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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).

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

2.2. Curtailed energy indicators

Two indicators were used to quantify the effect of PV orientation on the curtailed energy under feed-in limitations. The annual amount of lost energy is quantified with the curtailment loss ratio (CLR). This is the share of energy lost due to a power feed-in limitation (P_{Lim}) from energy that could be fed back without a feed-in limitations ($P_{\text{No lim}}$). The curtailed energy (E_{CE}) is defined as the difference between the maximum annual energy that is fed back to the grid without a feed in limitation ($E_{\text{No lim Max}(E_{\text{No lim}})}$) and with a feed-in limitation (E_{Lim}). CLR was calculated by dividing the curtailed energy with the produced PV energy, see Eq. (4).

$$P_{\text{No lim}} = P_{\text{PV}} - P_{\text{demand}} \tag{4a}$$

$$P_{\text{Lim}} = \begin{cases} P_{\text{No lim}} & \text{if } P_{\text{No lim}} \leqslant P_{\text{Lim}} \\ P_{\text{Lim}} & \text{if } P_{\text{No lim}} > P_{\text{Lim}} \end{cases} \tag{4b}$$

$$E_{\text{No lim}} = \sum_{t=1}^{t_{\text{end}}} P_{\text{No lim},t} \cdot \Delta t \tag{4c}$$

$$E_{\text{Lim}} = \sum_{t=1}^{t_{\text{end}}} P_{\text{Lim},t} \cdot \Delta t \tag{4d}$$

$$E_{\text{CE}} = E_{\text{No lim Max}(E_{\text{No lim}})} - E_{\text{Lim}} \tag{4e}$$

$$\text{CLR} = \frac{E_{\text{CE}}}{E_{\text{PV}}} \tag{4f}$$

The share of curtailed energy that can be fed back to the grid due to the change in orientation from maximizing annual energy production to minimize curtailed energy is defined by the reduced energy ratio (RCE). This is the relative change between the minimized curtailed energy ($E_{\text{CE Min(CE)}}$) and the curtailed energy under an orientation that maximizes energy production ($E_{\text{CE Max(PV)}}$) in absolute percentage, see Eq. (5).

$$\text{RCE} = \frac{E_{\text{CE Min(CE)}} - E_{\text{CE Max(PV)}}}{E_{\text{CE Max(PV|)}}} \cdot -1 \tag{5}$$

2.3. Added revenue indicators

Total revenue of a PV system (R_{tot}) is the sum of revenue from self-consumed energy (R_{SC}) and revenue from sold electricity to the grid (R_{grid}), see Eq. (6). This depends on the price of electricity bought from (π_{buy}) and sold to (π_{sell}) the grid. Revenues were analysed with fixed tariffs that have a constant price value throughout a year and with time-of-use tariffs that vary for each hour of the year. Added revenue (AR) shows the change between the revenue for an orientation with maximum energy production ($R_{\text{tot Max(PV)}}$) and an orientation with maximum revenue ($R_{\text{tot Max}(R_{\text{tot}})}$).

$$R_{\text{SC}} = P_{\text{self-consumed}} \cdot \pi_{\text{buy}} \tag{6a}$$

$$R_{\text{grid}} = \begin{cases} P_{\text{grid}} \cdot \pi_{\text{sell}} & \text{if } P_{\text{PV}} > P_{\text{demand}} \\ 0 & \text{if } P_{\text{PV}} \leqslant P_{\text{demand}} \end{cases} \tag{6b}$$

$$R_{\text{tot}} = \sum_{t=1}^{t_{\text{end}}} (R_{\text{SC},t} + R_{\text{grid},t}) \cdot \Delta t \tag{6c}$$

$$\text{AR} = \frac{R_{\text{tot Max}(R_{\text{tot}})} - R_{\text{tot Max(PV)}}}{R_{\text{tot Max(PV)}}} \tag{6d}$$

Taxes or grid network operator costs induce a difference between the price of electricity sold from and bought to the grid. The effect of this difference was examined using the sales to purchase ratio (SPR) and is given in Eq. (7).

$$\text{SPR} = \frac{\pi_{\text{sell}}}{\pi_{\text{buy}}} \tag{7}$$

2.4. Temporal contribution

Contributions of hour of the day and month of the year on annual ASC, RCE and AR values were analysed and defined as temporal fraction (TF). ASC_{TF}, RCE_{TF} and AR_{TF} were calculated according to Eqs. (8)–(10) respectively. Subsets for each temporal factor were defined as T_{TF} and each parameter was calculated for a subset time $t \in T_{\text{TF}}$. The temporal indicators of the corresponding maximum (Max) annual optimal orientation were selected. For example, $E_{\text{SC,TF,Max(SC)}}$ is the self-consumption for a certain temporal fraction, under the orientation that maximizes the annual self-consumption.

$$E_{\text{SC,TF}} = \sum_{t \in T_{\text{TF}}} P_{\text{self-consumed},t} \cdot \Delta t \tag{8a}$$

$$\text{ASC}_{\text{TF}} = \frac{E_{\text{SC,TF,Max(SC)}} - E_{\text{SC,TF,Max(PV)}}}{E_{\text{SC Max(PV)}}} \tag{8b}$$

$$E_{\text{No lim,TF}} = \underset{t \in T_{\text{TF}}}{m} P_{\text{No lim},t} \cdot \Delta t \tag{9a}$$

$$E_{\text{Lim,TF}} = \sum_{t \in T_{\text{TF}}} P_{\text{Lim},t} \cdot \Delta t \tag{9b}$$

$$E_{\text{CE,TF}} = E_{\text{No lim,TF Max}(E_{\text{No lim,TF}})} - E_{\text{Lim,TF}} \tag{9c}$$

$$\text{RCE}_{\text{TF}} = \frac{E_{\text{CE,TF,Min(CE)}} - E_{\text{CE,TF,Max(PV)}}}{E_{\text{CE Max(PV)}}} \cdot -1 \tag{9d}$$

$$R_{\text{TF}} = \sum_{t \in T_{\text{TF}}} (R_{\text{SC},t} + R_{\text{grid},t}) \cdot \Delta t \tag{10a}$$

$$\text{AR}_{\text{TF}} = \frac{R_{\text{TF,Max(R)}} - R_{\text{TF,Max(PV)}}}{R_{\text{tot Max(PV)}}} \tag{10b}$$

An overview of acronyms used in this study with corresponding indicators and equations is shown in Table 1.

2.5. Input data

Three kinds of patterns were required for our analysis; PV yield, electricity demand and wholesale electricity price patterns. PV yield patterns, containing AC power, were modelled through the open source package PVLIB (Andrews et al., 2014). This package provides validated atmospheric functions and PV system performance models. Solar radiation, ambient temperature, dew point temperature, wind speed and pressure were measured in De Bilt, the Netherlands, (latitude: 52.11°, longitude: 5.18°). Measurement interval of radiation was 10 minutes and for other weather parameters one hour. All weather parameters were linearly interpolated to a 5 minute interval and used as model input.

In addition, specifications of the Sanyo HIP-225HDE1 module and the Enphase Energy M210 inverter were used. This PV module has a relatively small temperature dependency, decreasing the influence of temperature within the results. Azimuth angles were varied from 75° till 285° and tilt angles from 0° till 50° tilt angles, with 1° steps.

Table 1
Overview of acronyms with corresponding indicators and equations.

Acronyms	Indicator	Eqs.
SCR	Self-consumption rate	(1)
SSR	Self-sufficiency rate	(2)
ASC	Added self-consumption	(3)
CLR	Curtailment loss ratio	(4)
RCE	Reduced curtailed energy	(5)
AR	Added revenue	(6)
SPR	Sales to purchase ratio	(7)
TF	Temporal fraction	(8) and (10)

Demand patterns of 48 households, with different dwelling types, were derived from measurements by a Dutch distribution system operator between 2012 and 2014 and are openly available (Liander, 2016). These residential patterns have an interval of 15 minutes and are valid for 2013. Commercial electricity demand patterns were measured at 42 commercial buildings, mainly offices, on a 15 minute interval in the Netherlands in 2013.

