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Battery Neighbourhood Storage for a Climate Protection Settlement

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Abstract. The strong expansion of renewable energies has led to the increasing importance of storage systems. Decentralized storage solutions, including home and neighbourhood storage systems, play an important role in this context. This study compares individual home storage systems with a common neighbourhood storage system. The use case is to optimize the use of photovoltaic energy generated in the settlement. The criteria investigated are the grade of autarky and self-consumption. A simulation tool was developed to perform load flow simulations based on household electricity consumption, electric vehicle charging profiles, heat pumps and photovoltaic generation data for different battery capacities and system boundaries. The results show that neighbourhood storage systems can achieve a maximum increase in the grade of autarky of up to 8.47 % and an increase in self-consumption of 6.87 % compared to individual home storage systems with equivalent cumulative battery capacities for the given use case. In the exemplary case the common neighbourhood storage requires only about halve of the battery capacity compared to the cumulated capacity of all individual storages to achieve the same grade of autarky for a typical operation case.

Keywords: Neighbourhood Battery Storage, Climate Protection Settlement, Autarky

1. Details

The increasing expansion of renewable energies requires new concepts for integrating decentralized generation into the existing energy system. A key component of this is energy storage, particularly in the form of battery storage [1]. Renewable energy communities (RECs), as defined by the European Union's (EU) Renewable Energy Directive 2018/2001 (RED II) and 2023/2413 (RED III), enable citizens to collectively generate, use and store energy with the aim of achieving environmental, social and economic benefits [2][3]. In this context, shared storage assumes a pivotal role as a technical component.

Although community-based storage solutions, particularly in the context of RECs, can support the more efficient use of renewable energy, reduce grid loads, and increase self-consumption, their practical feasibility and economic viability depend on a variety of external factors [2] These include the regulatory framework, which differs significantly between EU member states and regions, as well as dynamic influences such as the development of energy, photovoltaic (PV) and battery prices, applicable charges and tariffs, and the willingness of residents to participate [2][3][4].

Since these boundary conditions are highly variable and subject to change, this study focuses exclusively on the technical potential of shared storage systems to improve the local utilization of renewable energy, in line with the objectives set out in RED II and RED III.

The advantages of neighbourhood storage systems have already been demonstrated in [5], though different load types were not considered in that analysis. More recently, the effects of shared battery storage systems compared to individual storage systems were examined in various forms by the authors in [6]. That study focused primarily on aggregated results of district-level consumption and their overall influence on storage performance.

Building on this foundation, the present work advances the analysis by systematically combining different load profiles to explore temporal complementarity and its impact on the effectiveness of storage. The objective is to examine the underlying mechanisms that lead to the observed efficiency gains in shared storage solutions and to generalize the insights gained from previous findings.

1.1 Exemplary use case

In this study, various storage solutions are analysed for a future residential complex 'Klimaquartier Bergneustadt', Bergneustadt, North Rhine-Westphalia, Germany, which will consist of 36 single-family homes. Each house is to be equipped with a solar system, a heat pump and a wallbox for charging of electric vehicles (EV). The aim of the neighbourhood storage system is to improve the use of energy generated by PV systems with a storage solution in the neighbourhood.

1.2 Methods

For the calculations synthetic but realistic power generation and consumption data is used. Figure 1 illustrates exemplary consumption profiles for households (a), heat pumps (b) and EVs (c) as well as the generation profile for PV (d). The shown profiles correspond to the time period in which the respective load type exhibits its highest cumulative peak load.

The electricity consumption profiles of the households were created using the LoadProfileGenerator [7]. It generates realistic synthetic consumption profiles based on a behavioural model of virtual residents. Each household gets its own specific profile. 2 to 6 individuals per building, in total 113 residents are assumed.

