Article

A Comparative Evaluation of Community-Used District and Individual Battery Storage Systems for Photovoltaic Energy Systems

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Abstract: The significant expansion of renewable energies has led to an increased importance of storage systems. Decentralized storage solutions, including Home Battery Energy Storage Systems (HBESS) and District Battery Energy Storage Systems (DBESS), play a crucial role in this context. This study compares individual HBESSs with a community-used DBESS regarding the grade of autarky and self-consumption, specifically focusing on a planned residential area consisting of 36 single-family houses. A simulation tool was developed to conduct load flow simulations based on household electricity consumption, wallbox profiles for electric vehicle charging, and photovoltaic generation data across various battery capacities and system boundaries. The results demonstrate that the DBESS, compared to individual HBESS with equivalent cumulative battery capacities, can achieve a maximum increase in the grade of autarky of up to 11.6 %, alongside an 8.0 % increase in the grade of self-consumption for the given use case. In terms of capacity, the DBESS allows for a saving of up to 68 % compared to HBESS to achieve similar results for the studied neighborhood.

Keywords: Photovoltaic Energy; Community Storage; District Storage; Individual Storage; Battery Storage; Autarky; Self-Sufficiency; Self-Consumption; Residential PV Systems; Electric Vehicle Integration

Citation: Quernheim, J.; Waffenschmidt, E. A Comparative Evaluation of Community-Used District and Individual Battery Storage Systems for Photovoltaic Energy Systems. *Energies* **2024**, *1*, 0. https://doi.org/

Received:
Revised:
Accepted:
Published:

1. Introduction

The transition towards sustainable energy is accelerating the development and enhancement of both new and existing technologies. As traditional power plants are phased out, reliance on renewable energy sources with variable outputs becomes inevitable. Among these sources, solar energy holds significant potential in Germany, as evidenced by the steady increase in the country's photovoltaic (PV) capacity since 2008 [1]. However, the intermittent nature of solar energy necessitates the integration of effective energy storage solutions.

The adoption of private photovoltaic systems with HBESSs is increasing rapidly [1,2]. An alternative storage concept is the community-based DBESSs. This study evaluates different storage solutions for a planned residential community in Bergneustadt, North Rhine-Westphalia, Germany, comprising 36 single-family houses. Each house is equipped with a PV system and a wallbox for electric vehicle (EV) charging. The primary objective is to optimize the utilization of energy produced by PV systems by comparing individual HBESSs with a DBESS in terms of the grade of autarky and self-consumption.

2. State of the Art

HBESSs integrated with residential PV systems offer several benefits. They enhance the grade of self-consumption of solar energy, which potentially provides economic advantages to households [3]. When managed properly, these systems can also alleviate grid stress while maintaining high levels of self-consumption [4]. The study presented in [5] demonstrated the benefits of battery storages for a neighborhood of 22 households with various PV configurations. By implementing a storage system, the grade of autarky increased from 35 % to 75 %, and the grade of self-consumption improved from 25 % to 60 %, depending on the storage size. Various battery management strategies have been examined in [4], including fixed power limitations, charging interval timers, and strategies maximizing either self-consumption or grid benefits. A cost-optimized operational strategy for a DBESS was investigated in [6]. The authors presented a decentralized demand response framework for energy management within energy communities, focusing on a network of 50 participants, each with flexible loads, heating, ventilation, and air conditioning systems, as well as non-controllable loads. This network was connected to a shared DBESS, capable of storing energy from the public grid. The results indicate that the system effectively minimizes energy costs while adhering to grid capacity constraints and maintaining occupant comfort.

A multi-objective optimization approach for battery capacity in grid-connected PV and battery systems within a hybrid building energy-sharing community, considering the time-of-use tariff, was investigated in a recent study [7]. The authors developed a shared energy storage operation strategy aimed at maximizing PV self-consumption, minimizing the payback period, and reducing power transportation losses. They used an algorithm to optimize battery capacity across various building types, including factories, offices, and dormitories. The study revealed that the allocation of battery capacity, which continued to use individual batteries virtually aggregated into a shared system, is significantly influenced by factors such as the PV energy, the difference between peak and valley electricity prices, and grid power limits. The results demonstrated that optimizing battery capacity within this framework can effectively balance economic, technical, and environmental objectives, ultimately improving the overall performance of the energy-sharing community.

