Community battery storage dimensioning and scalability analysis with rule-based energy flow simulations

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Abstract:

Energy communities (EC) exhibit a high share of decentralized local energy generation based on renewable energy sources (RES) which in general do not chronologically fit the local energy demand. Flexibilities are needed to match the time series of demand and generation inside a community to allow an efficient operation and thus, to increase the self-consumption of a community. This work addresses this issue by using central electrical community storage. The focus is on determining a proper storage capacity according to the community setup through incorporating technical and economic related aspects. Energy related key performance indicators KPIs are used to investigate the scalability of such a community storage. Results are based on annual rule-based energy flow simulations with different sizes of storage capacity. Based on the defined KPIs a saturation in storage size can be determined to support community planning purposes. The shown work is done in course of the research project CLUE.

Keywords: Storage, Dimensioning, Community, Simulation, Scalability

1 Introduction

A couple of interconnected phenomena and trends promote the need for EC. The main driver is the ongoing accelerated climate change and corresponding need in decarbonizing the energy system through opting out of using fossil fuels and increasing the utilization of renewable energy sources. In power systems, photovoltaic, wind and hydro power plants represent the most promising sources for a sustainable energy system. Since especially photovoltaics enable small grid parties (e.g., a single-family house) to act as power plants, decentralization of the energy system takes place. The mentioned aspects lead to a reduced energy generation on high voltage levels with previously centralized big fossil driven power plants to an increased energy generation on low voltage levels with upcoming decentralized renewable energy sources. Since RES are highly dependent on weather conditions and hence cannot be utilized at any time compared to fossil-driven power plants, the demand must be matched somehow to the generation. This can be achieved with different flexibility mechanisms, e.g. using a storage to bypass the mismatch of generation and consumption times. The motivation is to maximize the local energy utilization and to exchange as little energy as possible with the upper level grid to avoid transmission losses and further ensure an efficient energy system. Due to the digitalization of the energy system, e.g. through a regulated smart meter rollout and better observability of the so far mostly unknown low voltage grid, techniques and automation processes that are already applied in the high voltage grid can also be applied to the low voltage grid. This is important, since the exchange between all stakeholders and for e.g. central storage inside an energy community must be measured and monitored to allow the clearing and balancing of the exchanged energy. Energy communities and their chance to meet a higher energy autarky need to be analyzed in detail. This work shows an approach to properly scale a community storage, which allows flexibility to meet electric generation and demand. The approach is applied on a specific energy community located in Gasen, Styria, Austria which represents a demo site of the project CLUE[1] in which a community storage is going to be installed based on the results of this work. Results are drawn out of annual energy flow simulations, where time series profiles are applied on all stakeholders, e.g. consumption loads or photovoltaic generation profiles. The physical (as well as virtual) energy flows within the community underlie a rule-based approach. The setup of simulations and the energy community under scope are described in Section 2. and 3. shows the simulations results and derived (KPIs). A conclusion about the results and the new topic energy communities is formulated in Section 4.

2 Methodology

This section describes the used community setting and simulation setup. The underlying electric grid is not considered in this work, which means that there is no limitation by exceeding voltage or loading values of physical components. Ideal storage without losses and ramp limitations is assumed. All mentioned energy and power values represent the energy form, electricity. The analysis is based on pure energetic observations.

2.1 Community setup

The considered energy community EC is located in Gasen, Styria, Austria and exhibits a high share of local photovoltaic energy generation (157 MWh/a) compared to the total consumption (160 MWh/a). Table 1 shows the electric loads inside the EC in more detail, where E1 represents photovoltaic systems, ULA and ULF interruptible loads and the rest commonly known loads (e.g., H0 for a standard house hold). All photovoltaic systems are modelled as surplus feed-in and not full feed-in power plants. Participants of the investigated EC are topologically located under the same transformer substation and hence located in the same geographical area.

