OPERATIONAL STRATEGIES FOR BATTERY STORAGE SYSTEMS IN LOW-VOLTAGE DISTRIBUTION GRIDS TO LIMIT THE FEED-IN POWER OF ROOF-MOUNTED SOLAR POWER SYSTEMS

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Abstract: Due to the high amount of installed solar power systems in Germany, the low-voltage distribution grids reach their maximum capacities in periods of high insolation. In order to ensure a proper integration of today's and especially the prospective solar energy, grid reinforcement is a common method to increase the transmission capacity. As an alternative to this costly and intricate approach, local battery storage systems can be used to store the surplus generation and limit the feed-in power of the solar power systems. In this paper, two different operational strategies for battery storage systems together with solar power systems for self-consumption are presented and evaluated. Results show that the feed-in power can be distinctly reduced without generating significant losses for the system-owner.

1 Introduction

The energy turnaround in Germany away from conventional to renewable generation led to a big growth of decentralized and fluctuating feed-in. Especially in southern Germany, the governmental promotion for PV power plants resulted in a much higher growth of the installed PV power than predicted. The published governmental forecast from 2008 assumed an installed PV-power of 17.9 GW for the year 2020, which was already exceeded in 2011. According to actual forecasts of the Deutsche Energie-Agentur, the installed power will be around 50 GW in 2020 [DEN-10].

In consequence of the dependence on the weather, the feed-in power of PV systems shows a high fluctuation. Therefore, a compensation of energy consumption and generation cannot be ensured. Moreover, the solar feed-in in one region mostly occurs simultaneously, which is why power supply lines, cables and transformers can reach their maximum load levels. Furthermore, due to the high grid load during periods of high insolation, permitted voltage limits can be exceeded [LOE-10].

The conventional solution in such cases comprises the costly reinforcement of the affected grids by installing new transformers and supply lines. Alternatively, the surplus energy can be locally stored in times of high PV-generation and be used when the feed-in is low. Because of the feed-in remuneration for solar power in Germany meanwhile being distinctly below the electricity costs, PV home storage systems for increasing the own PV consumption become more and more attractive.

Moreover, the German government subsidizes battery storages for small solar power systems with up to 30 % of the investment costs. In return, the system-owner has to limit his feed-in power to 60 % of the installed system power.

Conventional operational strategies for such battery storages together with solar power systems immediately start charging with the occurrence of the first solar energy surplus at the beginning of the day. Especially on days with high insolation, this results in a fully charged battery even before the peak feed-in is reached at noontide. This operational strategy does not support the grid and can even involve additional grid reinforcement [DEN-12]. Therefore, different operational strategies for home storage systems have to be developed and applied. The main goals of these control algorithms should be a limitation of the feed-in peaks during noontide and a maximum increase of the consumers own consumption. For this purpose, weather- and load-predictions as well as accurate real-time metering has to be used.

In this paper, two different simulation models for operational strategies are being developed, evaluated and compared regarding their benefits both for the grid operator and the owner of the solar power system.

2 Prediction Data

Because the research is based on simulations and no real systems are considered, actual forecasting data is not available. In order to get realistic predictions, the corresponding data has to be generated within the simulation models.

2.1 Weather Prediction

The accuracy of irradiation forecasts is characterized by its forecast error, which is defined by the difference between the sums of the energy of the irradiation predicted E_F and measured E_M for a specific time period [LOE-11].