No demand data from 2010 till 2012 and from 2014 till 2016 were available. Hence, data of 2013 was used to model demand patterns of these absent years. Weekdays of these missing years were matched with weekdays of 2013, and leap days of 2012 and 2016 were filled with the last day of February 2013. Both residential and commercial patterns were linearly interpolated to a 5 minute interval, matching the time interval of the PV yield pattern.

We normalized residential and commercial patterns to an annual consumption of 1 MWh. This allows comparison of the demand patterns variability. The influence of each individual demand pattern was visualized using violin plots (Hintze and Nelson, 1998). This type of graphical representation extends the regular box-whisker plot with a full smoothed histogram of the values. This gives a quick indication of the distribution of results obtained from each demand pattern. In addition, mean values of the distributions were indicated using dashed lines. Distributions of hour of the day and monthly electricity demand from residential and commercial buildings are shown in a violin plot in Fig. 1.

Dutch and German hourly electricity wholesale price patterns from 2010 till 2016 were obtained from the day-ahead action of EPEX SPOT markets. The Power NL market price was used as Dutch market price, and the Physical Electricity Index (PHELIX) price as German market price. The electricity price patterns were resampled to a 5 minute interval using zero-order hold interpolation, matching the PV yield and demand patterns.

Market prices for 2016 and hourly difference between Dutch and German prices are shown in Fig. 2. German market prices are different over time than Dutch prices, which influence the optimal PV orientation and added revenues. Hence, we included both price patterns in our analyses, leading to a better understanding of market price influence. An overview of measured and modelled input patterns used is given in Table 2.

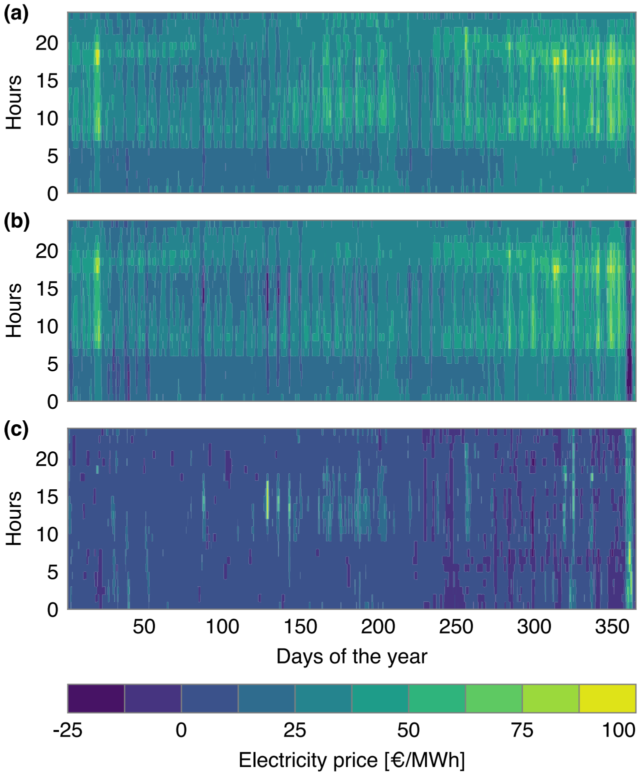

Fig. 2. Hourly Dutch (a), German (b) and difference in (Dutch-German (c)) day-ahead electricity market prices from 2016.

Table 2
Overview of input patterns used for this study.

Pattern	Amount	Measured	Modelled
PV yield	10,761	–	2010–2014
Residential	48	2013	2010–2012, 2014–2016
Commercial	42	2013	2010–2012, 2014–2016
Dutch prices	1	2010–2016	–
German prices	1	2010–2016	–

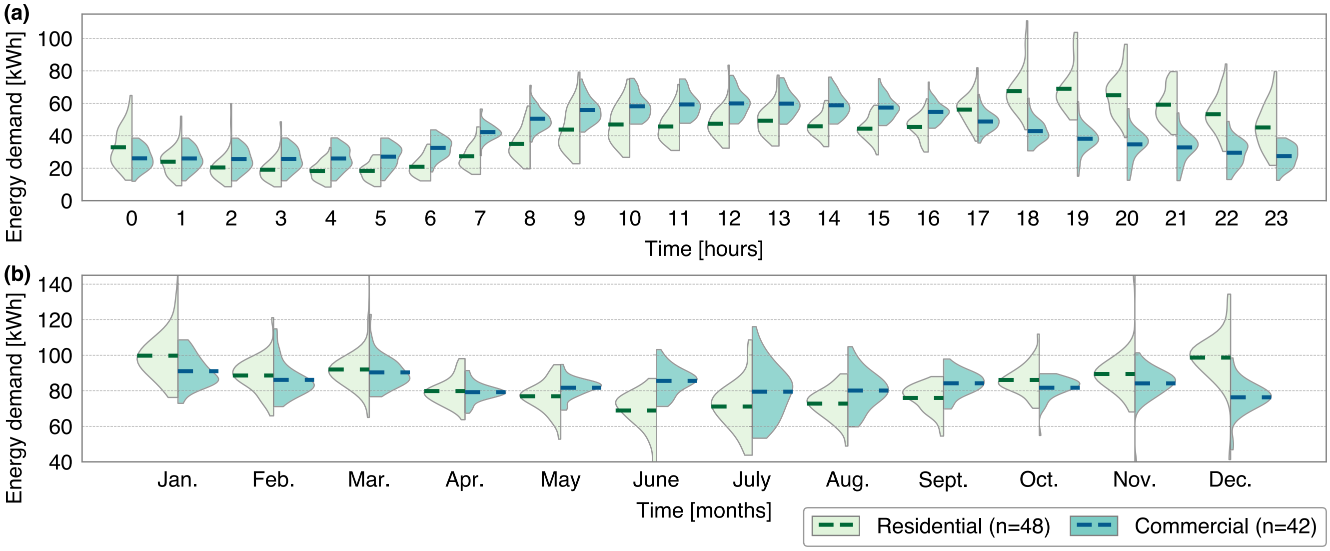

Fig. 1. Hour of the day (a) and monthly (b) energy (electricity) demand from shown using violin plots. Residential demand is shown at the left part of the violin and commercial at the right part of the violin. The demand patterns were normalized to an annual energy consumption of 1 MWh. Mean values of the distributions are marked by dashed lines.

3. Optimal orientation without self-consumption

Optimal orientations to maximize energy production and maximize profit without self-consumption are shown using Dutch and German market prices in Table 3. Also, the corresponding annual yield and added revenues are given for each year.

The optimal PV orientations to maximize energy production show a large range of annual differences. Optimal module azimuths are ranging from 181° to 188°, and tilt angles from 33° to 38°. It can be noted that the optimal azimuth is located 1° to 8° from the south orientation. Clearing of clouds appears more in afternoon hours than morning hours, resulting in larger share of radiation in the afternoon. Annual PV yield production varied between 1010 kWh/kWp and 1111 kWh/kWp.

Optimize PV orientation for market prices, without self-consumption, shows module azimuths from 177° to 184° for Dutch market prices and from 176 to 184° for German market prices. These orientations are between 3° and 8° lower than the optimal azimuth for maximum energy production. Module tilt angles are almost similar as found for maximum energy production. Small difference in optimal orientations between Dutch prices and German prices are shown, with maximum difference in azimuth of 2°. The maximum difference in module tilt is 1°. Furthermore, there is no clear annual relation between PV orientations and the electricity market prices of countries researched. A higher azimuth angle for Dutch than German prices is observed for 2010, 2013 and 2014, yet in 2015 the opposite is seen.

Additional revenues due to the change from an orientation to maximize energy production to an orientation to maximize revenues are between 0.02% and 0.14%. Added revenues increases with a larger difference in maximize energy production orientation and maximizing revenue orientation. Differences between Dutch AR and German AR are ranging from −0.08% to +0.06%. Furthermore, mean optimal orientations and added revenues are almost similar for Dutch and German market prices.

