ENERGY AUTARKY OF HOUSEHOLDS BY SUFFICIENCY MEASURES

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1. Introduction

A consciousness about being independent from energy suppliers is spreading due to several reasons. Many authors already analyzed photovoltaic (PV) battery systems with a focus on the degree of self-sufficiency and self-consumption [1], [2], [3]. But some users would be willing to renounce the use of electric devices at times, when it is necessary, in order to limit the expenses for the components of the PV battery system. With what does the person have to cope with and how can it be influenced? Up to date no comparable work was found trying to quantify the personal dimensions. This work, based on the master-thesis of the same name by Christian Brosig [4], focuses on being autarkic with a PV battery system and includes measures of sufficiency. It is an approach, which overcomes the assumption, that a change of the user's behavior is impossible and which states, that he is free to also renounce the usage of certain devices.

The aim is to identify, what a user has to renounce and to find a way of measuring how happy he can be in his autarky. A new parameter is developed and introduced to quantify the user's contentment. It is complemented by a survey, to characterize the needs and priorities of specific households. Using its results, the power demand of the individual electric devices is derived from a load-profile-generator (LPG). Measures of sufficiency are identified and applied to households with a PV battery system via a simulation tool in Matlab. A typical household is analyzed and the potentials of the sufficiency measures are shown.

2. Methodology

2.1. Definition of a sufficiency indicator

The term of (self-) sufficiency is used in reference to different significations. In this paper, sufficiency refers to a personal balance of not consuming more than what is needed, but also not consuming less. It does not set the maximum as an aim, but the optimum [5]. Thus, measuring it is linked to personal needs and preferences.

In lack of existing models, a new parameter is developed and introduced: the sufficiency indicator (SI). It describes the qualitative degree of self-sufficiency, involves personal ratings of devices and is expected to express the user's contentment. On the background of sociological interrelations regarding sufficiency and a personal sense of renunciation, the assumption is proclaimed, that the device rating (D_{ra}) of a user, which is identified by a survey, includes his physical as well as psychological needs.

The SI, which is described by equation 2.1, primarily depends on the percentage of renunciation of a device (D_{re}), where 0 signifies no renunciation and 1 represents the full renunciation of the device. The individual D_{re} values are then weighted by the personal D_{ra} to build the overall sum of personally experienced renunciation. The D_{ra} rating ranges from 1 – unimportant, to 5 – very important. To be able to directly compare the SI to self-sufficiency, the sum is subtracted from full renunciation and multiplied by 100 %. Thus, an SI of 0 % means that the user has to waive everything and 100 % signifies that he can use any device without limitation.

$$SI = \left(D_{re_{full}} - \frac{\sum_{i=1}^{n_{device}} D_{re_i} \cdot \mathrm{D_{ra}}_i}{\sum_{i=1}^{n_{device}} D_{ra_i}} \right) \cdot 100\ \% \qquad 2.1$$

First of all, different types of households are identified, based on the work of Noah Pflugrath et al. at TU Chemnitz and his load profile generator (LPG) [6]. It simulates households on a behavior-based approach, where needs of the inhabitants determine their use of devices, which leads to load profiles for every device in a household. A survey is conducted to quantify the D_{ra} concerning household devices of different people. These people are assigned to typical households on the basis of data addressing their personal situation.

2.2. Development of a simulation tool

A simple simulation tool is developed in Matlab, which is able to simulate the household as an off-grid PV-battery-system. As inputs, typical LPG profiles for every single device in a household on the one hand and two types of PV feed-in profiles on the other. One PV profile is measured with 15 minute resolution, the other one is a PV-simulation based on Sandia's PV-lib [7] and a weather-profile from the DWD, as used by Johannes Weniger 2011 [1]. The schematic of this simple model is shown in Figure 1. It is capable of scaling the installed PV-power, installed battery capacity, change the storage type from Li-Ion to Lead-acid and Redox-flow. It also connects the personal priority values as well as a limit to time-shift devices to the device-profiles. This way, it is possible to track any deviation in the balance of input and output directly to devices affected by a lack of energy.