For the use in a simulation model, predicted weather data has to be generated by modifying the real PV delivery profile according to the error distribution functions mentioned in [LOE-11]. Therefore, the PV feed-in profile is being segmented into days with low, medium and high irradiation values. Afterwards, the errors of the equivalent distribution functions for the three mentioned segments are added to the hourly average PV feed-in values. The simulated PV delivery forecast P_{ppv} is being integrated to receive the daily energy generation G (1):

$$G = \int P_{ppv} \, dt \qquad (1)$$

2.2 Load Prediction

Consumer load profiles also have to be predicted in order to optimize the operational strategy of PV home storage systems. Considering the difficulty to forecast a consumer's load for the next days, a simplified prediction of his load profile P_l is used. For this purpose, P_l is segmented into three main parts: midnight to sunrise, sunrise to sunset, and sunset to midnight. The daily energy consumptions

E_T at day i within these time-periods T are being calculated and averaged over the past five days (2-4):

$$E_{1,i} = \frac{\sum_{j=i-5}^{i-1} \int_{t_{midnight,j}}^{t_{sunrise,j}} P_{l,j}\, dt}{5} \tag{2}$$

$$E_{2,i} = \frac{\sum_{j=i-5}^{i-1} \int_{t_{sunrise,j}}^{t_{sunset,j}} P_{l,j}\, dt}{5} \tag{3}$$

$$E_{3,i} = \frac{\sum_{j=i-5}^{i-1} \int_{t_{sunset,j}}^{t_{midnight,j+1}} P_{l,j}\, dt}{5} \tag{4}$$

Those average values serve as prediction data for the energy consumption during the next two days.

3   Simulation model

The operational strategies are implemented in a time-discrete Simulink model with a simulation time of one year and a one minute step size. For the simulation of the PV power system, the PV profile of a roof-mounted system in upper Bavaria is scaled to the desired installed PV power. The load is simulated by using the BDEW standard load profile H0 for households [BAY-13]. Even though this load profile is only a statistical average and therefore not representative for one single household, it is still used in order to simulate a reasonable load to a certain degree. According to [LOE-10], the average PV potential for roof-mounted systems in suburban areas in Germany is 8.7 kW. This value is used to simulate the PV feed-in profile of the consumer, which is a German 4-person household with an annual consumption of about 5000 kWh [HEA-13]. The home storage system is assumed to be a lithium-ion battery with a maximum depth of discharge (*DoC*) of 20 %, whose capacity is varied between 5 kWh and 25 kWh. The PV power system is optimized for the coverage of the households own consumption, which means the PV power is primarily covering the load and only the remaining surplus can be delivered to the grid or used by the battery. This relation between PV system, load and battery is described by (5). Hereby, it is necessary to regard that P_{batt} is negative when charging and positive when discharging.

$$P_{grid} = P_l - P_{pv} - P_{batt} \tag{5}$$

4   Operational Strategies

Figure 1 shows the conventional operational strategy for PV home storage systems, which loads the battery whenever a solar surplus occurs. The storage reaches its maximum state of charge (*SoC*) at about nine o'clock and thereby causes a steep rise of the feed-in power. As mentioned before, this behavior is not reducing the maximum grid load and can even exacerbate the load-situation.
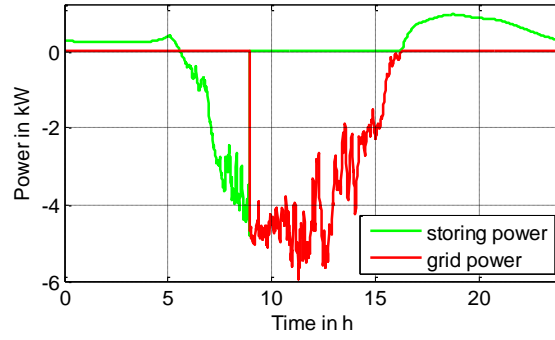
Figure 1: Conventional operation of PV home storage system

Battery storage control algorithms for limiting the feed-in power can be based on different approaches. In this paper, two corresponding operational strategies are being developed: Operational strategy 1 (OS-1) is based on the approach of a chopped PV feed-in profile, while operational strategy 2 (OS-2) uses a damped feed-in approach. To ensure a maximum storing of the solar surplus even on days with low insolation, OS-1 and OS-2 are only activated on days with suitable weather forecasts. Therefore, 70 % of the predicted PV energy for the actual day has to be enough to fill the spare battery capacity at sunrise $C_{spare,sunrise}$ (6). By only calculating with 70 % of the energy, forecast errors can be compensated.