4. Maximize self-consumption

Optimal PV orientations for maximized PV self-consumption, SSR and ASC of six different PV system sizes are illustrated using violin plots in Fig. 3. The influence of the residential and commercial demand patterns is shown in the distribution. The left part of the violin plot provides the distribution of results obtained from residential systems. Results of commercial systems are shown at the right part of the violin. Note that PV system sizes, indicated on the horizontal-axis, are not equally dispersed. Demand data were normalized to an annual energy consumption of 1 MWh and data of 2016 were used. Mean values of the distributions are indicated by dotted lines.

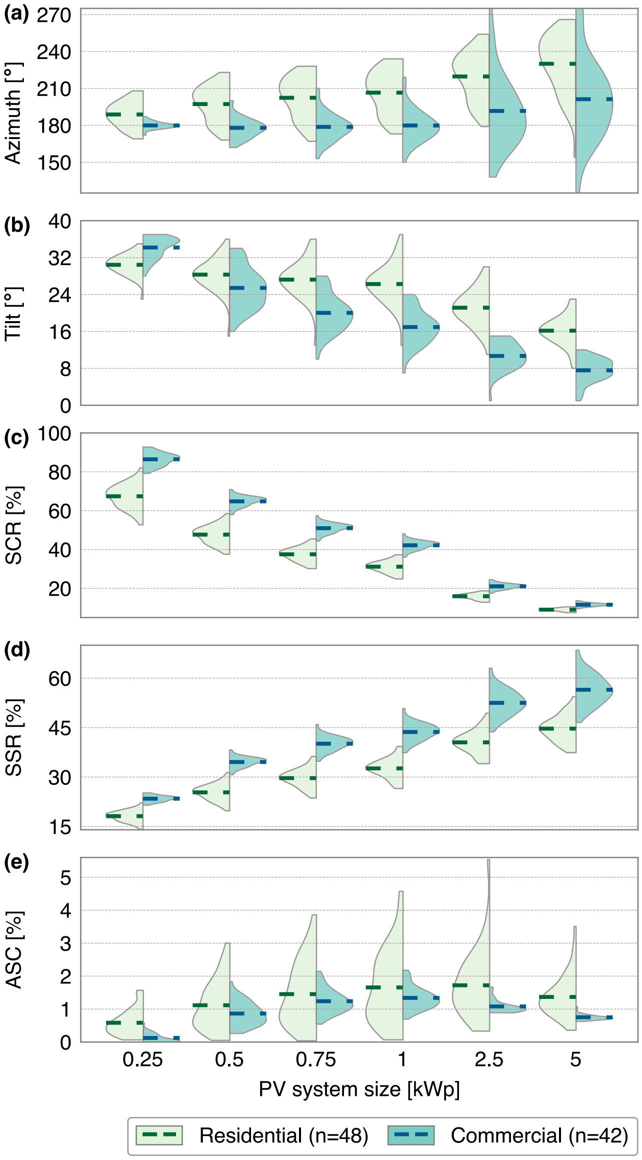

Fig. 3. Optimal orientation for annually maximized self-consumed energy (a and b), corresponding self-consumption rates (c), self-sufficiency rates (d) and added self-consumption (e) shown using violin plots. Distributions of residential systems (left part of the violin) and commercial systems (right part of the violin) are shown for six PV system sizes. Demand patterns were normalized to an annual energy consumption of 1 MWh and data of 2016 was used. Mean values of the distributions are indicated by the dashed lines.

Table 3
Optimal orientations to maximize energy production and optimal orientation to maximize revenue without self-consumption. Corresponding annual yield (AC) is given for a PV system of 1 kWp. Added revenue values are given for the optimal orientations to maximize revenue. Orientations are indicated by ori. and azimuth by azi.

Year	Max PV yield		Dutch prices		German prices	
	Ori. (°) Azi., tilt	E_{PV} (kWh)	Ori. (°) Azi., tilt	AR (%)	Ori. (°) Azi., tilt	AR (%)
2010	187, 33	1046	180, 33	0.12	179, 33	0.13
2011	188, 38	1078	184, 37	0.05	184, 37	0.05
2012	187, 35	1010	184, 36	0.02	184, 36	0.04
2013	183, 35	1027	178, 35	0.06	176, 37	0.14
2014	182, 35	1068	179, 37	0.05	178, 36	0.04
2015	187, 36	1111	182, 35	0.08	184, 36	0.02
2016	181, 37	1086	177, 38	0.06	177, 39	0.10
Mean	185, 36	1061	181, 36	0.06	180, 36	0.07

Note that a relative PV system size of 1 kWp for each MWh of annual energy consumption is commonly installed in the Netherlands, since this will approximately fulfil the annual demand. PV systems sizes smaller than 1 kWp per MWh of annual consumption are installed when there are space limitations. PV systems >1 kWp per MWh of annual consumption are normally not installed, but included in this analysis for a better understanding of the effect of demand patterns on PV orientation.

4.1. Optimal orientation for self-consumption

The optimal orientations to maximize self-consumption are closer to the optimal orientation to maximize energy production for smaller systems than larger systems. The latter orientation already results in a larger share of self-consumption, and lower export to the electricity grid, for these smaller systems. Therefore, the share of self-consumed energy that can be added due to optimizing the orientation is relatively small. Consequently, the influence of individual demand patterns on the self-consumption is lower, resulting in a slighter distribution range for smaller systems.

Larger PV systems have a relatively lower share of self-consumed energy at the optimal orientation to maximize energy production than the optimal orientation for self-consumption. Relatively more energy is produced and directly consumed in morning and evening hours. Consequently, the influence of individual demand patterns on the orientation increases as well for larger systems. Residential patterns have a higher volatility during the day than commercial patterns, see Fig. 1. Consequently, the orientation distribution for systems <1 kWp for each MWh of annual consumption have a broader range for residential than commercial systems, whereas for larger PV systems the opposite holds.

Azimuth angles for optimal energy production are between 181° and 188°, see Table 3. Residential systems show higher azimuth angles, whereas commercial systems have similar azimuth angles. The peak demand of residential buildings is during late afternoon, whereas commercial buildings have a peak at noon, see Fig. 1. Consequently, the mean azimuth angles for residential systems are oriented south-west and for commercial systems oriented south.

Mean azimuth for residential systems increases with larger relative PV system size, while commercial systems show a small decrease. The optimal tilt decreases with an increasing PV system size, especially for commercial PV systems. A lower tilt angle results in a broader but lower daily PV profile, since energy is produced for a larger range of solar azimuth angles. This leads to higher self-consumption for commercial systems. Furthermore, the distribution ranges of optimal tilt angles are similar for commercial and residential systems, indicating comparable influences of demand patterns on the tilt.

4.2. Effect on self-consumption

SCR decreases with larger PV system size and is larger for commercial than residential systems. Commercial systems show a higher SCR because of a better match between PV production and energy demand. The SCR distribution ranges decreases with larger PV systems, indicating a reduced influence of the PV pattern on PV self-consumption. Also, the SSR is larger for commercial than residential systems and increases with PV system size. Contradictory to SCR, the SSR shows an increased distribution spread with larger PV systems, related to the relatively increased influence of the individual demand pattern.

ASC for commercial is smaller than for residential systems, showing that optimal PV orientation of commercial systems is closer to the optimal orientation for maximizing energy yield. Consequently, ASC distribution range is considerable larger for residential than commercial systems. In addition, ASC increases with PV system size, peaks at 2.5 kWp, and decreases for 5 kWp. Thus larger PV systems will increase SSR, but decrease ASC. Annual SCR and SSR are around 10% point higher for commercial systems than residential systems. Furthermore, the average ASC is larger for residential systems than commercial systems, for all investigated PV system sizes.

5. Minimize curtailed energy under feed-in limitations

Optimal PV orientations to minimize the curtailed energy were analysed for a 1 kWp PV system per MWh annual energy consumption with feed-in limitations from 0.1 till 0.7 kW/kWp. Distributions of these optimal orientations, and corresponding CLR and RCE are shown in Fig. 4. The CLR and RCE were calculated with an annual yield of 1086 kWh/kWp, derived from the optimal orientation for energy generation for 2016 (181° azimuth and 37° tilt).