The charging profiles for the EVs are created with an own tool based on the mobility desire extracted from the simulated behaviour of the residents generated with the LoadProfileGenerator (see above). Holiday periods are included. This way the charging data fits to the consumption of the households. The simulated travel distances are based on mobility studies from Germany. A probability function calculates whether the EV will be connected to the wallbox upon arrival. The tool simulates various EV types with different consumption rates and capacities [8]. To each household one EV is assigned. The average energy consumption of EVs per 100 kilometres is assumed 18.3 kWh. Based on the average annual mileage of 12518 kilometres per vehicle and the resulting number of 129 charging processes per year and household, it can be deduced that each EV is charged every 2.8 days on average. Per charging instance 17.7kWh is charged on average.

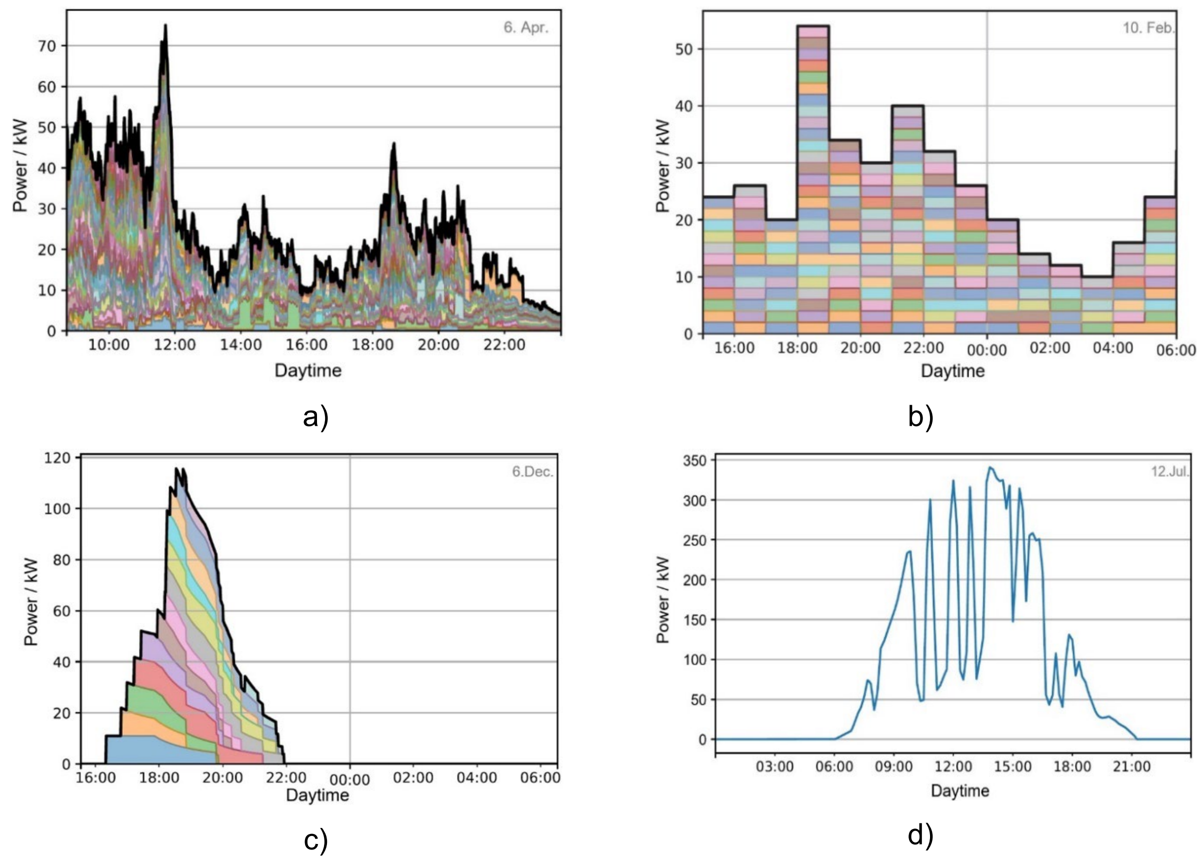


Figure 1. *Exemplary power profiles: a) Households. b) Heat pumps. c) Electric vehicles. d) Photovoltaic generation.*