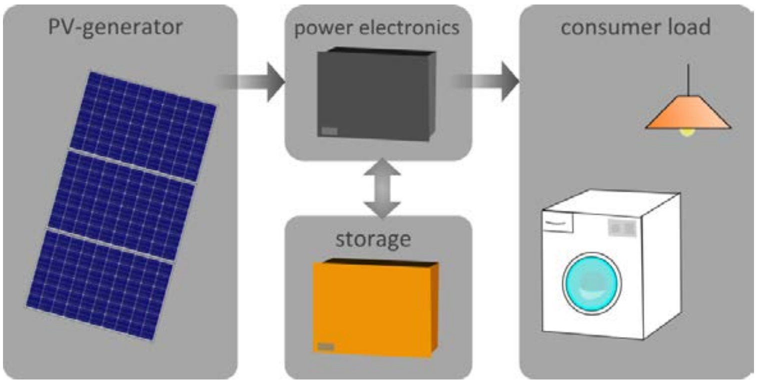

Figure 1: Scheme of the PV battery system

2.3. Identification and specification of sufficiency measures

Two measures are identified to maximize personal contentment: shifting of loads and prioritized shutdown of devices. Both are integrated as algorithms in the simulation tool and are calculated for a whole year and every single device.

2.3.1. Load shifting

In load shifting, at first it is checked for each time step if a device is turned off due to a lack of energy. If the device may be shifted, a time frame within the shifting-limits, where energy is available, is searched for. If available, the usage of the device is shifted to the other time-frame. There are two possibilities to check, whether energy is available: one is before and the other one after storage influence has been calculated. They will be called 'before storage' and 'after storage'. Figure 2 illustrates shifting before storage as implemented in the simulation.

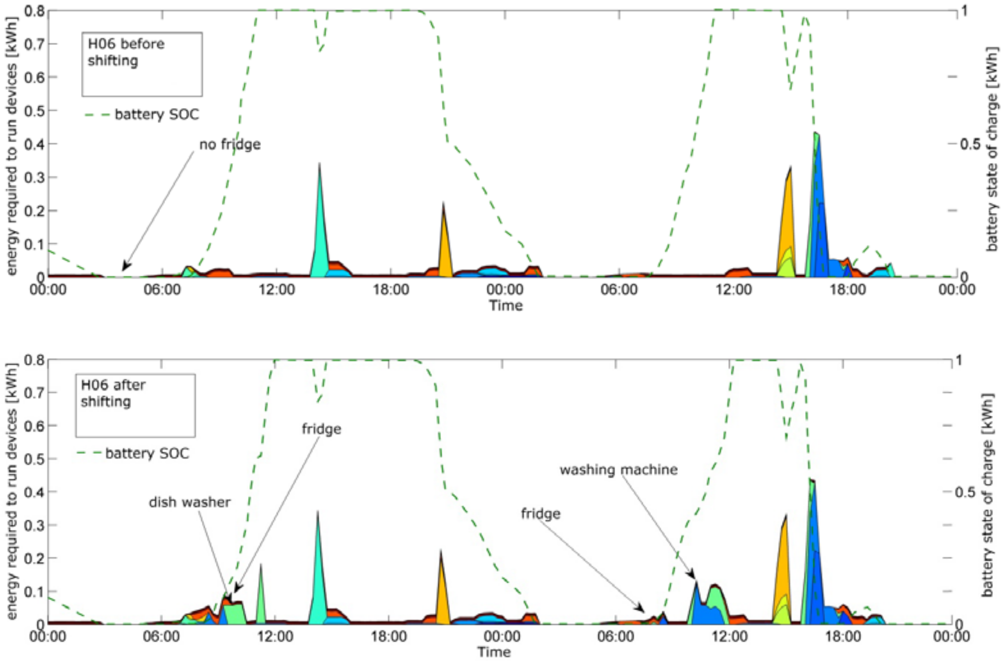

Figure 2: Usage of household devices before shifting due to PV generation and storage (Above); Shifting of washing machine and dish washer to other times, without affecting the usage of other devices (Below)

It shows the difference between the used devices before shifting and afterwards. In this example for H06, the dish washer and washing machine cannot be used, due to an empty storage. They are shifted into times, where energy is still available, at around 10’o clock. To preserve clarity, the PV-profile is not included in the figure.

2.3.2. Prioritized shutdown

Prioritized shutdown first checks the most important devices, whether they suffer from the lack of energy. The algorithm then analyses, if there are less important devices turned on before, that are responsible for emptying the battery. If so, they are shut down until enough energy can be saved to run the more important device. The results of this algorithm are shown in Figure 3: printer and television are used in the evening and empty the storage, so that there is no more energy for the bedroom light and fridge. As these last devices are more important, printer and television are shut down and the light and fridge can be used also during the night.