Load type	Number	Contractual kW(p)	kWh/a
ULA	2	31	8 832
E1	9	181.83	160 505
H0	2	12	9 706
B1	1	6.1	14 027
G0	5	58.3	96 509
L0	1	11	5 685
ULF	1	0	10 174
G3	2	12.3	8 637

[1] https://project-clue.eu/

G1	1	7.7	3 812

Table 1: Number, annual energy and contracted power of load types inside the local energy community

All consumption and generation loads are modelled via annual time series with 15-minute intervals. For the photovoltaic systems, one local representative profile is used and scaled for all power plants, assuming that all panels/customers have the same irradiation/weather conditions. Load types of ULA and ULF are modelled via the APCS standard load profiles [1]. All other load types are modelled through using the Simbench data set [2], which also provides more sophisticated annual load profiles for a variety of load types. Profiles are scaled according to Table 1. Figure 1 shows the residual day time statistics of all generated community participants profiles. Negative values imply generation surplus of a participant. Both positive and negative values can occur for prosumers over the whole year. The black line represents the mean, orange space the 25-75 percentile and red space the 0-25 and 75-100 percentile of values. The 0 and 100 percentiles hence are the occurring maxima and minima during a year.

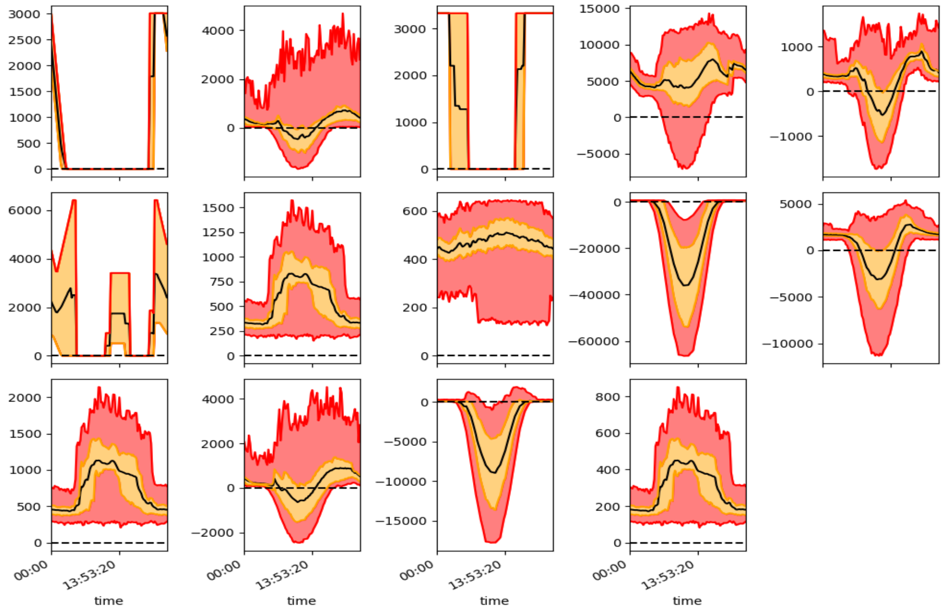


Figure 1: Day time statistics of community participants in W

2.2 Rule-based simulation approach

Annual energy flow simulations in 15-minute intervals are executed for different scenarios and storage sizes to generate results which are further used to investigate the scalability. A predefined set of rules is applied in the simulations for the virtual energy flows. These rules define which order functions are executed in terms of priority. The functions affect the energy allocation during the energy flow simulations and mainly define the possible interaction between prosumers, public grid and the central storage (see Figure 2). The functions are:

- “P2P” (P2P trading): Calculates the energy traded between Prosumer A and Prosumer B
- “Bat2P” (Battery exchange): Calculates the energy exchanged with Prosumer A and the battery

- "Grid2P" (Grid exchange): Calculates the exchanged energy between Prosumer A and the external grid
- "FB2Grid" and "FB2P" (Battery discharge strategy): Calculates the energy flows based on the discharge strategy of the battery

The most relevant part for the battery dimensioning is the implemented *"discharge strategy"* algorithm of the central storage, which is defined as follows:

1. If a prosumer charges the battery, the energy is reserved and can be reused by the same prosumer for 14 hours.
2. If the energy is not used within 14 hours, it is offered to other prosumers for another 22 hours.
3. If the energy is not used within these 36 hours from anyone in step 1 or 2, the remaining energy is sold to the energy retailer via the public grid.

