Rule-based energy simulation studies on different energy community compositions

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Abstract:

It is an ongoing open question if and how energy communities are going to play an important role in our future energy system. Besides ongoing regulatory processes and discussions there is a need to investigate how Renewable Energy Communities (RECs) can and should be operated in an energy and economy efficient way. Another need is to figure out, in what cases the concept of energy communities can be applied on a group of participants since it represents a composition of consumers, generators and prosumers. This work addresses these questions by comparing results of simulative energy flow studies between different compositions of such energy communities. The shown work represents an extension of [1] as part of the research project Blockchain Grid.

Keywords: Energy, Community, Simulation, Peer-to-Peer trading, self-consumption optimization

1 Introduction

A combination of trends like decarbonization, decentralization and digitalization of the energy system promote the concept of more locally operated energy communities (see [2] and [3]). Small prosumers with own generation units such as photovoltaics also have the possibility to act as a power plant and want to operate their system as efficient and sell their energy as economic as possible. Another aspect is the principle of local generation and consumption: Energy communities aim to consume local generated energy as much as possible – either to due environmental aspects or due to potential cost savings. Energy communities allow to sell energy target-oriented to other consumers. Reduced energy costs inside a community motivate prosumers to form groups with other potential participants. The temporal generation and consumption behavior hence play an important role if two individuals are a good match for such a community or not. So far, there is a lack of planning tools and frameworks to investigate such a composition of energy communities. This work presents a methodology how to do so, also including mechanisms like peer-to-peer (P2P) trading or a central community energy storage to increase the self-consumption of the entire community (and/or its participants).

The framework itself, examined energy community settings as well as the validation scenarios are explained in Section 2. Section 3 deals with the results, generated out of annual simulative studies. The results mainly relate to energy flows but also include an economic cash flow analysis. Section 4 provides a discussion and conclusion of the presented work.

2 Methodology

The entity energy community in this work is defined through the participating consumers, generators and prosumers, a central community energy storage, an external grid and a set of rules for possible virtual energy flows between all mentioned object types. Figure 1 shows the defined rules for these energy flows and the interconnections of participants where “P” are peers like consumers, generators and prosumers, “G” is the external grid which covers the residual load, “B” is the central community storage and “FB” is a specific function which represents the discharge strategy of the community storage. Summarized, the community can manipulate the virtual energy flows by doing the common exchange with the external grid, P2P trading amongst participants and interactions with the central storage, the physical energy flows are affected only but the battery utilization. The performed simulative study is done with a rule-based approach. This means that the depicted five community mechanisms (see Figure 1 (a)) could be executed in any order, resulting in 32 combinations. For this study, the eleven most relevant combinations are examined. In some cases, the number is further reduced to the four most important scenarios for the sake of clarity. Each combination is used as setting parameter for an annual simulation run with a 15 minutes time resolution. The resulting energy flows with different settings are compared afterwards. Besides the energy analysis an economic analysis is also done by applying defined prices, tariffs, and taxes on the virtual energy flows. The simulative study is done for two different energy communities which vary in their compositions of participants. An overview of both settings is shown in Table 1. Setting I is based on the demonstration site in Heimschuh, Styria, Austria with twelve pilot customers from the funded research project Blockchain Grid[1,2], Setting II represents a bigger community of 120 participants.

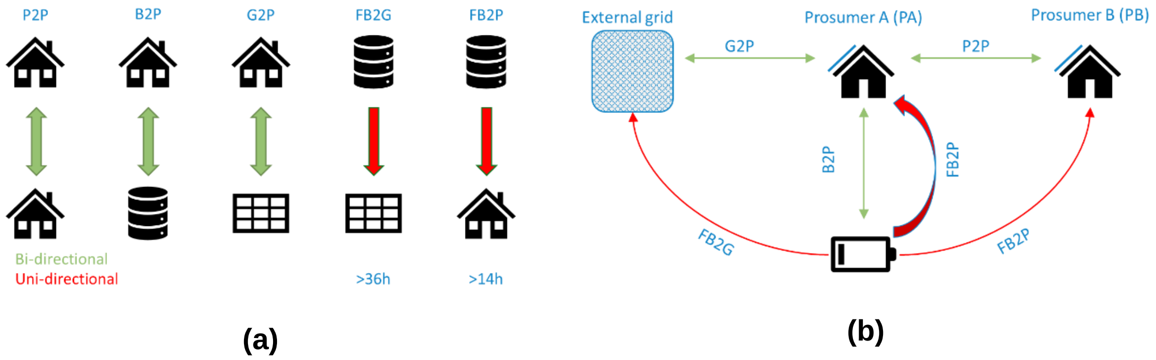


Figure 1: (a) Individual possible energy flows inside the community (b) Interconnection of defined rules and participants

[1] https://greenenergylab.at/projects/blockchain-grid/

[2] https://projekte.ffg.at/projekt/3089755

	Setting I	**Setting II**
Number of customers	12	120
Number of consumption objects	12	125
Total annual consumption	184.954 kWh	960.638 kWh
Number of generation objects (PV)	9	20
Total annual generation	57.777 kWh	124.263 kWh
Storage capacity	100 kWh	100 kWh
Battery reservation time	14 hours	14 hours
Battery release time	36 hours	36 hours
Simulation duration	365 days	365 days
Time resolution	15 minutes	15 minutes

Table 1: Overview of investigated community settings

Figure 2 gives an overview of the twelve customers of Setting I. Each plot represents the average daily profile in Watt (black line), the 25-75 % quantile (yellow), and the 0-25 % and 75-100 % quantiles (red). Positive values indicate demand, negative values indicate surplus. As already stated in Table 1, nine out of the twelve customers have their own PV production which can also be observed in the figure. An overview of the power profiles of the large Setting II with 120 customers is shown in Figure 2. The small community represents a subset of the large community. Profiles are generated out of [4] [5] and [6].