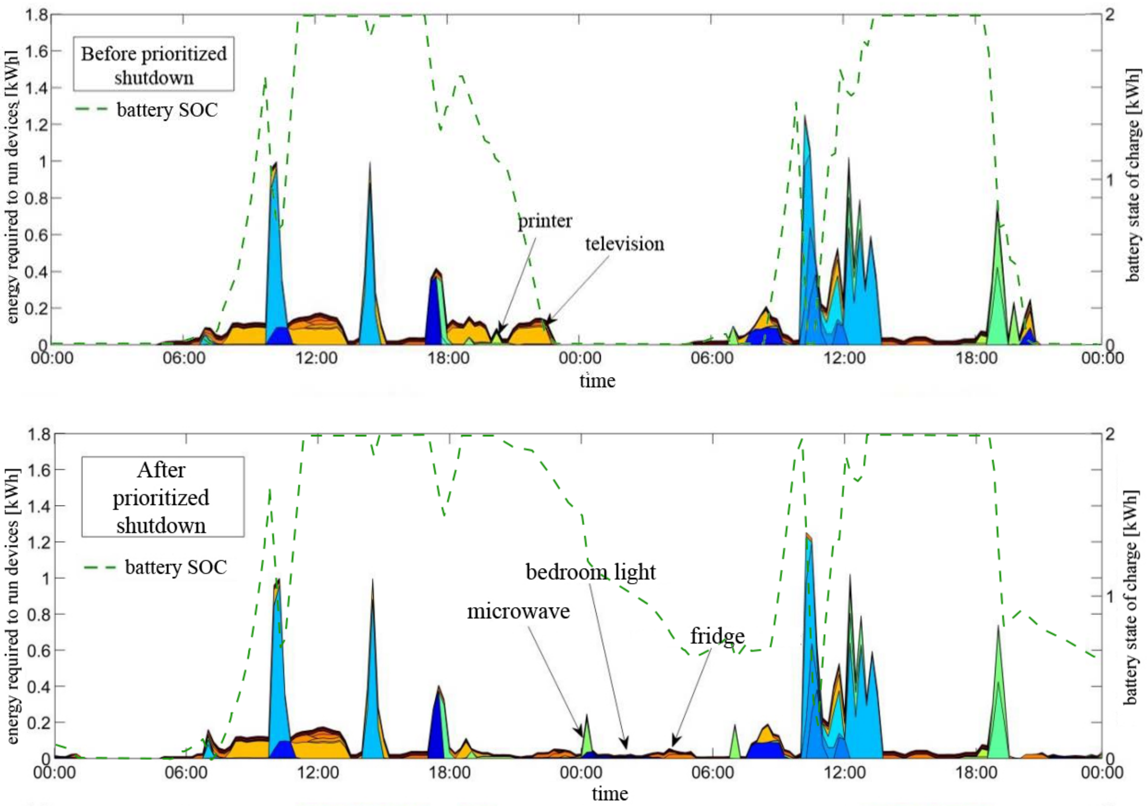

Figure 3: Above: Usage of household devices before prioritized shutdown due to PV generation and storage; Below: Prioritized shutdown of television and printer to be able to use bedroom lighting, microwave and fridge

2.4. Framework for the simulation

All further results are based on a measured PV profile with 15-minute time resolution from a PV generator in Kronenberg (Taunus, Germany) with an installed power of 4.51 kWp, an inclination of

30 ° and an orientation of 220 ° in direction south-west. Its annual output is 4940.8 kWh, which results in a specific output of 1095.5 kWh / kWp. The system is linearly scaled to be able to reproduce different installed powers. A Li-Ion system is chosen as battery with an assumed charging / discharging efficiency of 90 %, and a maximum charging / discharging power of 1.55 kW per kWh of installed capacity [8].

The simulation of the storage was evaluated by another PV-battery-simulation from TH Köln, written in Labview[9]. A typical household (further called H01) – a couple under 30 years of age, both working, with 41 devices and a yearly energy requirement of 2836,96 kWh - is analyzed to get a first impression. All households covered by the following survey were examined in the master-thesis and compared in their potentials for the sufficiency measures [4]. Two most extreme households are picked respectively, to reproduce maximum and minimum potentials for shifting and prioritized shutdown.