The advantages of DBESS over individual HBESS have been explored in several studies. The comparison of autarky grades between different battery concepts was conducted in [5], where the investigation showed that a common storage system offers improvements only if the storage capacity is smaller than the daily energy demand. The study presented in [8] examined the potential to increase self-consumption of PV energy in residential communities through battery storage and EV home charging. Conducted in Sweden, this research used high-resolution consumption and irradiance data to simulate various scenarios for 21 single-family houses. Unlike our work, this study did not investigate a purpose-built eco-friendly community but rather an existing one, where not all houses are equipped with PV systems due to unsuitable rooftops. Furthermore, the individual PV systems varied in configuration and, consequently, in their annual energy output. The total annual yield in the neighborhood was insufficient to meet the total annual household electricity demand, which is why autarky could not be achieved even with a large storage concept. The integration of households with EVs and battery storage systems, whether HBESS or DBESS, was not included in this system configuration. The findings indicate that the grade of self-consumption of the total generated energy could be increased from 64 % to 82 %, and the grade of autarky could be improved from 15 % to 18 %, excluding the energy needs of EVs. To determine the savings in battery capacity, a target self-consumption rate of 75 % was selected. A system with an aggregated HBESS capacity of 144 kWh combined with individual grid connection points at each household was compared to a 16 kWh DBESS with a shared grid connection. This capacity saving of 127 kWh is attributed to both the shared grid connection and the DBESS. The results for a shared grid connection in combination with HBESSs would differ from those presented in this study.

In contrast, [9] presents an economic analysis of DBESSs compared to HBESSs for an upstream network, a consortium of various microgrids consisting of approximately 1000 households in the city of Cambridge, Massachusetts, USA. The average solar adoption is 40 %. The battery storage systems are designed for each microgrid at both the household level (HBESS) and the microgrid level (DBESS) based on financial optimization. The results are then presented for the entire upstream network. The findings indicate that the financially optimal storage capacity for DBESS is 65 % of the total storage capacity required using HBESSs. Due to the network size and data availability, no consideration was given to individual household parameters, such as the grade of autarky or the grade of self-consumption. Likewise, no neighborhood-specific storage size or savings were presented.

The study in [10] examined the technical advantages of employing a DBESS over three separate HBESSs within a residential district. The study focused on three multi-family buildings comprising a total of 167 households in Ulm, Baden-Württemberg, Germany, each equipped with a PV system, heat pumps, and battery storage units. The heat pumps were preferentially powered by PV energy, either directly or via stored energy in the battery. Due to the differing orientations of the buildings and their associated PV systems, the overall efficiency and energy capture capabilities were affected. The annual energy demand exceeded the generation capacity, preventing the achievement of autarky. The findings indicate that adopting a DBESS could increase the grade of autarky from 41.1 % to 45.5 %, while PV self-consumption improves by approximately 10 %. Considering a system boundary with HBESSs at the district connection point could yield different results due to the neighborhood's use of excess PV energy.

Our focus is exclusively on the technical investigation of energy storage systems, independent of economic aspects. We consider the entire system, including PV installations, household electricity, and wallboxes, with either HBESSs or DBESS, and we account for peer-to-peer energy exchange of excess PV energy within the district across various system boundaries. Our results are presented for each household and for the entire district.

3. Materials and Methods

In the district, all houses are installed in an area network connected to the public grid. Each house is equipped with identical PV systems, oriented in a south-west direction at a slope angle of 30° with a nominal power at standard test conditions of $10\,\mathrm{kW_p}$ per building. The PV power output is calculated by simulating a $1\,\mathrm{kW_p}$ PV system with the Photovoltaic Geographical Information System (PV-GIS). PV-GIS estimates the performance of PV systems in Europe and Africa, using high-resolution satellite data to model solar radiation, validated against ground measurements. The system generates hourly power data for a simulated PV system at a specific location. The PV-GIS data has been scaled up, resulting in an annual yield of 8510 kWh and a peak power of 8.4 kW per PV system. [11]

The household electricity consumption profiles are generated using predefined households from the *LoadProfile Generator* (LPG), an application designed to create synthetic residential load profiles. It employs a desire-driven agent simulation to model the detailed behavior of residents, generating load profiles for residential energy consumption, primarily focusing on electricity. [12]

The demand for wallbox energy was quantified using the *Charge Profile Generator eMobility*. This tool utilizes the behavior of residents modeled by the LPG and simulates the use of EVs based on out-of-home activities. The simulated travel distances are based on mobility studies from Germany. Using the EV's battery state of charge (SOC), 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. [13]

The simulation with the LPG results in a neighborhood consisting of 2 to 6 individuals per building, totaling 113 residents. Each household has one EV. Through the simulation with the *Charge Profile Generator eMobility*, with 129 charging processes per year and household, it can be inferred that each vehicle is charged approximately every 2.8 days on average. The LPG also considers German holiday periods, which can be identified by reduced electricity consumption. During these times, no charging occurs at the wallboxes.