This discharge strategy supports an optimal utilization since the state of charge of the battery does not stagnate at full-charge state caused by "over-feed-in" and motivates the community members to use the energy for better prices in a 36-hour time window.

Peer-to-peer (P2P) trading is also included in this analysis to directly use the surplus of prosumers for other participants who need the energy simultaneously.

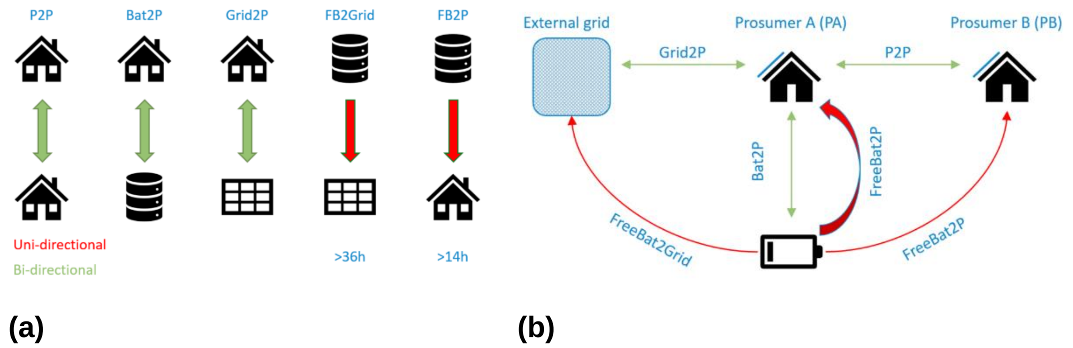


Figure 2: (a) Individual possible energy flows inside the community
(b) Interconnection of defined rules and participants

After executing energy flow simulations, tariffs are applied to the resulting energy flows to get detailed cash flows for the subsequent economic analysis. This analysis provides information about potential total cost savings per year compared to a basic scenario (see Section 2.3). Table 2 shows the chosen tariffs for the economic analysis. Three numbers in one cell represent stacked tariffs with 1000 kWh/a steps. Figure 3 shows how the cash flows are calculated based on the energy components.

From --> To (view of customer A)	1. Energy price in c/kWh	2. Grid use fee in c/kWh	3. Grid loss fee in c/kWh	4. VAT in %	5. Electricity delivery fee in c/kWh	6. Green electricity fee in c/kWh	7. Biomass contribution in c/kWh	Total costs / returns in c/kWh
Self-consumption (PA --> PA)	-	-	-	-	-	-	-	Through reduced grid delivery

P2P delivery (PA --> PB)	7.3	-	-	20	-	-	-	8.76
P2P consumption (PB --> PA)	7.3	1.968	0.126	20	0	0	0.066	11.352
Battery charging (PA --> Bat)	indirect through loss fee	0.21	0	20	0	0	0.066	0.3312
Battery discharging (Bat --> PA)	indirect through loss fee	1.968	0.126	20	0	0	0.066	2.592
Grid feed-in (PA --> Grid)	6.02, 3.33, 3.3	-	-	20	-	-	-	7.224, 3.996, 3.96
Grid delivery (Grid --> PA)	7.3	4.92	0.315	20	1.5	1.175	0.066	18.331