3. Results

3.1. The survey

150 persons filled out the online survey, among them 52 % students, 37 % workers, 6 % pensioners and a jobless person. Male (45 %) and female (54 %) participants are rather balanced. All were asked for basic data concerning their way of life and habits in the household. As the key part of the survey, they had to rate a list of devices and to indicate, whether or not they are willing to shift the device and what would be their time limit for shifting. Afterwards, the results were allocated to corresponding households. Table 1 shows an excerpt of ratings and shifting limits for some exemplary devices in (H01).

Table 1: Excerpt of device ratings and shifting limits for H01

Devices	Rating D_{ra}	shifting limit [minutes]
Bathroom - light	5	0
Bedroom - light	5	0
Electrical toothbrush	2	0
Hair dryer	3	0
Lawn mower	1	60
Fridge	4	300
Flat iron	3	30
Vacuum cleaner	3	60
Washing machine	4	1440
Coffee machine	3	0
Dish washer	3	1440
Kettle	4	30
Kitchen stove	4	30
PC	4	30
Fixed telephone	3	0
Television	3	30

3.2. A typical household

A relatively small PV battery system with an installed PV power of 2.59 kWp and a battery-capacity of 3.89 kWh is chosen to visualize and analyse the differences from self sufficiency to the SI: the PV generator exactly covers the yearly energy requirement and the battery capacity is as high as half of the average daily energy requirement. In Figure 4 the load-profile of the household and the associated renunciation-profile, visualising which devices cannot be used, are shown. The white areas in the renunciation profile are thus the unproblematic ones. Until day 100 and after day 300, renunciation becomes significant also during the daytime. In the meantime, during summer, it is rather limited to especially the morning (around 7 am).

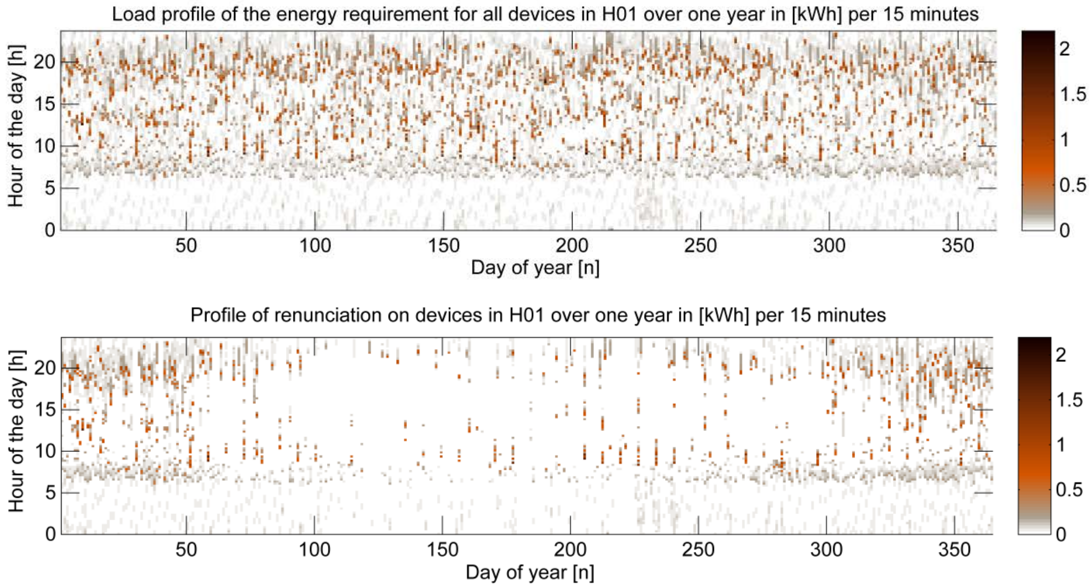

Figure 4: Above: Load profile of H01; Below: Profile of the renunciation on devices in H01, due to insufficient PV-generator and storage

This is obvious and as expected. E.g. devices used for gardening are really unproblematic, as they are used during the daytime and in summer – lighting especially in the morning is problematic. The degree of self-sufficiency in this example is at 61.4 % and the SI at 62.8 %. In this household the upper 15 % most important devices have a share of 41.3 % of the overall energy requirement. They consist among others of lighting, fridge, washing machine, oven and kettle.