Figure 1 illustrates the annual energy consumption of each household in the district. The red bars indicate the household electricity consumption, while the green bars represent the energy consumed by the EV charging using the wallbox. The horizontal dashed lines show the average annual energy consumption. When dividing the average annual wallbox electricity consumption by the number of charging events per year, it is found that, on average, 17.7 kWh is charged per charging session.

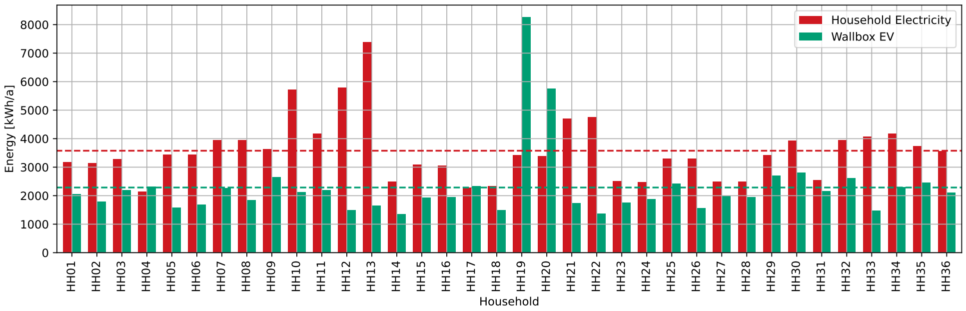

Figure 1. Annual household electricity and wallbox energy consumption for each household

The simulation framework has been implemented in Python. The program's core data are the generated load and PV time series for each individual household. The residual load is calculated from these time series to determine the energy flow and stationary battery SOC. The algorithm for managing battery use is designed to optimize self-consumption of generated PV energy. The system initially prioritizes the direct use of generated PV energy. Any surplus is then stored in the battery. Should the battery reach full capacity, the remaining PV energy is fed into the area network. In situations where the PV output is insufficient to meet demand, the system first draws energy from the battery. Once the battery is fully discharged, the required energy is sourced from the area network.

The energy produced by a household's PV system per year is defined as shown in Equation 1:

$$W_{\mathrm{pv}} = \Delta t \cdot \sum_{i=0}^{n} P_{\mathrm{pv}}(i) \tag{1}$$

where the variables are defined as follows:

- Δt: Time step duration
- i: Time step
- n: Number of time steps
- $P_{\mathrm{pv}}(i)$: PV power time series

The energy consumed by a household per year is defined as shown in Equation 2:

$$W_{\mathrm{load}} = \Delta t \cdot \sum_{i=0}^{n} (P_{\mathrm{hh}}(i) + P_{\mathrm{wb}}(i)) \tag{2}$$

where the variables are defined as follows:

- $P_{\mathrm{hh}}(i)$: Household electricity power time series
- $P_{\mathrm{wb}}(i)$: Wallbox power time series

To investigate various storage concepts, three cases are examined. The first case concerns HBESSs, with the system boundary located at each house connection point, representing individual household electricity meters. The second case involves a system boundary situated at the point of connection between the area network and the public grid, still using HBESSs. This system boundary enables the neighborhood use of PV energy, allowing neighbors to utilize excess generated energy when it is consumed directly through household electricity or a wallbox. It should be noted that the HBESS of each household can only be charged with the PV energy of the respective household since no communication with systems outside the household is considered. The third case pertains to a DBESS, with the system boundary located at the same point of connection between the area network and the public grid.

