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First Year of Smart Metering with a High Time Resolution—Realistic Self-Sufficiency Rates for Households with Solar Batteries

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Abstract

Measured data from distribution grids with a high time resolution is scarce although it is where most volatile power profiles occur. Electrical storage systems (ESS) can mitigate the imbalance of generation and demand. In this study smart meter data with a temporal resolution of 15 s is analyzed and an algorithm described, that allows identifying differently oriented generator in mixed PV plants. Various self-consumption scenarios are simulated with different setups and temporal resolution. The calculated self-sufficiency rates lead to recommendations for the dimensioning and give precise values for the correction of key parameters from simulations if data is not available in high temporal resolution.

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Keywords: residential smart meter; PV simulation; PV battery systems; self-consumption; dimensioning; temporal resolution

1. Introduction

PV solar power supplies a considerable share of the electrical energy demand in Germany, namely 5.9 % in 2015. In the federal state of Bavaria the share is even twice as high, 11.8 % in 2014. PV penetration is not evenly distributed and concentrated in rural areas. Comparing the annual PV generation and demand, some neighborhoods already exist that could provide for themselves electrically. One example is the district Epplas belonging to Hof/Bavaria. It generates more than twice the energy it consumes in a year because of a high presence of rooftop PV

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plants. The obvious restraint is that PV generation is highly volatile, underlies seasonal effects and is not controllable and therefore independent of the demand. Additionally most plants are connected on the lowest voltage level so if feeding into the grid is allowed and a surplus occurs it is technically challenging to transfer it to other areas. The political will to increase the share of renewables has to consider both the interest of the plant owner as an investor and the interests of the grid operator as the technical enabler. The financial benefit of a prosumer’s PV plant depends on decreasing electrical supply from the grid, which means an increase of the electrical self-sufficiency rate. From the grid operator’s perspective peak load and feed-in are the decisive parameters based on which the grid has to be designed or expanded. The aim of this paper is to give insight on the influence of varying PV generator orientation or installing an electrical storage system (ESS) on the electrical self-sufficiency rate—based on measured data.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
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<tbody>
<tr>
<td>A</td>
<td>Albedo factor, estimated to be 0.2</td>
<td></td>
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<tr>
<td>Cstor</td>
<td>usable storage capacity in kWh</td>
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<td>CFsim</td>
<td>correction factor that scales the simulated PV powers according to the measured values</td>
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<tr>
<td>Ediff.g</td>
<td>diffuse irradiance perpendicular to the generator in kW/m²</td>
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<tr>
<td>Ediff.h</td>
<td>diffuse irradiance on the horizontal plain in kW/m²</td>
<td></td>
</tr>
<tr>
<td>Edir.g</td>
<td>direct irradiance perpendicular to the generator in kW/m²</td>
<td></td>
</tr>
<tr>
<td>Eff,i</td>
<td>effective fraction of the irradiance Ei in kW/m²</td>
<td></td>
</tr>
<tr>
<td>Eglob.h</td>
<td>global irradiance on the horizontal plain in kW/m²</td>
<td></td>
</tr>
<tr>
<td>Erefl.g</td>
<td>reflected irradiance perpendicular to the generator in kW/m²</td>
<td></td>
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<tr>
<td>PSTC</td>
<td>rated module power in kW/(1000 W/m²) at standard test conditions</td>
<td></td>
</tr>
<tr>
<td>Wcons</td>
<td>annual electrical consumption of the household in MWh/a</td>
<td></td>
</tr>
<tr>
<td>η</td>
<td>overall efficiency of the PV plant, including modules and inverter</td>
<td></td>
</tr>
<tr>
<td>γg</td>
<td>elevation of the generator in °, horizontal = 0 °</td>
<td></td>
</tr>
<tr>
<td>γs</td>
<td>elevation of the sun in °</td>
<td></td>
</tr>
<tr>
<td>θ</td>
<td>angle between the normal of the generator and the direction of the sun in °</td>
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2. Methodology

In November 2014 15 households were provided with smart meters that measure voltages, currents and power factors on three phases with a time resolution of 15 seconds as part of the Smart Grid Solar project. The smart meters whose data is used in this study consist of 15 units measuring load demand and 12 measuring PV generation.

