Applied Energy 160 (2015) 94–107

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

East to west – The optimal tilt angle and orientation of photovoltaic panels from an electricity system perspective

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HIGHLIGHTS

- Adjustments of PV installation angles can reduce total electricity generation costs.
- However total benefits are small (<1% of total costs) even for high PV shares.
- In Austria and Germany adjustments toward east and steeper tilt can be beneficial.
- PV market values drop significantly with high PV shares also for adjusted angles.
- Also CO_2 reductions decrease but are still high even for a doubling of PV capacity.

ARTICLE INFO

Article history:
Received 7 August 2014
Received in revised form 19 August 2015
Accepted 21 August 2015

Keywords:
Photovoltaic
PV tilt angle and azimuth
Market value
Electricity system
Renewables

ABSTRACT

The integration of photovoltaic as a fluctuating renewable energy source has raised concerns about additional costs for the electricity system due to the variable nature of power output leading to more frequent and steeper ramping of conventional power plants and the need for backup capacity. One way to reduce those costs can be the variation of installation angles of PV panels at different locations to smoothen out the total production from PV in the whole system. To a certain extent steeper tilt angles can shift the production from summer months to winter months and the variation of the azimuth from east to west can partly shift production during the day increasing the production in morning or afternoon hours. However, for fixed mounted PV panels, there is one angle combination that maximizes the total output of the PV panel throughout the year and each deviation from this angle combination results in losses of total output. This paper evaluates the trade-off between annual energy losses and possible electricity generation cost reductions through adapting PV installation angles for the current electricity system and for potentially higher PV penetration levels in the future. A theoretical explanation why the annual maximum output of a PV system is not always the optimal solution from a system perspective is presented. To assess the effects of deviations from output maximizing angles at present, the wholesale market value of PV for various tilt angles and orientations in 23 regions of Austria and Germany using historic data on solar radiation and hourly electricity prices is calculated. For the analysis of future system states with potentially high shares of PV in the market, a linear optimization model representing the German and Austrian electricity wholesale market is applied. Furthermore the article provides additional insights on the market value of PV and CO_2 emission reduction potential at high PV penetration levels from the model.

Both, the historic analyses and the model results for Austria and Germany suggest that at present PV penetration levels, the angle combination that maximizes the output of a PV system also provides the highest spot market value and consequently minimal total system costs. For higher shares of PV in the system the model suggests deviations from those angle combinations to be optimal. For additional PV capacity of up to 40 GW (72 GW in total) a slight shift to easterly orientated PV modules is observed. For very high penetration levels of more than additional 100 GW optimal deviation angles deviate strongly from the output maximizing angles and the model shows optimal angles to be up to 20° steeper and orientations from east to west. However, the impact on total electricity generation costs is very low even for extremely high shares of PV in the system (<1% change in total costs). It is also found that despite of optimized installation angles, the average market value of electricity production from PV drops

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http://dx.doi.org/10.1016/j.apenergy.2015.08.097

significantly from 41 €/MW h at the base year 2012 to below 24 €/MW h for additional 40 GW which has strong implications for the competitiveness of PV in the future. Marginal CO_2 emission reductions however decline slower than the market values as PV cuts into production from coal power plants.

1. Introduction

The rapid growth of intermittent renewable energy sources (RES) in the electricity system has brought up challenges for the electricity system as a whole [1,2]. Electricity from Photovoltaic (PV) is by nature a fluctuating energy source due to the movement of the sun and varying cloud coverage causing variable availability throughout the day and seasons. This variability causes additional costs for the supply of electricity due to reserve capacity requirements, balancing reserves and ramping costs. Hirth [3] defines the effects of the predictable variability of PV and Wind as "Profile costs" stemming from lower values of the produced electricity at times of high RES feed-in, lower utilization of existing power plants which still have to serve as backup capacity and increased costs related to ramping and cycling of dispatchable power plants. In the case of PV, those costs which can also be interpreted as market value reductions of fluctuating PV feed-in, arise to a large part due to predictable changes in solar radiation on the surface. To a certain extent, the impact on electricity feed-in from PV also depends on the installation angles of PV modules. Some PV installers and also researchers claim, that a variation of those angles can therefore contribute to smoothen out the feed-in of RES which can help to reduce profile costs in the long run. The tilt angle of a solar panel can shift production between summer and winter while the azimuth angle shifts production throughout the day. For fixed angles without any tracking options there is one angle combination that maximizes the total output of a PV system throughout a year (see Fig. 1). Any deviation from this angle combination will reduce the total output to a certain extend. The tradeoff between these "energy losses" and the value of production shifts through varying installation angles is the main focus of this study and it is shown, that deviations from output maximizing installation angles are only preferable at high PV penetration levels, but not at present or in the near future.