The heat demand is simulated using the nPro tool [9]. To calculate the hot water demand, nPro uses a model that combines a basic demand profile with a time-of-day dependent demand profile. The room heating requirement is calculated using the assumption that the heating requirement increases linearly with the difference between the outdoor and indoor setpoint temperature [10]. The standard values from nPro are used to calculate the heating requirements, whereby the building type single-family house according to KfW 40 is selected. This results in a specific space heating requirement of 29 kWh/(m²a) and a domestic hot water energy requirement of 21 kWh/(m²a). The heat pumps are assumed no to modulate their power but switch on and off with nominal power of 2 kW_{el} for a time sufficient to generate the required heating energy. Small thermal storages, which can also be the materials of the houses, are assumed to level the heat.

All houses are equipped with similar PV systems with a nominal output of 10 kWp each. The tilt angle is 30° with a south-west orientation. The PV feed-in data is calculated with PV-LIB [11], using weather data retrieved from the open data server of Deutscher Wetterdienst (German Weather Service) for Lüdenscheid and Reichshof-Eckenhagen, which are 25 km and 5 km away from the Bergneustadt site, in a 10-minute resolution. The data was checked with data from PV-GIS [12] related to the region of the use case. The results are scaled to the size of the systems. For all houses the same profile is used.

Figure 2 illustrates the simulated annual energy consumptions of the individual households in the settlement, which result from summing up the generated profiles. The red bars show the electricity consumption of households, the green bars correspond to the energy consumption of the EVs and the blue ones are for the heat pumps. Energy consumption is assumed to be comparatively diverse for both households and electromobility, as the difference is up to a factor of four.

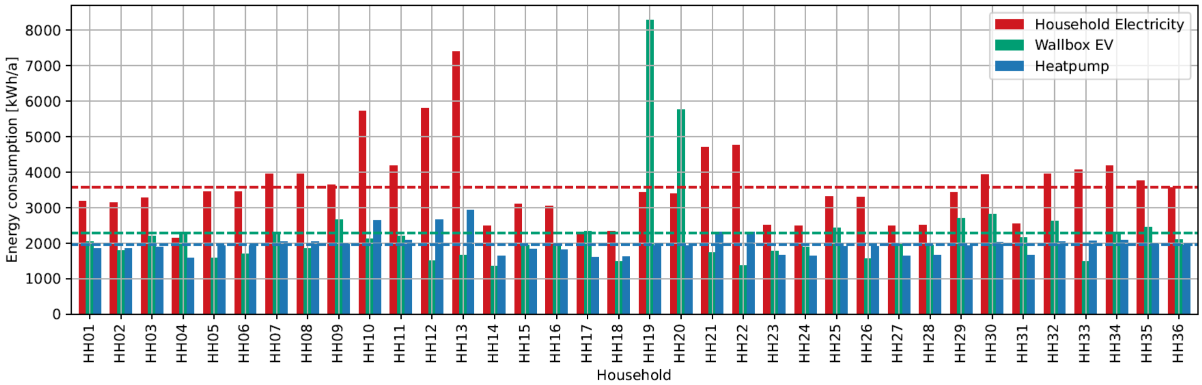


Figure 2. *Annual household electricity, electric vehicle and heat pump energy consumption for each household. Dashed lines represent the average.*

The use case of the battery is to optimize the grade of autarky of the settlement by storing excess PV energy until use. PV power is first used for the demand. An excess residual power is then used to charge the battery. It is considered as lossless. If it is full, the excess is fed into the power grid. If the demand is higher than the PV generation, first the battery is discharged. If it is empty, power is purchased from the power grid. This strategy is used for both, common battery and individual batteries. In case of the individual batteries, no correspondence between the batteries is assumed, such that they can be charged with their own PV power only. When comparing individual storage units and neighbourhood storage units, the neighbourhood storage unit is always dimensioned so that it corresponds to the cumulative capacity of the individual storage units. In both cases, the connection point of the neighbourhood to the public grid is considered as the system boundary for the grade of autarky and self-consumption. The simulation framework is implemented in Python, with simulations executed at an hourly resolution. The data of the time series profiles is calculated for each individual time step.