With a strict feed-in limitation (0.1 kW/kWp), the optimal orientation to minimize curtailment losses is adjacent to the optimal orientation for maximizing annual energy production for commercial systems. Residential systems show a larger difference. With an enlarged feed-in limitation (towards 0.1 kW/kWp), most energy that is produced during noon time cannot be fed back to the grid. Subsequently, optimal PV orientation converges towards an

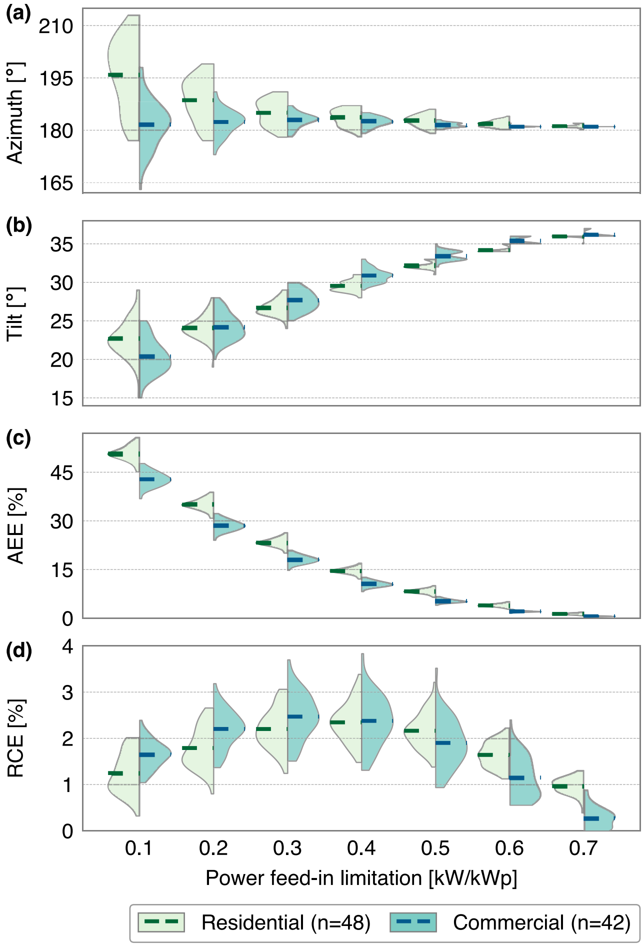

Fig. 4. Optimal orientation for annually minimized curtailed energy (a and b), corresponding curtailment loss ratios (c) and reduced curtailed energy (d) shown using violin plots. Distributions of residential systems (left) and commercial systems (right) are shown for seven power feed-in limitations. Demand patterns were normalized to an annual energy consumption of 1 MWh and mean values of the distributions are indicated by the dashed lines.

orientation that increases PV self-consumption for low power demand. This is achieved by reducing the tilt angle of the PV modules, thus flatten the PV yield profile and increase self-consumption in the early morning and late afternoon.

With a relaxed feed-in limitation (towards 0.6 kW/kWp), more energy can be fed-back to the grid. Thus, the optimal orientations converge towards the optimal orientation for energy production for both residential and commercial PV systems. Moreover, the influence of demand patterns on the optimal orientation decreases with reduced feed-in limitations. Consequently, the distribution range of optimal orientation is decreasing as well. Curtailment losses are larger for residential than for commercial PV systems and are reduced to a few percent for feed-in limitations of 0.7 kW/kWp.

Annual RCE is increasing till a limit of 0.3 and afterwards decreasing. A strict feed-in limitation of 0.1 kW/kWp has already a relative high curtailed energy loss under the optimal orientation for energy production, compared to a feed-in limitation of 0.3 kW/kWp. Consequently, the influence of changing the orientation to reduce curtailed energy losses is larger with an increase of feed-in limitation to 0.3 kW/kWp. A relaxed feed-in limitation of 0.7 kW/kWp has a relative low curtailed energy loss under the optimal orientation for energy production. Therefore, the change of curtailed energy losses by shifting the orientation is decreasing.

Annual reduced curtailed energy for feed-in limitations <0.3 is larger for commercial systems than residential systems, whereas for limitations >0.4 the opposite is seen. The benefit of optimizing PV orientation for RCE is larger for residential than commercial systems, and the RCE is below 4% for all patterns and feed-in limitations. A feed-in limitation of 0.5 kW/kWp has an averaged optimal PV orientation of 183° azimuth and 32° tilt for residential systems, and 181° azimuth and 33° tilt for commercial systems. This shows that reducing the tilt angle, compared to the orientation that maximizes energy yield, reduces the curtailed energy losses.

6. Maximize revenue

6.1. Fixed prices

Influences of price patterns with a constant price for a 1 kWp system are shown on the distribution plot of Fig. 5. Sold electricity has no economic value with a SPR of zero, thus maximizing self-consumption is most beneficial. Therefore, distribution of PV systems with different sizes and a SPR of zero are similar as in Fig. 3. Distributions for a SPR of 1 show optimal orientations for maximizing PV production.

Both PV orientations of residential and commercial PV systems converge towards the optimal orientation for maximizing PV yield. Influence of variation between demand patterns is decreasing with an increase in SPR. Furthermore, added revenue of SPR >0.5 is very limited with values below 0.1%. Overall, the added revenue of PV systems is decreasing with exponential behaviour from ≈1.7% for residential systems and from ≈1.3% for commercial systems towards zero with larger sales to purchase ratios.

6.2. Time dependent market prices

Distributions of optimal orientations for time dependent pricing patterns for 7 years are presented in Fig. 6. The right seven distributions show results using Dutch prices and the left seven results using German prices, both for a PV system size of 1 kWp and a SPR of 0. A SPR of 0 is chosen to show the orientations for maximizing the value of self-consumed energy. The value of sold electricity is zero with an SPR of 0. Thus, PV self-consumption on moments with a relatively higher electricity price is more valuable than PV self-consumption on moment with a relatively low electricity price.

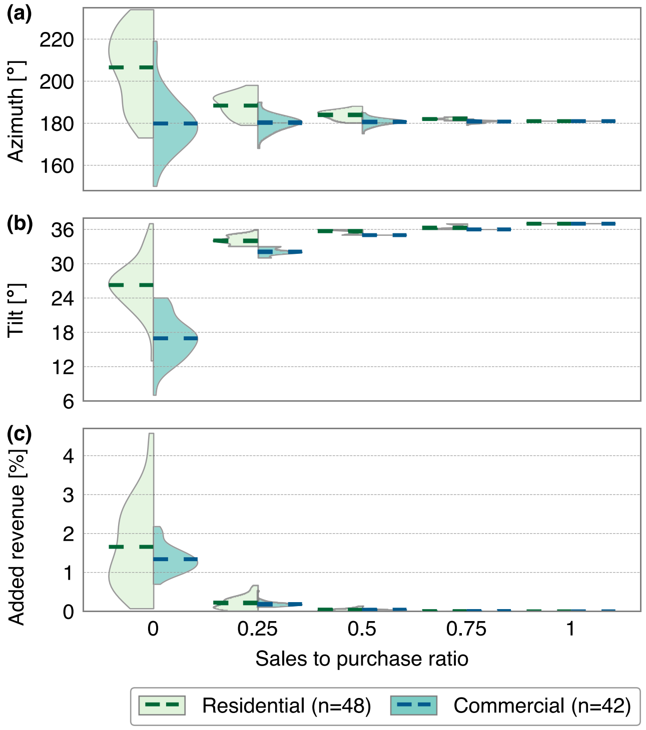

Fig. 5. Optimal orientation for maximized system revenue (a and b) and corresponding added revenue (c) shown using violin plots. Distributions of residential systems (left) and commercial systems (right) are shown for five fixed tariff pricing patterns. Demand patterns were normalized to an annual energy consumption of 1 MWh and data of 2016 was used. Mean values of the distributions are indicated by the dashed lines.

German market prices have a larger variance in prices between the early morning hours and afternoon hours than Dutch market prices, which influences the optimal orientation. This is especially visible for 2014 and 2015, shown by the difference in optimal azimuth angle. Residential systems show ≈3° higher azimuth angles for German prices than Dutch prices.