Table 2: Used tariffs applied on energy components

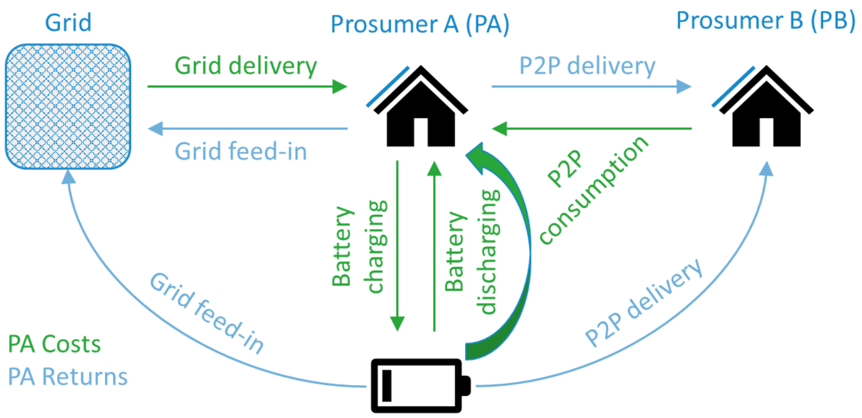


Figure 3: Mapping of tariffs to energy components

In a final step, the cash flow analysis of a community is done as follows:

1. Calculate community gains:

$$Gains = \sum_{P} (BatA2PB_P + PA2Grid_P + PA2PB_P + BatA2Grid_P) \tag{1}$$

   where P is one prosumer.

2. Calculate community costs:

$$Costs = \sum_{P} (\mathrm{Grid2PA}_P + \mathrm{PB2PA}_P + \mathrm{PA2BatA}_P + \mathrm{BatA2PA}_P + \mathrm{BatB2PA}_P) \tag{2}$$

   where P is one prosumer.

3. Calculate resulting gain-cost sum:

$$Gain\_Cost\_Sum = |Gains| - |Costs| \tag{3}$$

4. Compare scenarios with basic scenario

where PA is Prosumer A, PB is Prosumer B, $BatA$ is the charged energy by Prosumer A, $BatB$ is the charged energy by Prosumer B, $Grid$ is the external grid and “2” represents the energy direction (from – to). E.g. $PA2PB$ means that energy flows from Prosumer A to Prosumer B.

2.3 Scenarios

Four different scenarios are investigated and compared among each other:

1. Basic scenario: The entire demand of the community is covered through the external grid only, no P2P trading within the community, no battery storage utilization.
2. P2P trading scenario: P2P trading (within the community) is done primarily.
3. Storage scenario: Self coverage is done primarily, no P2P trading.
4. Storage utilization scenario with P2P trading: Self coverage is done primarily followed by P2P trading.

In all scenarios, the external grid covers the remaining energy demand of the community customers. The annual energy flow simulations with a 15-minute time resolution are executed for each scenario with following different storage sizes: 50, 100, 150, 200, 300 and 400 kWh.

2.4 KPIs

Since the main target is to determine a proper storage size for a given energy community, suitable KPIs must be defined with focus on the battery utilization and energy exchange with the external grid. Following KPIs are evaluated based on the simulation results:

- Battery charging and discharging patterns in kWh.
- External grid exchange patterns in kWh.
- P2P traded energy in kWh.
- Total annual returns in €.

3 Results

The impact of the storage size on the energy flows is analyzed in a first step. Resulting cash flows after applying the tariffs are shown in a second step. All presented values relate to the total community and not to individual participants. Notations “A” and “B” for prosumers and battery should clarify the contributions, since energy can go different ways with the the given setup.

3.1 Energy related results

Before discussing the results in detail, it must be mentioned that the four considered scenarios sometimes overlap for a couple of shown KPIs. Therefore, sometimes only 2 instead of 4 lines are visible in the figures.

Fehler! Verweisquelle konnte nicht gefunden werden. Figure 4 shows the battery related KPIs derived from the annual energy flow simulations:

Subplots (a), (b) and (c) depict how the battery is charged and discharged by community participants. All three graphs show a nonlinear behavior and increasing saturation with increasing storage size. A change point from linearity to non-linearity is visible at about 150 kWh. When comparing (a) and (b), it is noticeable that much more energy (factor of approx.