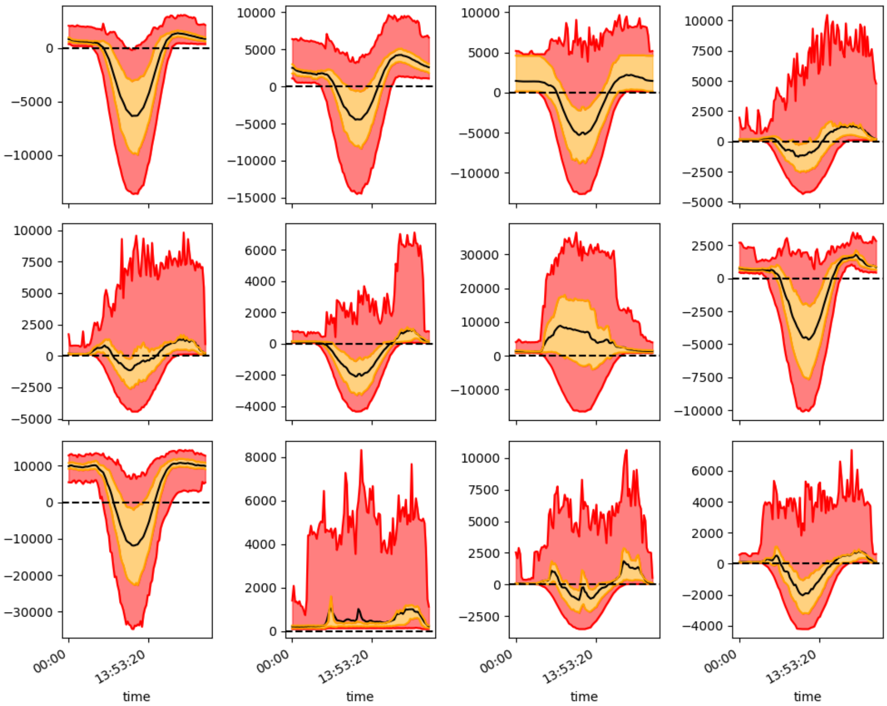


Figure 2: Overview of 12 customers from Setting I

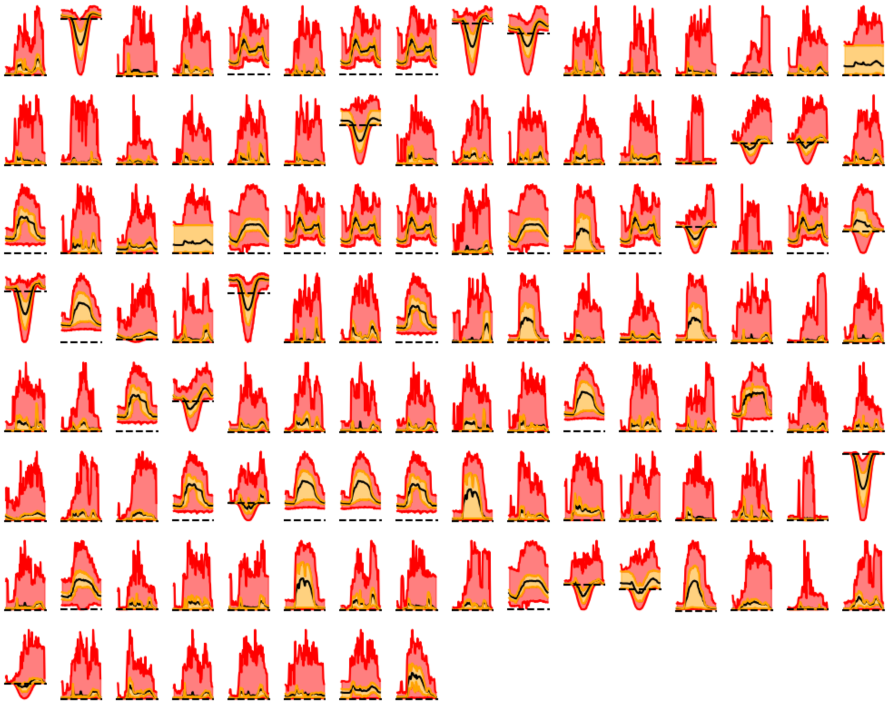


Figure 3: Overview of 120 customers from Setting II

The previously mentioned implemented mechanisms (see Figure 1) explained more concrete are:

- *G2P*: This function covers the remaining residuals through the external grid.
- *P2P*: Simultaneous surplus of prosumers or generators is matched with demand of prosumers or consumers. A system of equations hence is generated and solved for each simulation time step. The contribution to cover demand is done in a relative manner. E.g. if there is demand of D = 10 kW and two generators have a surplus of G1 = 8 kW and *G2* = 12 kW, the solved equation system results in G1 = 4 kW and G2 = 6 kW to match the needed demand.
- *B2P*: A function to manage the prosumer-storage interaction. Like the P2P trading, an equation system needs to be generated and solved for each time step to no exceed the state of charge (SoC) of the central storage. The contribution, how much a prosumer can charge or discharge, is likewise done in a relative manner.
- *FB2P*: This function represents the first part of the storage discharge strategy to avoid stagnation. If a prosumer charges the battery, the energy is reserved and can be reused by the same prosumer for 14 hours. If the energy is not used after the time window, it is offered to other prosumers in the community and the function becomes active for another 22 hours.
- *FB2G*: If the charged energy is not used after 36 hours, the function becomes active and releases the energy which is absorbed by the external grid.

All mechanisms can be executed in any preferred order. The considered eleven scenarios namely are:

- *G2P* (also named as "*Basic*"): Represents the as-it-is / basic scenario, when the grid covers the total energy demand.

- *P2P_G2P* (also named as “*P2P*”): Only primary P2P trading is used.
- *P2P_B2P_G2P*: Primary P2P trading, followed by battery usage without discharge strategy.
- *P2P_B2P_FB2G_G2P*: Primary P2P trading, battery utilization with simple discharge strategy.
- *P2P_B2P_FB2P_FB2G_G2P* (also named as “*Primary P2P*”): All mechanisms are used with highest priority on P2P trading.
- *B2P_G2P*: Only direct customer-storage interactions without discharge strategy.
- *B2P_FB2G_G2P*: Customer-storage interaction with simple discharge strategy.
- *B2P_FB2P_FB2G_G2P*. Customer-storage interaction with full discharge strategy.
- *B2P_P2P_G2P*: Primary customer-storage interaction trading without discharge strategy, followed by P2P trading.
- *B2P_FB2G_P2P_G2P*: Primary customer-storage interaction trading with simple discharge strategy, followed by P2P trading.
- *B2P_FB2P_FB2G_P2P_G2P* (also named as “*Primary storage*”): All mechanisms are used with highest priority on customer-storage interaction.

where the first term has highest and the last term has lowest priority. In all scenarios, the external grid covers the remaining residuals of prosumers in a very last step. E.g. in the scenario *B2P_FB2P_FB2G_P2P_G2P*, the interaction with prosumers and the central storage is done in a first place, followed by the battery discharge strategy, the peer-to-peer trading and at last the coverage through the external grid.

