ANALYSIS OF STATIONARY ELECTRICAL STORAGE SOLUTIONS FOR RESIDENTIAL DISTRICTS WITH HIGH PHOTOVOLTAIC PENETRATION

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ABSTRACT: Residential districts with high photovoltaic (PV) penetration can be equipped either with decentralized inhouse storage systems or with centralized district storage systems in order to increase the nearby self-consumed PV electricity. The objective of this work was to develop and to provide the methodical instruments to evaluate electrical storage systems for residential districts. As part of this work a case study based on a simulation model compared centralized and distributed storage solutions. It was found that the centralized storage solution exhibits several benefits like a significantly reduced storage capacity for reaching equal self-sufficiency rates and throughput (in this case study -18 % and -12 %, respectively). Moreover a conducted market analysis showed that larger battery storage systems also offer decreased specific system costs. Furthermore due to the boundary conditions given by the seasonal varying supply of solar irradiation and the specific load characteristics in residential buildings, the simulation series illustrated an economic optimum at 20 kWh of usable district storage capacity.
Keywords: distributed and centralized storages, modelling, PV system, electrical reference profiles

1 INTRODUCTION

The capital costs for photovoltaic systems have significantly and continuously decreased over the last decade. As a function of the particular local conditions coevally the height of the levelized cost of electricity (LCOE) of PV systems has also considerably decreased. Today PV has already passed the grid parity in many countries worldwide, in Germany the grid parity has been passed for rooftops PV systems in 2012 [1]. Parallel to the decreased PV LCOE also the German EEG feed-in-tariff for PV electricity has been steadily lowered. Due to this process many PV electricity producer experienced a paradigm shift. They stopped feeding the entire PV yield into the grid. Instead, it was now more attractive to consume as much as possible PV electricity by oneself.

Households with rooftop PV systems ordinarily consume 20-40 % of their self-produced PV electricity. Electrical storage solution can significantly increase the onsite self-consumption rate up to 100 % in dependence of the storage capacity and the installed PV nominal power. Nowadays economic reasonable dimensioning of PV storages can raise the self-sufficiency rate from 15-35 % (without storage integration) up to approximately 70-80 % (with storage integration) [2]. This enables residentials with an installed PV system on the roof top to reach a certain rate of self-sufficiency reducing the dependency of increasing grid electricity tariffs.

In order to achieve both high PV electricity self-consumption rates and high self-sufficiency rates in residential districts, there are two possible alternative solutions:

a) The storage integration takes place in a decentralized way on residential building level.

b) The storage integration takes place on residential district level with a common centralized mass storage for all residential buildings.

In our contribution we investigate and compare these two alternative storage solutions for residential districts with high PV penetration in order to address the question if one of these two approaches has a fundamental benefit concerning the occurring overall costs. Our investigations base on a market analysis and on modeling and simulating the PV storage operation in a residential district environment.

2 METHODOLOGY

2.1 Model Description

Basis for the assessment of distributed and centralized storage approaches in residential districts with high PV penetration was a simulation model consisting of 10 one family houses (see Figure 1). Each one family house has a PV rooftop installation in the range of 3-10 kWp (see Table I). Moreover, in one type of the model all one family houses are coevally equipped with distributed storage solutions exhibiting a usable storage capacity of 2-10 kWh. The second model type contains a centralized district storage system with a varied usable storage capacity instead of the installation of distributed storages in each one family house.

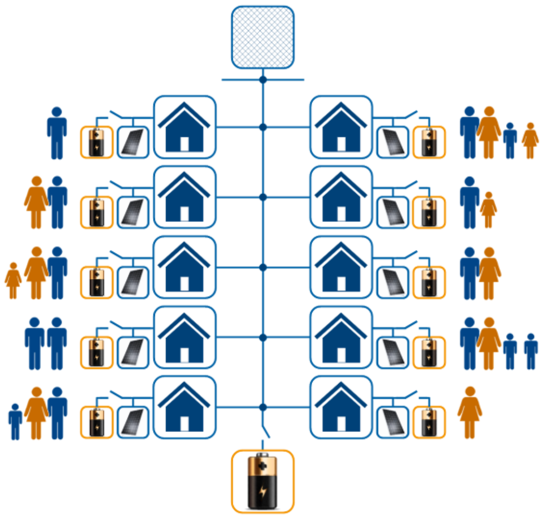

Figure 1: Conception of the modeled residential district.