$$0.7 \cdot G_{day1} \geq C_{spare,sunrise} \qquad (6)$$

4.1 Operational strategy 1 (OS-1): Feed-in chopping

In order to only chop off the top of the feed-in profile and therefore reduce the maximum grid load, the storing start time has to be delayed. The battery should only then start storing the PV surplus with the charging power $P_{batt,ch}$, when the current feed-in power P_{grid} reaches the desired maximum value f_{max} (7):

$$P_{batt,ch}|_{P_{grid}>f_{max}} = P_{grid} - f_{max} \qquad (7)$$

On days with lower insolation, as already mentioned in [WEN-13], a fix maximum feed-in power f_{max} can come to an uncompleted charge of the battery and in this way prevents its economical operation. Therefore, f_{max} has to be adjustable in order to generate a much higher SoC at the end of the day.

To do so, a daily fix maximum feed-in power $f_{max,f}$ has to be calculated using the predicted grid load $P_{grid,p}$. Therefore, $f_{max,f}$ has to be iteratively determined in order to achieve a maximum predicted SoC_p at the end of the day (8). At that, $f_{max,f}$ must not be greater than the desired maximum feed-in power $P_{grid,max}$, which has to be defined in advance.

$$SoC_p = \int_{t_{sunrise}}^{t_{sunset}} P_{grid,p} - f_{max,f} \, dt = Max \leq SoC_{max} \qquad (8)$$

The time curve $SoC_p(t)$ of this predicted value is used as control variable for the intraday adjustment of f_{max}: By comparing the actual SoC with the predicted value for every simulated time step, a multiplication factor for the fix maximum feed-in power $f_{max,f}$ is calculated, whereby $P_{grid,max}$ must not be exceeded (9):

$$f_{max}(t) = \frac{SoC(t)}{SoC_p(t)} \cdot f_{max,f} \leq P_{grid,max} \qquad (9)$$

If the actual SoC takes smaller values than the predicted one, f_{max} is decreased in order to achieve a higher $P_{batt,ch}$ and therefore a quicker charging (see Figure 2). On the other hand, if $f_{max,f}$ is very low at the beginning of the day and the SoC grows quicker than expected, f_{max} is rising during the day to keep the battery from getting fully charged too early.
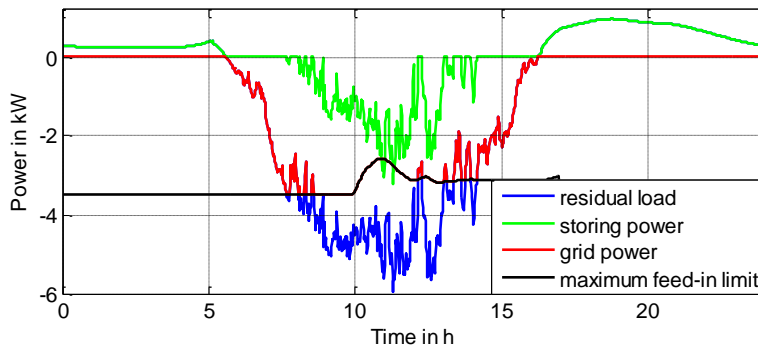

Figure 2: Operational strategy 1 of PV home storage system

4.2   Operational strategy 2 (OS-2): Feed-in damping

In order to damp the feed-in power by storing the surplus feed-in throughout the whole daytime and thereby ensure a maximum charge of the battery, a nearly constant charging power $P_{batt,ch,c}$ has to be implemented. Therefore, the spare battery capacity C_{spare} for every simulated time step is divided by the predicted remaining time until sunset t_{re} (10):