In the following, the term PV plant will be used for a setup that is measured by one smart meter but can consist of various, differently oriented generators. The orientation of one generator is defined by its azimuth $\gamma_g$ and elevation $\gamma_s$. In Epplas 6 PV plants are single-oriented. The other 6 include up to 4 generators, which are not measured independently but aggregated. For that reason an algorithm was applied to identify each single-oriented generator in the mixed setups as a first step to gain a broader variation of orientations.

2.1. Splitting mixed setups

The generated solar power $P_{pv}$ can be ascribed to three effects: direct, diffuse and reflected irradiation [1].

$$P_{pv} = P_{STC} \cdot \eta \cdot \left( E_{dir,g} + E_{diff,g} + E_{refl,g} \right)$$ (1)

Several models for the diffuse fraction have been described in the literature. For our approach the Klucher [2] model was chosen. There are a lot of factors, that influence the efficiency of the PV generation, for example the
module temperature. This temperature is not only a product of current conditions like ambient temperature and wind speed, but also influenced by past operation due to the thermal inertia of the modules. In a simplifying approach the efficiency at each time step is considered to be equal for all generators, because it is assumed that periods of high or low module temperatures affect all generators simultaneously. Furthermore, due to the proximity of the considered plants, $E_{\text{diff},h}$ and $E_{\text{glob},h}$ are assumed to be the same for all generators so the model does not take into account cloud movement which would only affect part of the PV plants. Individual skylines—i.e. objects that cast shadows on certain generators during a certain time of the day—are also not considered. Another simplification is that the rated power of the generators is supposed to be independent of their age. At this point we introduce the expression effective irradiance $E_{\text{eff}}$, which is the product of the PV plant efficiency $\eta$ and the irradiance. It stands for the irradiance that can be multiplied with $P_{\text{STC}}$ to obtain the generated electrical power at every time step. Please note that the STC power rating already includes the module efficiency at standard test conditions. Therefore $\eta$ only includes the efficiency of the PV inverter and all effects that lead to a reduced performance compared to the standard test conditions. The three irradiance fractions can then be expressed via the effective diffuse and global irradiance on a horizontal plain $E_{\text{eff, diff},h}$ and $E_{\text{eff, glob},h}$ [1,2].

$$E_{\text{eff, dir},g} = \eta \cdot E_{\text{dir},g} = \frac{E_{\text{eff, glob},h} - E_{\text{eff, diff},h}}{\sin \gamma_s} \cdot \cos \theta$$

$$E_{\text{eff, diff},g} = \eta \cdot E_{\text{diff},g} = \frac{E_{\text{eff, diff},h}}{2} \cdot \left(1 + F \cdot \sin^3 \frac{\gamma_g}{2}\right) \cdot \left(1 + F \cdot \cos^2 \theta \cdot \cos^3 \gamma_s\right)$$

$$E_{\text{eff, refl},g} = \eta \cdot E_{\text{refl},g} = E_{\text{eff, glob},h} \cdot A \cdot \frac{1 - \cos \gamma_s}{2}$$

$$F = 1 - \left(\frac{E_{\text{eff, diff},h}}{E_{\text{eff, glob},h}}\right)^2$$

Since the term

$$\left(1 + F \cdot \sin^3 \frac{\gamma_g}{2}\right)$$

exceeds the value 1.05 only on very sunny days and for steep generator elevations $> 45^\circ$ it is estimated to be always 1. In case of mixed setups the smart meter measures a composed power $P_{\text{PV,mixed}}$ of $n$ single-oriented generators.

$$P_{\text{PV,mixed}} = \sum_{i=1}^{n} \left[ P_{\text{STC},i} \cdot \left(E_{\text{eff, dir},g,i} + E_{\text{eff, diff},g,i} + E_{\text{eff, refl},g,i}\right)\right]$$