In order to get representative results statistical data were taken to characterize the simulation model.

Therefore the varying number of residents in each household represents the statistical number of residents in a German district. These data were collected by the German Federal Statistical Office [3]. It has a significant effect on the consumer load profile characteristics because the amount of energy consumed by the households is mainly dependent on the number of residents. For reflecting the typical annual German household electricity demand, data collections of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety were taken into account [4] (see Table I). Based on these data the electricity demand and load profiles were modeled for each family house of the residential district. Annual electricity consumptions in the range 1500-4000 kWh were defined depending on the number of household inhabitants.

The dimensioning of PV generator size and residential storage capacity of each one family house (Table I) is based on the corresponding annual electricity consumption. Target of dimensioning was to realize both high PV self-consumption and high self-sufficiency rates. Furthermore the PV generator size is oriented on the typical installed PV system size in Germany in the year of 2015 [5]. The key data of the distributed residential storage systems like capacity, power (c-rate) and efficiency vary and depend on the selected manufacturer and type. Only residential storage systems were considered that are funded by the KfW Group in 2015 [6].

Table I: Key simulation data of the residential district model.

Number of inhabitants	Annual electricity demand [MWh]	Installed PV power [kWp]	Usable electrical storage capacity [kWh]
1	1.5	4	2.0
2	2.1	5	4.0
3	2.7	7	4.0
2	3.0	6	4.6
3	3.5	9	4.7
4	3.0	8	8.0
2	2.7	6	5.8
2	2.5	5	2.0
4	4.0	10	10.0
1	2.2	3	2.0
24	27.2	63	47.1