The simulation for the HBESS is conducted for each household, resulting in a time series that quantifies the power that flows into or out of the area network. The variables are defined as follows:

- $P_{\text{household},k}(i)$: Power flow for household k at time step i
- $P_{\text{household},k}(i) > 0$: Power flow to the area network
- $P_{\text{household},k}(i) < 0$: Power flow to the household

The public grid power flow is calculated by summing the individual power time series, as shown in Equation 3:

$$P_{\text{grid}}(i) = \sum_{k=1}^{j} P_{\text{household},k}(i) \tag{3}$$

where the variables are defined as follows:

- $P_{\text{grid}}(i)$: Power flow time series to / from the public grid
- k: Index of the household
- j: Total number of households

The energy fed into the grid is calculated as shown in Equation 4:

$$W_{\text{infeed}} = \Delta t \cdot \sum_{i=0}^{n} P_{\text{grid}}(i) \quad \text{for} \quad P_{\text{grid}}(i) > 0 \tag{4}$$

3.1. Grade of Autarky

The grade of autarky, denoted as g_{autark}, represents the fraction of electricity consumption that is covered by self-generated PV energy relative to the total energy consumption. The self-generated energy includes both the immediate direct use of the generated PV energy and the energy discharged from the battery storage. The formula is given by Equation 5. This ratio describes the utilized PV energy in relation to consumed energy, capped at 1.

$$g_{\text{autark}} = \min\left(\frac{W_{\text{pv}} - W_{\text{infeed}}}{W_{\text{load}}}, 1\right) \tag{5}$$

3.2. Grade of Self-Consumption

The grade of self-consumption quantifies the ratio of internally used PV energy to the total generated PV energy. This energy is utilized either directly by electrical consumers or for charging the stationary battery storage. An increased ratio of self-consumption indicates a reduction in PV energy exported to the public power grid. The formula is given by Equation 6:

$$g_{\text{self}} = \min\left(\frac{W_{\text{pv}} - W_{\text{infeed}}}{W_{\text{pv}}}, 1\right) \tag{6}$$

4. Results

4.1. Comparison of Autarky Grade Across Different Storage Sizes and Concepts

The grade of autarky is analyzed for the HBESSs and the DBESS, both with the system boundary at the connection point to the public grid, where W_{infeed} is the annual energy fed into the public grid. The results, depicted in Figure 2, show how the grade of autarky varies with the battery size.

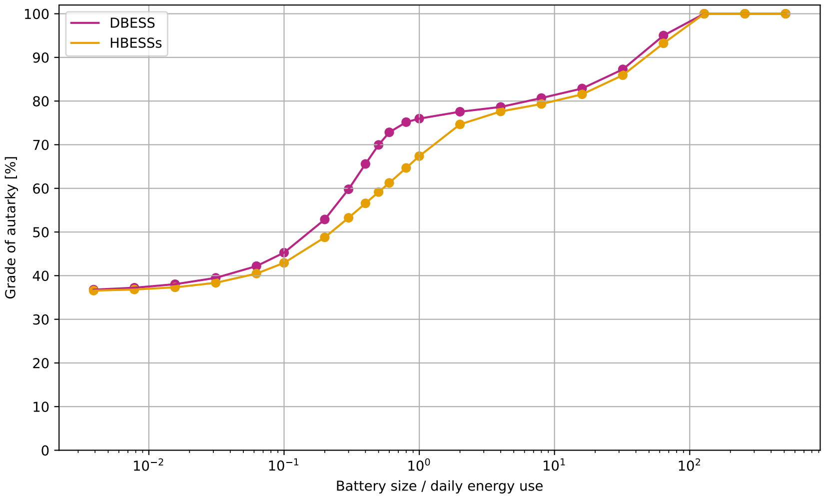

Figure 2. The grade of autarky as a function of the storage size for HBESSs (yellow) and DBESS (violet).

In Figure 2, the yellow graph represents the grade of autarky for the second case, where each household has its own HBESS in addition to the installed PV system. The violet graph represents the third case, using a DBESS. The x-axis has been normalized to represent daily storage, which is defined as the average daily consumption of the participating households. This includes both the household electricity consumption and the wallbox consumption. This axis illustrates the expansion of storage capacity from daily to seasonal or even annual storage.

Both curves emerge from the same initiation point, indicating that the initial storage size exerts minimal influence. From this common point, the separation between the two curves in terms of autarky grade increases, attaining a peak at 0.6 times the daily storage capacity. Following this peak, the curves begin to converge, adopting an almost similar path from 1.2 times the daily storage capacity onwards. The curves exhibit two notable peaks. The first peak occurs when the DBESS capacity surpasses the daily energy consumption. Notably, the first peak of the HBESS curve occurs at the same grade of autarky but with a greater storage capacity. The second peak marks the transition to a seasonal storage capacity. Between the initial value and the first peak, as well as between the first and second peaks, the graphs display fluctuations. These variations are attributed to daily and annual oscillations.