$$P_{batt,ch,c}(t) = \frac{C_{spare}(t)}{t_{re}(t)} \qquad (10)$$

In cases of the feed-in power still being larger than the desired maximum value $P_{grid,max} = f_{max}$, $P_{batt,ch}$ is calculated according to (7). As soon as $P_{grid} \leq P_{grid,max}$, the battery is charging with $P_{batt,ch,c}$ again, which is lower than before due to the lowered C_{spare} (see Figure 3).
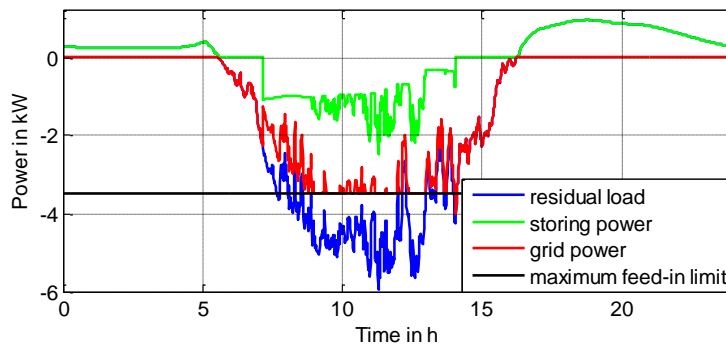

Figure 3: Operational strategy 2 of PV home storage system

4.3 Comprehensive discharge behavior

The battery discharge behavior is equal for both OS-1 and OS-2, as it is determined by the load and not the grid. More precisely, the battery discharge is based on the coverage of the consumer load on the one hand and the provision of spare capacity for the next day on the other hand. In order to be capable of storing all the surplus energy and therefore limiting the feed-in power, the battery storage has to be as empty as possible at every sunrise. To fulfill this requirement, the battery is discharging redundant stored energy into the grid during nighttime. In order to make sure that only the redundant energy is discharged, the necessary remaining energy E_{demand} for covering the own-consumption for the next two days has to be calculated every sunset using prediction data (11):

$$E_{demand,i}(t) = (E_3 + E_1) + (E_2 + E_3 + E_1 - G_{day\ 2}) - \int_{t_{sunset}}^{t} P_l\ dt \qquad (11)$$

The corresponding battery discharge power $P_{batt,dis}$ is determined by using the actual SoC at sunset, the energy demand calculated in (11), the time between sunset and sunrise t_{night}, the current PV power P_{pv} and the current load P_l (12-13):

$$P_{batt,dis}|_{SoC > E_{demand}} = (P_l - P_{pv}) + (\frac{SoC_{sunset} - E_{demand}}{t_{night}}) \qquad (12)$$

$$P_{batt,dis}|_{SoC \le E_{demand}} = (P_l - P_{pv}) \qquad (13)$$

5 Results

The simulation is executed for the conventional battery operation as well as both grid-optimized operational strategies. The battery capacity is varied in 5 kWh steps for each of the three operational strategies. Furthermore, 30 %, 40 % and 50 % of the installed PV power (8.7 kW) are used as values for the desired maximum feed-in limit $P_{grid,max}$. The evaluation of the resulting 45 simulation stages enables an economical and technical comparison of the examined operational strategies.