With the mentioned settings, scenarios and mechanisms, results are generated in annual simulations which provide the information of detailed energy flows. Tariffs for individual energy flows are applied afterwards on top, resulting into cash flows (see Figure 4). This allows an economic comparison of all investigated scenarios. The detailed list of prices, taxes and fees of an energy component is shown in Table 2.

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

1. Calculate community $gains$ (sum of green cash flows in see Figure 4)
2. Calculate community $costs$ (sum of red cash flows in see Figure 4)
3. Calculate resulting gain-cost sum

$$Gain\_Cost\_Sum = |Gains| - |Costs| \tag{1}$$

4. Compare scenarios with *G2P* (*Basic*) scenario

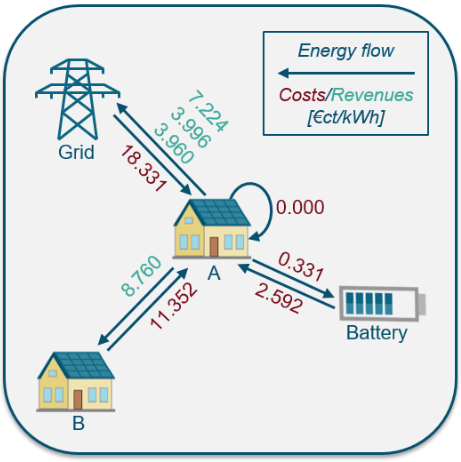


Figure 4 Overview of total costs (from perspective of customer A)

Type	Energy [€ct/kWh]	Grid fee [€ct/kWh]	Loss fee [€ct/kWh]	Electricity tax [€ct/kWh]	Green electricity tax [€ct/kWh]	Biomass subsidy [€ct/kWh]	Tax [%]	Total [€ct/kWh]
Self-consumption	0.000	0.000	0.000	0.000	0.000	0.000	0	**0.000**
A → B	7.300	0.000	0.000	0.000	0.000	0.000	20	**8.760**
A ← B	7.300	1.968	0.126	0.000	0.000	0.066	20	**11.352**
A → Batt	0.000	0.210	0.000	0.000	0.000	0.066	20	**0.331**
A ← Batt	0.000	1.968	0.126	0.000	0.000	0.066	20	**2.592**
A → Grid	6.020 3.330 3.300	0.000	0.000	0.000	0.000	0.000	20	**7.224** **3.996** **3.960**
A ← Grid	7.300	4.920	0.315	1.500	1.175	0.066	20	**18.331**

Table 2: Used energy prices, fees, and taxes

3 Results

One annual simulation run from the perspective of a prosumer in Setting I for the scenario *B2P_G2P* exemplarily is shown in Figure 5. The very top subplot shows the individual profile of the prosumer under scope and the resulting contributions of different functions like P2P trading, battery exchange, etc. in different colors. The x-axis represents the time with a resolution of 15-minute intervals and the y-axis is energy in kWh. Negative values indicate surplus and positive values demand. The second subplot gives an overview of the total community. Red indicates the prosumer profile under scope, blue the sum of all community member residuals and black the other individual participant profiles. All profiles are normalized to the absolute maximum. The subplot at the bottom shows the total and individual SOC contribution of the storage in kWh. Without a discharge strategy, the utilization of the SOC band stagnates in the summer season with higher PV generation. Figure 6 shows the same prosumer perspective in Setting I with an activated discharge strategy (scenario

B2P_FB2P_FB2G_G2P), allowing a better utilization of the SOC band over the whole year. Figure 7 provides a zoomed view of the applied discharge strategy on three days in March.