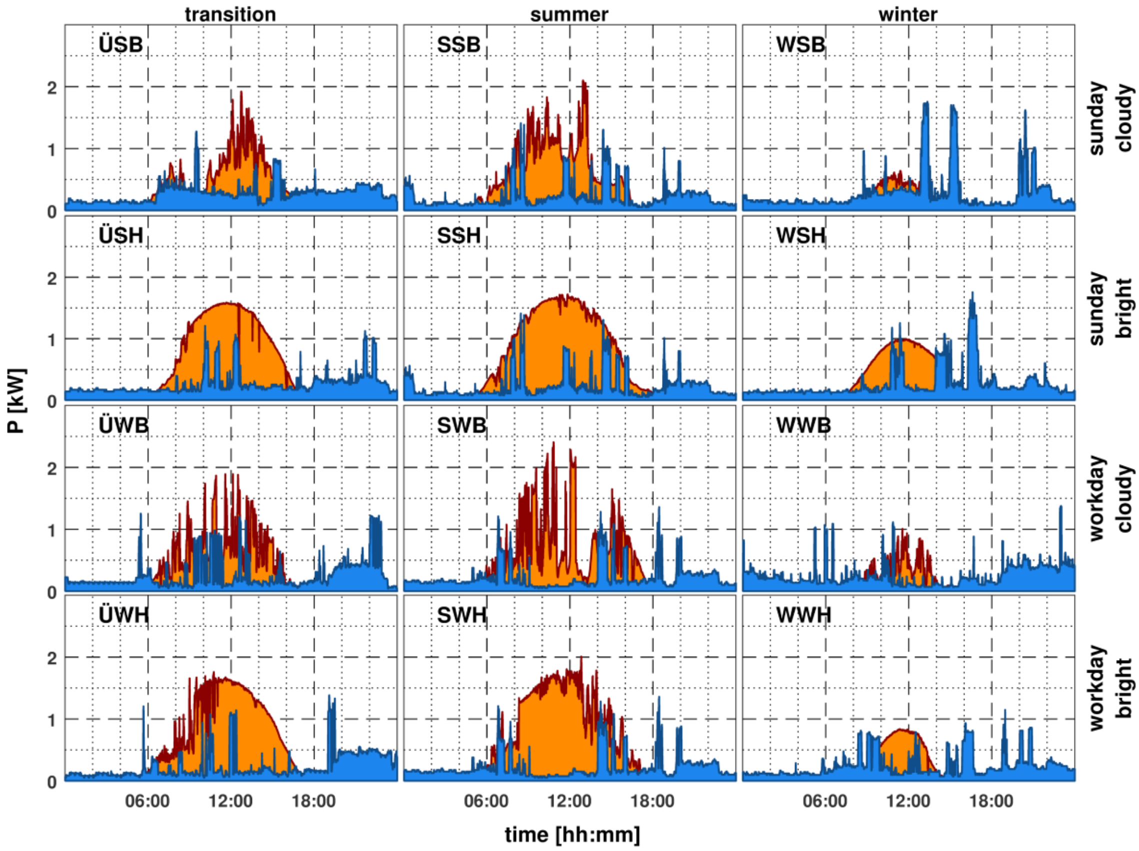

Figure 2: Electrical load profiles according to VDI 4655 [7] (blue line and area) and PV generation profiles [8] (orange line and area) of reference days. The profiles relate to a one family house with 2.2 MWh annual electricity demand and with a 3 kWp PV installation exhibiting a performance ratio of 80 %.

2.2 High-resolution load and PV generation profiles

Highly resolved load and PV generation profiles are a key issue for a realistic simulation of PV storage systems. Real load profiles that were available had rarely no representative character. Therefore, guideline VDI 4655 standard load profiles were taken from [7]. One objective of this guideline is to provide reference electrical load profiles in a one minute resolution for simulation and design purposes. The methodology of the VDI 4655 provides the possibility to create a typical test reference year based on representative days. A typical day represents the electrical load profile for each day category comprising the electricity demand that can be calculated in dependency of the number of residents living in a household or by a given yearly electricity demand. One calendar year is categorized by summer (S), winter (W) and transition (Ü). All profiles during one week are subdivided into working days (W) and Sundays (S) partitioned into bright (H) and cloudy (B) sky. Moreover, VDI 4655 guideline divides Germany into different climate zones taking variable weather conditions into account. However, VDI 4655 guideline possesses no standardized PV generation profiles. Hence we applied data from [8] that provides PV generation profiles in the manner of the VDI 4655.

Applying the mentioned key simulation data (Table I) and load and PV generation profiles, a test reference year with the climate conditions of Oldenburg (Northern Germany) was generated along the guideline method-logy. By this procedure an entire reference year was disposable with one minute data resolution ensuring a reliable simulation basis. Figure 2 shows exemplarily the load and PV generation profiles of the one family house with an electricity demand of 2.2 MWh. The corresponding installed PV capacity was 3 kWp, as performance ratio a value of 80 % was defined.

3 RESULTS AND DISCUSSION

3.1 Market analysis

First a market analysis of more than 100 residential and district storage types of 26 different manufacturers has been conducted for the German market in 2015. For this analysis the overall system costs were taken. Thus the costs include the battery, power electronics, housing and assembly.

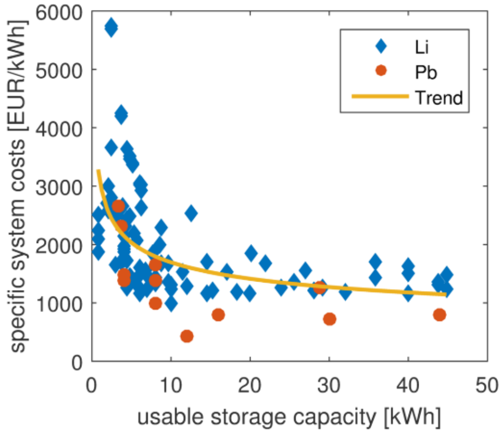

Figure 3: Results of a market analysis for residential and district storage systems collected for the German market in 2015 showing the correlation between usable storage capacity and specific system costs.

Figure 3 shows the results of this analysis that exposes the tendency for storage systems to drop in specific costs (€/kWh) by increasing storage capacity. This can be attributed to the effect that large district storage systems basically requires less capital costs due to less specific costs per usable kWh storage capacity. Likewise, the specific costs for power electronics decrease with increasing nominal power.

3.2 Self-sufficiency rate

The electricity supply of the modelled residential district was simulated for one calendar year including a couple of scenarios:

a) First the simulation was performed without storage integration. The obtained value served as reference in order to study the self-sufficiency rate gain due to storage integration.
b) Afterwards the distributed storage scenario of Table I was simulated with a usable cumulative storage capacity of 47.1 kWh.
c) The scenario of centralized district storage was totally simulated 14 times varying the usable storage capacity from 5-70 kWh in 5 kWh steps. The c-rate of the district storage was varied in relationship to the capacity.

