarte and Lorenzo, 2008; Capdevila et al., 2013; Kim et al., 2013), and/or economic aspects (Kim et al., 2013). For a field consisting of only a few dishes, the surroundings and the outline of the terrain play a major role, but the optimal layout can be determined freely using algorithms with reasonable computational efforts (Diaz-Dorado et al., 2011). With increasing field size, these optimizations quickly reach their limit and regular grids are required, such as rectangular with and without staggering of rows (Igo and Andraka, 2007; Stephens and Angel, 2012). In this work, we focus on maximizing the solar radiant energy collected by dishes in large fields at fixed ground coverage ratios and derive theoretical limits for the shading and collection efficiencies. This methodology enables rating of layouts as a function of location, ground coverage ratio, dish perimeter shape, as well as sun-tracking system. The results have a general validity and are applicable for finding optimal layouts with favorable economics. Whereas previous studies usually analyze one location only, we compare 21 different locations using modelled (Laue, 1970; Meinel and Meinel, 1976) and measured (Ohmura et al., 1998) irradiation data.

2. Maximum performance of large solar fields

Layouts of large solar dish fields are usually based on regular grids of various shapes, e.g. square, equilateral, rectangular, and rectangular with staggering of rows (Igo and Andraka, 2007; Stephens and Angel, 2012). Here we consider the most general case of a regular layout by using a 2-dimensional Bravais lattice, applied in crystallography (Bravais, 1949). Fig. 1(a) illustrates its construction. The two primitive vectors $\mathbf{a}$ and $\mathbf{b}$, $\mathbf{a}\cdot\mathbf{b} = |\mathbf{a}|\,|\mathbf{b}|\cos(\gamma_{a,b})$, define the layout where the position $\mathbf{p}$ of any tracker is given by $\mathbf{p} = n_a\mathbf{a} + n_b\mathbf{b}$ with n_a and n_b being integer numbers. The ground coverage ratio GCR is given by the area of the dish A_d divided by the area it occupies on the ground A_g, $GCR = A_d/A_g$, where $A_g = |\mathbf{a}\times\mathbf{b}|$ corresponds to the norm of the cross product of the two primitive vectors.

2.1. Efficiencies

There is evidently a trade-off between harvesting maximum solar irradiation per ground area and shading between the dishes.

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Nomenclature

Latin characters

$\mathbf{a}$	primitive grid vector, m
A	area, m^2
$\mathbf{b}$	primitive grid vector, m
c	collected fraction of light incident on ground, –
E	east, –
E	solar irradiance, W/m^2
GCR	ground cover ratio, –
h	altitude above sea level, km
H	radiant exposure, J/m^2
N	north, –
Q	radiant energy, J
R	outer dish radius, m
s	shaded fraction of dish, –
S	south, –
t	time, s
$\mathbf{v}_{\mathrm{sun}}$	solar vector, unit vector pointing in direction of sun
W	west, –
(x, y, z)	global coordinate system, m
(x_d, y_d, z_d)	dish coordinate system, z_d collinear with $\mathbf{s}$, m

Greek characters

α	altitude angle, °
γ	azimuth angle, °
η	efficiency, –
θ	zenith angle, °

Subscripts

bh	beam (direct), measured on horizontal surface
bn	beam (direct), measured on normal surface
c	collecting
d	dish
g	ground
gn	ground projected on normal surface
s	shading

