ANALYSIS OF THE VALUE OF ADDITIONAL FLEXIBILITY PROVIDED BY COMMUNITY BATTERY STORAGES FOR THE GERMAN ELECTRICITY SYSTEM

Simon Koderer, FfE[1], +49 89 158121 86, skoderer@ffe.de
Michael Hinterstocker, FfE, +49 89 158121 53, mhinterstocker@ffe.de
Joachim Ferstl, FfE., +49 89 158121 65, jferstl@ffe.de
Simon Martin, FfE, smartin@ffe.de

1. Introduction

The ongoing transition of the European energy system towards renewable sources and thus, towards decarbonization, requires increased flexibility in the system. Besides the existing market-based monetary incentives, advanced solutions for labeling of energy generation and consumption, as designed and developed in the project InDEED, can incite the installation of additional flexibility options. One of the technologies which can contribute substantially to meet these requirements are battery storages, which can be seen as the prototypical flexibility option. Various operation strategies and operator models are possible for battery storages: from home energy storage systems, providing flexibility for increased self-sufficiency and reduced purchasing costs on a household level, over community storages, serving districts or municipalities, to large-scale batteries mainly active in control power markets.

Household-level batteries are on the one hand already covered in a large number of scientific analyses and on the other hand still pose a financial barrier for the individual household and thus, may slow the overall expansion of storage capacity. Therefore this paper focuses on the benefits and effects of community storages. These are considered to be jointly operated by and for the households within a municipality in order to improve their common energy costs and/or emissions. The approach on a municipal level is required to keep the whole system manageable, but the results are expected to be also applicable on smaller geographical entities within these municipalities like districts or quarters.

The scope of the presented analyses is on the effects of community storages regarding increased self-sufficiency, increased integration of renewables and improved procurement for the residential sector in the respective municipalities. Therefore, renewable energy sources are considered on the generation side and only residential demand constitutes the electric consumption within the model. In particular, commercial or industrial consumption is out of the system boundaries for this paper, but could of course also benefit from the expansion of storage capacity.

2. Method

In this chapter, the methods to analyse the value of additional flexibility provided by community battery storages for the German electricity system in 2035 are described. In the first section the Municipality Simulation Model is introduced which serves as the basis for the work described in this paper. The second section contains the description of the modifications applied to the Municipality Simulation Model. The modified model is later used to quantify the value of flexibility. The third section gives an overview over the battery storage and simulation parameters. In the last section, three different methods for the regional distribution of the storage capacity in Germany are described and discussed.

2.1 Municipality Simulation Model

The hourly demand and supply of every German municipality in the year 2035 is based on a municipality-level simulation framework called *Municipality Simulation Model* (depicted in Figure 1 to the left) [1,2]. This model facilitates various datasets of the FfE regionalized energy system modelling tool (FREM) [3] to represent energy-related components of the municipality. This includes buildings and households, residential and commercial PV systems, residential storages as well as wind, hydro and biomass power plants. Due to its original purpose, which among others includes simulation of peer-to-peer energy communities, it is focused on renewable energy sources on the generation side and private households on the demand side, neglecting generation from fossil sources and load of industrial applications and the tertiary sector. Every asset in the municipality (e.g., renewable power plants or households) is associated with an hourly resolved load profile. Households can be equipped with a PV system, a PV battery storage, and electric vehicles – all of which are included in the individual residual load of each household. The Prosumers (household with PV system) and Flexumers (household with PV system and PV battery storage) are