Now, for each time step $E_{\text{eff, diff},h}$ and $E_{\text{eff, glob},h}$ are varied to fit the power values from the model to the measured smart meter values—for both mixed and single-oriented setups. Due to the considerable number of 12 measured values a sound fitting can be achieved, even in case of measure outtakess. Individual power values for each generator in mixed setups $P_{\text{PV,i,mixed}}$ can then be simulated by means of eq. 1–2 and the respective orientation and STC power of the generator. For each plant the generator values are aggregated and finally scaled with a correction factor $CF_{\text{sim}}$ so that the aggregated power matches the measured value $P_{\text{PV,mixed}}$. The correction is done for each mixed setup in every time step.
At this point it is probably helpful to visualize the additional information gained and the assumptions made by the described algorithm. For every time step values for $E_{\text{eff,diff,h}}$ and $E_{\text{eff,.glob,h}}$ are calculated thus giving a detailed description of the current irradiation intensity and level of cloudiness while also including the information of past conditions which influence the modules temperature and therefore the efficiency of the PV plants. Using these parameters within the model described above allows splitting up the generation in mixed setups according to different orientations. As a result the number of individual PV profiles is increased from 6 to 22, including 20 different orientations (two orientations occur twice).

The fitted irradiance parameters can also be used to simulate missing data, where the correction factor can be estimated with the median value from the remaining time steps of the same PV plant, or even whole plants. In this paper however only the first scenario applies: power values from mixed plants are split up into the different generators. No power values for missing time steps or further PV plants are simulated.

Table 1. ESS parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
</tr>
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<tbody>
<tr>
<td>usable storage capacity relative to annual consumption in kWh/(MWh/a)</td>
<td>0.5/1/1.5/2</td>
</tr>
<tr>
<td>one way efficiency in %</td>
<td>90</td>
</tr>
<tr>
<td>max. (dis)charge power in kW</td>
<td>4.6</td>
</tr>
</tbody>
</table>

2.2. Calculating self-sufficiency rates

The considered households operate their PV plants according to the old German remuneration model, where all power generated is fed-in and rewarded with a fixed price, depending on the time of commissioning. The energy demand is completely provided by the grid, and no energy from the generators is consumed within the household. So, any self-consumption calculations, regardless whether with or without storage, have to be based on a simulation. Since the number of households is still quite small to have a statistically sound number of results, we decided to match each of the 15 load profiles with each of the 22 power profiles of the generators described in the previous chapter. To create comparable conditions the load profiles are kept at their original values while the PV power is scaled to fixed $P_{\text{PSTC}}$ : $W_{\text{cons}}$ ratios. In the base scenario no ESS is considered so only direct self-consumption occurs. Next, different sized ESS are included in the simulation for each match. The usable storage capacity $C_{\text{stor}}$ is also scaled proportionally to $W_{\text{cons}}$. The maximum (dis)charge power for the storage is set to 4.6 kW according to the valid German framework for single-phase connected devices [3]. The ESS parameters are summarized in table 1. In an additional scenario an ESS with infinite capacity and no power restraints is assumed. This case is meant to demonstrate the maximal theoretical benefit of an ESS. The ESS operation strategy is greedy, which means whenever generation and demand do not match, the ESS (dis)charges first, as long as it stays within its power and capacity limits. In a second instant, further power demand or surplus is supplied by or fed into the grid. Based on this data realistic self-sufficiency rates can be calculated.

When working with load profiles in form of time series in simulations, the temporal resolution has a very high impact. This correlation has been investigated in [4] and a similar method has also been applied in [5]. It consists of running a simulation with the highest temporal resolution available. After that the same calculations are repeated but based on mean values of coarser temporal resolutions. The deviation of key parameters like self-sufficiency from their original values is then determined. The direct self-consumption $P_{\text{SC}}$ achieved for each time step $i$ is determined by the minimum of the two power values for load and PV generation, see also the example in figure 1 (a).

\[
P_{\text{SC},i} = \min\left(P_{\text{PV},i}, P_{\text{load},i}\right)
\]
If you consider a period where load and PV do not intersect, like in figure 1 (b), the self consumption is not affected by the temporal resolution. But imagine two profiles with the same mean value in the time interval considered. Consequently self-consumption reaches the theoretically maximum, see also figure 1 (c).

\[ P_{SC,j} = P_{PV,j} = P_{load,j} \]  \hspace{1cm} (6)