After performing the prioritized shutdown, the SI rises to only 62.89 %. This is due to the fact that a lot of devices have to be shut down to run the most important ones, which have a relatively high energy requirement. The degree of self sufficiency sinks to 60.13 %, because shutting down devices to save energy for later use requires more storage, which is responsible for a loss of energy.

After shifting after storage, the degree of self-sufficiency rises to 62.3 % and the SI to 63.04 %. Mostly the washing machine and a kitchen machine profit from shifting. Shifting before storage reaches a lot more machines, such as the fridge and smaller devices. In turn, other devices like lighting suffer a bit, because some devices are shifted to time periods, where energy is stored for later usage. The SI reaches 63.74 % and the degree of self-sufficiency is at 62.94 %. Figure 5 shows an overview for the described parameters and their behavior. It also features a combination of shifting before storage and prioritized shutdown, which simply leads to an addition of both effects. It shows again, that the SI is always slightly higher than the degree of self-sufficiency, which suffers especially from the prioritized shutdown and profits from device shifting. The SI does not profit as much from shifting, as the degree of self-sufficiency.

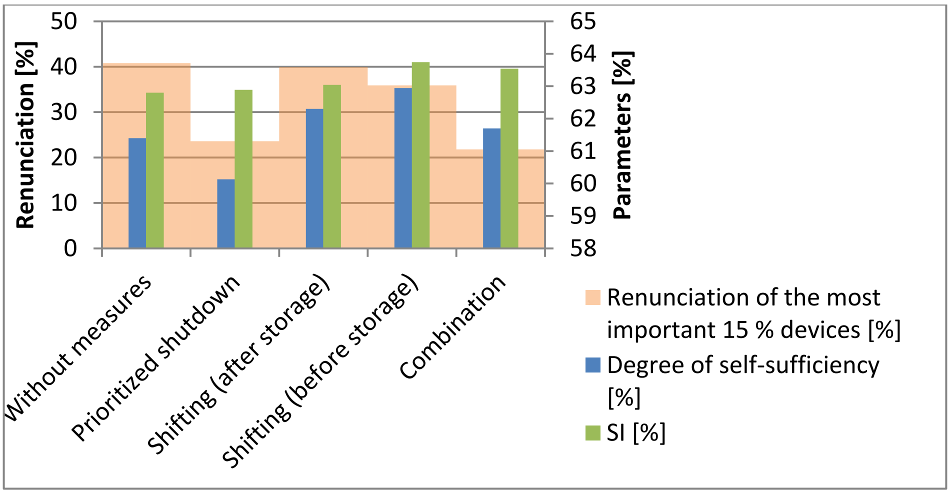

Figure 5: Comparison of SI with the degree of self sufficiency for H01

The household was also further examined on the average renunciation of the 15 % most important devices. Therefore an exponentially distributed variation of PV power and battery capacity was simulated with an additional measure combination as explained above. A PV generator covering twice the yearly energy demand and a battery covering the average daily energy requirement is sufficient to be able to overall use the most important devices more than 90 % of the time. Further increasing this value is requires much bigger systems and leads to only moderate enhancements.

3.3. Overall potentials of the sufficiency measures

As the households react very different, the ability to display a range, which includes the behavior of all households, is important. Therefore all households were compared, to find the ones, which react in the most extreme ways. $H06_{es}$ – a single jobless man, with an energy saving attitude – represents the maximum for shifting and will be focused on in this work. The PV battery system for the household is matched to the households' energy requirements. 10 x 17 operating points are simulated to logarithmically visualize the potentials. Figure 6 shows the initial results for the degree of self-sufficiency and for the SI. Differences are not obvious, as the SI has the same limits as the degree of self-sufficiency. Comparing lower values of this degree to the SI at the same system size reveals that the SI is higher and shows a slightly different behavior in the area of small storage sizes.