The average annual azimuth angles varied between 203° and 214° for residential systems, indicating a significant influence of each year on the optimal azimuth. The average optimal tilt angle varies between 24° and 27°. Furthermore, the distribution range for residential systems is larger than the range show for maximizing self-consumption, see Fig. 3. Commercial systems have average annual azimuth angles between 178° and 195° and tilt angle between 17° and 19°. The range of annual difference between azimuths is larger for commercial than residential systems. The optimal orientation for commercial systems is closer to the orientations presented for the electricity markets without self-consumption (see Table 3) than residential systems. Hence, the influence of the annual variation in market prices is larger on commercial than residential systems.

There is a small correlation between the orientations for the electricity markets without self-consumption and including self-consumption. Relative high azimuth angles for maximizing profit with self-consumptions were found for 2011 and 2012 for Dutch market prices, and for 2011, 2012 and 2015 for German market prices. Residential and commercial systems show for these years a higher azimuth angle than the seven years average azimuth angle.

Mean tilt angles of residential and commercial systems are always lower than the optimal tilt angles for scenarios without

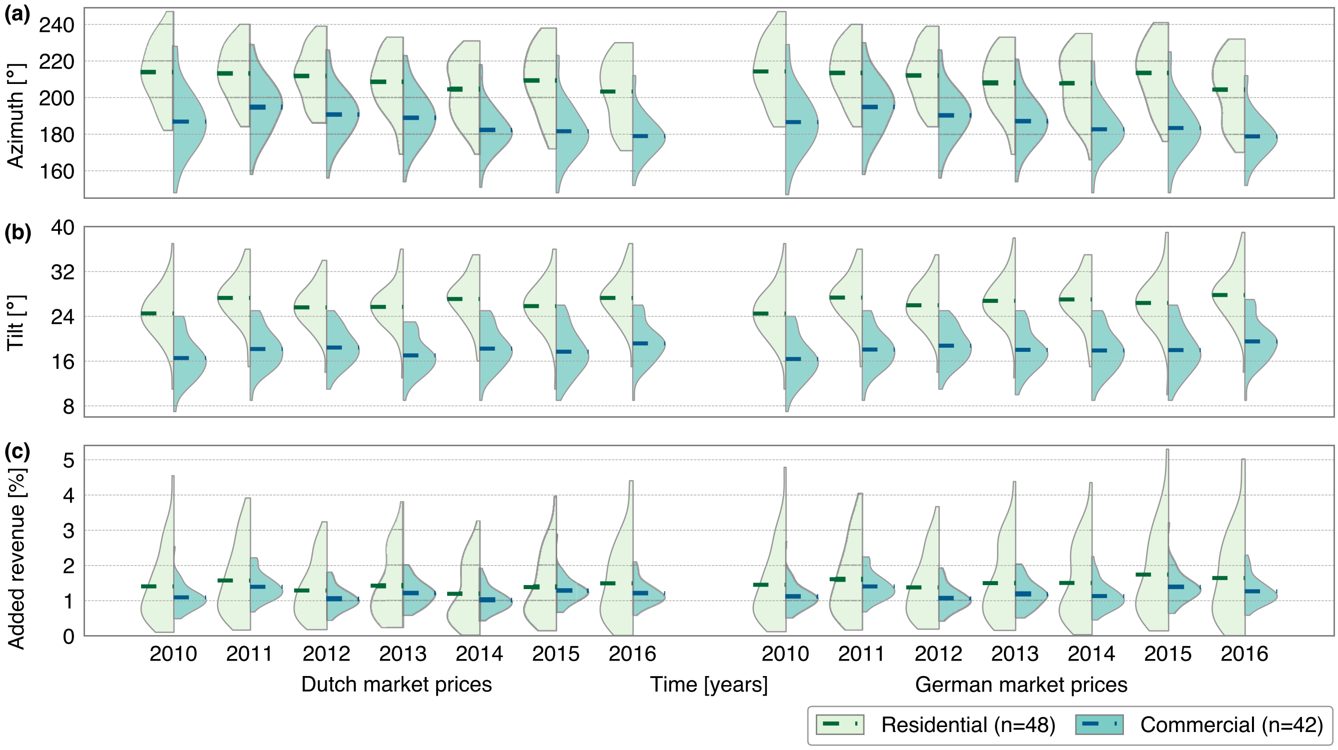

Fig. 6. Optimal orientation for maximized system revenue (a and b) and corresponding added revenue (c) shown using violin plots. Distributions of residential systems (left) and commercial systems (right) are for two markets and seven years. Results are shown for a PV system size of 1 kWp, a SPR of 0 and demand patterns were normalized to 1 MWh of annual energy consumption. Mean values of the distributions are indicated by the dashed lines.

self-consumption, see Table 3. Commercial systems show lower tilt angles than residential systems. A lower tilt angle results in a lower, but broader, daily PV yield. Hence, more moments in time have PV energy production, which increases the self-consumption for commercial systems.

The larger variance in market prices results in slightly more benefits for German prices than the Dutch prices. Average annual added revenue for residential systems is between 1.2% and 1.6% for Dutch prices and between 1.4% and 1.7% for German prices. Commercial systems show benefits between 1.0% and 1.4% for both markets.

6.3. Comparison of nine scenarios

Optimal orientations to maximize added revenue for nine different scenarios is presented in Table 4. The scenarios are created by varying the price patterns and SPR for residential and commercial systems. The price patterns were varied between fixed price patterns and time-of use price patterns (Dutch and German market prices). SPR were varied between 0, 0.5 and 1, therefore representing minimum and maximum values of energy fed back to the grid. A 1 kWp PV system was used with annual data from 2010 till 2016. Corresponding added self-consumption is presented in the last column.

Residential PV systems with an SPR of 0 show a large range in azimuth and tilt angles. This range indicates a large variance among the demand patterns. Differences in values between the R1 and the R4 scenario are small due to the low variance of the Dutch price pattern. The R1, R4 and R7 scenarios show the largest range of optimal orientations with azimuth angles from 166° till 249° and tilt angles from 10° till 39°. Largest revenues are observed for scenarios with an SPR of 0.

Commercial systems have lower mean azimuth angles in almost all pricing scenarios compared to residential systems. Especially, optimal orientation values for fixed pricing scenarios are closer to the maximum orientation for energy generation. Also, mean AR values from fixed pricing scenarios are lower for commercial systems. In SPR 0 scenarios, Dutch and German market price show higher mean AR values for residential systems than commercial systems.

The influence of market prices is larger in the SPR 0.5 and 1 scenarios. Consequently, the difference in mean AR between residential and commercial systems is smaller. Also, in the SPR 0.5 and 1 scenarios, the AR for commercial systems is larger than residential systems. Commercial systems have comparable AR values as shown for maximized revenue without self-consumption, see Table 3. Residential and commercial systems show small differences in optimal orientations between scenarios with German market prices and Dutch market prices.

SPR 0 scenarios show a larger range of corresponding ASC and a higher mean ASC for residential than commercial systems. However, the opposite is seen for the scenarios with time dependent market prices and a SPR of 1. These scenarios even show negative corresponding ASC values for residential systems, indicating a conflict in orientation between maximizing revenue and maximizing self-consumption. Optimal orientations for maximizing revenue are closer to orientations that maximize self-consumption for commercial systems than for residential systems. Consequently, the larger difference between these orientation results in lower corresponding ASC values for residential systems. Especially, the R6 and R9 scenario have respectively mean ASC values of −0.18% and −0.20%, with maximum self-consumption losses up to −0.88%.

6.4. East-West orientation

A common PV system design on flat roofs is the dual-tilt (or east-west) design. This reduces wind load on PV modules, decreases shading losses and increases the amount of PV modules

Table 4
Comparison of optimal orientation to maximize revenue for 9 different scenarios. Residential system scenarios are indicated by a R, commercial with a C. Values are for a PV system of 1 kWp, an annual consumption of 1 MWh and for each year between 2010 and 2016.