The primary advantage of the DBESS over individual HBESSs, regarding autarky and storage size reduction, stems from the reduced relative fluctuations in daily energy consumption across the community as a whole, compared to the more pronounced fluctuations observed at the individual household level. Consequently, a smaller DBESS can be installed to achieve the same grade of autarky. The storage reduction can be seen by examining the horizontal distance between the curves on the x-axis in Figure 2. At the point of maximum relative size reduction, the DBESS requires only 32 % of the HBESS's capacity to achieve a grade of autarky of 75 %. Here, a DBESS size of 0.8 times the daily storage size is required, while the HBESSs require a cumulative capacity of 2.5 times the daily storage size. In the context of the district studied, this means that to achieve this, the DBESS must be 463 kWh in size, while the combined HBESSs must be 1446 kWh.

4.2. Comparison of Autarky Grade Across Different Load Types

To investigate the impacts of load types, separate simulations were conducted. Figure 3 displays the autarky level of the network comprising solely household electricity profiles (left) and solely wallbox electricity profiles (right). In this context, the PV nominal power was adjusted according to the average annual consumption. For the simulation of the household electricity profiles, it was reduced to 60 % of its nominal power, and for the wallbox electricity profiles, it was reduced to 40 % of its nominal power. This leads to a peak production of 5.03 kW and 3.34 kW per PV system, respectively.

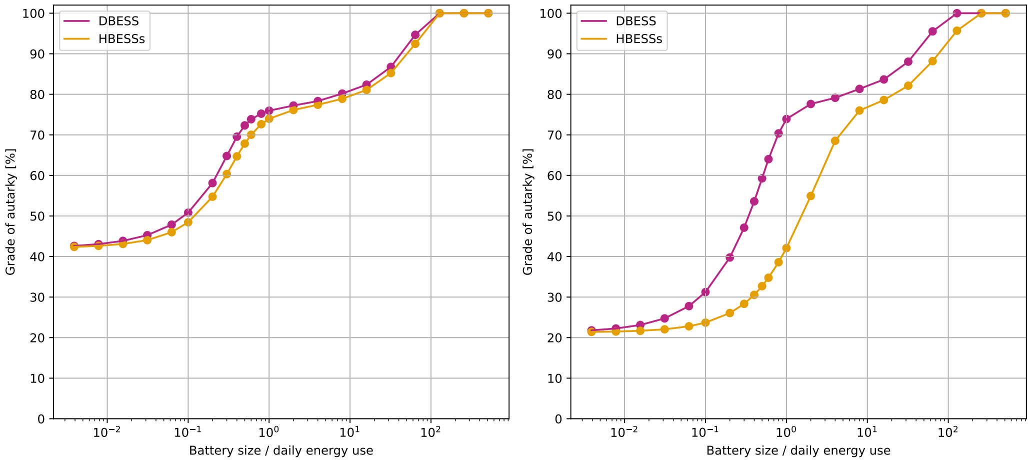

Figure 3. The grade of autarky as a function of storage size for the district, where each household has its own HBESS (yellow) and the district with one central DBESS (violet). In the left-hand panel, only household electricity profiles were simulated, and in the right-hand panel, only wallbox electricity profiles were simulated. Both simulations were performed with the public grid system boundary.

Comparing the two graphs, the initial grade of autarky significantly deviates between them. While the grade of autarky for household electricity consumption starts at approximately 42 % with a negligible storage size, the network with EV profiles begins at around 22 %. This difference is due to the fact that EVs are predominantly charged during evening and nighttime hours, periods when no PV energy is available without storage. In contrast, the load profiles of household electricity show a higher relative consumption during the day compared to the wallbox profiles.

Furthermore, it is observed that the increase in grade of autarky through the use of the DBESS is significantly pronounced for EV profiles. The uneven charging patterns of EVs contribute to this observation. Figure 4 shows the wallbox power in green and the SOC of the stationary energy storage system from June 18 at 00:00 to June 23 at 23:00. The left graph illustrates the power of the wallbox and the HBESS SOC of household HH03, where HBESS size corresponds to the daily storage size. The right graph depicts the cumulative power of all wallboxes in the district and the SOC of the DBESS, where the DBESS size corresponds to the daily storage size of the district.

Examination of the graph on the left shows that during the night of July 18 to 19, an EV charging session occurs, during which 11 kWh is charged into the EV. The HBESS, with its SOC at 100 %, can provide 6 kWh. The difference is taken from the grid. During the day on July 19, the HBESS is fully charged by PV generation. After reaching a SOC of 100 %, all of the PV energy generated, especially on June 20 and 21, is fed into the local grid, as the vehicle is not reconnected to the wallbox until the evening of June 21. The interval between the two EV charging sessions is about the same as the average of 2.8 days shown above.