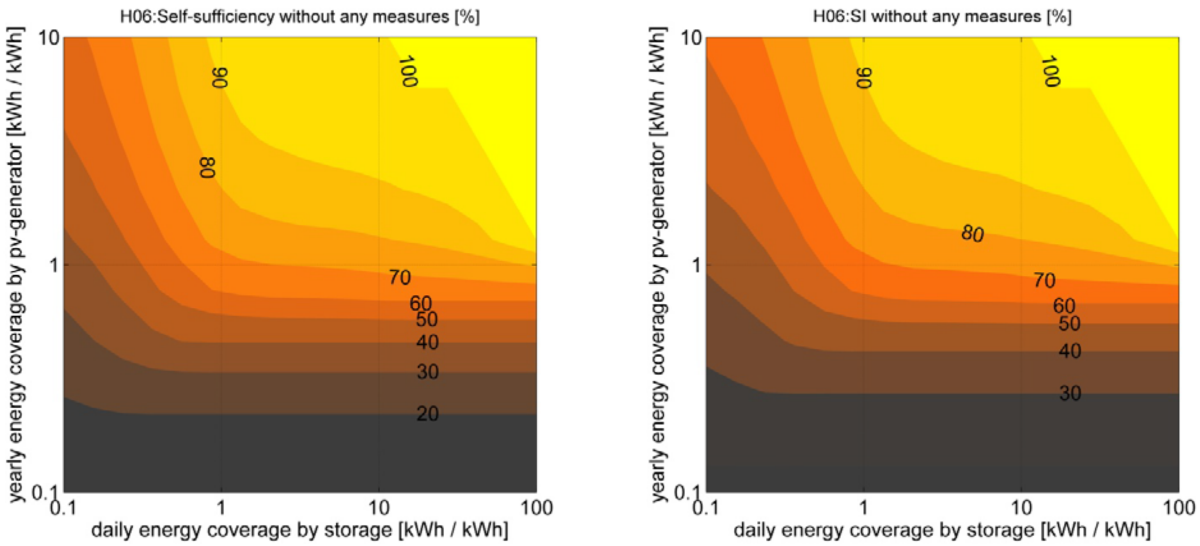

Figure 6: Self-sufficiency (left), SI (right) of $H06_{es}$ in dependence of PV generator and battery size [%]

The potential to improve the user's contentment via shifting is relatively low compared to the achieved higher self-sufficiency, as seen in Figure 7. This is due to the fact, that users are less willing to shift the more important devices. An absolute gain of 16 % in self-sufficiency and only 6 % for the SI are possible. Another important observation is the direct concurrence of storage and shifting.

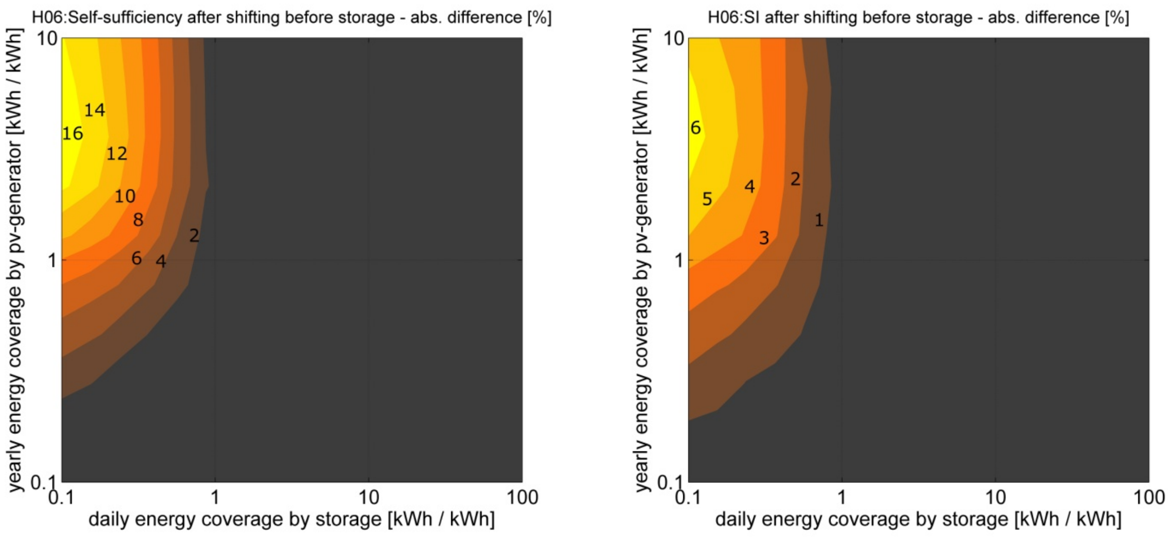

Figure 7: Absolute difference achieved by shifting before storage in the degree of self-sufficiency (left) and for the SI (right) [%]

The potential of prioritized shutdown, as shown in Figure 8, is much more diffuse. The degree of self-sufficiency decreases at the same time as the SI and personal contentment is increasing. The reasons are already explained in the individual household. Prioritized shutdown shows the highest potential for systems, where either the PV generator or the battery are insufficient. In Figure 8 on the right, this is illustrated for a small yearly coverage by the PV generator at the bottom right in the diagram and in the left upper corner for low daily energy coverage by the storage.

