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Optimal solar tracking strategy to increase irradiance in the plane of array under cloudy conditions: A study across Europe

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ABSTRACT

In this study, we have performed an analysis of potential irradiation increase across Europe, derived from moving photovoltaic (PV) modules to a horizontal position during cloudy and overcast situations. The motivation of research is that PV technology has expanded outside countries endowed with high solar irradiation and it is nowadays present in high-latitude regions and areas with frequent cloud cover. Unlike concentrating solar technologies, PV panels can make use of both beam and diffuse irradiance. During cloudy or overcast situations, most of solar irradiance comes from the diffuse component, which approaches an isotropic behavior under those circumstances. Then, a PV panel facing the zenith would receive more irradiation than a PV panel following the Sun's path.

In our approach, we have used data from several Baseline Surface Radiation Network stations. Results showed a yearly potential irradiation increase of 3.01% with respect to a reference single-axis tracking system (SATS) in the northern-most station. Values for other stations were correlated to climate. Thus, the sunniest station would increase its annual irradiation by 0.16% compared to a reference SATS. Daily irradiation increases of up to 19.91% were registered.

Two predictive models were created to develop a SATS, which could determine in advance the optimum position of PV panels. Model 1, which was based on the persistence of irradiance, was designed to work real time in order to increase production. Yearly gains of up to 2.51% of irradiation were registered. However, Model 2 was developed to update production forecasts in the intra-day electricity markets so that PV plant owners can maximize their revenues. It is based on irradiance predictions from a numerical weather prediction service and underperformed current SATS.

1. Introduction

Photovoltaic (PV) technology has seen an incredible reduction in prices amidst a steady increase in efficiency. This combination has boosted the development of solar plants across the entire world, amounting to a total installed capacity of at least 303 GW at the end of 2016. Additionally, the size of utility scale solar plants has increased, reaching the 1 GW milestone with the construction of the Yanchi project (China) (REN21, 2017).

Efficiency can not only be optimized through materials or manufacturing progresses, but also by ensuring an optimal alignment between the Sun and the PV module. In addition to fixed-tilt PV panels, where modules are set to an optimal orientation and inclination (latitude dependent), PV panels can be mounted on a structure enabling them to follow the Sun's path. There are single axis tracking systems (SATS) and dual axis tracking systems (DATS). Dual axis tracking systems follow the Sun's beam radiation to get a perpendicular incidence over the module. Reflectance losses due to the incidence angle are thus minimized. Electric yield may be increased up to 25–45% (Lave and Kleissl, 2011) compared to fixed structures with an optimum tilt angle. On the other hand, installation and maintenance costs, along with complexity, increase. Single axis systems are aligned N-S, with a degree of freedom in the E-W direction. Hence, PV panels follow the Sun's path from sunrise to sunset and electric yield can be increased in the order of 10–20% compared to fixed structures. Optimal alignment cannot always be reached, but there is significant reduction in installation and maintenance costs, as well as complexity, compared to the dual axis systems.

Focusing on the afore-mentioned SATS, several control algorithms exist to align beam radiation with the module. Translational and rotational movements of the Earth around the Sun are described by physical equations, which enable us to determine the Sun's position at every

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Nomenclature

α	solar elevation (°)
B	beam horizontal irradiance (W/m^2)
β	tilt angle (°)
D	diffuse horizontal irradiance (W/m^2)
$DATS$	dual axis tracking system
δ	declination (°)
ϵ	sky view factor blocked by PV rows (°)
G	global horizontal irradiance (W/m^2)
G^{ref}	effective irradiance in the plane of array obtained with a SATS with backtracking (W/m^2)
G^{pot}	estimated effective irradiance in the plane of array obtained with a SATS with backtracking and the diffuse irradiance modification (W/m^2)
G^{pred}	predicted effective irradiance in the plane of array obtained with a SATS with backtracking and the diffuse irradiance modification (W/m^2)
γ	solar incidence angle (°)
k_t'	modified clearness index
λ	latitude (°)
μ	effective sky view factor (°)
ω	solar angle (°)
PV	photovoltaic
ϕ	solar azimuth (°)
ϕ_s	azimuth of a surface (°)
R	reflected irradiance (W/m^2)
ρ_g	ground albedo
$SATS$	single axis tracking system
θ	solar zenith angle (°)

