CAN RESIDENTIAL SELF-CONSUMPTION CONTRIBUTE TO LOAD REDUCTION IN LOW-VOLTAGE GRIDS?

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Kurzfassung: In the German residential sector, a dynamic increase of photovoltaic self-consumption can be noted at present. The feed-in of the excess electricity of this additional generation systems could lead to voltage overloads, particularly in rural low-voltage distribution grids. Recent studies suggest that battery systems could be used to promote a more grid-friendly self-consumption.

In this study a self-consumption optimization model is coupled with a distribution grid model, to analyse the benefits that could come from the battery operation in low-voltage grids. As a result it was found that batteries, if they are only used with the purpose to increase self-consumption, have very little effect on grid loads. But if grid restrictions are considered in addition to the self-consumption increase, loads can be reduced significantly. Although the load reduction is generally positive for the grid, occurring voltage violations could not be completely avoided in the generic grid of this study.

Keywords: self-consumption, distribution grid, storage optimization, load modelling

1 Motivation and research question

At present a dynamic increase of self-consumption in the German residential sector can be noted (Elsland et al. 2015). No levies are charged (particularly no EEG allocation and grid charges) for self-consumed electricity, which is produced with an own small PV power plant. This indirect incentive makes self-consumption financially very attractive (BMWi 2015).

On the one hand, this privileged treatment may be understandable as such electricity remains within the customer's premises and does not touch the public grid. On the other hand self-consumers only contribute to an effective reduction of the grid load and therefore to diminished grid extensions, if they help to reduce voltage and load peaks in the long term. (EU Commission 2015). In most cases, self-consumers use the grid even more than an average customer, when they feed-in excess electricity from their PV generation.

A grid-friendly operation of PV generation will be particularly crucial, because the majority of the installed PV systems is connected to the low-voltage distribution grid and they can lead there to inadmissible high voltages and loads, especially in sparsely populated areas (Oehsen et al. 2012). Due to increasing residential self-consumption additional systems would enhance this problem. But the solution could also be already at hand: Several studies evaluate the use of solar power storage systems as a possibility to promote grid-friendly self-consumption (e.g. Weniger et al. 2015).

Especially as investment costs for battery storage systems are expected to drop rapidly in the coming years, from the current 20 ct/kWh to 5 ct/kWh in 2030 (Deutsch and Graichen

2015), as many automotive manufactures are looking for a second use of their electric cars' batteries (EnBauSa 2015).

Recent studies have found possibilities to use battery storages to reduce the maximal PV output to the grid (see, Hatta et al. (2013), Riffonneau (2011)) and others have already analysed the increased integrability of PV systems through the use of battery systems (e.g. Tant et al. (2013), Appen et al. (2014)). But with the increasing relevance of storage systems in low-voltage distribution grids and very little empirical data, the achieved results have to be constantly discussed and improved.

In this contribution we therefore aim to add to the discussion by analysing to what extent self-consumption in combination with battery storage systems can help to reduce grid extensions on the low-voltage level.

2 Methodology

In this study, a self-consumption optimization model will be coupled with a distribution grid simulation model, to calculate to what extent self-consumption in private households can contribute to reducing feed-in peaks and related grid loads.

2.1 Self-consumption optimization model

The self-consumption model represents the operation of a battery storage system for a residential household with photovoltaic electricity production. The battery operation is determined via an optimization in which the total costs for electricity purchase are minimized.

2.1.1 Storage model

In this simple battery model, charging $P_{Batt,pos}$ and discharging $P_{Batt,neg}$ act as (mathematical) control variables within the optimization interval $[i_{min}; i_{\max}]$. They are constrained by the battery's power limits $P_{Batt,min}$ and $P_{Batt,max}$:

$$P_{Batt,min} \leq P_{Batt,neg,i} \leq 0, \qquad \forall\, i \in [i_{min}; i_{\max}]$$

$$0 \ \leq P_{Batt,pos,i} \ \leq P_{Batt,max}, \qquad \forall\, i \in [i_{min}; i_{\max}]$$

and are also subject to the limits of the storage capacity SFL_{min} and SFL_{max}:

$$SFL_{min} \leq \sum_{h=h_{min}}^{i} [(1-d)^i \, SFL_o + (1-d)^{i-h} \, P_{Batt,h}] \leq SFL_{max}$$

The storage fill level $SFL(t)$ is a function of the battery load $P_{Batt} \ = \ P_{Batt,pos} \ + \ P_{Batt,neg}$ and considers self-discharge with the discharge rate *d* and an initial storage fill level $SFL_0 \ = \ SFL\ (t_0)$ at the beginning of the optimization interval.