5.1 Comparison of the operational modes

In order to illustrate the grid-relieving effect of the optimized operational strategies in the critical summer months with high insolation, Figure 4 shows the grid load caused by the simulated household between June and August. In this example, a battery capacity of 10 kWh and a $P_{grid,max}$ of 3.48 kW (40 % of the installed PV power) are assumed. In the case of no installed home storage system, the feed-in power to the grid reaches values up to 7.5 kW. The grid load profile is not distinctly influenced by the battery storage when using the conventional operation and the feed-in power still reaches values up to about 7 kW. In contrast, the grid load is significantly reduced by the use of OS-1 and OS-2. The maximum feed-in limit of 3.48 kW is met during most of the time and only exceeded in a few cases.
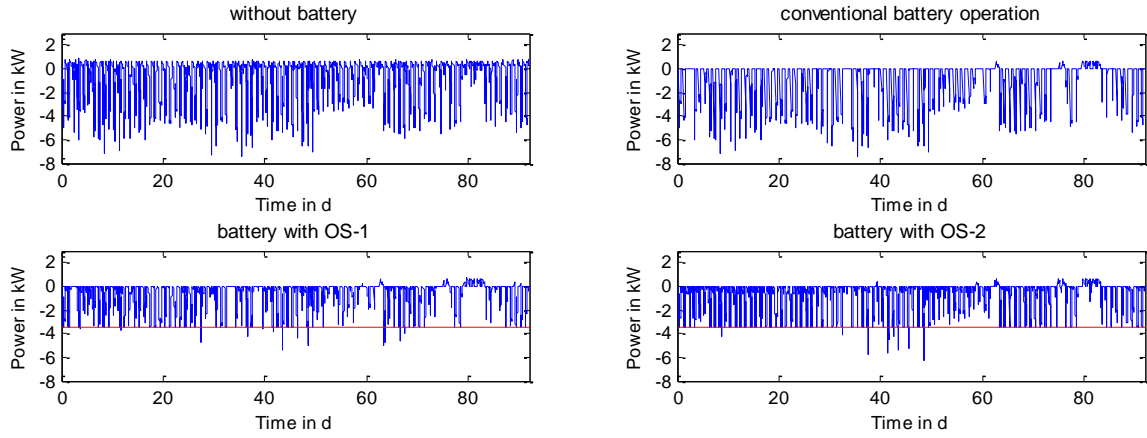
Figure 4: Grid load (blue line) and maximum feed-in limit $P_{grid,max}$ (red line) for different operational modes of a PV home storage system

If the PV system is throttled down in cases of exceeding $P_{grid,max}$, the feed-in power is fully limited to this value without causing significant losses for the system owner. Those throttling-losses are denoted as $E_{loss,th}$ (14).

$$E_{loss,th} = \int \left| P_{grid,feed} \right| - \left| P_{grid,max} \right| \, dt \qquad (14)$$

Another form of occurring losses for the PV system owner is a moderate reduction of the households own consumption when using a grid-optimized operational strategy instead of the conventional one. Reasons for this reduction are forecast errors when calculating E_{demand} on the one hand and an insufficient charging of the storage due to the grid-optimized behavior on the other hand. Those losses of the own consumption E_{own} are defined as the difference between the own consumptions of the conventional and the grid-optimized operational strategies according to (15).

$$E_{loss,own} = E_{own,conventional} - E_{own,OS-1/2} \qquad (15)$$

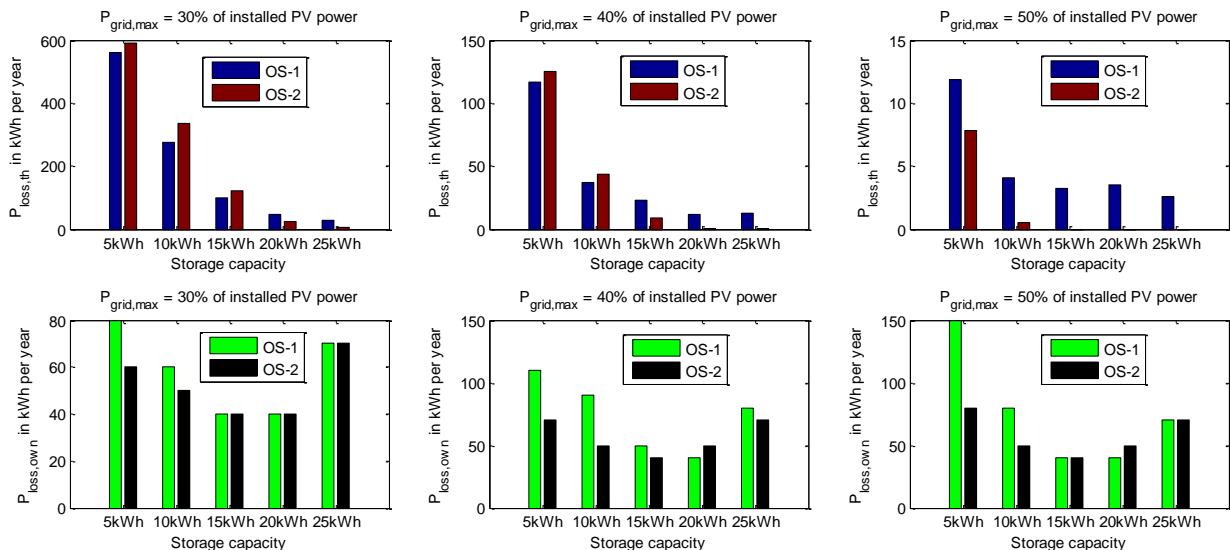Both losses $E_{loss,th}$ and $E_{loss,own}$ are confronted in Figure 5.