Subscripts

y	annual
d	daily
m	minute

Superscripts

T	tilted surface
eff	effective irradiance

moment with a high degree of precision. During sunrise and sunset, when the solar zenith angle is at its maximum, solar panels following the Sun project their shadows to the rows of panels located behind them, an issue called self-shadowing. Shadows over PV panels produce hot-spots and lower yield, making operation more difficult. A simple solution to that problem would be to allow enough spacing between rows of panels so that no shadows reach other modules, but this is not practical as it significantly increases the required area. For this reason, backtracking algorithms are implemented, in order to eliminate self-shadowing. A number of backtracking strategies have been developed (Panico et al., 1991; Schneider, 2012). Shadows are eliminated by varying the tilt angle of the panels during low solar elevation angles to a non-optimal tilt angle so that the projected shadows do not reach the subsequent rows of panels. Shadows effect yield to a larger extent than a non-optimal incidence angle. With a backtracking algorithm, solar modules are horizontal at night. When the first sun rays reach the panels, they shift to the largest tilt angle that avoids inter-array shadowing. Tilt angle then increases to improve the incidence angle, in an effort to avoid shadows. At a certain solar elevation angle shadows are no longer projected and the tracking algorithm works as usual. This process is repeated symmetrically with respect to solar noon in the afternoon.

We have already seen that pursuing the optimal incidence angle may not result in yield increase due to practical reasons (self-shadowing). But there is another situation where a planned misalignment would increase production, that is, when global horizontal irradiance (G) is larger than irradiance in the plane of array of a module following the sun's path. The increase in production is possible because, during cloudy or overcast days, most of irradiance is diffuse. In such moments, diffuse irradiance comes from the sky dome with a similar intensity, without any direction in particular, approaching an isotropic behavior. Hence, following the sun is ineffective and it is more convenient to orientate the panels to the zenith (horizontal position). As a disadvantage, reflected irradiation from the ground is not collected in that position. The effect of ground albedo will be discussed along the paper. At first, large-scale PV plants were restricted to areas with high solar irradiation, whereas nowadays they have expanded to Northern countries and other areas not rich in solar irradiation. For instance, most of new PV installations in Europe were located in high-latitude countries in 2016; United Kingdom, Germany and France were the leading markets (REN21, 2017). For this reason, it is important to assess the potential gains of an optimized SATS for cloudy conditions. During these periods, PV production is limited, but not negligible, especially when considering large PV plants. There are a few number of studies that address this issue.

Kelly and Gibson (2009) studied the possible improvement of a DATS for heavily overcast situations. In such conditions, they found that nearly 50% of yield increase was obtained if PV panels were horizontally orientated instead of tracking the sun. They proposed three enhanced tracking systems to take advantage of these situations. In the first one, whenever global irradiance were lower than a predefined value (relative to the clear sky index), PV panels would be set to a horizontal position. In the second system, the difference in irradiance measurements between tilted and horizontally set pyranometers would trigger the shift from tracking the sun to a horizontal position. The third algorithm would make use of two pyranometers pointing to the zenith. One would measure global irradiance and the other only diffuse. When the difference of measurements of both sensors approaches a certain value, modules would switch its tracking mode to a horizontal position. Kelly and Gibson (2011) extended the previous study with a larger set of measurements, reaching similar conclusions. During cloudy periods, a horizontal module could harvest up to 40% more energy than a module that tracks the sun with a DATS, and reaching up to 50% more energy for heavily overcast periods. However, they anticipated that the annual yield increase derived from a combined tracking system would be around 1% due to the low energy captured on cloudy days. Koussa et al. (2001) studied different tilt and tracking configurations for different sky conditions (18 days) in Algeria and found out that during cloudy days no tracking system captured more energy than a horizontal panel. Quesada et al. (2015) investigated SATS in Canada. They determined the "critical hourly global solar radiation", a threshold below which it was recommended to move panels to the horizontal. Daily yield increases of up to 27.4% were obtained, although in absolute terms the improvement was modest due to cloudy conditions. Relative gains were not homogeneous throughout the day. During early morning and late afternoon a horizontal module is preferable to a tracking module. Differences in periods around solar noon were of small magnitude. They proved that sun-tracking during cloudy summer days was ineffective. Nevertheless, during winter months, the presence of snow on the ground indicates the best strategy favors a sun tracking mode, even under cloudy conditions, given the high albedo of snow. They proposed a qualitative decision algorithm based on the previous statements to know when to track the sun and when to move to a horizontal position.