The actual battery load, i.e. charging plus discharging, is then determined in an optimization, in which the costs for the necessary electricity purchase are minimized. The objective function

$$\text{Min} \sum_{i=i_{min}}^{i_{max}} C_i \left((2-\eta)\, P_{Batt,pos,i} + \eta\, P_{Batt,neg,i}\right)$$

considers efficiency losses due to energy conversion in the battery and the AC-DC inverter via the efficiency factor η.

2.1.2 Pricing signal

The pricing signal plays a crucial role in this approach as it acts as a control signal for the battery operation. Different pricing signals can therefore be used to calculate scenarios.

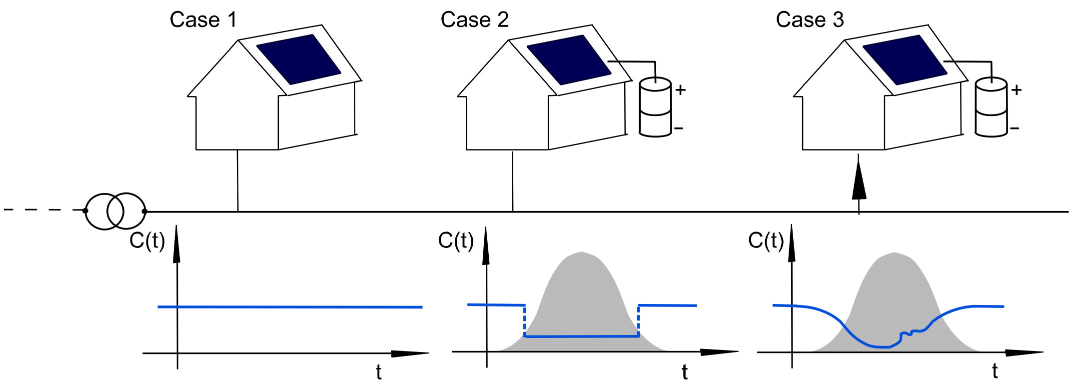

Figure 1: Schematic representation of the case without self-consumption (case1), with price optimal self-consumption (case 2) and with optimal self-consumption for optimal grid loads; the related pricing signal C(t) in blue; the PV power output in grey.

In the present contribution three cases are analysed (see Figure 1): In the reference case (Case 1) no self-consumption takes place and the entire electricity is purchased at the constant domestic price of 28.81 ct/kWh. The generated electricity of the PV system is fed into the grid.

$$C_{1,i} \coloneqq 28.81, \qquad \forall\, i$$

In Case 2, the electricity price is reduced, for the self-consumed amount, to the cost of lost feed-in remuneration of 12.31 ct/kWh (as of Sept. 2015). With $r \coloneqq 0.01$ we consider a kind of risk surcharge, as the consumer is likely to fill his battery as soon load as the PV generation exceeds his demand, due to the uncertainty of the weather.

$$C_{2,i} \coloneqq \begin{cases} 12.31 + r \cdot i, & P_{HH,i} + P_{Batt,i} \le P_{PV,i} \\ 28.81, & \text{else} \end{cases}$$

with the household's electricity demand P_{HH} and the photovoltaic generation P_{PV}.

In Case 3, grid restrictions are considered in addition to self-consumption benefits. To this end, the grid model described below calculates grid violations, using the non-optimized loads of Case 1. The grid model's results are translated into maximal or minimal loads and fed back to the self-consumption model. Here, the electricity price is adapted additionally by the a factor $g \coloneqq 5$ for the hours with grid violations to promote battery charging in hours with a high PV generation excess or discharging in hours with a high demand.

$$C_{3,i} \coloneqq \begin{cases} 12.31 - g + r \cdot i, & P_i \le P_{min} \\ 28.21 + g, & P_i \ge P_{max} \\ 12.31 + r \cdot i, & P_i \le 0 \\ 28.81 + r \cdot i, & \text{else} \end{cases}$$

with the households net demand $P_i = P_{HH,i} + P_{Batt,i} - P_{PV,i}$. Please note that the net demand will be negative in case of PV overproduction.

2.1.3 Scenario data

The major input data for the self-consumption model are hourly profiles for an entire year, i.e. 8760 h profiles. Using yearlong profiles has the advantage of taking into account seasonal differences and variations in temperature and solar radiation. In this study, the input profiles consist of PV generation and residential load profiles. Based on generation and load, the residential self-consumption is optimized, taking into account techno-economic specifications and restrictions.

