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Design of rural photovoltaic water pumping systems and the potential of manual array tracking for a West-African village

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Abstract

Photovoltaic (PV) power systems are attractive for use with water pumping systems in remote, off-grid areas with naturally high solar insolation. Two simplified design procedures for these systems are reviewed and compared to a more detailed analysis for a specific village (Ying, 9.7°N, 0.8°W) in West Africa. The simple design methods result in too little flow during months with below-average insolation. A rule-of-thumb chart is presented to predict flow losses for similar installations. To explore possible benefits of tracking strategies, ten different array configurations were simulated: three with fixed orientation, six with single axis tracking, and one with dual axis tracking. Of the three fixed orientation arrays, the configuration to maximize insolation and flow was an equator-pointing array with slope slightly greater than local latitude. The single and dual axis trackers were simulated with seasonal, monthly, and hourly tracking periods, the latter being a good representation of a continuous tracking system. For single axis tracking, a vertical axis array with slope fixed at 30° and variable azimuthal angle provided the best performance. For dual axis tracking, hourly array re-orientation results in significantly more received insolation (17.6% greater than non-tracking horizontal array) while adjustments only on a seasonal or monthly basis still yield 8.5% relative gain. In general, there is little predicted difference between monthly and seasonal re-adjustment of array orientation. A single vertical axis variation allows almost the same benefit as a full two-axis variation if re-oriented on a monthly or seasonal basis. Using one of these strategies could translate into reduced array size, reduced capital costs, or could provide extra margin for future increased water flow requirements due to community growth or unexpected weather. Simple monthly or seasonal adjustment by residents also could increase the sense of ownership in those served by the system.
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Keywords: Solar photovoltaic water pumping; Rural development; Array tracking

1. Introduction

After the first decade of the 21st century, a majority (87%) of people worldwide have access to safe drinking water sources. However, in particular regions, such as sub-Saharan Africa, access to safe drinking water is still a luxury. In this region, only approximately 60% of people have access to safe drinking water, and only half have access to improved water sources (WWAP, 2012). Lack of safe drinking water causes many direct health problems, the most significant of which are diarrheal-based diseases, recently attributed to 1.5 million deaths each year, mostly of children (Prüss-Üstün et al., 2008). Because children drink and eat significantly more than adults per unit of body weight, they are particularly vulnerable to contami-

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Nomenclature

Latin letter notation

a	coefficient for Collares-Pereira fit (Collares-Pereira and Rabl, 1979)
b	coefficient for Collares-Pereira fit (Collares-Pereira and Rabl, 1979)
D	inner diameter of piping in flow system
f	friction factor
G_T	instantaneous irradiance on tilted array
h_T	total head change for flow system
h	elevation change of flow system
$h_{l,major}$	major head losses
$h_{l,minor}$	minor head losses
H	average monthly insolation
I	average hourly insolation
K_L	minor loss coefficient
K	incidence angle modifier
k_t	hourly clearness index
L	length of piping in flow system
MPPT	maximum power point tracking
PV	photovoltaic
PSH	peak-sun-hour
r_t	ratio of hourly to monthly insolation
R_b	beam ratio; ratio of beam irradiance on tilted array to that on horizontal array
STC	standard test conditions
T_a	actual ambient temperature
T_0	reference temperature
T_{NOCT}	published operating temperature at nominal operating cell temperature conditions
U_L	heat transfer loss coefficient for array
v	average velocity through flow system
V_{mp}	nominal voltage at maximum power point
$\dot{V}$	flow rate
$\dot{W}$	power input to motor-pump

Greek letter notation

A	north–south axis incline angle
Γ	north–south axis rotation
ω	solar hour angle
ω_s	solar sunset hour angle
ε	absolute pipe roughness
ζ	ratio of hydraulic energy to rated array power
α	slope of array relative to horizontal
β	effective array slope for calculation of incidence angle modifier
γ	azimuthal angle of array relative to south
η	first-law efficiency
η_{elec}	efficiency of PV electrical subsystem
η_{pump}	efficiency of motor-pump subsystem
η_{mp}	efficiency of array at maximum power point (actual operating conditions)
$\eta_{mp,0}$	efficiency of array at maximum power point (reference conditions)
μ_{mp}	temperature coefficient of array at maximum power point
$\tau\alpha$	transmittance–absorptance product for array
μ_{Voc}	temperature coefficient of open-circuit voltage at maximum power point
ρ_g	reflectance of ground

Subscripts

(none)	insolation on horizontal array at Earth's surface
0	insolation on extra-terrestrial (outside Earth's atmosphere) array
t	insolation on tilted array at Earth's surface
b	beam radiation
g	ground
d	diffuse
mp	maximum power point

nated food and water (Children in the New Millennium, 2002).

In water stressed regions such as sub-Saharan Africa, finding and transporting safe water can be a large task. In this region, most people in rural areas live apart from a reliable electric grid, with a recent estimate suggesting only 12% of rural inhabitants of the region had access to electricity (Addressing the Electricity Access Gap, 2010). Without the possibility for reliable electrical pumping systems, gathering and carrying water often becomes a manual task that falls predominantly to the women and girls of a community (Faeth and Weinthal, 2012; Nossiter, 2012). Thus, the opportunity cost of water gathering can contribute to other societal problems, such as enlarging gender gaps in education. In 2010, the United Nations adopted a resolution acknowledging access to sufficient, safe water as a basic human right (General Assembly of the United Nations, 2010).

Regions of high water stress often also have high solar insolation (Qiblawey et al., 2011; Bilton et al., 2011). Therefore, using solar photovoltaic (PV) power to pump water to these types of communities has been considered for several decades. In 1985, Kenna and Gillett developed a handbook focused on providing design guidelines for solar PV-based water pumping systems for rural communities (Kenna and Gillett, 1985). More recent handbooks have also focused on solar PV systems for water pumping as well as general small scale electrification (Hankins, 1995; Hankins, 2010). Solar PV technology for water pumping has historically been considered well-suited for applications