The grade of autarky g_{autark} defines, how much of the used energy W_{load} in the settlement is self-generated. It considers directly generated PV energy W_{pv} including energy taken from the battery storage. Energy fed into the public grid W_{infeed} does not count to the balance. More than 100% is not possible, thus the value is limited to 1. This results in the following equation [6]:

$$g_{\text{autark}} = \min\left(\frac{W_{\text{pv}} - W_{\text{infeed}}}{W_{\text{load}}}, 1\right) \tag{1}$$

The grade of self-consumption g_{self} defines, how much of the generated energy W_{pv} is used in the settlement. In this instance, W_{pv} also considers the directly utilised PV energy, in addition to the energy that is discharged from the storage system. More than 100% is not possible, thus the value is limited to 1. This results in the following equation [6]:

$$g_{\text{self}} = \min\left(\frac{W_{\text{pv}} - W_{\text{infeed}}}{W_{\text{pv}}}, 1\right) \tag{2}$$

2. Results

2.1 Individual Storages

First, a simulation without any storage is performed. As a result, the average grade of autarky of households is 33.7%, while the proportion of self-consumption is 20.5%.

Then, simulations were carried out with a typical storage size. In detail, the storage energy capacity corresponds to 0.8 times the daily energy requirement, which is where the biggest difference between individual home storage systems and a neighbourhood storage system is found (see below). Figure 3 shows the grade of autarky. The values for each individual household are shown in grey bars. The yellow bar represents the grade of autarky of the whole system with individual storage units at the point of common connection. The purple bar shows the grade of autarky with a neighbourhood storage unit.

The introduction of individual batteries has enabled an improvement in the autarky of individual households by increasing the average grade of autarky to 63% and the self-consumption rate (not shown) to 46% on average. The graph also shows that at 70%, the grade of autarky with neighbourhood storage is significantly higher than with any individual solution.

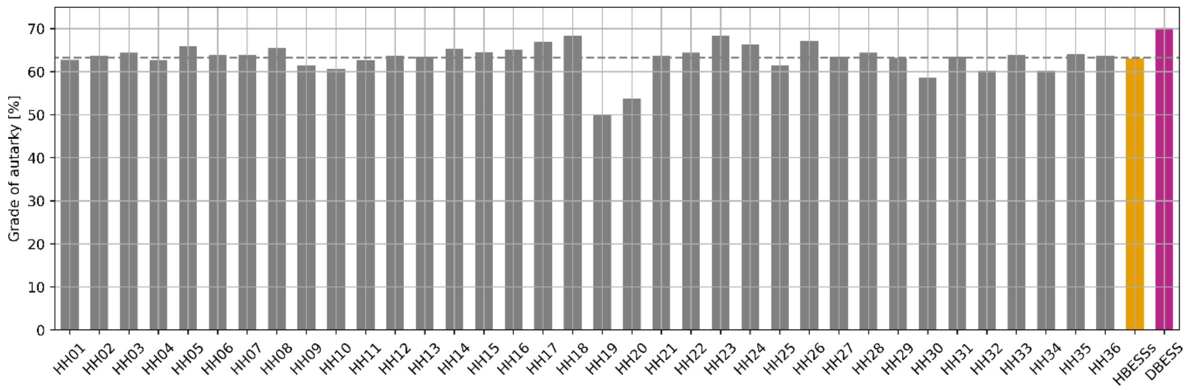


Figure 3. *Grade of autarky for individual households (grey bars), the system with individual batteries (yellow bar) and district storage (purple bar). The dashed line represents the average of the results for the individual households. It includes household loads, electric vehicles and heat pumps.*