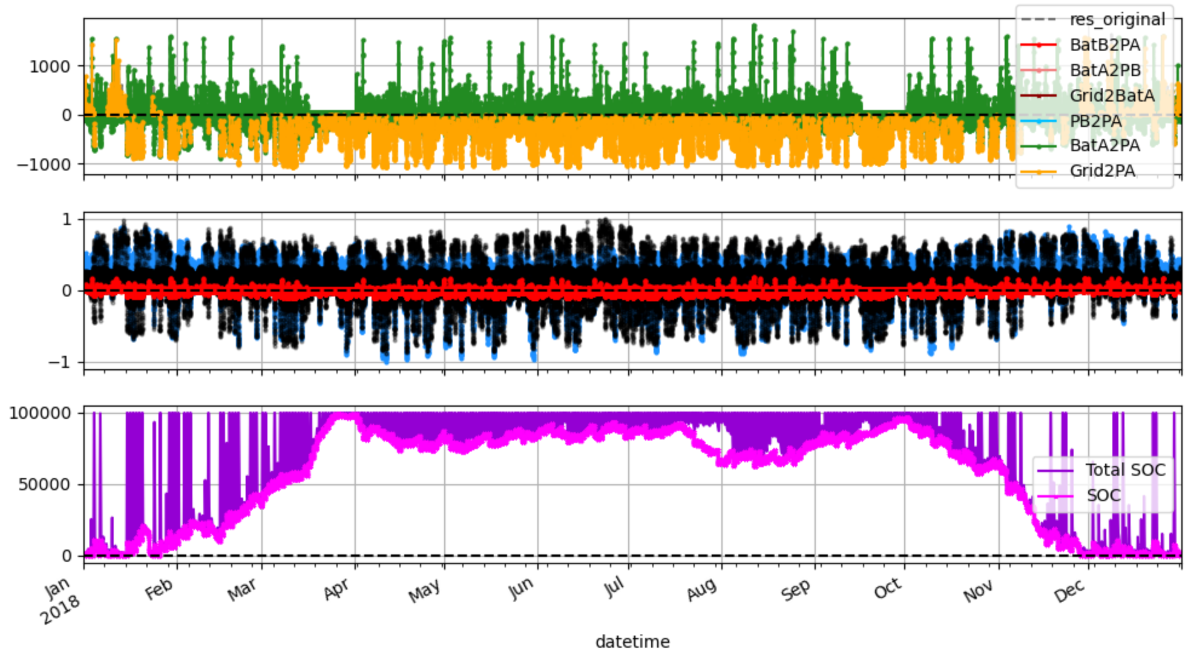


Figure 5: Annual simulation results without discharge strategy

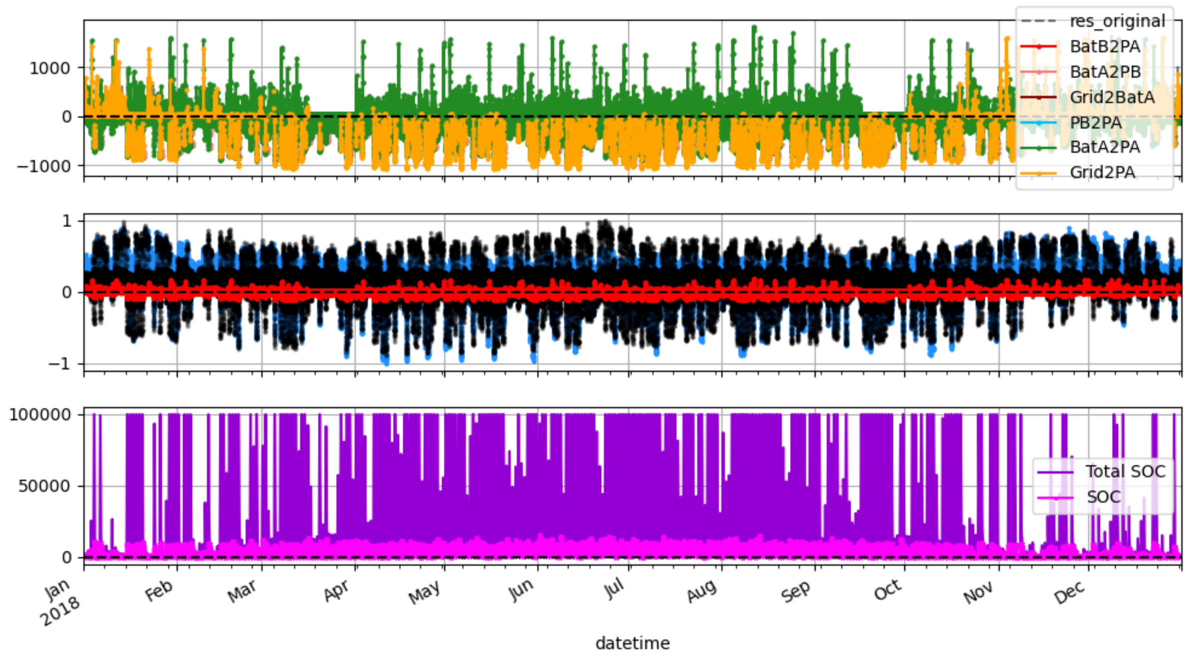


Figure 6: Annual simulation results with discharge strategy

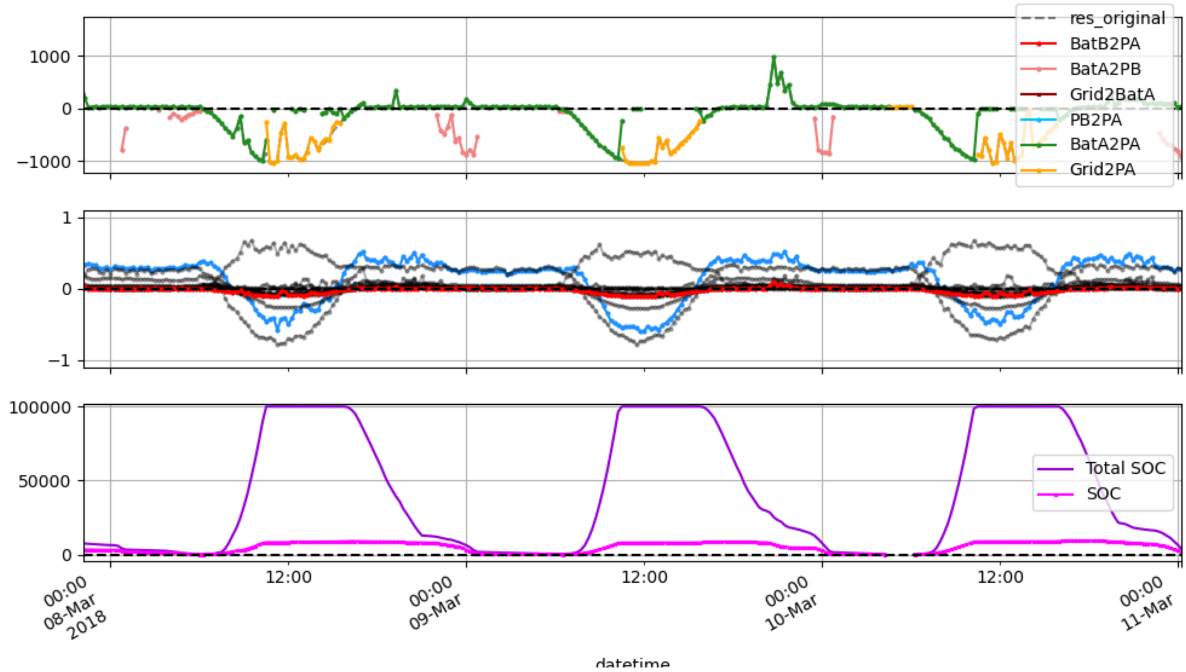


Figure 7: Validation of the discharge strategy

Table 3 and Table 4 show the resulting aggregated community energy flows over all scenarios. Orange marks the basic scenario, green scenarios with primarily P2P trading and blue scenarios with storage utilization as highest priority. In case of the large community (Setting II) the numbers for P2P trading (*PA2PB*) are rather high compared to the community surplus (*PA2G*) from the basic scenario. Almost 97 % of the surplus (~124 MWh) can directly be used without a storage in this case. In the small community, only 51 % (~29 MWh) can directly be used via P2P trading. This is due to the ratio between consumption and generation, which is greater in the big consumption-dominated community with 120 customers. Another reason is the better chronological match between the total generation and consumption time characteristic.

