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Influence of demand patterns on the optimal orientation of photovoltaic systems

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ABSTRACT

Photovoltaic (PV) systems are usually orientated to maximize annual energy yield. This may not optimize other system indicators, specifically: direct consumption of self-generated PV power, reduced feed-in power and annual revenue. Also, these indicators are influenced by the energy demand of a building in relation to the PV system size. Therefore, we evaluate how demand patterns influence the optimal PV orientation for self-consumption, feed-in power and revenue. Historical Dutch demand patterns of 48 residential and 42 commercial buildings were used. We combined Dutch and German electricity prices from day-ahead markets with different ratios of electricity sales to purchase prices. Differences between demand patterns caused large variations in optimal PV orientations. On average, PV self-consumption is maximized for residential systems with an azimuth of 212° and a tilt of 26°. Commercial PV systems have an average of 188° azimuth and 17° tilt. Self-consumption can be increased 5.4% for residential systems and 2.7% for commercial systems, by optimizing orientation for self-consumption rather than for energy production. Curtailment losses are significant reduced by decreasing the module tilt angles. Optimizing for revenue can increase annual revenue of PV systems with 5.4% for certain demand patterns and pricing scenarios. The ratio of sales to purchase electricity price has a larger influence on the economically optimal orientation for residential systems than for commercial systems. Differences between Dutch and German market prices have minor effects on PV orientation. Analysed demand patterns significantly affect optimal PV orientation. Therefore, we recommend that optimal PV orientation should not only be based on maximizing energy production, but also on expected demand patterns and market prices.

1. Introduction

Commonly, PV (photovoltaic) modules are oriented to maximize their annual generated electricity. A variety of methods have been developed to determine this orientation (Mehleri et al., 2010; Yadav and Chandel, 2013; Portolan dos Santos and Rüther, 2014; Lave and Kleissl, 2011). However, the economic value of rooftop PV generated electricity varies for time intervals shorter than one year. This value of grid-connected PV systems is influenced by electricity markets, policy regulations and the electricity consumption pattern of the PV yield producer. This consumption is typically the electricity demand of a building on which the PV system is installed.

The current increase of installed PV capacity results in larger fluctuations of time-dependent value. In addition, the maximum feed-in power is expected to become more and more regulated with an increasing share of variable renewable sources in the electricity generation mix. Consequently, self-consumption of PV energy (or PV self-consumption) is supported by new policies in many European countries (European Commission, 2015). Thus, PV orientation should not only be based on maximizing energy production, but also on expected demand patterns and market prices.

Feed-in limitations set restrictions to the maximum power flow that can be exported back to the electricity grid, and are typically given as a ratio of the maximum installed PV capacity. Consequently, high injection peaks of PV power on the local electricity grid are avoided which lowers grid disturbances. For example, currently in Germany, PV-battery systems that limit the power fed back to the grid to 0.5 kW/kWp of the PV installed capacity can apply for financial support (KfW, 2017). PV generated energy that is not exported nor used is lost, and is usually defined as curtailment losses.

Previous studies mainly focused on effects of PV orientation by comparing maximized energy yield and revenue. Economical

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optimization of PV orientation could increase annual revenue up to 4%, with module azimuth angles ranging from 178° to 223° azimuth in the Northern hemisphere (Hummon et al., 2013). Another study showed optimal azimuth angles between 200° and 223° for Austin, TX, USA (Rhodes et al., 2014). A difference of 10° azimuth between a flat rate pricing regime and a spot market price regime was presented for Ottawa, Canada (Rowlands et al., 2011). A different study including Ottawa, showed an increase in revenue of 19% for an azimuth of 234° and a tilt of 41° for a peak-dependent tariff (Haysom et al., 2016). The economically optimal PV orientation from an electricity system perspective was examined for Germany and Austrian regions. For a total installed PV capacity of 70 GWp, an optimal azimuth of 165° was presented (Hartner et al., 2015).

Only a few studies were found that included consumer demand patterns. A German study combined 74 residential demand patterns with a 1 kWh battery storage size and different PV system sizes (Tjaden et al., 2014). PV systems with 0.5 kWp installed capacity for each MWh annual consumption were found to have an averaged optimal orientations around 185° azimuth and 36° tilt. Systems with 2 kWp installed PV capacity for each kWh storage were found to have 200° azimuth and 22° tilt. In addition, variance in optimal PV orientations is lower for smaller systems than larger systems. Another study investigated electricity bill savings of PV systems, using 215 residential demand patterns from California, USA. It was found that south-west facing PV systems had a slightly higher bill saving, <5%, compared to south facing PV systems (Darghouth et al., 2011). PV self-consumption of apartments and detached houses in Sweden can be increased by respectively 2% and 3% through optimizing the PV orientation (Widén et al., 2009). An west oriented PV system showed a higher share of directly consumed energy than east oriented systems for a residential Germany demand pattern (Lahnaoui et al., 2017).

