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Case study showing that the tilt angle of photovoltaic plants is nearly irrelevant

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Abstract

What is the optimum tilt angle of photovoltaic plants in mid-latitudes? This question is of practical importance for the mounting of photovoltaic systems. The present work states a nearly irrelevant difference of the yearly performance of solar cells at various tilt angles. The measuring system included eight multicrystalline silicium solar cells and was mounted on the roof of the Institute of Meteorology and Climatology (IMuK) in Hannover, Germany, for a 1-year period that started from November 2008 until October 2009. Each solar collector was mounted at a different tilt angle between 0° and 70° in steps of 10°, in a southward orientation. The measurements covered the short circuit current (I_{sc}), the open circuit voltage (U_{oc}) and the cell temperature (T) of each cell. From this the maximum power (P_{mp}) was calculated and analysed. The data has been assessed for monthly sums. Maximum values of P_{mp} were found to appear in a wide angular range, about 50°–70° in the winter months and 0°–30° in the summer months. The yearly optimum tilt angle was found to be nearly the same as for summer months. The largest difference of the plant yield was less than 6% for tilt angles between 0° and 70°. This holds for both yearly sum and for the summer months. Theoretical calculations performed with INSEL software, however, showed larger deviations than the experimental findings. This is probably due to temperature effects, which tend to level off differences at different incident angles. Further investigations are necessary to test whether the tilt angle is generally irrelevant or whether other sites or years will show different results.

Keywords: Tilt angle; Photovoltaic; Solar cells; Experimental; Maximum power

1. Introduction

Energy production by solar power systems has found a ready market in the last decade, and is currently experiencing a boom that is not least due to government aid. These subventions are to be decreased to lower costs for customers. This is why it is important to optimise any aspect of solar power systems, and hence, make them more economic.

One way is to install the solar collectors in the correct tilt and orientation angle, in which they would obtain the maximum insolation over a specific period of time. The tilt angle depends mainly on the position of the sun and, therefore, differs from location to location in the world. The best orientation angle is advised to be directed towards the equator. There are already plenty of investigations dealing with this subject to optimize solar power systems according to the correct tilt angle or orientation. Many authors have provided empirical or analytical models to calculate the optimum tilt angle (β_{opt}) by searching for the maximum total solar radiation on the collector surface. In reference to a specific period of time and purpose, daily, monthly, seasonal or yearly values have been calculated, e.g. (EL-Kassaby, 1988; Soulayman, 1991; Ibrahim, 1995; Lewis, 1987).

Elsayed (1989) also presented an analytical model based on long-term averaging of solar data. He outlined values of

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Nomenclature

β_{opt}	optimum tilt angle (°)	P_{mp}	power at maximum power point on I–U-curve (W)
Δ	difference between angles of minimum and maximum values of $P_{mp_{mon}}$ (°)	$P_{mp_{mon}}$	monthly cumulated values of P_{mp} (W h)
Φ	latitude	q	charge ($1.602 \times 10^{-19} C$)
$C_1 \cdots C_8$	numbers of solar cells	R_s	inner resistance (Ω)
E_{tilt}	calculated irradiances on tilted surfaces and cumulated according to P_{mp} (W h m^{-2})	T	cell temperature (°C)
I_0	diode current (A)	U_T	thermal voltage (V)
I_{il}	current generated by illumination (A)	U_{mp}	voltage at maximum power point on I–U-curve (V)
I_{mp}	current at maximum power point on I–U-curve (A)	U_{oc}	open circuit voltage (V)
I_{sc}	short circuit current (A)	IMuK	Institute of Meteorology and Climatology
k	Boltzmann constant (1.38×10^{-23} J K^{-1})	INSEL	INtegrated Simulation Environment Language
m	diode factor ()	ISFH	Institute for Solar Energy Research Hameln
N_{meas}	number of measuring days	PVSYST	Software for photovoltaic systems
N_{mon}	number of days of each month	TRNSYS	TRaNsient SYstems Simulation

optimum tilt angles given in different literature and conducted that value of tilt angle that can be recommended. In fact there is a wide range of tilt (±20°) dependent on the applied model and the location. Some authors noted a correlation between the optimum tilt angle and the latitude. Frequently, it is recommended to apply the rule of thumb, in which the yearly optimum tilt angle is about $\Phi \pm 10°$ (Φ: latitude) and a difference of tilt with about 10° would hardly affect the performance.

Gunerhan and Hepbasli (2007) determined monthly optimum tilt angles for Izmir, Turkey. They found the optimum tilt angle (β_{opt}) to be equal to Φ throughout the year, while for summer $\beta_{opt} = \Phi - 15°$ and for winter $\beta_{opt} = \Phi + 15°$ was suggested. They advised to mount the solar collector at the monthly average tilt angle.

During the last decade there have also been investigations by using simulation software. This software, which was developed in order to simulate an entire solar power plant, takes the most influential parameters into account. The software usually possesses a database of monthly mean global radiation data and different empirical models. For example Hussein and Ahmad (2004) applied the simulation software TRNSYS to calculate the optimum tilt angle for Cairo, Egypt. They calculated monthly mean solar radiation data and compared it with the output power of solar cells. They stated the yearly optimum tilt angle to be $\Phi \mapsto \Phi - 10°$.

Cheng et al. (2009) used the simulation software PVSYST to investigate the correlation between the tilt angle of a fixed solar collector and the latitude. Their calculations encompassed 20 locations on the northern hemisphere. Hence, a solar power plant yields an average of 98.5% of its full capacity using the latitude angle for the tilted panel.

There are just a few experimental studies however that present long-term measurements of the output power of solar cells at different tilt angles. In most cases, irradiances were measured at different tilt angles with pyranometers.

Another investigation conducted by Nakamura et al. (2001) refers to temperature dependency and output power of solar cells in Hamamatsu, Japan. They adjusted pyranometers and solar panels at six different orientations and three tilt angles. Their analysis covered only sunny days in a period of 6 months (September–February). For this period the optimum tilt angle was found to be 30° facing south, i.e. $\beta_{opt} \approx \Phi$.

The previous review shows that there is a wide range of stated optimum tilt angles in different literature. Therefore many investigations refer to only certain locations, especially to subtropical areas. Some authors, e.g. (EL-Kassaby, 1988) conducted calculations that includes mid-latitudes and high-latitudes as well, but there are just a few results obtained from measurements.

With regard to photovoltaics, the optimum electric power for a certain period is of economic interest. The electric power of a solar cell is defined as the product of electric current and voltage ($P = I \cdot U$) that is a function of the irradiance and the temperature $P = f(E, T)$. Although P increases in higher irradiances, it decreases in higher temperatures. In general, higher irradiances lead to higher temperatures of the solar collector and, hence, the performance is reduced. Furthermore, the reflection characteristics of the collector surface should be taken into account. As presented by Balenzategui and Chenlo (2005), diverse surface covers behave differently according to reflection losses.

For this reason the objectives of this paper are as follows:

(1) To provide experimental measurements to state the monthly optimum tilt angle for Hannover, Germany, whose location aptly represents the cloudy mid-latitudes weather conditions. Therefore, the maximum electric power (abbr.: maximum power – mp)