	BA2PA	BA2PB	G2PA	PA2BA	BA2G	PA2G	PA2PB
G2P	0	0	184954	0	0	57777	0
P2P_G2P	0	0	155560	0	0	28383	29394
P2P_B2P_G2P	14182	0	141378	14182	0	14201	29394
P2P_B2P_FB2G_G2P	14893	0	140667	15281	388	13102	29394
P2P_B2P_FB2P_FB2G_G2P	14815	1110	139635	15925	0	12457	29394
B2P_G2P	11133	0	173821	11133	0	46643	0
B2P_FB2G_G2P	23085	0	161869	24748	1663	33028	0
B2P_FB2P_FB2G_G2P	24643	3035	157276	27678	0	30099	0
B2P_P2P_G2P	11133	0	153284	11133	0	26107	20536
B2P_FB2G_P2P_G2P	23085	0	149458	24748	1663	20618	12411
B2P_FB2P_FB2G_P2P_G2P	24643	3035	146155	27678	0	18978	11121

Table 3: Annual energy flow results for setting I

	BA2PA	BA2PB	G2PA	PA2BA	BA2G	PA2G	PA2PB
G2P	0	0	960638	0	0	124263	0
P2P_G2P	0	0	840335	0	0	3959	120304
P2P_B2P_G2P	2025	0	838310	2025	0	1934	120304
P2P_B2P_FB2G_G2P	1972	0	838362	2083	111	1876	120304
P2P_B2P_FB2P_FB2G_G2P	1831	287	838216	2119	0	1840	120304
B2P_G2P	2176	0	958462	2273	0	121990	0
B2P_FB2G_G2P	22965	0	937674	27738	4763	96525	0
B2P_FB2P_FB2G_G2P	26374	9105	925160	35481	0	88781	0
B2P_P2P_G2P	2176	0	840431	2273	0	3959	118031
B2P_FB2G_P2P_G2P	22965	0	845092	27738	4763	3943	92582
B2P_FB2P_FB2G_P2P_G2P	26374	9105	840279	35481	0	3900	84881

Table 4: Annual energy flow results for setting II

Following figures show some more detailed energy components of the small community (Setting I) via duration curves. Figure 8 depicts the exchanged power between the community and external grid. Positive values represent community demand and negative values community surplus situations. Scenarios with highest priority on P2P trading result in longer times with zero exchange between the external grid and the community (idle mode). Figure 9 shows the duration curves of SOC. Scenarios without a discharge strategy result in most of the time upper SOC bound usage. The ideal case would be a linear function with rare occurrences of fully empty or fully loaded SOC values.

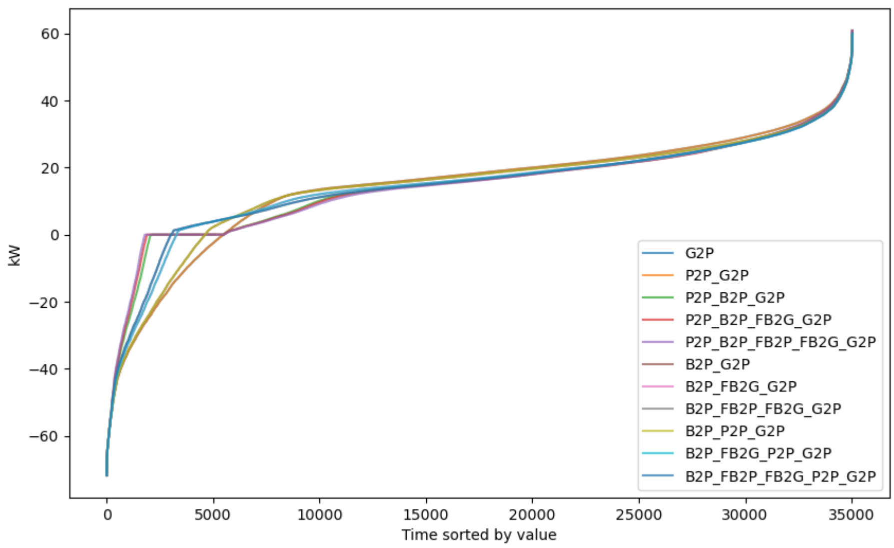


Figure 8: Exchange with external grid with Setting I

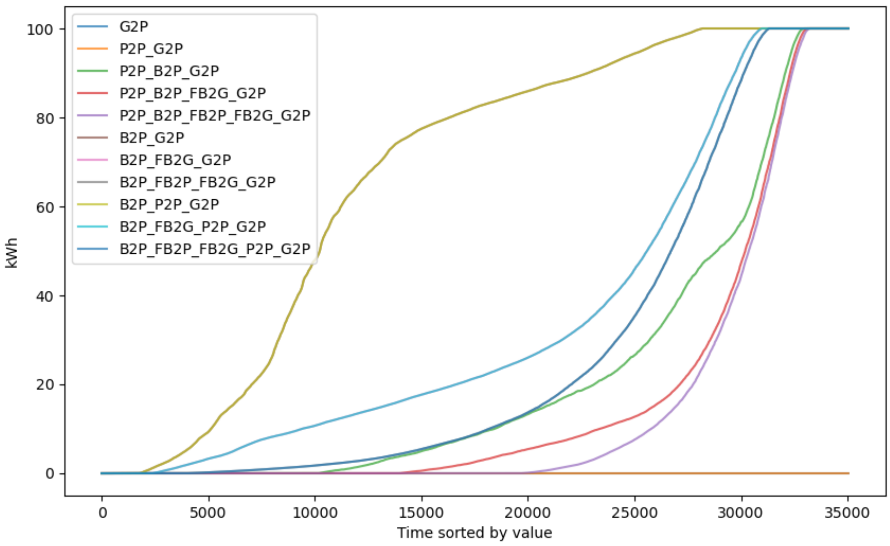
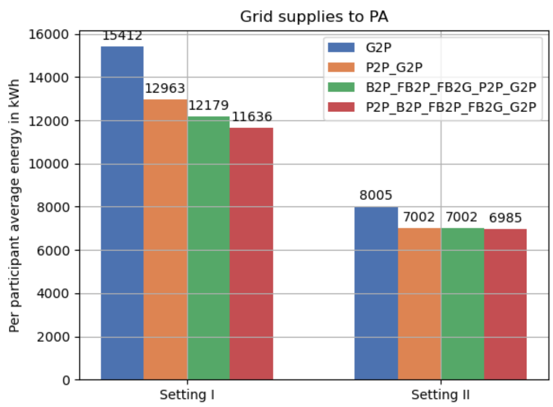
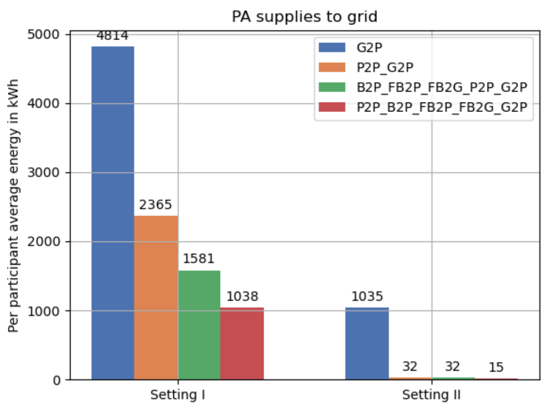