In contrast, the right graph shows the cumulative profile. When the individual load profiles of the 36 households are added together, the combined load is subject to the random fluctuations of the individual loads, especially the daily fluctuations, which smooths out the stochastic fluctuations and makes the daily energy consumption much more uniform. This results in an average number of charging sessions per day of 12.75. As a result, more of the DBESS energy is discharged during the evening and night hours, allowing the PV energy

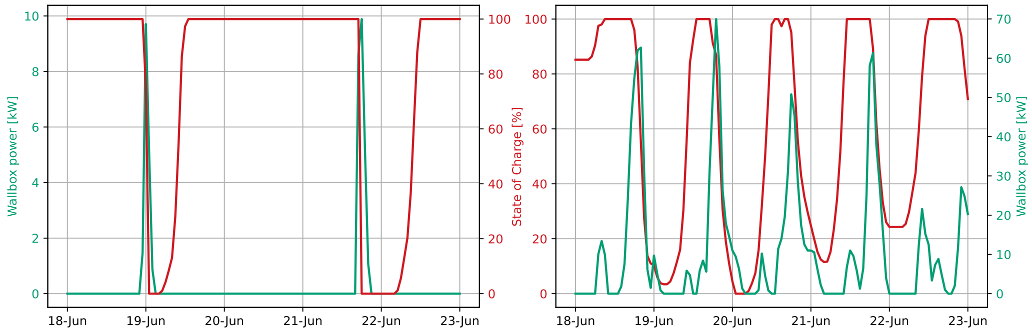

Figure 4. Comparison of wallbox power (green) and SOC (red). Left: Wallbox power and SOC of HBESS for household HH03 with a HBESS size of 6 kWh. Right: Cumulative power of all wallboxes in the district and SOC of DBESS with a size of 451 kWh.

produced the next day to be stored. This is illustrated by the pronounced amplitudes of the SOC curve of the DBESS..

In addition, the cumulative wallbox profile indicates that some EVs also charge during the day. This can be seen, for example, in the first peak of about 13 kW on June 18th in the right panel of Figure 4. Since the DBESS SOC does not drop at this time, it is clear that the cumulative PV generation is sufficient to meet the energy demand directly from PV. This results in an increase in the grade of autarky. Since the system boundary for the HBESS study was also chosen at the point of connection to the public grid, the PV energy available to each individual household is equal to the cumulative PV energy of the district if the energy is used directly by household electricity or wallbox load and does not need to be stored. Therefore, this affects the grade of autarky of both the HBESS and DBESS studies equally and does not affect the difference in the grade.

Figure 3 shows that the difference in the grade of autarky for the household electricity profiles is significantly smaller, because the daily energy demand of the household load profiles fluctuates much less. However, one influencing factor is the holiday periods. As described earlier, the load profiles include holiday periods during which very little energy is consumed. During these periods, the respective HBESS is either not used or hardly used, so that most of the PV energy of the household is fed into the local grid. By aggregating the load profiles, the impact of the vacation periods is averaged out, resulting in more optimal utilization of the DBESS and, consequently, greater utilization of the PV energy.

4.3. Autarky Grade and Self-Consumption at the Peak of Autarky Difference

Without storage, the average grade of autarky for households is 29 %, with the self-consumption rate at 20 %. Figure 5 illustrates the grade of autarky (top) and the grade of self-consumption (bottom), pinpointing the sector of maximum autarky difference, specifically at a storage size equivalent to 0.6 times the daily storage size. In both graphs, the grades for each individual household equipped with a HBESS are depicted in grey bars. Here, the system boundary is the house connection point. The mean value of the household grades is represented by the dashed grey lines. The yellow bars delineates the grades of the system outfitted with HBESSs, with system boundaries established at the connection point to the public grid. The specific value, whether autarky or self-consumption, for the DBESS is illustrated by the violet bars.