2.2 Explanation with exemplary profiles

The advantage of a common battery storage over individual storages as shown in the previous chapter will be explained with exemplary profiles of power and state of charge (SoC) on two days in summer. To illustrate the effect, two extreme cases are shown, which are the demand of two EVs of two different households. In addition, the battery sizes of 20 kWh each are somewhat exaggerated for illustration purposes. Losses and self-depletion are neglected. Both EVs charge with 11 kW. The PV systems have 10 kWp each. The profiles are the same as described in the previous chapter and are for the same two summer days (18.-19. Jun. 2023). The common battery has a capacity of 40 kWh summed from both individual batteries and in this case both PV systems are added as well. For illustration purpose batteries are assumed to be empty at the beginning.

Figure 4 shows the profiles for a first EV 01, Figure 5 the corresponding ones for a second EV 19. Figure 6 shows profiles for both connected to a mutual battery storage. The figures show the power demands of the EV (dark red and lighter red), the related PV feed in (yellow, positive values corresponds to generation), the power taken from the grid connection (grey, positive values correspond to purchase from the grid) and SoC of the batteries (green, related to right vertical axis). In the diagram for the mutual battery Figure 6, the grey curve relates to the sum of the individual grid powers of both EVs. In addition, the blue profile corresponds to the grid power of the solution with the common battery.

EV 01 is charged only once and with available PV and battery power (Figure 4). The battery is charged at the first day and remains at a high SoC during most of the time. EV 02 is not directly charged with PV power and only partly with battery power (Figure 5), because the battery is depleted. Instead, power must be purchased from the grid (see grey curve).

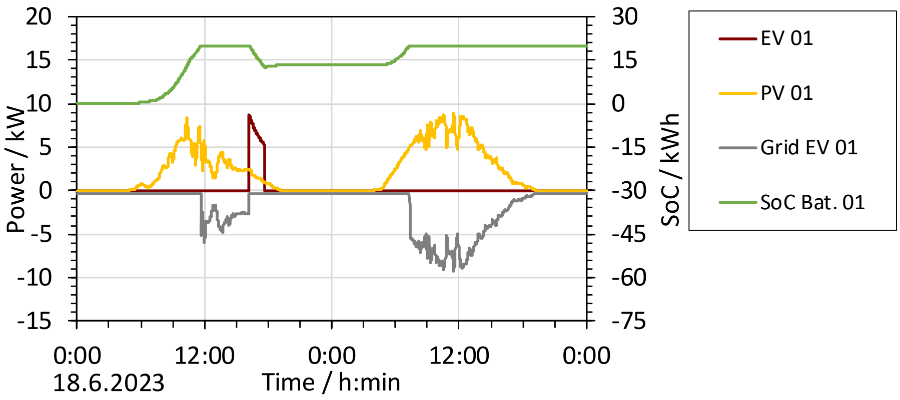


Figure 4. *Power profiles for electric vehicle 01, state of charge (SoC) of the related home battery and grid power on two exemplary days.*