---

[1] Forschungsgesellschaft für Energiewirtschaft mbH (FfE), Am Blütenanger 71, 80995 Munich, Germany

assumed to act with a focus on own consumption.[1] By default, the asset stock represents the state of 2019, but the functionality to modify the assets is also provided in the Municipality Simulation Model, enabling the use of custom scenarios during simulation. The scenario is based on overarching figures for Germany defining the total installed capacity of renewable power plants (separated by energy source), the total installed capacity of PV battery storages as well as the total number of electric vehicles. These values are first regionalized to the municipality level and then used as input for the Municipality Simulation Model which in turn distributes the assets within the municipality. A detailed description of the methodology and the scenario can be found in [1]. The overall hourly demand ($E_{Demand,t}$) and supply ($E_{Supply,t}$) per municipality is derived from the load ($E_{L,t}$) and generation ($E_{R,t}$) of all assets within the municipality. The dataset is partially simulated and partially emulated using machine learning techniques [1]. Because almost none municipality is energy-autonomous, a grid connection is added to the model. The grid is assumed to be a perfect grid, which can provide all the missing energy ($E_{Demand,t}$) and take all the overproduction ($E_{Supply,t}$).

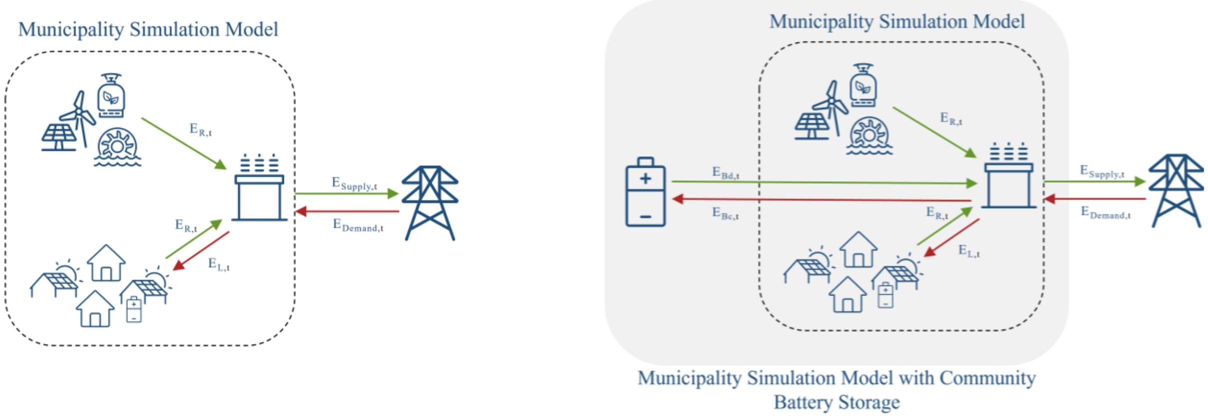

Figure 1: Municipality Simulation Model (left); Municipality Simulation Model with added Community Battery Storage (right)

2.2 Municipality Simulation Model with Community Battery Storage

In order to quantify the value of additional flexibility provided by community battery storages for the future German electricity system, a simple model was developed in Python. For the purpose of this paper the previously introduced Municipality Storage Model is extended by a community battery storage, which can either be charged ($E_{Bc,t}$) or discharged ($E_{Bd,t}$) in every timestep (depicted in Figure 1 to the right).

2.2.1 Model Description

The model takes various battery parameters, the initial residual load of a municipality represented as a time series, and the prices to be optimized for, also given as a time series, as input. It provides several outputs, including the residual load of the municipality after incorporating the battery storage, the absolute and relative energy contents of the battery storage, the power charged or discharged at each timestep, and the overall cost over the specified period.

The model employs two different logical approaches. The first logic referred to as the self-sufficiency optimized battery storage, working like a decision tree. In this approach, the battery storage is charged when there is a surplus of generation in the municipality and discharged when there is a deficit – in each case assuming that there is enough remaining capacity or energy in the battery storage. The second logic, known as the cost optimized battery, optimizes the battery's operation to minimize overall costs by leveraging perfect foresight of upcoming conditions. Costs are in this case not only interpreted as financial costs but also as emissions. At each timestep, the energy charged to the battery storage and the energy discharged from the battery operate as decision variables and are optimized over the entire period to achieve the optimal total cost. The battery intelligently charges or discharges energy during advantageous timesteps, thereby optimizing the residual load, i.e., interaction with the grid, in terms of costs. The model allows for the consideration of various ratings, depending on the specific use case. The aim of the optimization is to minimize these ratings. In this paper two types of ratings are considered, namely (financial) cost and emissions. The optimization framework employed in the model is PULP, along with the CBC solver, whichh facilitates efficient and effective optimization processes. Overall, this Python model serves as a valuable tool for simulating battery systems and their impact on the residual load, energy storage, power flow, and cost optimization within a municipality or similar settings.