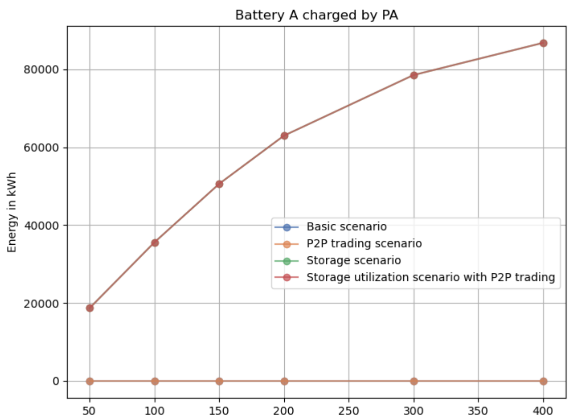
10) is charged from a prosumer than discharged from the same prosumer. (c) shows that the energy can still be used by other participants after 14 hours of a surplus situation.

Subplot (d) describes the released unused energy out of the battery absorbed through the external grid, forced by the implemented discharge algorithm. Up to a size of 200 kWh, all generated energy inside the community can also be used throughout the whole year in a 36-hour storage operation window. Increasing the size further results in a non-linear increase of released energy.

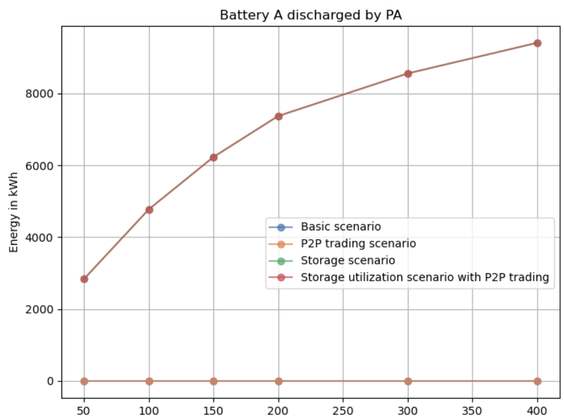
Subplot (d) shows how many times the external grid operates in idle mode, meaning no energy is exchanged with the community during a year. 35 040 15-minute intervals represent one year.

Subplots (e) and (f) show the occurred annual storage charging and discharging power peak. Compared to the steadily increasing charging peak, which ends up in saturation at about 250 kWh, the discharging peak significantly increases starting at 200 kWh. This is due to the implemented discharge strategy. This situation can be interpreted as an energy buffer that is not needed at all in the 36 hours operation time window which signals an over-dimensioned storage size.

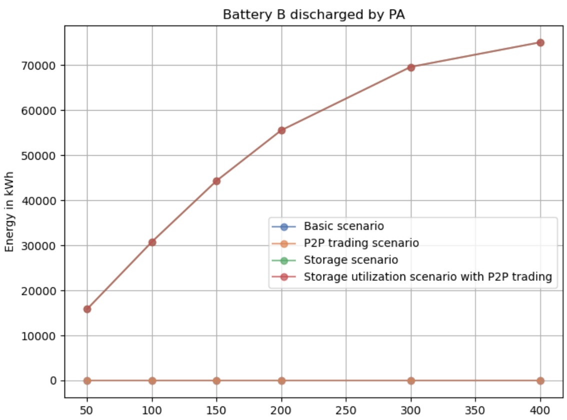
Subplot (g) shows the duration with full or empty storage. Under-dimensioned storage with e.g. 50 kWh is fully loaded in the given community most of the time and not suitable with the chosen operation time windows. An over-dimensioned instead leads to a worse utilization of the capacity and e.g. operates in the upper band in summer for most of the time without using the lower State-of-Charge (SoC) band.



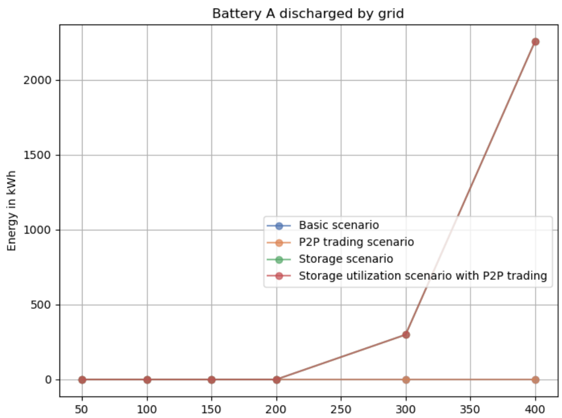
(a)