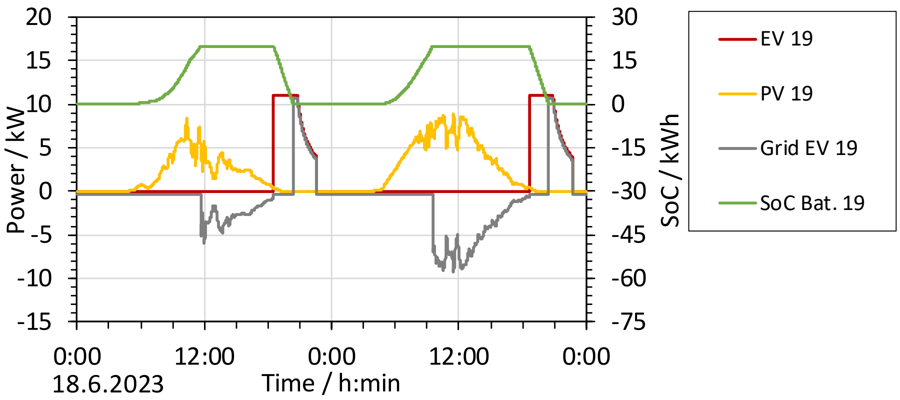


Figure 5. *Power profiles for electric vehicle 19 state of charge (SoC) of the related home battery and grid power on two exemplary days.*

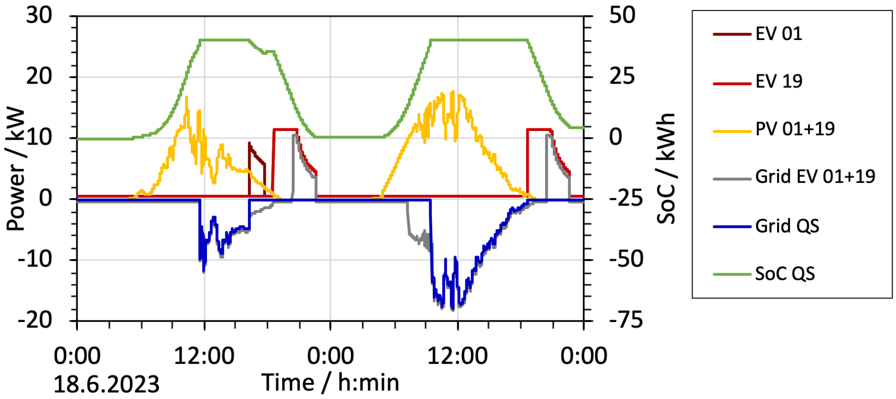


Figure 6. *Power profiles for electric vehicle 01 and 19, state of charge (SoC) of the related common storage (QS) and grid power on the point of common connection on two exemplary days.*

Looking at both together (Figure 6) the charging profiles of both EVs don't overlap. With the common battery, both EVs are charged from PV power and the common battery. No power purchase from grid is necessary (blue curve), contrary to individual batteries (grey curve). Thus, without grid purchase the grade of autarky of the common battery case is higher than for the case of individual batteries.

The figure illustrates the reason: Obviously, both EVs can share the sum of both battery capacities and PV power. Since the power demand doesn't overlap, both benefit from the double battery and PV. While this example is an extreme one, it demonstrates the general principle: A common storage is advantageous over individual storages only, if the individual power demand profiles differ from each other in time. The more they differ the large the advantage is to be expected. Then each user can benefit from an enlarged battery and PV.

2.3 Storage Size

In further simulations, the storage size was varied over several orders of magnitude. Figure 7 presents the results for the grade of autarky as a function of the storage size. The yellow curves represent the grade of autarky for individual storage systems. The purple slopes represent the community battery concept. The x-axis is normalized to the daily energy demand. It thus illustrates the expansion of storage capacity from daily to seasonal or even annual storage.

Figure 7a shows the results considering all consumers households, EVs and heat pumps. Figure 7b shows the results for household loads only, Figure 7c for EVs only and Figure 7d for heat pumps only. In all cases, the full installed PV power of 10 kWp for each house has been considered. The x-axis is scaled to the daily demand of the particular load type.