Scen.	Price patterns	SPR	Azimuth [°]			Tilt [°]			Maximized AR [%]			Corresponding ASC [%]		
			Mean	Range		Mean	Range		Mean	Range		Mean	Range	
R1	Fixed	0	212	171	249	26.0	10.0	37.0	1.53	0.05	5.43	1.53	0.05	5.43
R2	Fixed	0.5	188	180	196	34.4	31.0	37.0	0.04	0.00	0.15	0.35	0.01	1.55
R3	Fixed	1	185	181	188	35.6	33.0	38.0	0.00	0.00	0.00	0.00	0.00	0.00
R4	Dutch	0	209	169	247	26.2	11.0	37.0	1.40	0.01	4.55	1.52	0.03	5.40
R5	Dutch	0.5	184	176	192	34.7	32.0	38.0	0.03	0.00	0.15	0.07	-0.27	0.74
R6	Dutch	1	182	177	187	35.5	33.0	38.0	0.04	0.00	0.12	-0.18	-0.71	0.25
R7	German	0	210	166	247	26.5	10.0	39.0	1.55	0.01	5.30	1.52	0.00	5.41
R8	German	0.5	184	175	194	35.0	31.0	39.0	0.03	0.00	0.13	0.08	-0.29	1.06
R9	German	1	182	176	188	35.8	32.0	39.0	0.04	0.00	0.13	-0.20	-0.88	0.22
C1	Fixed	0	188	147	234	16.8	6.0	25.0	1.26	0.48	2.66	1.26	0.48	2.66
C2	Fixed	0.5	185	175	192	33.6	30.0	36.0	0.04	0.01	0.20	0.26	0.08	1.15
C3	Fixed	1	185	181	188	35.6	33.0	38.0	0.00	0.00	0.00	0.00	0.00	0.00
C4	Dutch	0	186	148	229	17.9	7.0	26.0	1.19	0.43	2.88	1.25	0.48	2.66
C5	Dutch	0.5	181	171	188	34.0	31.0	36.0	0.08	0.00	0.44	0.22	-0.03	1.46
C6	Dutch	1	181	175	186	35.3	32.0	37.0	0.06	0.00	0.22	0.06	-0.36	0.97
C7	German	0	186	147	230	18.1	7.0	27.0	1.23	0.42	3.22	1.25	0.48	2.65
C8	German	0.5	180	170	189	34.2	31.0	37.0	0.08	0.00	0.47	0.20	-0.08	1.46
C9	German	1	180	174	186	35.4	32.0	39.0	0.06	0.01	0.23	0.04	-0.41	1.15

that can be placed on a roof. This setup requires an azimuth difference of 180° between the first (m1) and second (m2) module and can have a tilt from 10° to 15° for both modules. The optimal azimuth angles for this setup, combined with a tilt angle of 13° for both modules, for each scenario, is presented in Table 5.

Mean optimal orientation for residential PV systems is in all scenarios between 91° and 94° for the panel oriented eastwards. Commercial PV systems have lower azimuth values, with mean values between 85° and 91°. Furthermore, the difference between scenario C7 and C8 is comparable to the result that includes optimal tilt, see Table 4.

Table 5
Comparison of optimal orientation to maximize revenue for 9 different scenarios with a dual-tilt PV system design. The PV modules are placed under a tilt angle of 13°. Residential system scenarios are indicated by R, commercial by a C. The values are for a PV system size of 1 kWp, an annual consumption of 1 MWh and for each year between 2010 and 2016. The range presents the minimum and maximum value of the first module.

Scen.	Price patterns	SPR	Azimuth (°)		
			Mean (m1, m2)	Range (m1)	
R1	Fixed	0	94, 274	75	105
R2	Fixed	0.5	91, 271	84	97
R3	Fixed	1	90, 270	85	94
R4	Dutch	0	91, 271	75	105
R5	Dutch	0.5	92, 272	84	99
R6	Dutch	1	92, 272	86	97
R7	German	0	91, 271	75	105
R8	German	0.5	91, 271	84	97
R9	German	1	91, 271	86	96
C1	Fixed	0	88, 268	75	105
C2	Fixed	0.5	90, 270	81	96
C3	Fixed	1	90, 270	85	94
C4	Dutch	0	85, 265	75	105
C5	Dutch	0.5	90, 270	78	98
C6	Dutch	1	91, 271	85	96
C7	German	0	85, 265	75	105
C8	German	0.5	89, 269	79	97
C9	German	1	90, 270	85	96

7. Temporal influences

We analysed the hourly contribution and monthly contribution of added self-consumption, reduced curtailed energy and added revenue of 2016. The contributions of ASC were determined using the orientation found for maximizing self-consumption annually, see Fig. 3. Contributions of RCE were analysed using the orientations found to minimize the annual energy curtailed and a feed-in limitation of 0.5 kW/kWp was used. Contributions of AR were determined using the orientations found for maximizing annual revenue for the Dutch market. The analysis was conducted for a PV system size of 1 kWp and demand patterns were normalized to an annual energy consumption of 1 MWh. Added revenues were calculated with a SPR of 0.5 and with Dutch market prices from 2016. The orientation was kept constant over the year for each system.

7.1. Hour of the day contribution

Hour of the day contributions are shown in Fig. 7. Residential PV systems have negative ASC values between 6.00 and 9.00, due to the optimal module azimuth for self-consumption of 212°. Subsequently, ASC is increasing in the afternoon and positive in evening hours. Commercial PV systems show a relatively constant ASC value during the day. Furthermore, the distribution range increases in morning and evening hours, especially for residential systems. This is a result of the larger distribution of residential demand, especially shown in the afternoon.

Reduced curtailed energy distributions for a feed-in limitation of 0.5 kW/kWp clearly indicate the hours for in which losses and benefits are gained by minimizing the curtailed energy. PV peak production occurs more in the afternoon than in the morning hours thus more PV energy is curtailed within these hours. Therefore, the effect of optimizing on curtailed energy is positive in the afternoon, yet negative in morning hours. Lower RCE fractions are shown for residential systems than commercial systems in morning hours and the opposite is seen in the afternoon hours. Residential systems have a higher optimal azimuth angle for RCE compared to