---

[1] For methodological details on how the assets are modelled in the Municipality Simulation Model refer to the original publications.

2.2.2 Battery Optimization

The battery storage can be operated in three different ways. As a self-sufficiency optimized storage it gets charged as soon as the energy supply in the municipality is greater than the demand. Its discharging behaviour is just the opposite. For the other two use cases a linear optimization is used. The battery storage can either be used to minimize costs or emissions. The linear optimization model is shown in the following.

$$\min \sum_{t \in T} c_{i,t} \cdot E_{Demand,t} - c_{e,t} \cdot E_{Supply,t} \qquad T \in \{1, \dots, 8760\} \tag{1}$$

$$s.t.\ \forall t \in T: E_{Demand,t} + E_{Bd,t} + E_{R,t} - E_{Supply,t} - E_{Bc,t} - E_{L,t} = 0 \tag{2}$$

$$\forall t \in T: E_{Bd,t} = E_{B,t-1} + E_{Bc,t} \cdot \eta_c - E_{Bd,t} \cdot \frac{1}{\eta_d} \tag{3}$$

$$\forall t \in T: E_{B,t} \leq E_{Bn} \cdot SOC_{max} \tag{4}$$

$$\forall t \in T: E_{B,t} \geq E_{Bn} \cdot SOC_{min} \tag{5}$$

$$\forall t \in T: P_{Bn} \cdot 1 \geq E_{Bd,t} \tag{6}$$

$$\forall t \in T: P_{Bn} \cdot 1 \geq E_{Bc,t} \tag{7}$$

$$\forall t \in T: c_{i,t} \geq c_{e,t} \tag{8}$$

$$E_{B,0} = E_{Bn} \cdot SOC_{t,0} \tag{9}$$

The dataset representing the grid, which is assumed to be a perfect grid, is taken from a scenario in the energy system model ISAaR. In this scenario, a future European energy system is created for the year 2035, assuming a low amount of flexibility in the electricity system. The dataset contains the hourly day-ahead prices ($c_{e,t}$) and specific emission factors ($c_{i,t}$ and $c_{e,t}$) . The import prices ($c_{i,t}$) are calculated separately by adding concession levies to the day-ahead prices, as this are the minimum levies, which need to be paid by battery storage operators, which are the municipalities in this case. Backlashes from the single municipalities on the grid by changing the day-ahead prices and specific emissions are not considered, as the optimization is calculated individually for each municipality. The battery storage can be designed individually using the parameters nominal energy (E_{Bn}), nominal power (P_{Bn}), charging efficiency (η_c), discharging efficiency (η_d), initial state of charge ($SOC_{t,0}$), minimum state of charge (SOC_{min}) and maximum state of charge (SOC_{max})

2.2.3 Battery storage and simulation parameters

The battery storage and simulation parameters, which are used identically in all the simulations, are listed in Table 1. All timeseries have a temporal resolution of one hour and represent one year.

Table 1: Battery storage and simulations parameters

Parameter	**Value**
Residual load ($E_{Suppl–,t} - E_{Demand,t}$)	Individual timeseries for every municipality [1,2] in kWh
Specific grid emissions	Timeseries from ISAaR in gCO_2eq/kWh
Day-ahead prices	Timeseries from ISAaR in ct/kWh
Levies	1,64 ct/kWh [4]
Nominal energy (E_{Bn})	Individual for every municipality
Energy to power ratio (E_{Bn} / P_{Bn})	1
Charging efficiency (η_c)	95 %
Discharging efficiency (η_d)	95 %
Initial state of charge ($SOC_{t,0}$)	0 %
Minimum state of charge (SOC_{min})	0 %
Maximum state of charge (SOC_{max})	100 %

The nominal energy of the battery storage is individually determined for every municipality. The methods to determine the storage capacity for every municipality are described in the following sub-section.