Figure 5: Losses in case of using the grid-optimized operational modes

In the case of the conventional battery operation, both $E_{loss,th}$ and $E_{loss,own}$ can be assumed to be zero. This operational strategy can therefore be thought as the optimal one from the system-owners point of view.

As indicated in Figure 5, the throttling-losses $E_{loss,th}$ increase with a lowering of the maximum feed-in power $P_{grid,max}$. Limiting the feed-in power to 30 % requires a battery capacity of about 15 kWh to keep $E_{loss,th}$ beneath 5 % of the total feed-in, which amounts about 3.600 kWh on condition of the used simulation parameters. However, batteries with capacities above 10 kWh cannot be assumed for average PV system owners. On the other hand, when limiting the feed-in power to only 40 % or 50 %, a battery capacity of 5 kWh or even less is sufficient. Basically, OS-1 achieves slightly smaller throttling-losses in case of using the quite conceivable battery capacities of 5 kWh to 10 kWh and applying a $P_{grid,max}$ of 30 % or 40 %.

Looking at the losses of own consumption, OS-2 reaches distinctly better values than OS-1 especially for the interesting capacities of 5 kWh and 10 kWh. In almost every case $E_{loss,own}$ stays beneath 100 kWh per year, which can be considered as non-critical under the condition of a total own consumption of about 3.700 kWh generated by the used simulation model.

In order to illustrate the economic effects of using the grid-optimized operational modes for PV home storage systems, the actual financial losses are calculated. Therefore, an electricity price of 31.35 ct/kWh and a feed-in remuneration of 13.03 ct/kWh are assumed for the year 2014. Figure 6 shows the resulting financial losses per year when using the grid-optimized instead of the conventional operational mode.
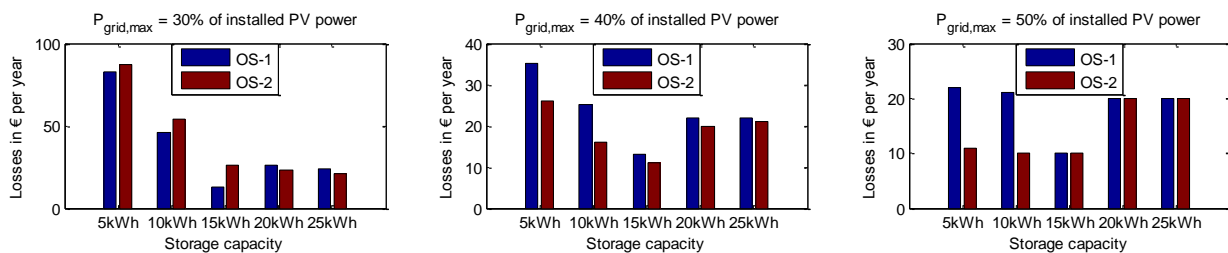

Figure 6: Financial losses when using grid-optimized instead of conventional battery operation

While OS-1 seems to be the convenient operational mode for a heavily limited feed-in power of 30 % or less, especially for the smaller battery capacities up to 10 kWh OS-2 results in lower financial losses when using a $P_{grid,max}$ of 40 % or 50 %. Basically, the financial losses range between 5 % and 15 % of the whole profit generated by conventional battery operation. When using corresponding battery capacities of 5 kWh to 25 kWh, this profit amounts about 200 € to 300 € per year due to the increase of own consumption in comparison to an operation without storage system.