If the profiles are more volatile in reality and therefore intersect within the considered time interval, like in figure 1 (d), using a coarse temporal resolution which smoothes out the load profiles would even up short periods of surplus and deficit, here depicted as the grey area labelled error. This temporal shifting or moving of energy is equivalent to a small, virtual storage capacity. Because of this effect a coarser temporal resolution will always lead to higher values for self-sufficiency or self-consumption rates. Or put in other words: running simulations with a coarse temporal resolution means having a virtual ESS with perfect efficiency that smoothes out micro charge cycles. In this paper the simulations for the calculation of the self-consumption were repeated with the same power profiles, but this time mean values over longer intervals of 30 s, 60 s, 120 s, 300 s, 900 s and 3600 s were used.

Figure 2: (a) Boxplots showing the distributions of the correction factor. The thicker lines are actually overlaying outliers indicating the limits of the whiskers; (b) Comparison of the annual yield from the simulation (background) and the measured values from the plants (smaller circles).
3. Results

Despite of the simplifications mentioned in the generator identification algorithm before, it produces reliable results. Furthermore the error that is made is only of a relative nature affecting the individual shares of the different generators in a mixed setup. The absolute, aggregated power in mixed plants is scaled to the measured value with the correction factor. To give an insight into the precision of the used model the distributions of the correction factors are displayed as boxplots in figure 2 (a).

Another way to compare simulation and measured data is to analyze the annual yield in dependency of the orientation, which is visualized in figure 2 (b). It shows the size and orientation (by means of power-weighted average values for mixed setups) of the PV plants and how they perform compared to simulation with the fitted irradiance parameters. The color, the smaller plant circles are filled with, indicates the yield measured by the smart meter. The color of the big circle in the background stands for the simulated yield values. In general, simulated yields are highest at a slightly eastwards (azimuth = 175 °) and by 35 ° tilted orientation. Please note that this results relate to the smart meter data of the year 2015 and could look different for other years, which will be investigated in following studies.

Figure 3: Impact of orientation, installed PV power and usable ESS capacity on the self-sufficiency rate (a) and on the self-consumption rate (b). Each point represents a match of one PV profile with one load profile. Lines indicate the mean value of the points at a certain azimuth.
Considering the self-sufficiency rates in dependency of the orientation it is important to keep one aspect in mind. The \( P_{SIE} : W_{cons} \) ratios are set to fixed values in this study, i. e. the size of a plant in correlation to the residential consumption is kept on a comparable level. Consequently a lower absolute PV yield is to be expected when the orientation of the generator shifts toward less optimal settings. If for matches with less optimal orientations self-sufficiency rates stay on the same level, this means that although less energy is produced the same absolute share is used for residential consumption. Only the amount that is fed into the grid—or curtailed if feed-in is no option—is decreased. The results are summarized in figure 3 (a). When comparing the self-sufficiency in case of no ESS it becomes visible that the influence of the orientation decreases with the size of the PV generator. Generally an orientation towards east produces slightly higher self-sufficiency rates. In the case of Epplas this is solely due to the higher energy yield for east-oriented generators—because as you can see in figure 3 (b) the self-consumption rates are actually slightly higher in the west. For small PV sizes the self-sufficiency gained even with medium sized ESS is close to the theoretical maximum. This is especially true for eastwards or westwards orientation.

Another important factor for the implementation of ESS is the number of charge cycles that are expected within one year. A charge cycle is defined as the complete discharge and charge of the usable capacity. Figure 4 summarizes the number of cycles for the different setups.

![Figure 4: Impact of orientation, installed PV power and usable ESS capacity on the number of ESS charge cycles. Each point represents a match of one PV profile with one load profile. Lines indicate the mean value of the points at a certain azimuth.](image-url)
4. Discussion

Analyzing the correction factors in figure 2 (a), it becomes visible which plants tend to perform better or worse in reality than in the model. The obvious assumption that older plants—like PV01, PV09 and PV10 that mostly consist of generators installed in 2005—show reduced power production is not supported by the data. While the highest performing plants PV07 and PV12 are of younger age (2011 and 2012) the lowest performing plant compared to the model still ranks among the newer installations, namely PV03 dating to 2008–2010. The quality of performance compared to the simulation shows also no clear correlation to the orientation. PV03 consist of generators with almost optimal orientation and scores low. PV04, PV06, PV07 and PV12 with close to optimal orientation perform considerably better. Then again PV08 with the most extreme, northern orientations performs close to the simulation. This leads to the conclusion that the chosen simulation approach takes orientations correctly into consideration. One reason for the deviation of the simulation from measured data could also be, that the $P_{STC}$ values of the plants we received from the distribution grid operator’s data base are contain errors.