Generation profiles.

The generation profiles were taken from the PV system “SonnJA!”, which is located at the HTW in Berlin on a rooftop with an orientation of 35° south-west and an inclination of 14.57°. The system was installed in September 2013 and is operated by the association “einleuchtend e.V.” (einleuchtend e.V. 2016).
The profiles were scaled to represent a PV system with 5.7 kW_p installed capacity, which is the average system in use on rooftops of single family homes in Germany.

Load profiles.

For the load profiles, synthetic profiles of 2 person single family homes (SFH) from the Association of German Engineers are used (VDI 2008). These profiles were originally created for the dimensioning of combined heat and power (CHP) systems and are here applied to the case of PV self-consumption.
The yearlong profiles are compiled using reference profiles for typical days, which are classified into ten categories according to the criteria workday/Sunday, fine/cloudy and transition/summer/winter. The necessary temperature and cloud coverage values for the profile creation were provided by the German Meteorological Service (DWD 2015).

Battery specifications.

Following the current discussions, the battery specifications are derived from the 7 kWh Tesla Powerwall which the manufacturer intended “for daily cycle applications” such as self-consumption (Tesla Motors 2015). Additional information was taken from (Bandhauer et al. 2011) and (Bosch 2015). All used specifications can be found in Table 1.

Table 1: Battery system specifications

Parameter	Abbrev.	Value
Maximum discharging rate	$P_{Batt,min}$	- 2 kW
Maximum charging rate	$P_{Batt,max}$	2 kW
Minimal battery fill level	SFL_{min}	1.4 kWh
Battery capacity	SFL_{max}	7 kWh
Efficiency factor of battery and inverter	η	88%
Self-discharge rate	d	3%/month

2.2 Distribution grid simulation model

In the distribution grid model different grid topologies of rural, suburban and urban distribution grids are represented via grid elements like transformers, cables, electric lines and nodes. Occurring currents, voltages, resistance and powers are calculated.

2.2.1 Grid model

The distribution grid model has been built in Java. Within the model every cable is represented by the Pi-Model for short electrical lines. Here, each cable is modelled as one inductive element and two capacitance elements. The inductive elements represent the inductive part of every cable and also connect two nodes, while capacitance elements represent the capacitive part of each cable between a node and ground potential. With Kirchhoff's laws all cable elements are transformed into a nodal admittances matrix (NAM). Therefore, the NAM is a representation of all complex resistances of the grid.
With the NAM and power demand and power supply on each node for each hour, the resulting voltages and currents are calculated with the Gauß-Seidel algorithm. Here we divide voltages by the nominal voltage of the distribution grid to transfer units into the per unit (p.u.) system to directly analyze relative voltage differences. Details of the methodology are found in (Schwab 2009).

2.2.2 Scenario data

The major input data for the distribution grid model is the grid topology and the cable specifications. In this study, two different grid types are selected to simulate the effects of PV self-consumption in a sub-urban and rural low-voltage grid.

For the sub-urban grid, an established generic topology was taken from (Dallmer-Zerbe 2014). Unlike the urban or sub-urban grids, the rural grid type is usually the weakest low-voltage grid type, as those grids are seldom mashed. To get a better understanding and focus of this type of distribution, a generic rural grid was constructed for this study.
Electrical grids are built based on the circumstances where electrical power is needed and where power can be supplied. Therefore, grids differ strongly. For this study, we use a 25 nodes grid where cables are connected by the cable type NAYY 150 m^2. On each node the two person single family home (SFH) and PV System from section 2.1 is connected (see figure 2).