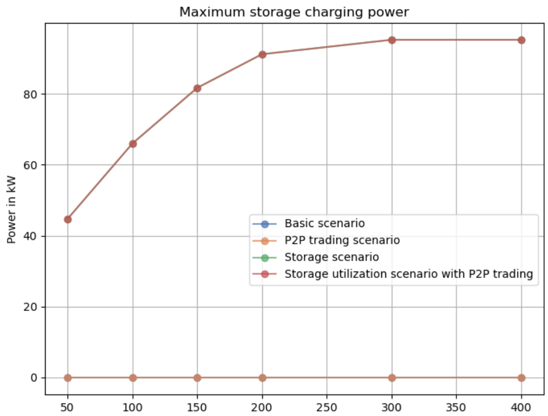
(b)



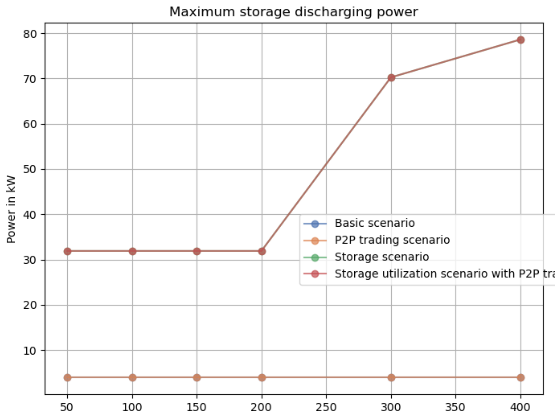
(c)



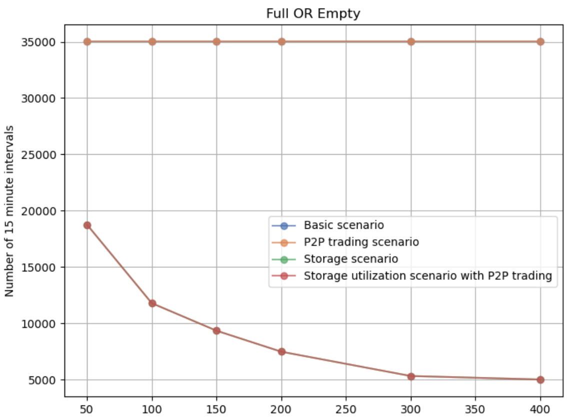
(d)



(e)



(f)



(g)

Figure 4: Battery related KPIs:
(a) Battery A charged by Prosumer A
(b) Battery A discharged by Prosumer A
(c) Battery B discharged by Prosumer A
(d) Battery A discharged by external grid
(e) Maximum occurred charging power

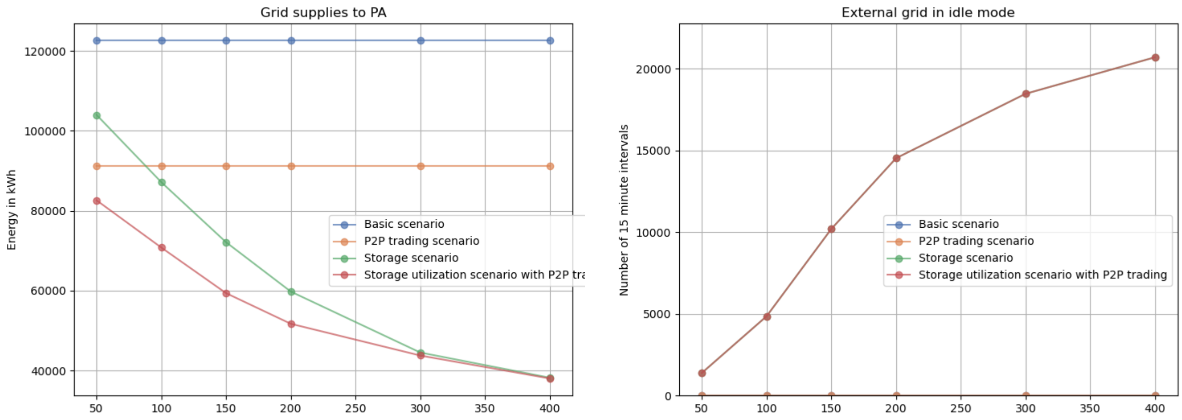
(f) Maximum occurred discharging power
(g) Times when storage is completely full or empty