5.2   Areas of application for the grid-optimized operational modes

The results presented in chapter 5.1 are only based on the circumstances given above. Regarding different values for the installed PV power and the consumer's annual power consumption, different results and conclusions could occur. The application of the grid-optimized operational modes for instance only makes sense in cases of a sufficient ratio of installed PV power to consumer load. Otherwise, the generated PV surplus does not even reach the maximum feed-in limit $P_{grid,max}$ and

therefore makes a grid-optimized storage operation needless. On the contrary, if this ratio is too big, disproportional storage capacities would be necessary to limit the feed-in power and to keep the throttling of the solar power systems on a reasonable level.

In order to determine the useful range of the ratio PV power to consumer load, simulations with varying circumstances are carried out: the consumer load is varied within the range of 2000 kWh/year and 10000 kWh/year, the installed PV power is between 2.6 kW and 14.8 kW and the battery capacity takes values between 1 kWh and 30 kWh.

The useful areas of application for each of the three values for $P_{grid,max}$ are determined according to the following conditions:

- financial losses below 10 % of the whole profit generated by conventional operation
- financial losses lower than using the conventional operation with throttling the solar power system
- necessary storage capacity for $P_{grid,max} = 50$ % of installed PV power: ≤ 6 kWh
- necessary storage capacity for $P_{grid,max} = 40$ % of installed PV power: ≤ 10 kWh
- necessary storage capacity for $P_{grid,max} = 30$ % of installed PV power: ≤ 16 kWh

Figure 7 graphically shows the resulting combinations of installed PV power P_{in} and annual power consumption $E_{consumer}$ in which the grid-optimized operational strategies can usefully be applied.
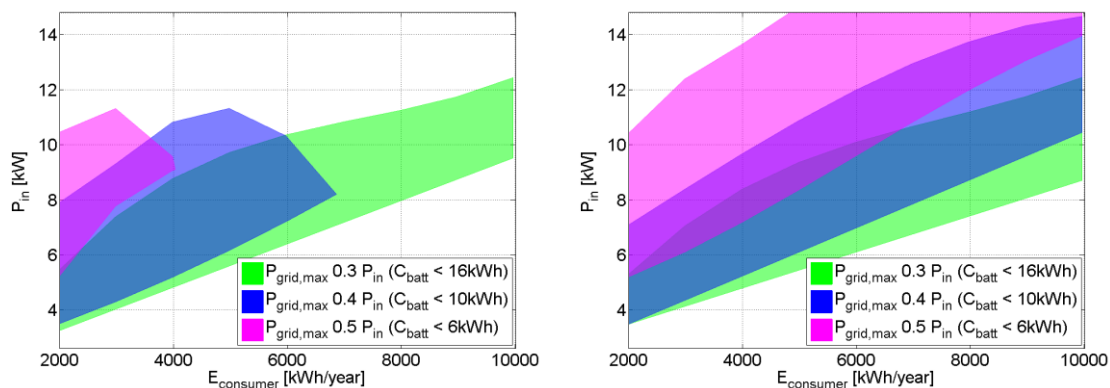

Figure 7: Useful areas of application for OS-1 (left) and OS-2 (right)

The installed PV power has to get higher with increasing power consumption in order to stay within the useful area. This behavior can be observed for both operational strategies and all three maximum feed-in values. For small annual power consumptions below 3000 kWh/year, both OS-1 and OS-2 almost show equivalent areas of application. When looking at consumptions above 3000 kWh/year, OS-1 is inappropriate for a feed-in limitation of 50 % and for consumers with an energy demand above 5000 kWh/year even a limitation of 40 % should not be applied by this operational strategy. Solely a $P_{grid,max}$ of 30 % can unrestricted be implemented with both grid-optimized strategies.