2.4 Regionalization of Storage Capacity

To quantify the value of additional flexibility provided by community battery storages for the future German electricity system, the total battery storage capacity installed in Germany is estimated as 6 GWh. This figure is analogue to the predicted capacity of large-scale battery storages in Germany in the year of 2035, which is the analysed year in this paper [5]. Solar battery home storages are not considered, as they are already implemented in the municipality dataset (section 2.1). Capacity given by pumped-storage power plants are also not considered, because they cannot be easily distributed to all German municipalities, as they have very specific topographic and environmental requirements.

Three different heuristic methods are chosen to distribute the total installed capacity of 6 GWh among all municipalities in Germany included in the result dataset of [3]. This dataset includes multiple features from different domains such as demography, energy-economy, and settlement structure. Some of these features (i.e., installed renewable capacity, yearly renewable energy production and peak load) are used to conduct the three distribution methods. The results of the different distribution methods are shown in Figure 2.

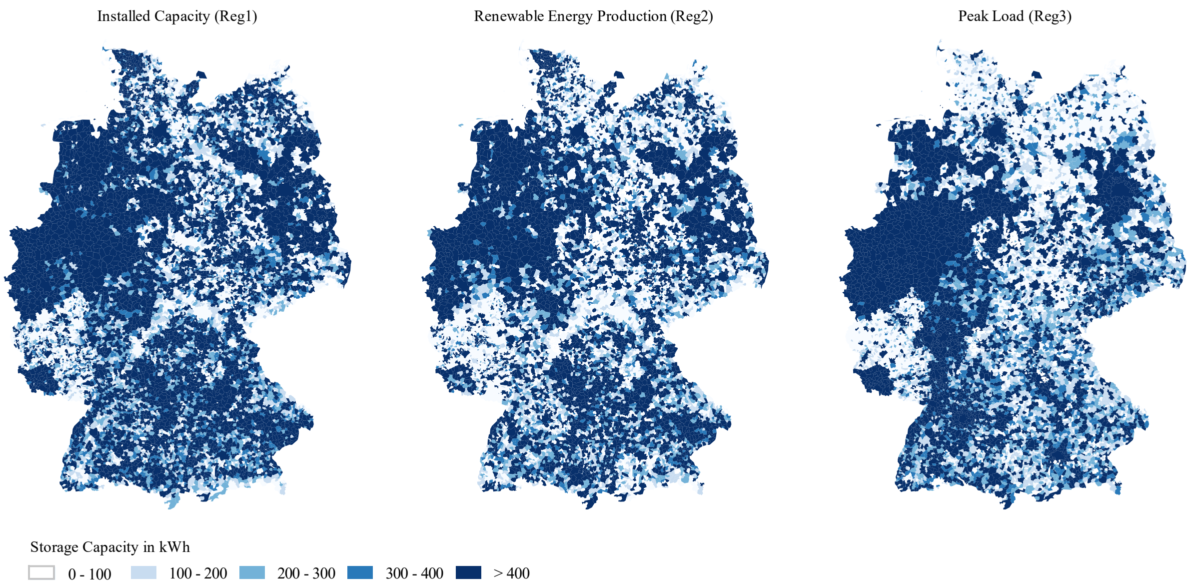

Figure 2: Regionalization of storage capacity

The first heuristic method (Reg1) distributes storage capacity based on the installed renewable capacities in the municipalities. Five clusters of a high storage capacities can be identified. The first one is in Schleswig-Holstein in the top north of Germany. Due to good wind conditions a decent amount of wind power plants is installed in this region. The second cluster is located in eastern Germany in the area of Berlin and Brandenburg. The area of Bavaria in the south builds the third cluster with renewable capacities especially provided by solar power plants. The fourth cluster in the western part of Germany is located in the area of the Saarland. North Rhine-Westphalia and the northern part of Lower Saxony build the fifth cluster with mainly wind turbines as installed renewable capacities.