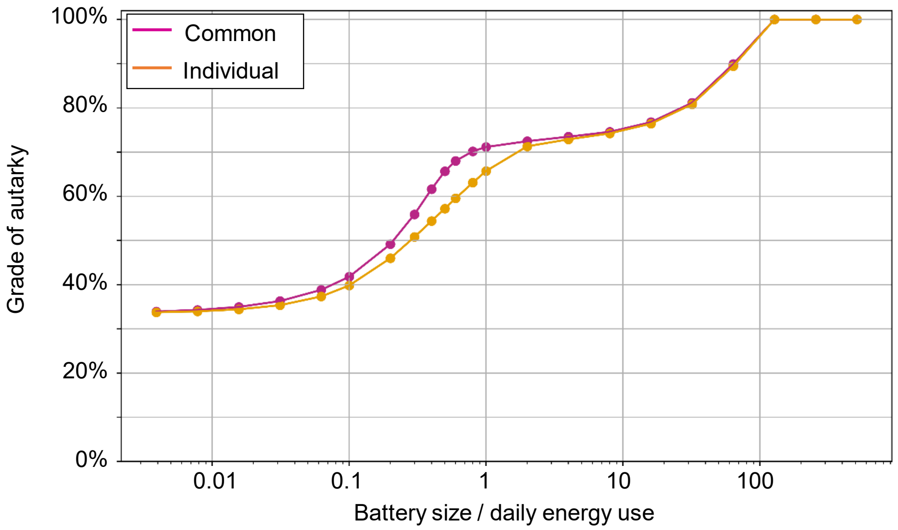
First Figure 7a is discussed: Both curves for the common storage and for individual storages have a similar course: After an initial increase as storage capacity increases, the grade of autarky remains at an almost constant level for nearly two orders of magnitude as capacity increases further. Only when the capacity is close to 100 times the daily requirement, the grade of autarky increases up to 100%. A detailed analysis of the capacity profiles provides an explanation for the slope: The first plateau occurs when the storage size has reached approximately one value of the daily energy requirement. This allows a balance to be achieved between day and night. However, this does not achieve a balance between summer and winter. This is only possible with a seasonal storage system, which is many times larger.

For small storage systems, the curves for the individual storage systems and the neighbourhood storage system hardly differ. Only when the capacity reaches the range of the daily energy demand, a clear difference is recognisable with an advantage for the common storage system. With even larger storage capacities, the curves equalise again. Therefore, a common storage system is most advantageous, when it is used as a daily storage system. It then delivers up to 8% points better autarky. Or interpreted differently: It can have significantly less capacity than the sum of the individual storage units for the same grade of autarky. In this exemplary case, the capacity can be reduced to around half with a grade of autarky of 70%.

To explain the difference, a detailed investigation shows that if the storage units are very small, they cannot withhold energy so that energy is exchanged between households. The behaviour is therefore similar to that of a shared storage system. With very large storage systems, the fact that the power profiles of the households essentially differ only in the daily range comes into play. As the storage units compensate for differences in the daily profiles, it levels out the profiles such that they do not differ on a larger time scale. But this also levels out the advantage of the common storage. Only if the storage is close to the size of the daily energy demand the effect explained in the previous chapter takes effect and the loads can make use of the larger mutual storage. In addition, then energy can be exchanged directly in the neighbourhood at certain times without using the storage system. When individual storage units are used, this hardly ever happens because the individual storage units are charged first.

In order to get more insight, the different load types are investigated alone. The slope for household loads only in Figure 7b is quite similar. The grade of autarky is higher simply because less energy is needed in total. The difference between common and individual storage is reduced to about 25% capacity reduction, because the power profiles are more similar to each other compared to profiles including all loads.

The slopes for EVs charging (Figure 7c), however, look quite different. Here, an even larger advantage for the mutual storage is clearly visible. The individual storages must have a size of 2 to 3 time the average daily energy demand to take effect. This is due to the EVs are not charged every day, but often with a longer period. The summed profile, however, has a significantly higher frequency requiring a storage size of only less than an average daily demand. Furthermore, no plateau for storages larger than the daily demand is visible. It is assumed that this results from the charging profiles having no seasonal component.