The generated simulation results offer a time-resolved examination of all load-flows in the residential district model. First the self-sufficiency rate for the district was analyzed and the obtained simulation results are shown for each calendar week in Figure 4. Seasonal differences were taken into account by the reference year indicating lower self-sufficiency rates in the winter and transition period compared to the summer period. The reference case without storage integration and the scenario with distributed residential storages are also presented.

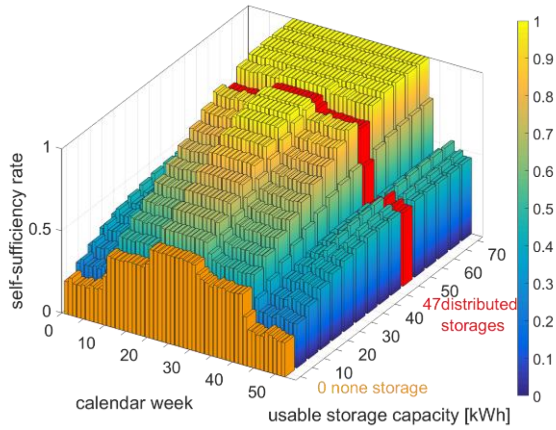

Figure 4: By simulation obtained self-sufficiency rate of a modeled PV equipped residential district within a calendar year as function of the usable storage capacity of a centralized district storage. Data in orange indicate the self-sufficiency rate without storage integration (reference). As comparison the red filled bars show the simulation results for the case of the distributed storages with a usable total capacity of 47.1 kWh.

An overview of the annual self-sufficiency rate as function of the usable storage capacity is shown in Figure 5. Without storage integration, the total PV capacity of 63 kWp leads to a self-sufficiency rate of 37 %. By installing the centralized district storage the self-sufficiency rate increases up to 80 % at the maximum usable storage capacity of 70 kWh. For the scenario of distributed residential storages with a usable total capacity of 47.1 kWh, a self-sufficiency rate of 74 % was determined. For realizing the same self-sufficiency rate with a centralized district storage solution, a significantly less capacity of 38.7 kWh is required (-18 %).

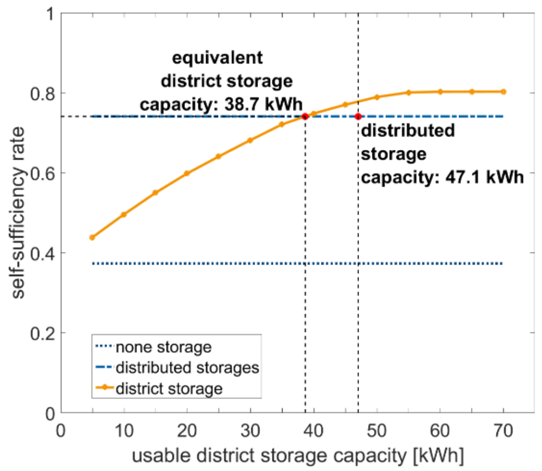

Figure 5: Annual self-sufficiency rate as function of the district storage capacity. The self-sufficiency rate for the distributed storage scenario is shown as constant (blue dash-dotted line). The red markers represent the required storage capacity resulting in the same self-sufficiency rate for both cases (central vs. distributed storage approach).

3.3 Throughput

One important criterion for the assessment of the cost effectiveness of a storage solution is the scored throughput as measure for the utilization level. Both considered storage integration scenarios for the residential district (centralized vs. distributed) were compared referring to this and the results are shown in Figure 6.

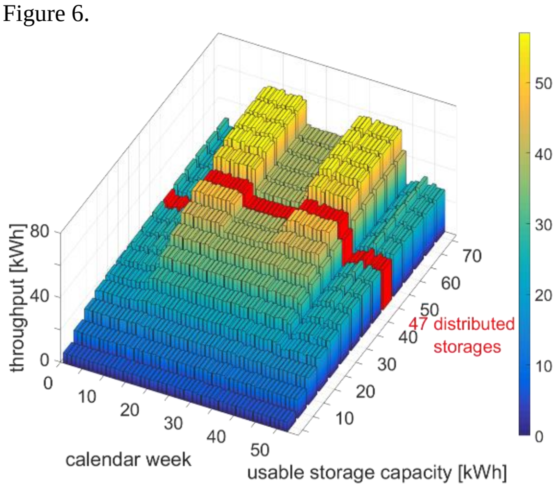

Figure 6: Throughput vs. calendar week for each varied district storage capacity (5-70 kWh). The red filled bars mark the simulation result for the scenario of the distributed storage solution with a usable cumulative capacity of 47.1 kWh.