The second heuristic method (Reg2) distributes storage capacity analogously to the annual renewable energy production in the municipalities. Therefore, the installed renewable capacities are multiplied with local specific load factors for wind and solar in every municipality [3]. Due to higher astimated load factors of wind compared to solar, municipalities with higher installed wind power capacity will gain additional storage capacities, whereas the other municipalities will lose storage capacity compared to the first heuristic method (Reg1) . This changes the shape of the identified clusters. Especially in Bavaria a decreasing number of municipalities forming the cluster can be recognized. This observation can be made in every other cluster.

The third heuristic method (Reg3) distributes storage capacity analogously to the peak load of every municipality. Compared to the first two heuristic methods, rather different clusters can be recognized. The first and main cluster is located in North Rhine-Westphalia and the northern part of Lower Saxony. This area is characterized by energy-intensive primary industry. This characteristic also matches the second identified cluster in western Germany in the area of Saarland. The third cluster spreads over Rhineland-Palatine, Hesse and Baden-Wuerttemberg. The fourth cluster consists of the city of Berlin and its suburbs. Next to the main clusters several micro clusters can be recognized in and around the major German cities like Munich and Hamburg.

3. Results

The results of the analysis of the value of additional flexibility provided by community battery storages for the German electricity system in 2035 are presented in the following three sections. In the first section, the input dataset, which consists of hourly day ahead prices and hourly specific emissions, is analysed with respect to the correlation of the day-ahead price and specific emissions. Within the simulation the dataset is used to represent the grid, which is assumed to be a perfect grid. The results are also compared to historic hourly day-ahead prices and specific emissions. The impact of additional flexibility added to the German electricity system in 2035 is presented in the second section. In this case a systematic approach is used to quantify the value added. Therefore, bar charts showing the reduction of overall costs and emissions for the purchase of electricity for the different battery use cases and distribution methods are presented. The last section describes the individual impact on every municipality using an actor-based approach, showing added value measured using costs and emissions individually for each municipality.

3.1 Correlation between Day-ahead prices and GHG-emissions

Day-ahead prices are influenced by the produced electricity from renewable energy sources. This mechanism is caused by the merit order principle, which is the price building mechanism for the German day-ahead market [8]. A high electricity production of the renewable energy sources solar and wind extrudes conventional powerplants in the merit order, which lowers the marginal costs and therefore the day-ahead prices. On the other hand, the produced electricity from renewable energy sources influences the specific emissions of the grid electricity. Due to its low specific GHG emissions, electricity from renewable energy sources helps to reduce the grid emissions.

Based on these preliminary considerations, a correlation between hourly day-ahead prices and hourly specific emissions can be assumed. The actual correlation between those two ratings is shown for the years 2017–2020 in Figure 3. Day-ahead prices are published for every year on an hourly resolution by the ENTSO-E [6]. Besides the day-ahead prices, the ENTSO-E also publishes produced energy per generation type in Germany with a temporal resolution of 15 minutes [6]. This data is aggregated to an hourly resolution and multiplied by specific emission factors in order to calculate the hourly emissions [7].