Figure 9: SOC duration curve with Setting I

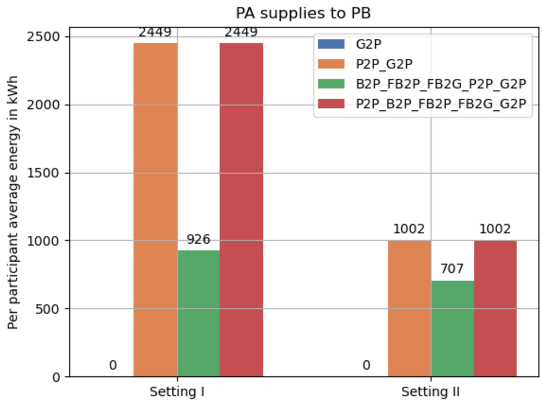
Figure 10 shows a comparison between the large and small community with the same storage size of 100 kWh. All values are normalized to the number of customers to allow a better comparison. For the sake of clarity, only the most relevant four scenarios are considered in this visualization. Subplot (a) and (b) show the average energy a participant receives/provides from/to the external grid per year. For the small setting is makes a much bigger difference which scenario is used. This is not the case for the large setting, because the highest impact is due to the P2P trading. Thus, every used mechanism plays a relevant role in the small setting. Subplot (c) shows the average interaction between participants through the P2P trading mechanism. In the small setting, the ratio of generation to consumption is greater than in the large setting. This allows a higher contribution to the P2P exchange per participant. Subplots (d), (e) and (f) show the interaction between participants and the community storage. In case of the large setting, the battery interaction becomes obsolete for the P2P primarily scenario whereas it is still useful for the small setting. In all scenarios it never happened that battery is discharged through the grid by the second stage of the discharge strategy, all released energy was consumed by the community.



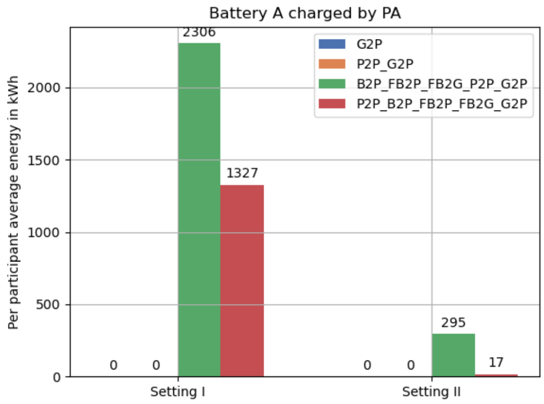
(a)



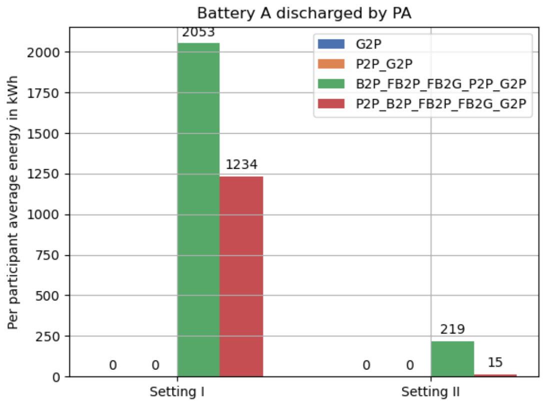
(b)



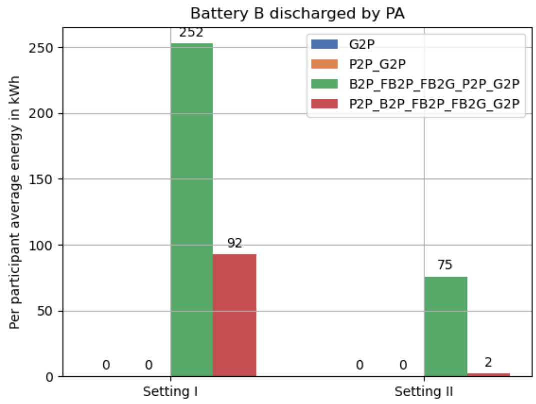
(c)



(d)



(e)



(f)

Figure 10: Setting comparison – results are normalized to the number of customers.

The baseline scenario (*G2P*) without any battery usage or energy sharing within the community shows that 47 % / 54 % (depending on the community setting) of the generated energy is used within the community (see Figure 11). This share can be further increase by activating energy sharing and/or the utilization of the community storage. The best results can be achieved when focusing on energy sharing within the community (*P2P_**), followed using the storage (*B2P*) and including battery release (*FB*). In these scenarios the usage of the locally generated energy can be increased up to 90 % / 99 %. When using the battery storage as highest priority, the results as slightly lower (*B2P_**).