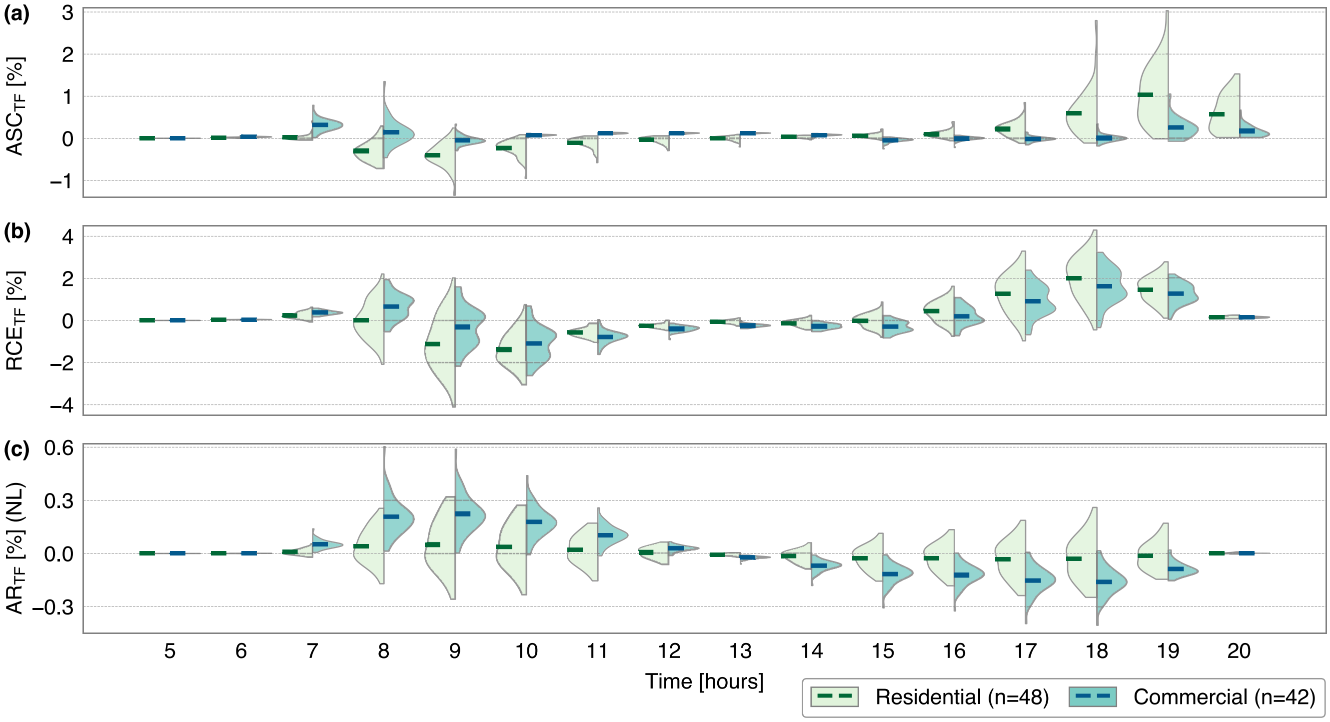

Fig. 7. Hour of the day contribution for added self-consumption (a) reduced curtailed energy (b) and added revenue for the Dutch prices (c) shown using violin plots. Distributions of residential systems (left) and commercial systems (right) are for a PV system size of 1 kWp and for 2016. Demand patterns were normalized to an annual energy consumption of 1 MWh. Reduced curtailed energy was calculated with a feed-in limitation of 0.5 kW/kWp and added revenue was calculated with a SPR of 0.5 and the year 2016. Mean values of the distribution are indicated by the dashed lines.

commercial systems. Hence, less PV energy is produced in the morning hours, resulting in lower RCE values.

AR distributions of the Dutch market prices show on average a constant value for residential systems, but a variance for commercial systems. Residential systems have a higher optimal module azimuth than commercial systems. Hence, residential systems produce less PV energy and have lower added revenue in the morning. More energy is produced by residential than commercial systems in the afternoon, resulting in larger benefits for residential systems. AR distributions using German market prices show a similar daily pattern as shown with Dutch prices, and are therefore not shown here.

7.2. Monthly contribution

Monthly contributions are visualized with the distribution plot of Fig. 8. ASC distributions show negative values for the first, second month, and last three months of the year for both residential and commercial PV systems. These months have an optimal tilt angle higher than the annual optimal tilt angle for self-consumption, resulting in a relative loss of self-consumption, especially for residential systems. However, ASC values are positive from April till September, with averages of $\approx$0.3% for commercial and $\approx$0.5% for residential PV systems. Thus, the lost self-consumption from winter months is overcompensated by the gain from summer months. Furthermore, a large distribution range is shown for higher absolute ASC values, especially visible for residential systems.

Monthly contributions of RCE show only positive mean average values for April till August. These months have a higher share of PV power production which excesses the feed-in limitation. The lower optimum tilt angle for RCE, compared to the optimum tilt angle for energy production results in a broader but lower daily PV profile. Therefore less energy has to be curtailed, which is especially visible for these months. Residential and commercial systems show a similar pattern over the year which is comparable with the ASC pattern.

Monthly AR contribution using Dutch and German market prices shows very small variation over 2016, with all values between -0.10% and +0.13%. Positive values are shown in summer months and negative values in winter months. However, German market prices have positive AR contributions in the winter months, and negative in the summer months, especially for residential systems. German market prices were relative lower than Dutch market prices for these periods, resulting in a lower benefit from PV-self-consumption.

Market prices in April and May were relatively ow between the 11th and 15th hour of the day. Thus, the value of self-consumed energy during the day increased. Between these hours, self-consumption for residential systems is lower than commercial systems. Consequently, April and May showed larger added revenues for commercial systems than residential systems.

8. Discussion

In this research, we presented different optimal orientations, depending on optimization goal, demand patterns, PV system size and electricity prices. Clear trends are observed between the various optimization goals. Maximizing self-consumption is profitable with fixed prices, especially when there is no income from electricity fed to the grid. Reduced curtailed energy due to optimizing PV system orientation is 2.3 % for residential and 2% for commercial systems, for a feed-in limitation of 0.5 kW/kWp. Optimizing orientation to maximize profit is interesting for time-of-use tariffs especially when a large difference between the sales and purchase prices is present.

Results on the influence of PV systems size and demand patterns on the optimal PV orientation are comparable with previous studies that included German demand patterns (Tjaden et al.,

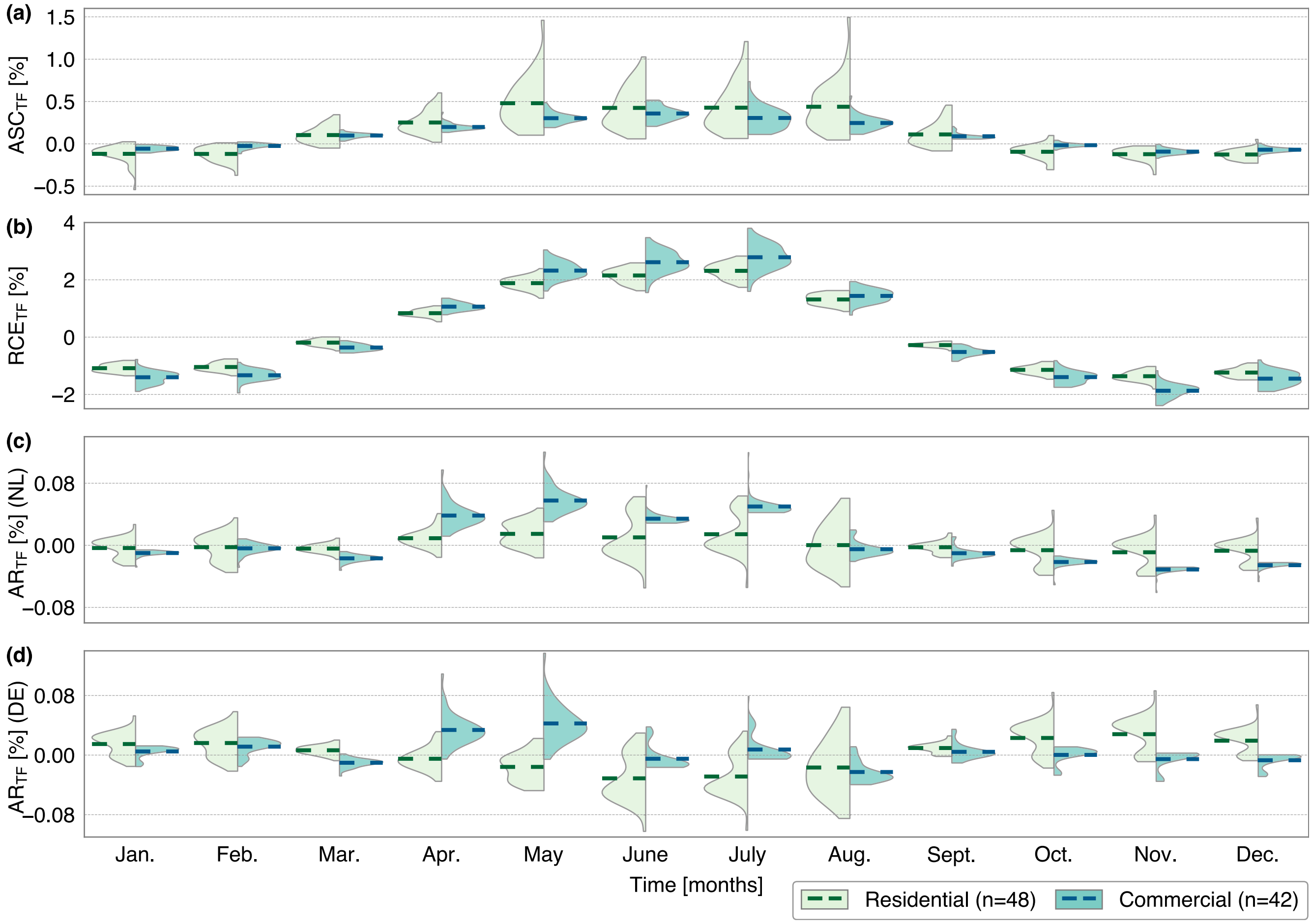

Fig. 8. Monthly contribution for added self-consumption (a) reduced curtailed energy (b) and added revenue for the Dutch prices (c) and German prices (d) shown using violin plots. Distributions of residential systems (left) and commercial systems (right) are shown for similar assumptions as used for Fig. 7.