Like in Figure 4 all week results of a calendar year are illustrated for both the scenario of a distributed storage solution (usable total capacity 47.1 kWh) and the scenario of a centralized storage solution (usable capacity 5-70 kWh). With increasing centralized storage capacity a considerable difference occurs concerning the throughput in the winter months and the remaining part of the year. The lower throughput during the winter months can be observed at usable storage capacities of ≥ 20 kWh. Moreover, for usable storage capacities ≥ 40 kWh the throughput values increase variably so that the highest throughput values are achieved during the transition time.

The overall annual throughput for each simulated usable storage capacity is shown in Figure 7. The distributed storage solution with a usable total storage capacity of 47.1 kWh achieves an annual throughput of 13.3 MWh. For scoring the same annual throughput, the centralized storage solution requires merely 41.4 kWh usable storage capacity (-12 %).

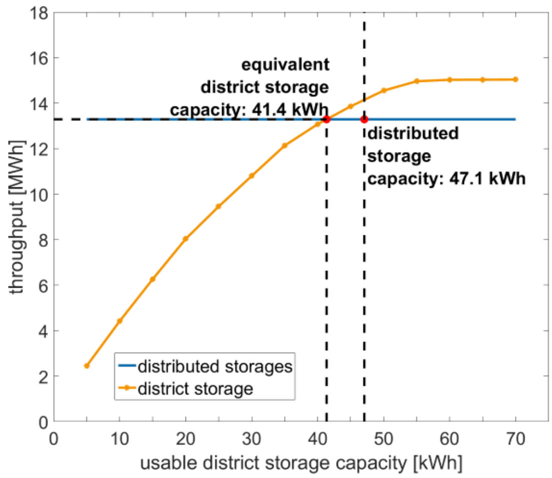

Figure 7: Annual throughput as function of the usable district storage capacity. The orange line is displaying the results for the centralized district solution whereas the constant blue line is representing the results for the distributed residential storages. The intersections representing the equality of throughput of both solutions are marked with red dots.

3.4 Further aspects

Existing buildings in residential districts usually offer a lot of roof space for the installation of PV systems. Providing space for on-site electrical storage systems, however, was not state of the art when the buildings were constructed. Thus the installation of such storage systems in existing buildings could be limited. Even in modern buildings it could be difficult to find enough space for an on-site PV storage since these buildings are often equipped with huge ventilation systems. Therefore in many cases there is no acceptance to provide space for more technical installations like electrical storages.

Finally it has to be pointed out that in addition to the realization of high PV self-consumption rates and high self-sufficiency rates the establishment and dissemination of electricity storage systems basically has an essential meaning on macroscopic scale in matters of the transformation of the global energy system toward a full supply with renewable energies. The approach to buffer electricity produced by volatile renewable energy sources nearby the consumer instead of a long distance transmitting may lead to the benefit of significantly reduced investment costs concerning the expansion of electrical transportation grids.

4 CONCLUSION

In this case study we compared centralized and distributed storage solutions for residential districts with high PV penetration. It was found that the centralized storage solution exhibits several benefits like a significant reduced storage capacity for reaching equal self-sufficiency rates and throughput values (in this case study -18 % and -12 %, respectively). Moreover, larger battery storage systems also offer decreased specific system costs.

The case study also demonstrated that the self-sufficiency rate of PV equipped residential districts can be distinctly increased by storage integration. Due to the boundary conditions given by the seasonal varying supply of solar irradiation and the specific load characteristics in residential buildings, the simulation series in 5 kWh storage capacity steps illustrated an economic optimum at 20 kWh usable storage capacity. An increased storage capacity leads to nearly no further self-sufficiency gain in the winter period due to the limited supply of solar irradiation. If the storage capacity is further increased, also for the summer period a saturation effect arises.

5 REFERENCES

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