The influence of orientation on the self-sufficiency or self-consumption rate has been studied before [6, 7] but mostly based on simulated profiles. Self-sufficiency rates from [6] are about 5 % higher, while the self-consumption
rates from [7] proved to be too optimistic with a difference of 10% to 15%. One of the reasons why the rates calculated in other studies are higher is probably due to the coarser temporal resolution they are based on.

As described, the simulations were repeated with coarser time resolution. The deviations are depicted in figure 5 (a) and (b) and confirm the results in [7] concerning the error which is in the range of plus 15–20% for an hourly aggregation and a setup without ESS. A very interesting fact is that the same error reduces to roughly 2% for hourly aggregated simulations when a usable ESS capacity of 1 kWh/(MWh/a) is chosen. This makes perfect sense when we recall the explanation from above: coarse time resolution corresponds to having a virtual ESS. When simulating a setup without ESS the error is high because actually no ESS at all in case of the 15 s data is compared with some virtual capacity in case of the coarser temporal resolution. On the other hand the error is small when simulating a setup with for example 1 kWh/(MWh/a) because it means comparing an ESS with precisely that capacity (15 s data) with an ESS that has 1 kWh/(MWh/a) plus some extra virtual capacity because of the coarser temporal resolution.

The deviations of simulations with longer time intervals become also evident in another key parameter: the number of charge cycles of the ESS. The results from the simulation with the 15 s temporal resolution are compared with those of 1 h-time-intervals in figure 6. This time the results of the coarser temporal resolution are lower, because the ESS is exposed to less micro cycles which are ignored due to the mean values of the longer intervals. The error is most prominent for small capacities of 0.5 kWh/(MWh/a) resulting in 20–30% less charge cycles. For the other capacities it is in the range of minus 10–20%.

![Figure 6: Deviation of the charge cycle results based on the 1 h mean values from the original 15 s data results. Each point represents a match of one PV profile with one load profile. Lines indicate the mean value of the points at a certain azimuth.](image-url)
5. Conclusion

It is not as straightforward as one might think to give recommendations on dimensioning residential solar battery systems, as it depends also on the regulatory framework. Nevertheless, it is possible to give recommendations on the following scenarios. In case of no ESS and a fixed PV size under the premise that the orientation can be chosen it is advisable to do so according to the highest yield. When feed-in is not financially compensated the benefit solely depends on the self-sufficiency rate which is only slightly lower for generators facing east or west. If the life expectancy of a generator decreases with the amount of produced energy it might even be advisable to choose an east or west orientation because the self-consumption is higher. A battery size of more than 1 kWh/(MWh/a) is in general not recommended for the considered setups, as the extra benefit on the self-sufficiency quickly decreases with higher capacities. One interesting effect concerns the combination of small PV plants—which tend to be the most economical in future low feed-in tariff scenarios according to [7]—with extreme east or west orientation, which might be a given fact due to the roof structure. In that case even a small sized ESS of 0.5 kWh/(MWh/a) gets close to the theoretical maximum self-sufficiency rate of an infinite storage.

As shown, the temporal resolution is vital to the calculation of key parameters like self-sufficiency rate or number of charge cycles. If due to metering infrastructure no high temporal resolution is available the results presented in this paper can be used to correct the key parameters gained from own simulations. Furthermore, the results from this study can be interpreted as good news for ESS. Since most past studies were based on data with longer time intervals the rate of direct self-consumption has probably been over-estimated while the benefit of ESS was under-estimated.

The additional effect of grid relief depends strongly on the operation strategy of the ESS, where only the greedy mode was applied in this study. In future research the relation between different operation strategies and grid effects will be investigated also based on the measured data.

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References