Figure 5 illustrates the grid related KPIs derived from the annual energy flow simulations:

Subplot (a) shows the amount of energy covered through the external grid. With a storage size of 400 kWh the provided energy through the external grid could be reduced by about 68 %.

Subplot (b) shows that the external grid would be operated in idle mode at 60 % of the year when using a storage size of 400 kWh. This is the only KPI which provides a turning point fitting to a well dimensioned storage size.

Simulation results also show that the external grid delivery peak (~108 kW) and surplus absorption peak (~33 kW) stay the same during the year for all scenarios without any additional control to reduce the peak.



(a) (b)

Figure 5: Grid related KPIs:
(a) Energy supplied from grid to the community
(b) Times when grid is in idle mode

Figure 6 shows the traded energy between participants within the community. At a storage size of 300 kWh, the secondary priory P2P trading does not scale linear anymore because there is no more need inside the community to exchange surplus energy in a 36-hour time window. The larger the storage is, the less energy is contributed through the P2P trading mechanism since its priority is secondary after the primary storage utilization.

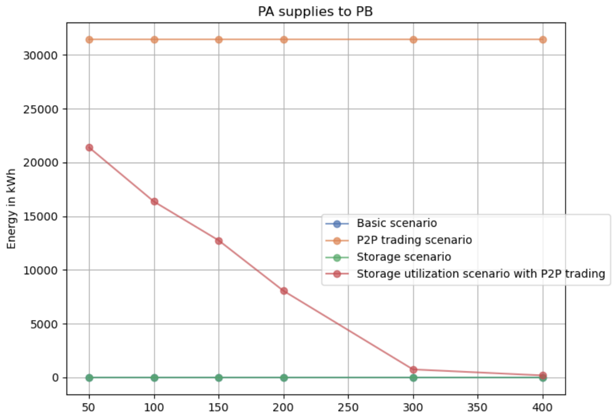
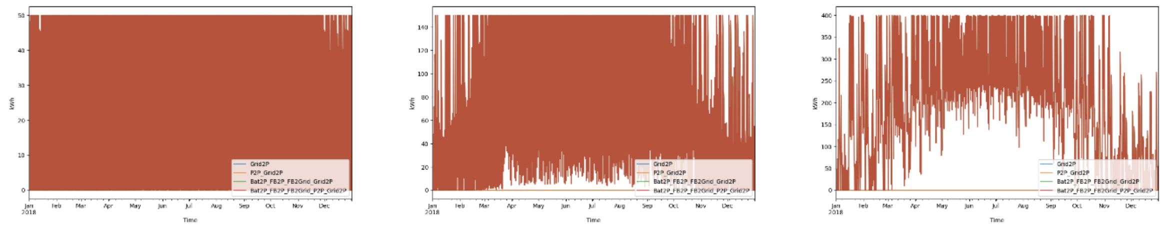


Figure 6: Exchanged energy between community participants via P2P trading

Figure 7 shows the annual SOC for three different storage sizes. In terms of a under-dimensioned storage (a), the battery is operated on the lower and upper SOC limit most of the time. An over-dimensioned storage (c) does not make efficient use of the total SOC band for different seasons. In case of a proper dimensioned storage (b), the SOC band is utilized equally over the whole year. This comparison stresses the need to take all seasons into accounts since consumption and generation follow a seasonal pattern.



(a) (b) (c)

Figure 7: Annual SOC characteristic for 50 kWh (a), 150 kWh (b) and 400 kWh (c)

The depicted KPIs show a saturation or change point at 150 kWh, which can be interpreted as the optimal size for this community and storage operation setup.