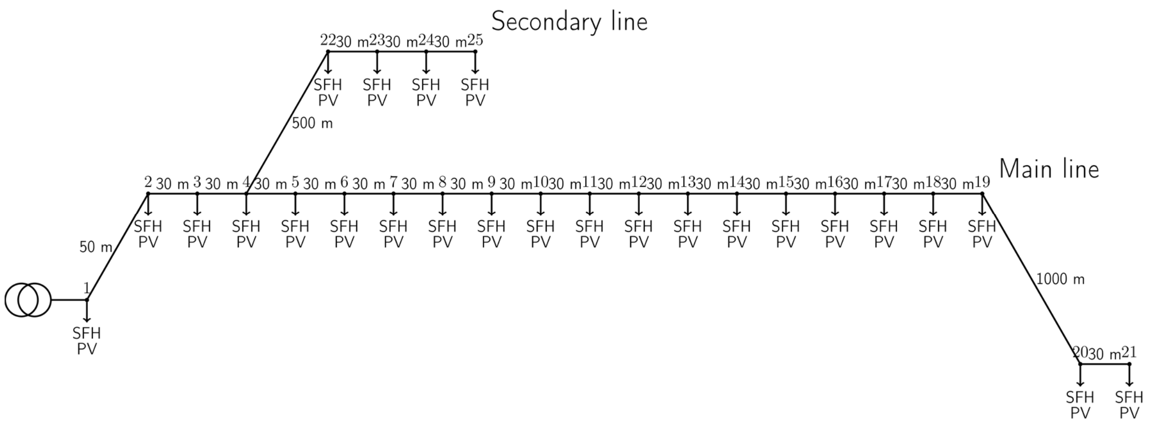

Figure 2: The 25 node rural distribution feeder with connected single family homes (SFH) and photovoltaic (PV).

Electrical grids are constructed based on peak power and therefore worst case scenarios. To construct such an extreme case, the same demand profile for each SFH and the same supply profile for each PV system are used on each grid node.

3 Results and conclusions

The results of the self-consumption model show that battery storages scarcely contribute to load reduction, if they are only operated to increase self-consumption rates: In summer, batteries are already fully charged in the morning and therefore barely reduce the PV generation peaks at noon. In winter time, the generated electricity is almost completely consumed directly and the battery is used very little. But the highest loads only occur in the evening, when they cannot be reduced much with the small amount of electricity stored. In both cases peak loads are not shaved and the maximal grid load is the same as in the reference case.

This is different for a grid-friendly operation of the battery storage. Although in winter the result is almost the same, in summer the battery is charged during peak PV production and therefore reduces the grid load in the midday hours. The average loads for all three cases are depicted in Figure 3.

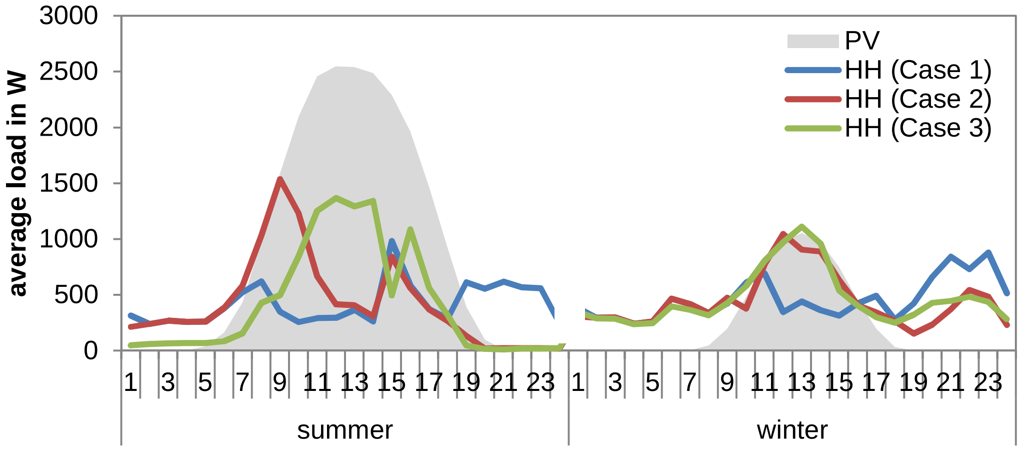

Figure 3: Average loads of the 2 person single family home in summer and winter without optimal storage operation Case 1 (red), with storage operating to increase self-consumption (Case 2) (blue) and a grid-friendly storage operation (Case 3) (green); average PV generation in grey.

As described above, the effects on the grid of the storage operation in Case 2 are expected to be very small. To prove this assumption, the resulting voltages for Case 1 and Case 2 are calculated with the distribution grid model.

During the model runs, the in-feed of excess PV generation proved to be the relevant criterion for the grid. Therefore only the week with the highest PV production, the week of June 9 to June 15, is used as input into the grid model (see Figure 4).