6   Discussion

The results in chapter 5 show the advantage of OS-2 over OS-1. The throttling-losses of OS-1 might be slightly smaller, but OS-2 has lower losses of own consumption. While the feed-in remuneration meanwhile has quite small values, the electricity price is already comparatively high and expected to further increase. Therefore, it is much more important to keep the own consumption on a high level than to minimize the throttling of PV power systems.

The principle reason why OS-1 fare less well than OS-2 on this term is its stronger dependence on weather predictions and therefore higher sensitivity to forecast errors. While OS-1 has to predict the energy content of the PV surplus peak in order to achieve a complete charging of the storage, OS-2 only has to predict the necessary constant charging power until sunset for fully charging it. Figure 8 shows the dependence of $E_{loss,own}$ and $E_{loss,th}$ on the weather forecast error.

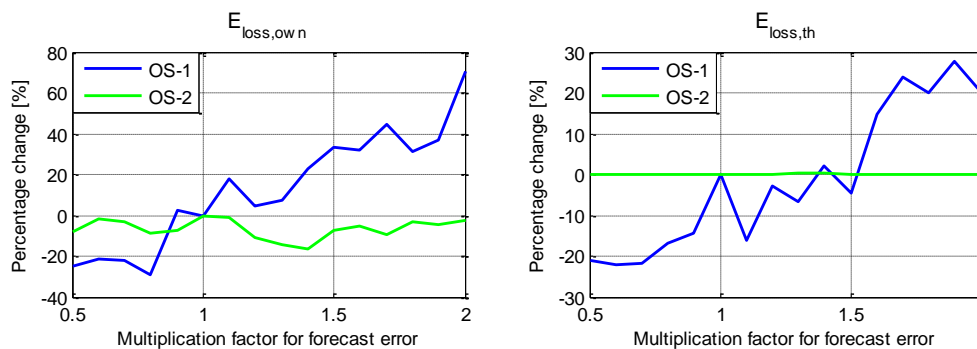**Figure 8:** Exemplary dependence of $E_{loss,own}$ and $E_{loss,th}$ on the weather forecast error

Regarding the results in chapter 5.2, the useful areas of application cover the most conceivable combinations of installed PV power and consumer load. For consumers with high loads, OS-1 is less suitable due to the higher losses of own consumption.

7   Conclusion

The represented simulation results in this paper show, that regular PV home storage systems with realistic dimensions and a grid-optimized operational strategy together with a throttling of PV power systems can operator-friendly limit the feed-in power up to 40 % of the installed system power. The still existing financial losses stay beneath 10 % of the possible income resulting from the conventional use of a home storage system. Because of the operational strategies' grid-optimized behavior, a promotion by the grid-operator is an imaginable solution for compensating these losses and in addition to it making the still expensive PV home storage systems more affordable. Considering actual li-ion storage retail prizes of about 2000 €/kWh [EWM-13] and the comparatively low financial benefit mentioned in chapter 5.1, a sharing of the investment costs between PV-system owner and grid-operator seems reasonable.

The two grid-optimized operational strategies evaluated in this paper are based on a feed-in chopping approach (OS-1) on the one hand and a feed-in damping approach (OS-2) on the other hand. The chopping approach, which in a simplified version was already presented in [WEN-13], exhibits distinct disadvantages due to its strong dependence on weather predictions. For OS-2 on the other

hand, only very rough prediction data is needed. Therefore, an operational strategy based on the principle of OS-2 is recommended for a grid-optimized application of PV home storage systems.

Since the current simulations were only run with the BDEW standard load profile H0 for households, further research with real load profiles is required to evaluate the grid-optimized operational strategies. Therefore a laboratory test using real components including PV-system and lithium-ion battery is planned. Furthermore, an advancement of the presented control algorithms for both strategies should be intended.

8   Literature

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