3.2 Economic results

Figure 8 shows the result of the cash flow analysis with the applied tariffs on the resulting energy flows. The value on the y axes represents the savings of the respective scenario compared to the basic scenario. A saturation at about 150 kWh can be identified.

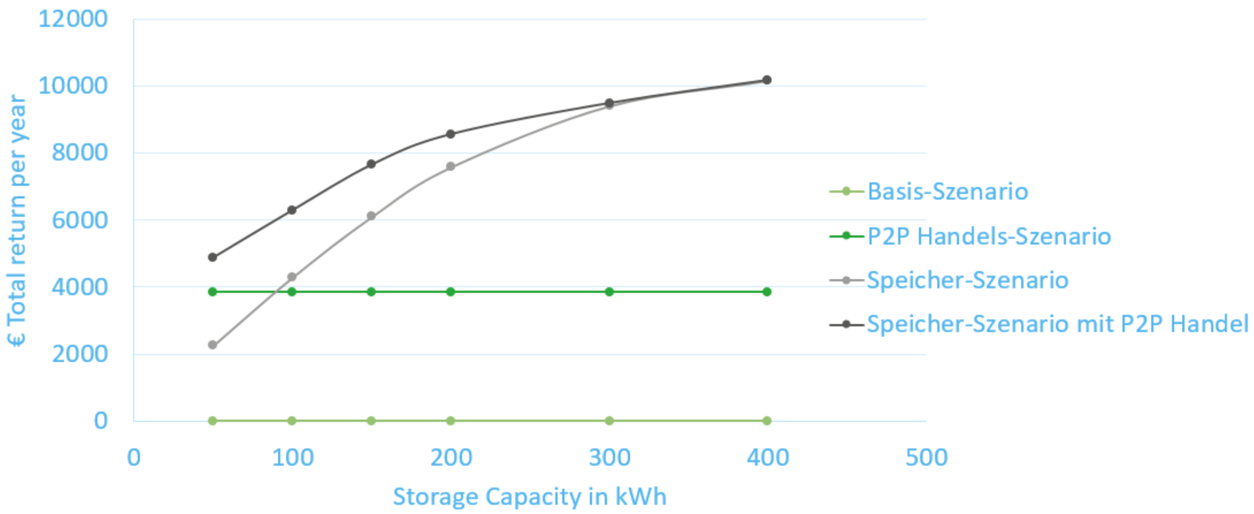


Figure 8: Cash flow analysis

With increasing storage size, the secondary P2P mechanism becomes more and more obsolete. With smaller storage sizes, the combination of both mechanisms could be beneficial. An over-dimensioned storage leads to under-utilization of the P2P trading mechanism. The point of intersection between the P2P trading scenario and the storage scenario marks the limit when a storage becomes more economic compared to P2P trading. Investment costs are not considered in this work.

4 Discussion and conclusions

Dependent on the community setup, it is meaningful to do a pre-analysis based on the shown approach to allow efficient planning of flexibility utilization in an energy community. Investors can specify the planned rules and time frames in which the planned storage should be utilized. The results clearly show a saturation in storage size for the given community. The KPIs in the given example show the best economic utilization when using a storage with about 150 kWh. Every additional kWh would result in a worse utilization of the storage capacity. The P2P trading analysis provides meaningful insights about the community, e.g. how much locally generated energy could be utilized simultaneously.

More studies of different communities about different kinds of community setups must be done, since for some communities' storage solutions make more sense compared to P2P trading solutions and vice versa. Different community setups include varying compositions of consumption and generation types with individual times characteristics. The communities in this work e.g. only consider photovoltaic-based generation and mainly residual consumption loads.

The used discharge strategy might be difficult to implement in the real field but provides relevant information about a suitable storage size in simulations for planning purposes and potentials about the self-coverage capability of a community. Blockchain technology could be one potential technology for implementation, providing transparent, non-erasable, and unforgeable documentation of (energy/financial) transactions. [3]

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