A study including residential demand for and time-of-use tariffs from Las Vegas, USA, showed an economical optimal orientation of 220° azimuth. A large part of residential electricity demand was cooling load in the afternoon, due to the desert climate. Consequently, a significant drop in peak demand due to PV generation was observed (Sadineni et al., 2012). However, for locations with a relatively large heating demand, especially in winter months, there was no significant drop of peak demand related to PV production observed. Hartner et al. (2017). Demand patterns that had relative more load during morning and evening hours benefit from PV systems with a relatively lower tilt angle (Mondol et al., 2009).

Little is known about how demand patterns influence the optimal PV orientation for self-consumption, feed-in power flows, and revenues. Therefore it is not clear to what extent self-consumption or revenue can be increased by optimizing PV orientation, leading to suboptimal revenues.

With this paper, we aim to determine the influence and sensitivity of demand patterns on the optimal PV system orientation for self-consumption, curtailed energy under feed-in limitations, and PV revenue. Demand patterns of 48 residential and 42 commercial buildings in combination with historical Dutch and German electricity market data were used. We present new insights on PV system design that help the PV market to maximize PV self-consumption and revenues. Furthermore, increased PV self-consumption leads to reduced grid losses and therefore potential energy savings and reduced CO_2 emissions from backup power generation.

2. Methods

A model was developed and written in Python to determine the optimal orientation for each PV system. Demand patterns were combined with pricing patterns and a range of PV orientation to find optimal PV orientations for three aims:

- Maximize self-consumption.
- Minimize curtailed energy under feed-in limitations.
- Maximize added revenue.

For each optimization aim, indicators were defined which describe influences of demand patterns on optimal PV orientation. Used indicators were annually evaluated by patterns with a 5 minute interval. Furthermore, PV module azimuth was varied from 75° till 285° and module tilt from 0° till 50°. Both angles were varied with 1° steps, resulting in 10,761 different orientations analysed. Each orientation has corresponding indicators. The optimization function selects the maximum or minimum indicators and the affiliated PV orientation for each demand pattern. Details about used PV model, demand patterns and price patterns are provided in Section 2.5.

2.1. Self-consumption indicators

Three indicators were used to analyse the effect of PV system orientation on PV self-consumption of residential and commercial systems; self-consumption rate (SCR), self-sufficiency rate (SSR), and added self-consumption (ASC). SCR, SSR are quantified for a certain corresponding PV orientation. ASC quantifies the difference in self-consumption caused by a change from optimal orientation for energy production to optimal orientation for maximized self-consumption. The optimal orientation for energy production is commonly used as ideal orientation and therefore a good reference to evaluate.

Self-consumed power ($P_{\text{self-consumed}}$) is the amount of PV power (P_{PV}) that is directly consumed by the electricity demand of a building. (P_{demand}). Self-consumption rate specifies the share of PV yield that is directly consumed. This is calculated by dividing self-consumed energy (E_{SC}) with total produced energy (E_{PV}), see Eq. (1). Total self-consumption was calculated by the sum of self-consumed power of each 5 minute (Δt) interval between timestep t = 1 and t_{end}.

$$P_{\text{self-consumed}} = \begin{cases} P_{\text{PV}} & \text{if } P_{\text{PV}} < P_{\text{demand}} \\ P_{\text{demand}} & \text{if } P_{\text{PV}} \geqslant P_{\text{demand}} \end{cases} \tag{1a}$$

$$E_{\text{SC}} = \sum_{t=1}^{t_{\text{end}}} P_{\text{self-consumed},t} \cdot \Delta t \tag{1b}$$

$$E_{\text{PV}} = \sum_{t=1}^{t_{\text{end}}} P_{\text{PV},t} \cdot \Delta t \tag{1c}$$

$$\text{SCR} = \frac{E_{\text{SC}}}{E_{\text{TC}}} \tag{1d}$$

Self-sufficiency rate indicates the share of building demand directly covered by PV yield, and is defined as the ratio between self-consumed energy (E_{SC}) and total consumed energy (E_{TC}) on annual basis, see Eq. (2).

$$E_{\text{TC}} = \sum_{t=1}^{t_{\text{end}}} P_{\text{demand},t} \cdot \Delta t \tag{2a}$$

$$\text{SSR} = \frac{E_{\text{SC}}}{E_{\text{TC}}} \tag{2b}$$

Added self-consumption indicates relative change between the maximum self-consumption ($E_{\text{SC Max(SC)}}$) which is obtained from the orientation that maximize the annual self-consumption, and the self-consumption obtained for a PV orientation that maximizes energy production ($E_{\text{SC Max(PV)}}$) in percentage, see Eq. (3).

$$\text{ASC} = \frac{E_{\text{SC Max(SC)}} - E_{\text{SC Max(PV)}}}{E_{\text{SC Max(PV)}}} \tag{3}$$