The implementation of HBESSs has facilitated a notable enhancement in the grade of autarky, elevating it by 32 % and raising the grade of self-consumption by an average of 21 %. The top graph illustrates that the grade of autarky associated with DBESS exceeds that of any individual solution, whereas the grade of self-consumption for five of the 36 households is greater than that of the DBESS. The discrepancy between the household average and the yellow bar is 1.5 % for the autarky and 1.0 % for the self-consumption, which can be attributed to differences in system boundaries. The grades calculated from

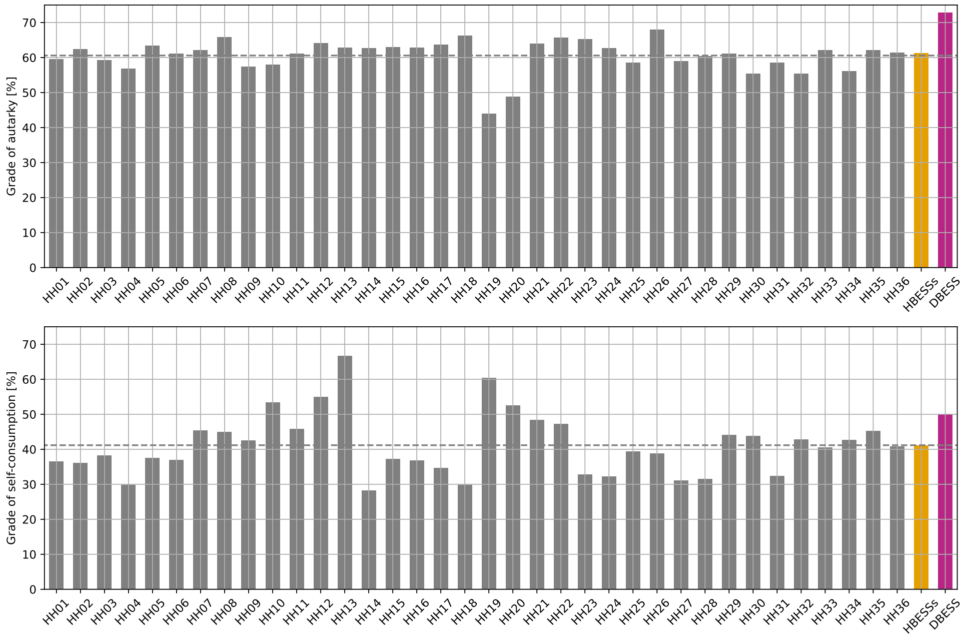

Figure 5. Grade of autarky (top) and grade of self-consumption (bottom) for each individual household with HBESS (grey bars), the district with HBESSs (yellow bar), and the DBESS (violet bar) with a storage size equivalent to 0.6 times the daily storage size.

the average household energy balance fail to consider the potential for neighborhood utilization of surplus PV-generated energy. When comparing the district-level autarky and self-consumption rates achieved with HBESSs versus the DBESS, it becomes evident that the grade of autarky increased by 11.6 % and the grade of self-consumption by 8.0 %.

An analysis of the top diagram in Figure 5 shows that the autarky grades of HH19 and HH20 deviate significantly from the average. Closer examination of the annual electricity demand, as depicted in Figure 1, reveals that these households have the highest total demand, including the highest wallbox electricity demand. In contrast, HH13 has a similar total energy consumption to HH20, but with a significantly smaller proportion attributed to wallboxes. Due to the charging behavior, a larger portion of the total demand for HH19 and HH20 occurs during the evening and nighttime hours. Consequently, the baseline grade of autarky in systems lacking a battery is considerably lower in the EV simulation, necessitating a larger battery storage capacity to cover this demand with PV energy. The comparison with the lower graph in Figure 5 reveals that the self-consumption rates of these three households are above average. Despite the overall load profile, these households can self-consume a substantial portion of their PV energy, even though the PV systems are not sized relative to the total energy demand. This indicates that the HBESS in HH19 and HH20 is capable of storing PV energy at least partially and providing it during the evening hours.

When comparing the increase in autarky between the individual households and the DBESS concept, it is clear that HH19 and HH20 would benefit the most from a community-based energy balancing approach. Although they already self-consume a large portion of their PV energy and thus contribute less excess energy to the community, their autarky grades would still increase by approximately 29 % and 24 %, respectively.

5. Discussion

The findings of this study demonstrate a significant advantage of using a DBESS over individual HBESSs in terms of increasing the grade of autarky and self-consumption within a residential community. The results highlight the benefits of managing energy storage at a community level, where the aggregated load profile can effectively smooth out fluctuations in individual household consumption. A key observation is the substantial reduction in required storage capacity for a DBESS compared to the cumulative capacity needed for HBESSs to achieve the same grade of autarky. This reduction is particularly significant for daily storage needs, though it diminishes for seasonal storage requirements. This observation aligns with previous studies that have emphasized the efficiency of centralized storage systems in reducing overall storage capacity.