2014; Lahnaoui et al., 2017). Also, results from the German market are similar to a study including German and Austrian markets (Hartner et al., 2015). Other results presented in this paper are different from results from previous studies due to the different power markets (Rhodes et al., 2014; Rowlands et al., 2011; Haysom et al., 2016).

Our study did not account for the obvious limitation of predefined building characteristics. Optimizing the PV orientation is only possible for buildings with flat roofs. The orientation for most PV systems depends on the roof orientation of a building. In the Netherlands, most residential buildings have a pitched roof, yet most commercial buildings have flat roofs available, enabling optimized orientation. Also, a change in orientation could lower the maximum power output of a PV system. Consequently, potential smaller inverters can be used for these systems. These inverters could reduce PV system costs, leading to additional benefits that are not included in our study.

8.1. Data limitations

Our research has several limitations that could affect the findings. Residential and commercial load is influenced by weather conditions, mainly by temperature (Hekkenberg et al., 2009). Only measured demand data of 2013 was used, therefore results of other years are influenced by this effect. The difference between the mean optimal orientation values of 2013 and the mean orientations values of other years (2010–2012 and 2014–2016) were analysed for nine scenarios and shown in Table 6.

Residential and commercial systems show similar difference in mean azimuth, ranging between $\approx -4.6^\circ$ and $\approx +3.2^\circ$. Differences in optimal tilt are significant lower for both residential and commercial systems, between $\approx -0.16^\circ$ and $\approx +0.09^\circ$. The difference in optimal orientation between the measured year and modelled years is smaller than the range in optimal orientation observed, see Table 4. Therefore, we suggest that the influence of the individual demand pattern on the optimal orientation is larger than the influence of weather.

The measurement interval of demand patterns was 15 minutes, resulting in a more smoothed pattern than the actual pattern. The PV yield pattern is smoothed out by 10 minutes, therefore missing

Table 6
Difference between mean orientation values of 2013 with mean values of other years (2010–2012 and 2014–2016) for residential (Res.) and commercial (Com.) systems for nine scenarios, previously explained in Section 6.4.

Scen.	Price patterns	SPR	Δ Azimuth [°]		Δ Tilt [°]	
			Res.	Com.	Res.	Com.
1	Fixed	0	-0.74	1.92	-0.09	-0.06
2	Fixed	0.5	-2.16	-1.92	-0.14	-0.16
3	Fixed	1	-2.33	-2.33	-0.10	-0.10
4	Dutch	0	-0.66	3.24	-0.08	-0.15
5	Dutch	0.5	-2.47	-2.01	-0.13	-0.13
6	Dutch	1	-2.62	-2.37	-0.09	-0.15
7	German	0	-2.87	1.06	0.04	-0.01
8	German	0.5	-4.24	-3.76	0.05	0.05
9	German	1	-4.58	-4.33	0.03	0.09

high PV power peaks caused by cloud enhancement. As a result, the overlap of the PV pattern with the demand pattern changes, which leads to slightly different results. However, a previous study found that relative errors were below 6% when using 15 minute data to calculate PV self-consumption (Beck et al., 2016). In addition, irradiance and demand patterns were measured for locations in the Netherlands, however our results could be used for other locations that show similarity in irradiance and demand patterns. A study for other countries with different irradiance and demand patterns is recommended for further research. Also, we modelled PV patterns without additional losses. In the built environment shade losses could occur, resulting in lower production in morning and evening hours.

8.2. Future trends

We used historical demand patterns, whereas future residential and commercial demand could shift due to increasing electrification by heat pumps and electric vehicles. Especially electric vehicles are expected to shift the peak demand for residential buildings to the evening, when residents arrive home and charge their electric vehicle. As a result, west oriented PV systems can increase their revenue even more. On the other hand, charging of electric cars can also increase energy demand of commercial buildings. When employees charge their electric vehicles in the morning hours, east oriented PV systems could be more beneficial for self-consumption. Alternatively, electric vehicle using charging algorithms aimed at optimizing PV self-consumption have been suggested (van der Kam and van Sark, 2015).

PV systems combined with energy storage change the optimal orientation, depending on the battery storage size and algorithm. With sufficient battery storage capacity, the optimal orientation for maximizing energy production will be more beneficial, as found in a previous study (Tjaden et al., 2014; Weniger et al., 2014). However, additional energy loss occurs due to charging and discharging of the battery, resulting in a lower efficiency of the total system.

Demand side management applications could shift the load towards moments with high solar irradiance, therefore influencing the optimal orientation significantly. Furthermore, electricity price signals can influence the electricity time-of-use for residential and commercial buildings. The effect of energy storage, demand side management and price signals on the optimal orientation from a system perspective is unknown. Therefore, we recommended investigating the optimal PV orientation with demand patterns including these opportunities.

It is expected that electricity market prices become more volatile with an increasing share of renewables. An increase of PV production during day time will lead to decrease of market prices, causing more benefits for east and west oriented PV systems. This is already visible from differences between the results using Dutch and German market prices. German market prices are influenced by a larger share of renewables compared to Dutch market prices. Therefore, lower prices are observed during moments when a larger share of electricity is produced from renewables. Furthermore, the difference in market design and limited interconnector capacity between the Dutch and German electricity markets affects the results. Yet, this could change in the future by integrating markets and increasing interconnection capacity, resulting in smaller differences between these two markets.

9. Conclusion

We combined 48 residential and 42 commercial demand patterns with different PV system sizes, feed-in power limitations and market prices to determine the optimal PV orientation for seven individual years. Annual values for self-consumption, curtailed energy and revenues under the optimal orientation were compared with an orientation that maximizes annual energy production. Furthermore, nine different pricing scenarios were compared on the optimal orientation for maximizing added revenue. Our findings show a clear relation between PV orientation and demand pattern and electricity prices.

Commercial systems have relative more energy consumption during noon, whereas residential systems during the evening. Consequently, residential systems have a higher average azimuth angle for optimizing self-consumption compared to maximizing energy yield, whereas commercial systems have a similar average azimuth angle. Maximizing self-consumption can be achieved with an azimuth of 212° and a tilt of 26° for residential and 188° azimuth and 17° tilt for a commercial PV systems. Maximum increase in self-consumption found for residential systems was 5.4% and commercial systems 2.7%.

A significant impact of reducing curtailment losses of the PV orientation was observed, dependent on the feed-in limitation. This can be achieved by a lower module tilt angles, therefore flatten the PV yield profile which decreases the curtailment loss. Annual curtailed energy losses can be reduced with ≈2.2% for residential and ≈1.9% for commercial systems, under a feed-in limitation of 0.5 kW/kWp.

A small difference among optimal orientation for maximizing added revenue was found between Dutch and German market prices. Azimuth angles for German market prices are ±1° different than Dutch market prices. Variances concerning tilt angles between these two markets are of the same order. Therefore, similar added revenue for Dutch as for German market prices was found. Low sales to purchase ratios lead to a higher influence of demand patterns, resulting in a larger variance of optimal orientations.

The maximum revenue for PV systems can be increased up to 5.4% for certain demand patterns and scenarios. Furthermore, orientations that were maximized for revenue showed corresponding negative ASC values, indicating a conflict between the orientation for maximizing self-consumption and the orientation for maximizing revenue. Nevertheless, this shows that a loss of self-consumption could be beneficial.

Analysing the contribution of three different temporal factors provided useful insight in the obtained results. Hour of the day analysis indicated that increasing self-consumption occurs in the evening hours for residential systems. Curtailed energy is reduced significantly around noon as a result of a lower module tilt angle. Furthermore, a small monthly variation was found for added revenue.

Including PV, demand and market price patterns gave a better insight on the optimal PV orientations. Especially, the variance between investigated demand patterns largely affects the orientation. To conclude, we advise that decisions related to the orientation of PV systems should not only focus on maximizing energy production, but also include expected demand patterns and market prices.

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