Among others, Hussein et al. [4], Benghanem [5], Chang [6], and Gharakhani et al. [7] have studied output maximizing angles of PV panels in different locations. As a rule of thumb, the output maximizing azimuth (α^{max_out}) is pointing south for the northern hemisphere and the tilt angles (β^{max_out}) are between the latitude of the location (φ) and $\varphi - 15°$ with only minor losses in total output (below 5%) in the area of ±15° of the maximizing angle combinations. Fig. 1 illustrates the influence of the installation angles for a site close to Vienna, Austria (longitude: 16.2°, latitude: 48.3°).

While the output maximizing angle combination is strictly an engineering issue which can be determined for each location and PV system independently, this angle combination might not represent the maximum value from an economic perspective. This research takes an economic perspective on optimal angle combinations and tries to evaluate whether the system optimum deviates significantly from purely output optimizing approaches. Several studies have been conducted in this direction.

Mondol et al. [8] studied the variance of seasonal and daily solar radiation and PV output for Northern Ireland and the effect on potential savings in residential electricity bills. They find that slightly westerly (190°) angles result in the maximum savings over a year for a real time price tariffs. Also in a study by Liu et al. [9] on techno-economic optimization of a grid-connected PV system electricity tariffs are used to calculate optimal tilts of panels.

However, as Borenstein [10] and Oliva et al. [11] point out in their studies, the social or system value of PV production should be measured using hourly electricity prices and (marginal) emissions[1] as the value of PV production is given by the cost of the alternative technology to provide electricity. In functioning markets the hourly prices should represent those costs.[2] Rowlands et al. [12] evaluate the optimal tilt angle and azimuth of a PV panel for two locations and hourly price series in Canada and they find only slight deviations from output maximizing angle combinations. Borenstein [10] uses price and radiation for three different cities in California and finds that southwest orientated PV panels can lead to higher total values due to demand peaks in the afternoon where capacity costs add to short run production costs reflected in very high wholesale prices at those times. He also points out that using historic price data does not always reflect the real production costs (e.g. because of price caps, market power, etc.). He repeats the analyses using a wholesale electricity market model to simulate prices. The model output supports the results that southwest angles lead to the highest value, especially because the modeled capacity prices in afternoon hours are even higher than in the actual price series.

While those approaches and the presented results were used to assess system optimal PV angles at current or historic system states, the results for future electricity systems with high shares of RES can be significantly different. In this research a methodology to estimate system optimal PV installation angles for different system states and locations is presented. The methodology also takes geographic diversity (see [13]) and the effect of PV production on hourly prices into account (see [14]).

In summary, the paper contributes to the existing research in the following way:

- The methodology used by Rowlands et al. [12] is applied for Austrian and German solar radiation data and historic spot market prices.
- A methodology to assess the market optimal installation angles of PV systems for varying PV penetration levels using a wholesale electricity market model with hourly resolution, which extends the approach of Borenstein [10] to allow for endogenous choices on optimal angles is presented.
- We assess the relevance of deviations from output maximizing installation angles for increasing PV penetration levels in Austria and Germany is assessed and the impact of support schemes for PV is discussed.
- Additionally further insights on the development of market values and CO_2 emission reductions at high PV shares in the electricity system of Austria and Germany is provided.

The main research question in this study is the following:

- To which extend can deviations from output maximizing PV installation angles contribute to reducing electricity generation costs at high PV penetration levels in the Austrian and German electricity system?

[1] As opposed to retail prices which often do not reflect the hourly changes in costs and emissions of the whole electricity system.

[2] At least they should be an approximation for the costs of alternatives at each time step.