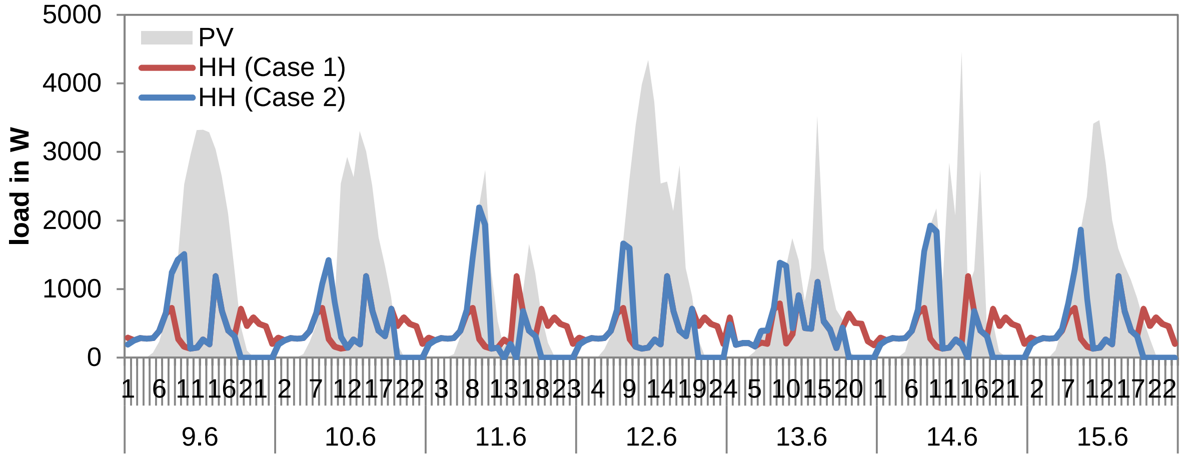

Figure 4: Loads of the 2 person single family home for Case 1 (red) and with a storage operating to increase self-consumption (Case 2) (blue) for the week June 9 - 15; PV generation in grey.

In simulations with the two different grid topologies we have found that grid violations occurred only in the weaker rural distribution grid. The following section focuses therefore on the rural grid simulations.

The results for the calculation of occurring voltages in the rural grid are displayed in figure 5. For this diagram, the voltages for each simulation step were collected on every node and allocated to quartiles.

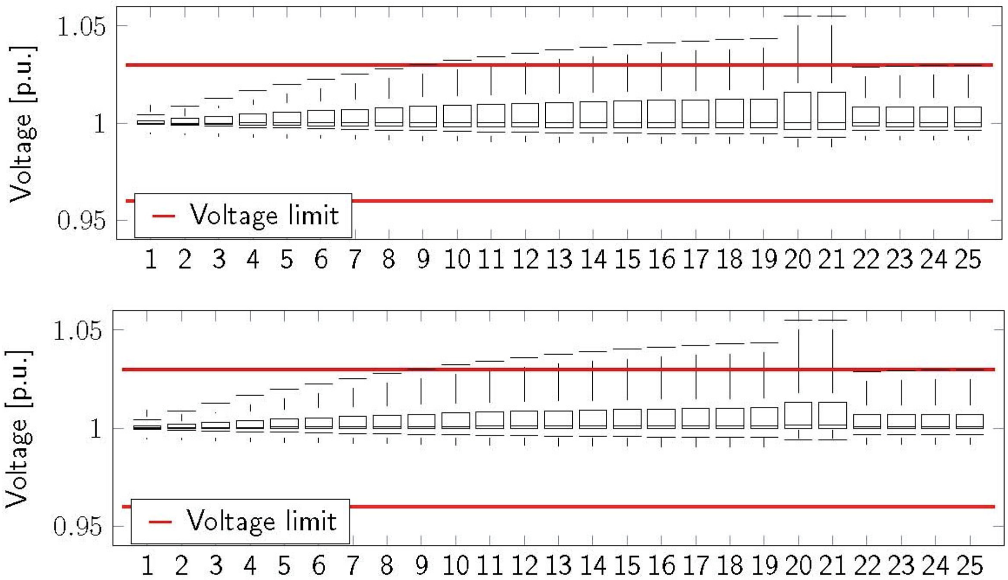

Figure 5: Quartiles of occurring grid voltages in the per unit system for each node of the rural low-voltage grid; Case 1 (above) and Case 2 (below).

The figure illustrates that without self-consumption and therefore without optimization (Case 1), the voltages on nodes 9 to 21 rise higher than the allowed 1.03 p.u. boundary. The highest voltage violation of 1.055 p.u. occurs on node 21, where voltages only remain between their boundaries of 0.994 and 1.013 p.u. for 75% of all hours for the given week.
As already assumed when analysing the optimized loads of Case 2, the grid is also overloaded for the loads with a battery use to increase self-consumption. In Case 2, the maximal voltage violation at node 21 has the same height as in Case 1 and voltages for nodes 9 to 21 reach out of bounds at some point.