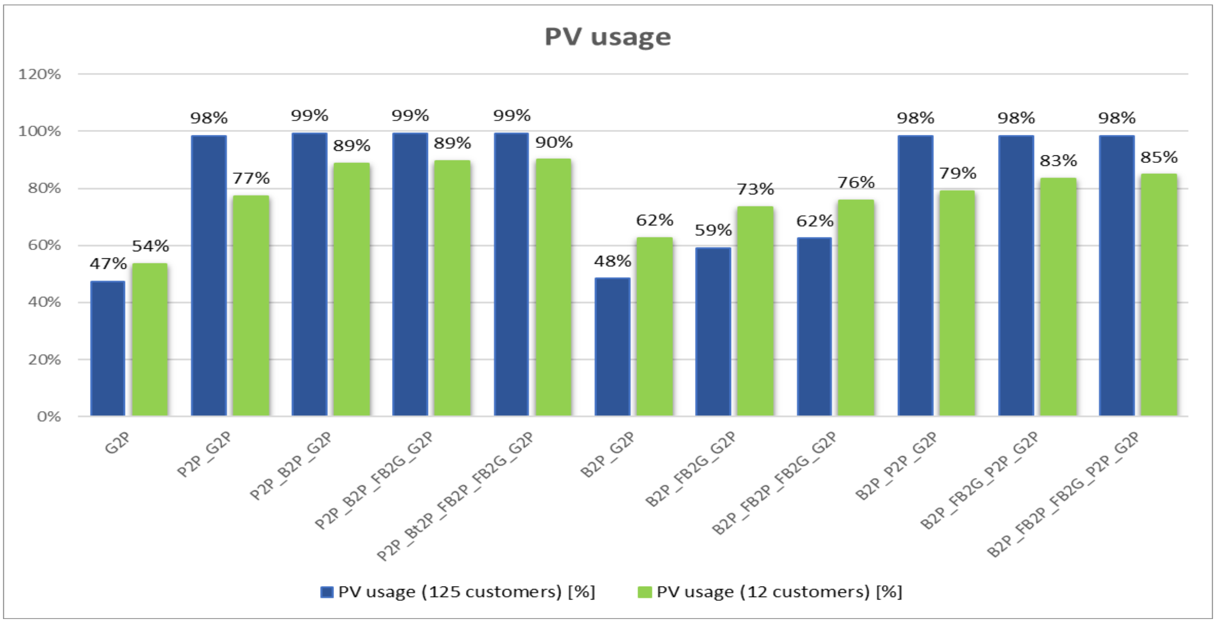


Figure 11: PV usage on community level: Comparison of simulation scenarios.

In the baseline scenario (G2P) 26 % / 10 % of the total community consumption is covered by the locally generated energy (see Figure 12). This share can be further increased up to 44 % / 22 % when using energy sharing and the community storage. Similar to the PV usage, scenarios with focus on energy sharing, followed by the battery show the most promising results.

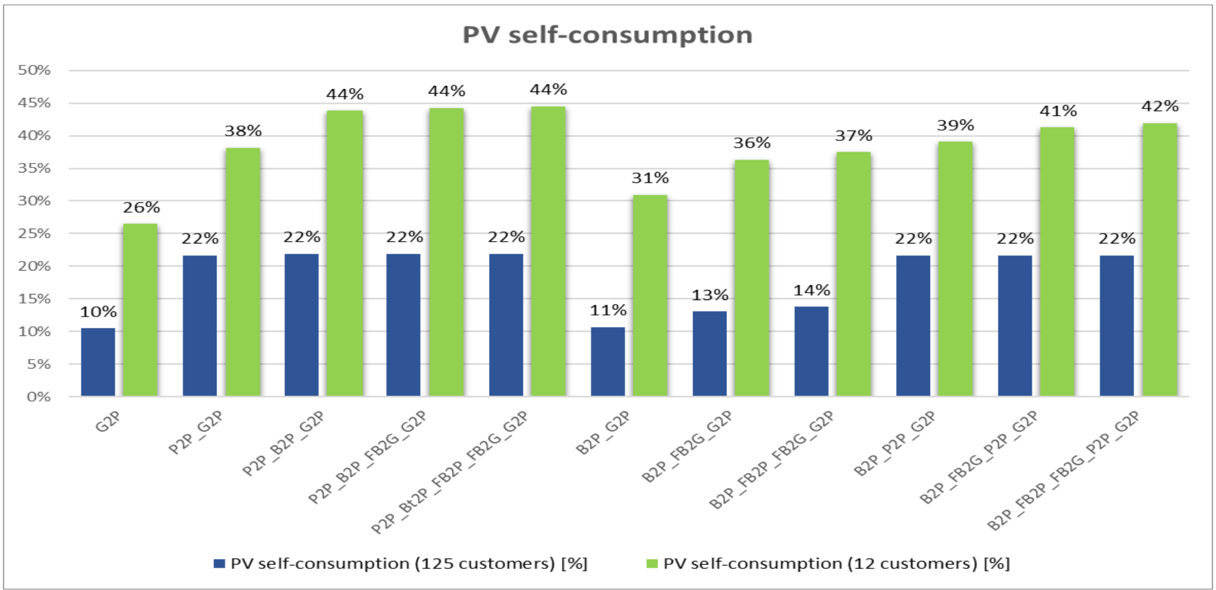


Figure 12: PV self-consumption on community level: Comparison of simulation scenarios

Figure 13 shows the total annual community returns for the four most relevant scenarios, based on the defined tariffs (see Table 2). In (b) it is clearly visible that the battery does not provide additional benefits on top of the P2P trading, since all the surplus energy in such a consumption dominated community can be utilized simultaneously without using the storage as flexibility.

Figure 14 shows the same plot normalized on the number of customers. An individual in the small setting, which is mainly composed out of prosumers, has higher benefits/returns compared to an individual in the large setting.