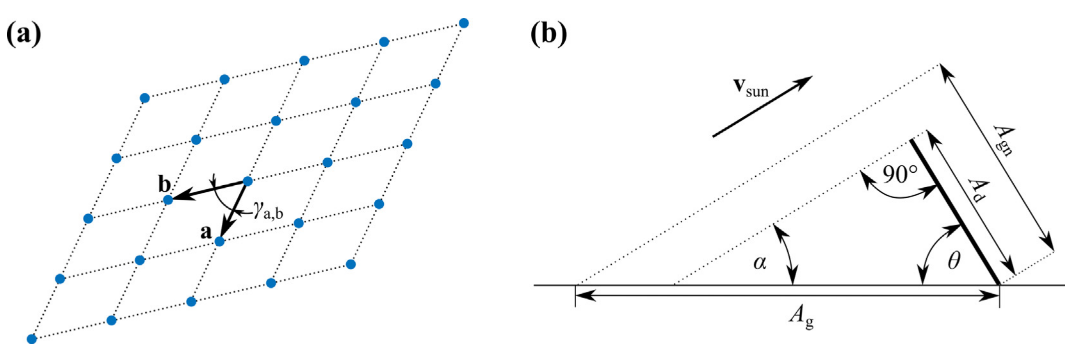

Fig. 1. (a) Lattice for large fields defined by the primitive vectors **a**, **b** and the enclosed angle $\gamma_{a,b}$. (b) Projection of the ground area to a plane perpendicular to the direction towards the sun. Legend: A_g: occupied ground area, A_{gn}: projected ground area, A_d: dish area, α: solar altitude, θ: solar zenith angle, and $\mathbf{v}_{\mathrm{sun}}$: direction towards sun.

The former asks for dense fields with high GCR, while the latter asks for sparse fields with low GCR. The collected radiant energy Q_c by a solar dish is obtained by integrating over time t.

$$Q_c = \int (1-s) E_{bn} A_d dt = \int c E_{bh} A_g dt, \quad (1)$$

where E_{bn} is the direct beam normal irradiance (DNI), s is the fraction of the dish that is shaded, and c is the fraction of the collected beam irradiation on the horizontal surface E_{bh}. Here, we only consider beam irradiance as for concentrating applications diffuse irradiance is insignificant. Thus, c also represents the fraction of the ground that is shaded. c and s are related by $c\cos\theta = (1-s)GCR$. The shading efficiency η_s is defined as the ratio of collected energy Q_c over the energy that could be collected by an always fully irradiated (not shaded) dish $Q_{c,no-sh}$ (Groumpos and Khouzam, 1987),

$$\eta_s = \frac{Q_c}{Q_{c,no-sh}} = \frac{\int (1-s) E_{bn} A_d dt}{\int E_{bn} A_d dt} = 1 - \frac{\int s E_{bn} dt}{\int E_{bn} dt}. \quad (2)$$

The collection efficiency η_c is defined as the ratio of Q_c over the energy incident on the occupied ground area Q_g (Stephens and Angel, 2012),

$$\eta_c = \frac{Q_c}{Q_g} = \frac{\int (1-s) E_{bn} A_d dt}{\int E_{bh} A_g dt} = GCR \frac{\int (1-s) E_{bn} dt}{\int E_{bh} dt}. \quad (3)$$

η_s and η_c are inherently linked by

$$\eta_c = \eta_s GCR \frac{\int E_{bn} dt}{\int E_{bh} dt} = \eta_s GCR \frac{H_{bn}}{H_{bh}}. \quad (4)$$

2.2. Limits

A_{gn} is the projection of A_g to a plane perpendicular to the sun direction, as illustrated in Fig. 1(b). If $A_{gn} = A_d$ at a zenith angle $\theta = \mathrm{acos}(GCR)$, full collection ($c = 1$) and no shading losses ($s = 0$) are ideally achieved. This ideal condition implies that the dish perimeter must tessellate when projected to a plane normal to the direction of the sun. For $\theta < \mathrm{acos}(GCR)$, there are no shading losses in the ideal case. However, it is not possible to collect all sunrays incident on A_g as $A_{gn} > A_d$, yielding $s = 0$ and $c = A_d/A_{gn}$. For $\theta > \mathrm{acos}(GCR)$, $A_{gn} < A_d$, inevitably leading to shading losses while full collection can be maintained, yielding $s = (A_d - A_{gn})/A_d$ and $c = 1$. These considerations lead to the derivation of the theoretical maximum c and minimum s for a given solar elevation,

$$c_{max} = \min\left(\frac{A_d}{A_{gn}}, 1\right) = \min\left(\frac{GCR}{\cos\theta}, 1\right)$$
and
$$s_{min} = \max\left(\frac{A_d - A_{gn}}{A_d}, 0\right) = \max\left(1 - \frac{\cos\theta}{GCR}, 0\right). \quad (5)$$