A different result is achieved with a grid-friendly storage operation in Case 3. In Figure 6 the same week, June 9 to 15, with the highest PV production is depicted, showing that the battery is now charged during the hours with the highest electricity generation and therefore reduces the maximum grid load by 24%.

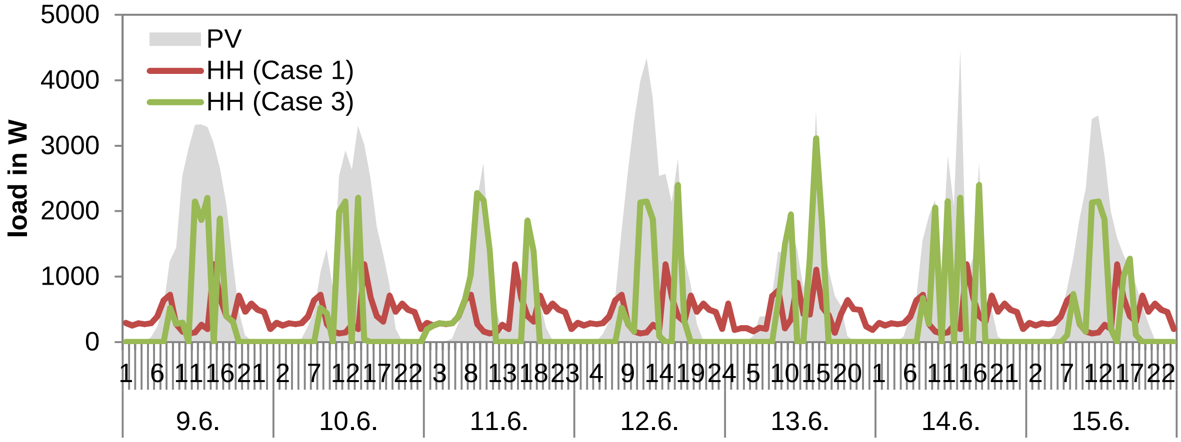

Figure 6: Loads of the 2 person single family home for Case 1 (red) and with a storage operating to increase self-consumption (Case 2) (blue) for the week June 9 - 15; PV generation in grey.

And indeed, the simulations with the grid model show reduced voltage violations. In the grid-friendly case, voltages rise only to 1.042 p.u. on node 20 and 21. Also only on nodes 15 to 21 voltage violations can be detected. Here voltage violations occur on six nodes less compared to cases 1 and 2 (see figure 7). But grid violations cannot be avoided completely, which implies that further action must be taken, like a grid extension or controlled PV power reduction.

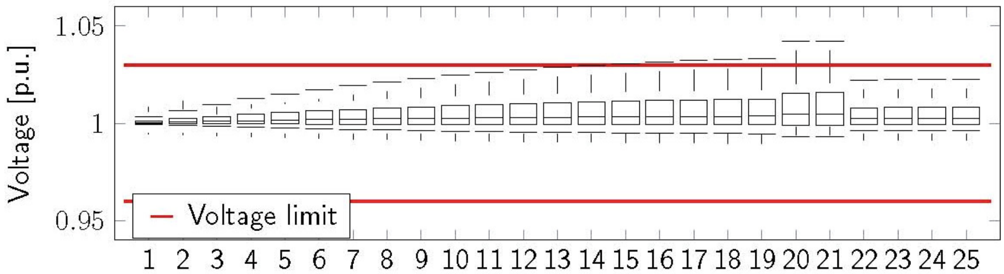

Figure 7: Quartiles of occurring grid voltages in the per unit system for each node of the rural low-voltage grid in Case 3.

We conclude that an incentive for grid-friendly self-consumption can be useful, as grid overloads loads can be reduced significantly with its implementation. But the usefulness is somewhat limited, as the grid-friendly load optimization only avoids grid overloads in very distinct cases completely. For the analysed strong sub-urban low-voltage grid, the additional PV systems were not a problem anyway and for the weaker rural grid, a grid-friendly storage operation proved to be not enough and additional measures, like curtailment, would be necessary to avoid grid violations.

From a methodological point of view, the coupling of the self-consumption model with the distribution grid model offered the possibility to better assess the impact of different battery operation strategies. In future work, the two models should be applied in an expanded study that includes other storage technologies in the self-consumption optimization.

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