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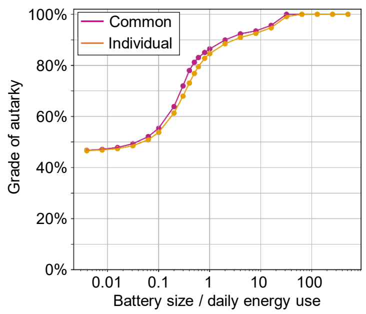
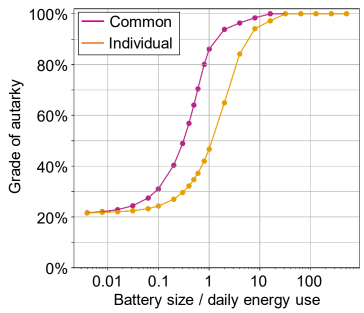
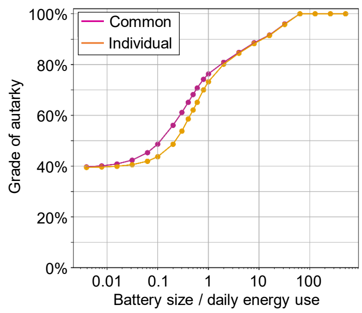


b)



c)



d)

Figure 7. *Grade of autarky as a function of storage size for common storage (purple) and individual storages (yellow). a) All loads b) Households only. c) Electric vehicles only. d) Heat pumps only.*

The slopes for the heat pumps differ in a different way (Figure 7d). The common storage exhibits an advantage only for comparably small storage sizes of less than the daily demand. The individual profiles differ in time level because of the on-off-switching mode of the heat pumps. For a larger time frame this is levelled out such that a larger common storage has no advantage above individual storages. However, for larger storages, there is no plateau visible. Instead, the grade of autarky increases continuously with larger storages. The reason has not been analysed in detail, but it can be assumed that intermediate sized storages can cover bad weather periods of a few days to weeks, depending on the storage size.

3. Discussion

Beyond these observations, further influencing factors on the effectiveness of shared storage concepts can be identified in the underlying generation and consumption patterns. In this study, an identical orientation and PV system configuration are assumed for all 36 households. Diversifying the PV generation profiles would likely enhance the benefits of the neighbourhood storage system, as the community would gain from a more temporally distributed generation profile. Since individual systems are first charged to full capacity before any excess is fed into the local grid, the examined configuration leaves less PV surplus available for the community. The impact on the change in the grade of autarky with diversified PV profiles, however, is heavily dependent on the specific generation patterns and their synchronization with electricity consumption.

A particularly notable increase in the grade of autarky is observed when using a neighbourhood battery storage system in scenarios involving only EV charging profiles. This increase can be attributed to the low correlation among individual charging profiles. On average, EVs are charged every 2.8 days, resulting in the home storage systems keeping stored energy unused for a significant portion of the time between two charging events. The neighbourhood storage system benefits from the fact that within the aggregated charging profile, charging events occur much more frequently. If the charging profiles were highly identical, this would diminish the advantage of the neighbourhood storage system, as substantial amounts of energy would be discharged over short time periods, leaving the storage system underutilized thereafter.

4. Conclusion

This study shows that shared battery solutions can be realized with significantly less battery capacity for the same grade of autarky of a settlement. The neighbourhood storage system shows the greatest advantage in the range around daily storage capacities, which is a typical application. The advantage improves as the power profiles differ from each other in time. In the exemplary case of a climate protection estate with 36 houses, it was calculated that the neighbourhood storage system as a daily storage system for a grade of autarky of around 70% only requires around half the capacity of a solution with individual household battery storage systems.

While these results clearly demonstrate technical benefits regarding the local utilization of renewable energy, they do not allow for direct conclusions about the economic viability of such systems. This depends on a broad set of location-specific and regulatory factors, which are subject to change.

Data availability statement

All related data can be accessed at the following link: https://th-koeln.sciebo.de/s/4XWM5zFQ5ICXIh5

Author contributions

Contributions by Eberhard Waffenschmidt are: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft.

Contributions by Jonas Quernheim are: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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