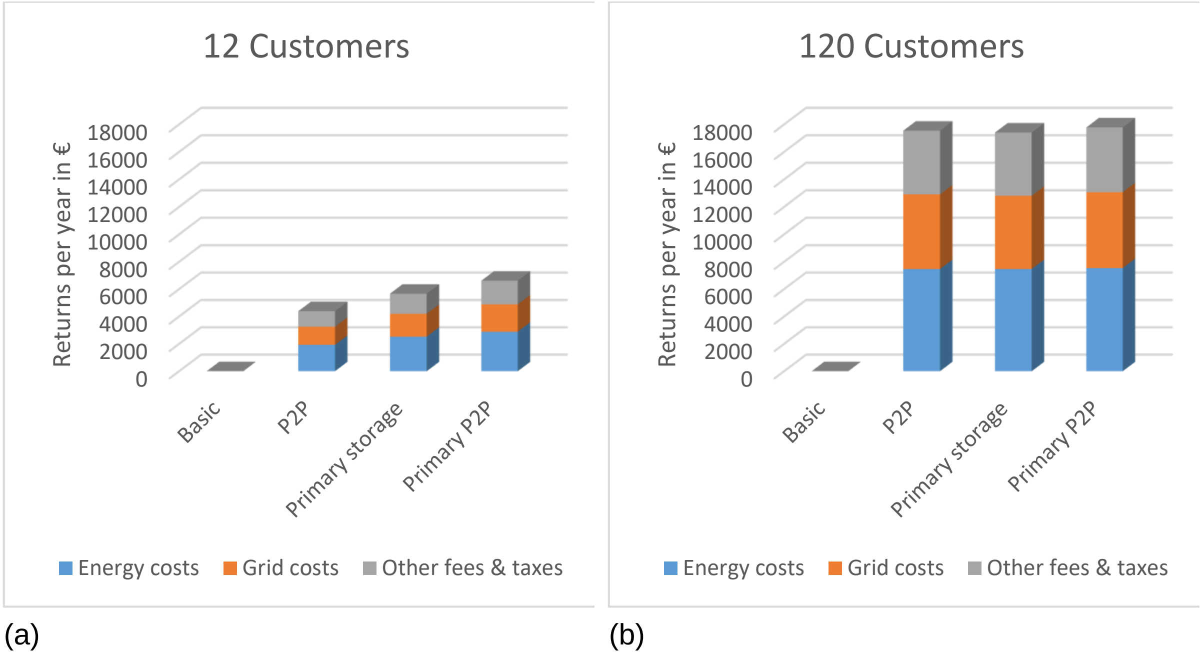


Figure 13: Annual returns for the total energy community for both scenarios

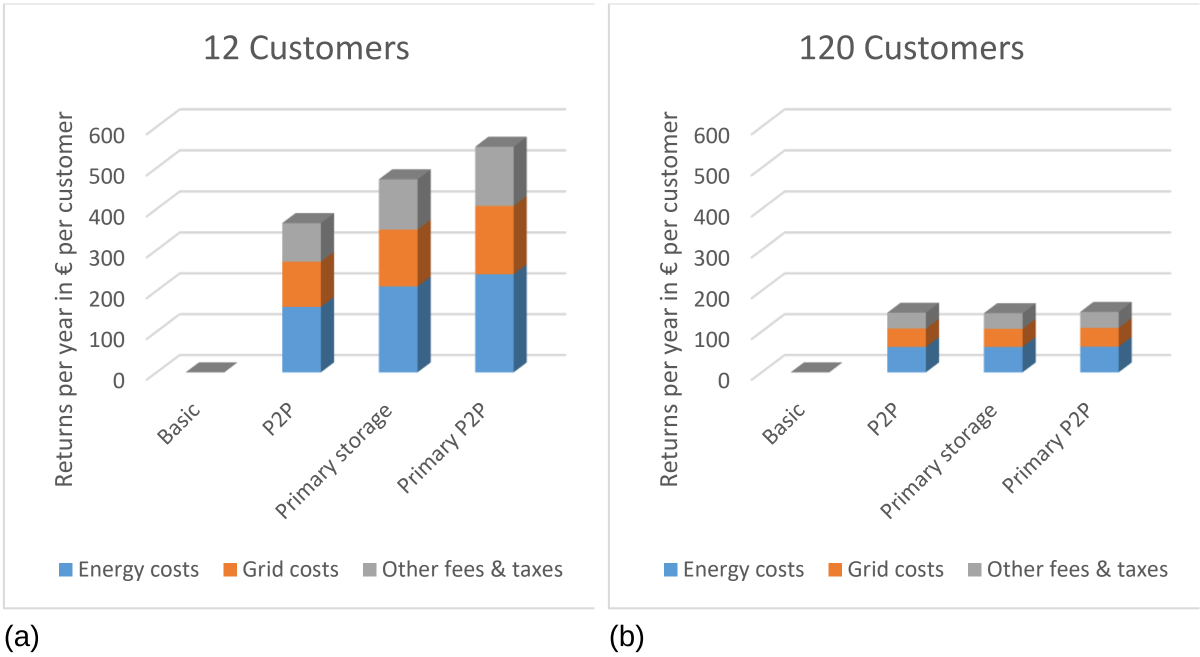


Figure 14: Annual returns per customer for both scenarios

4 Discussion and conclusions

This work represents a framework for energy community planning and, including mechanisms like P2P trading or a central community storage for self-consumption optimization on a community level. Eleven different combinations of rules (scenarios) are investigated in annual simulative studies for two different energy community settings, resulting in 22 annual simulation runs. Energy flows and cash flows between the external grid, community storage and participants are analyzed and compared in detail and the impact of the community structure with different combinations of manipulative energy flow mechanisms is discussed.

Results show a potential of increased community self-consumption, cost savings for the participants, and provide recommendations, when different compositions of energy communities should favor different rules since the numbers show, that it is sometimes better to just focus on P2P- trading or storage utilization instead of both. E.g. communities with a high consumption compared to generation achieve good result just by using P2P trading instead of an additional community storage. On the other hand, communities with an equal share of generation and consumption should aim for a flexibility solution like a storage to allow local energy utilization.

The size, composition of participants and their coherent customer types and temporal behavior, mix of generation and consumption, battery storage size and operation strategy and used rules for the virtual energy flows of an energy community are the most important factors to do an in-depth assessment. Further analysis of different energy communities and how rules scale need to be further investigated to allow concrete planning of energy communities. Shown results between two communities already show the need of an individual treatment for different kinds of energy communities.

Future extensions of the framework could include the activation of flexible devices on customer level (e.g., controllable devices such as heat-pumps or private charging stations) or on community level (e.g., public charging stations).

Acknowledgement

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