The simulation further revealed the varying impacts of different load types on the effectiveness of energy utilization. Household electricity profiles, which typically exhibit more evenly distributed daily consumption patterns, showed less improvement in the grade of autarky with a DBESS compared to EV charging profiles. The latter, characterized by more irregular and evening-peaking loads, benefited more significantly from a centralized storage approach. This suggests that the type of load profile within a community is crucial in determining the optimal energy storage strategy. Moreover, the advantage of DBESSs over HBESSs is likely to increase with the inclusion of even more irregular load profiles, particularly those with high variance in daily energy demand. The ability of DBESSs to aggregate and balance these irregularities across multiple households enhances its effectiveness compared to individual HBESSs.

The impact of uncertainty, particularly in user behavior, can significantly affect the validity of the results. Changes in user behavior, such as shifting regular routines within a day, can alter the energy demand profile and, consequently, the required storage capacity. For instance, rescheduling energy-intensive activities to periods when PV energy is abundantly available could reduce the need for storage. A critical factor in this context is the charging behavior of users at EV wallboxes. If users adopt a more uniform charging pattern, such as charging their vehicles daily rather than irregularly, the comparative advantage of the DBESS over individual HBESSs will diminish.

A critical consideration for the scalability of these findings to other regions is the exclusion of heating and cooling demands in the household electricity profiles. In regions with significant reliance on electric heating or cooling, the additional energy demands could substantially alter the outcomes. The inclusion of electrically supported heating systems, for instance, is likely to cause greater distortions in the results, as these demands typically occur during periods of low PV generation. The associated increased storage requirements would particularly affect the results concerning seasonal storage. Another influential factor is the location-specific PV generation profile. While Germany experiences a moderate annual solar yield, significantly more PV energy can be generated in southern regions. A key factor is the variability of monthly solar production, which influences the extent to which the integration of storage systems can increase the grade of autarky. In regions with lower variance, typically found in southern latitudes, autarky levels are likely to shift significantly. The more consistent solar irradiance throughout the season in these regions enables higher autarky levels to be achieved with smaller storage capacities, particularly for storage systems exceeding daily storage needs. Conversely, in northern regions, autarky levels would correspondingly decrease.

Further research is required to address the regulatory constraints associated with the operation of DBESSs. There are country-specific differences regarding the conditions under which fees and charges apply to such systems, and these regulations significantly impact the economic viability of DBESS projects. The extent to which the benefits achieved at the district level can be distributed to individually metered households largely depends on the billing framework. This framework must be developed with careful consideration of technical, social, economic, and legal factors. Another critical issue is the ownership and operational model of a DBESS. The typically high investment costs associated with DBESSs can pose challenges for implementation within a neighborhood. One potential solution is for energy providers to purchase and operate these storage systems, subsequently selling the locally generated electricity back to the residents. This approach could facilitate the deployment of DBESS by mitigating the financial burden on individual households and ensuring professional management of the energy storage system.

In summary, the DBESS consistently outperforms the HBESS across all investigated scenarios and parameters. The enhanced grade of autarky and self-consumption observed with the DBESS are attributable to the system's ability to efficiently manage surplus PV energy during peak production times and redistribute it during periods of high energy demand. The findings suggest that, for communities, a centralized storage system can provide substantial benefits.

6. Conclusion

The main conclusions of this study can be summarized as follows:

(i) The grade of autarky and self-consumption of PV systems installed in a planned residential community of single-family houses can be significantly improved when using a community-based DBESS instead of individual HBESS. (ii) The required battery storage capacity can be substantially reduced when using a DBESS compared to the cumulative capacity of individual HBESSs to achieve similar grades of autarky and self-consumption. Specifically, the DBESS can achieve the same grade of autarky with only 32 % of the storage capacity needed by individual HBESSs. (iii) The improvement in autarky is particularly pronounced for EV wallbox charging profiles due to the irregular and evening-peaking nature of the load, which benefits more from centralized storage solutions. (iv) The DBESS shows a maximum increase in the grade of autarky by up to 11.6 % and in the grade of self-consumption by 8.0 % compared to individual HBESSs, demonstrating the efficiency gains from community-level energy management.

Acknowledgments

We would like to express our gratitude to the *Deutsche Bundesstiftung Umwelt* for the realization of this work through the funding of the project *Quartierspeicher für eine Klimaschutzsiedlung*.

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