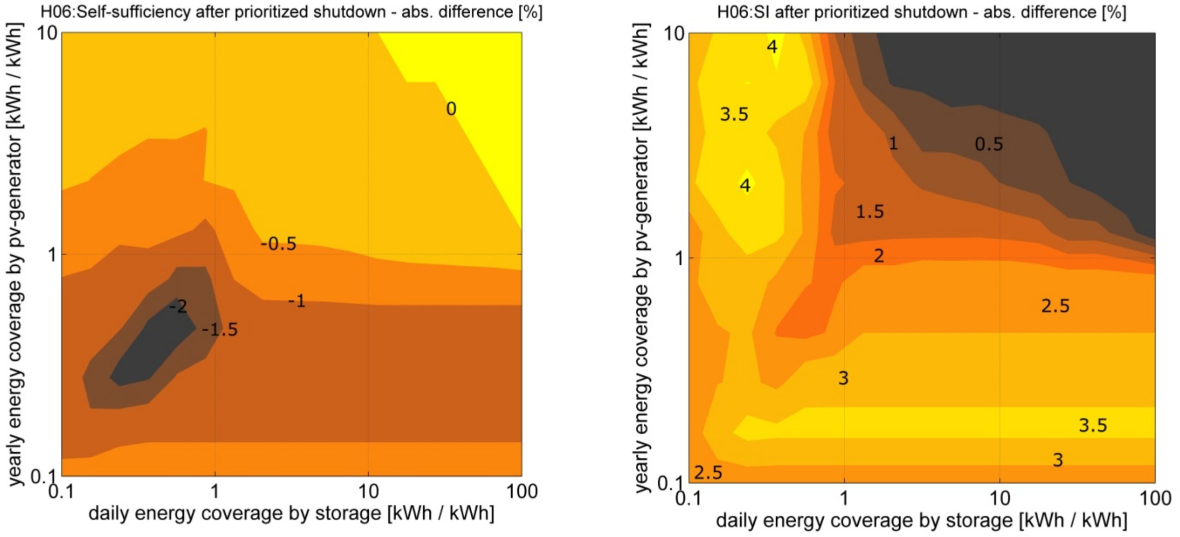

Figure 8: Absolute difference achieved by prioritized shutdown in the degree of self-sufficiency (left) and the SI (right) [%]

4. Discussion

All results are based on simulation and on profiles of the LPG. Exact household load profiles are unpredictable. Thus the simulations of several different households are supposed to be plausible cases and the same counts for the results, which also aren't surprising.

The significance of the SI is discussable. It is indeed not a value to be used for simple calculations with a dimensioning purpose as calculations are very complex and assumptions for a household can be very uncertain. To indicate the usage of the sufficiency-measures, especially for the prioritized shutdown, it is better suited, than the degree of self-sufficiency. It allows another point of view on energy consumption and consumer behavior and is also able to quantify the user's contentment. If this quantification corresponds to real user's judgments could be a (complex) topic to be evaluated.

5. Conclusion

The sufficiency indicator can be proved as meaningful to visualize how sufficiency measures affect the contentment of the household. Shifting of devices does not always lead to more contentment, as important ones, such as lighting, cannot be shifted. Prioritized shutdown brings more contentment, but reduces the grade of self-sufficiency in general. Some general rules are derived. In systems with minimum 200 % coverage of the yearly energy demand by the PV generator and a battery capacity covering the daily energy demand, the most important devices (accounting for 41.3 % of the overall energy requirement) can be run 90 % of their required time.

The winter is the biggest problem and seasonal storage not an option. Nevertheless autarky is an option, if the household is willing and able to renounce the usage of less important devices during winter and about 10 % of the whole year also on important devices. If the PV system would be supported by other technologies (e.g. wood or biogas) as well as energy-efficient devices, this would possibly lead to higher potentials.

6. References

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