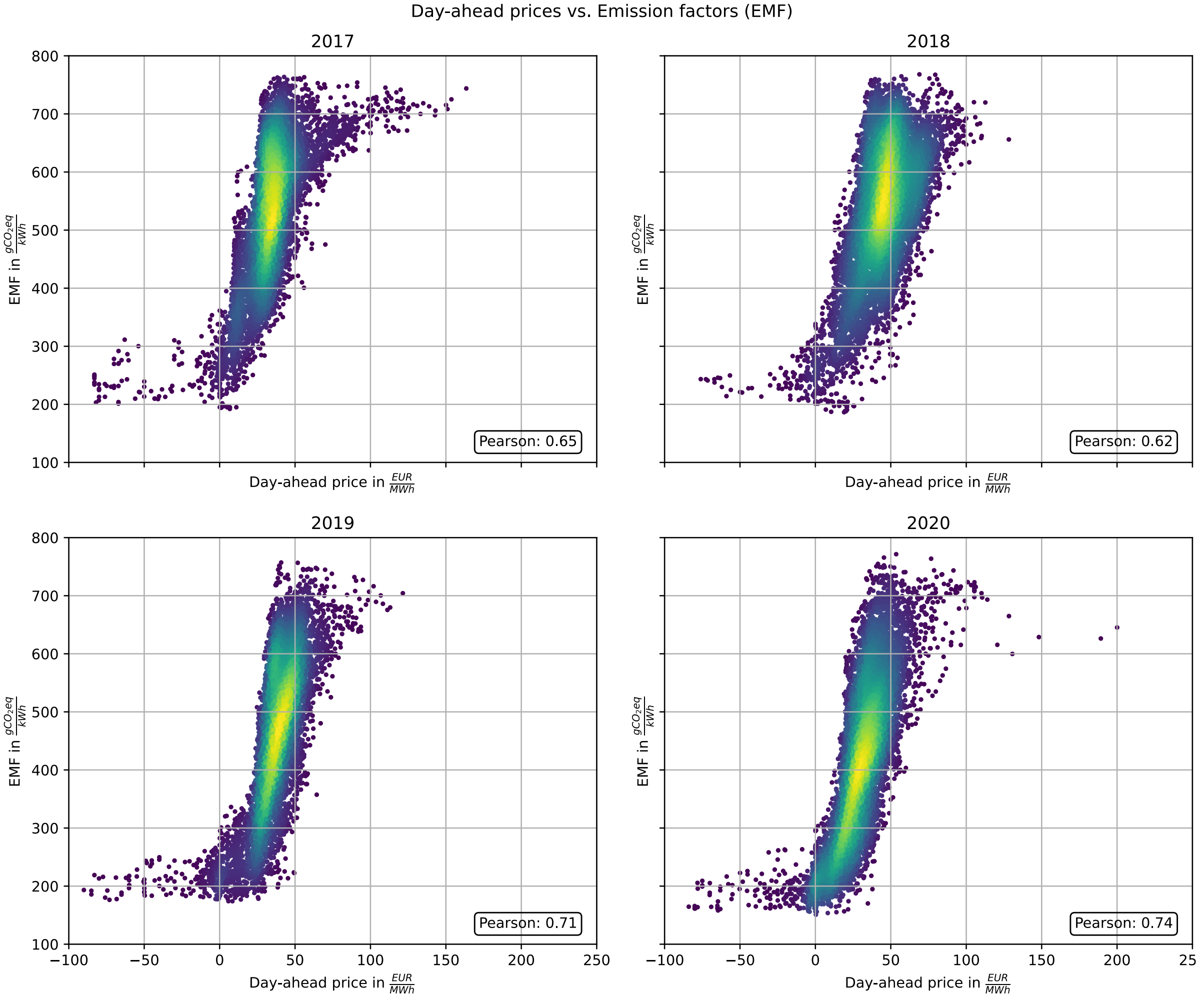

Figure 3: Historic corelation between day-ahead Prices and GHG emissions in Germany

The figure shows one plot for every year between 2017 and 2020. Each point in the plots represents a tuple of an hourly day-ahead price and the corresponding emission factor (EMF). The colour of the points represents their density relative to each other, where yellow shows a high density and purple a low density. The correlation between day-ahead prices and GHG emissions is measured using the Pearson correlation coefficiI (r), which is calculated in the following way:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} {x_i}^2 - n\bar{x}^2} \cdot \sqrt{\sum_{i=1}^{n} {y_i}^2 - n\bar{y}^2}} \tag{10}$$

The Pearson correlation coefficient is used as an indicator for linear correlation of two variables. A Pearson correlation coefficient of one corresponds to a perfect linear correlation, while a coefficient of zero indicates no correlation The greater the absolute value of the pearson coefficient is, the greater is the correlation [9]. Therefore, the historic day-ahead prices and GHG emissions can be considered as highly correlated.

The same analysis isalso performed for the dataset of future day-ahead prices and GHG emissions from the energy system model ISAaR (section 2.2.2). The results are shown in Figure 4.

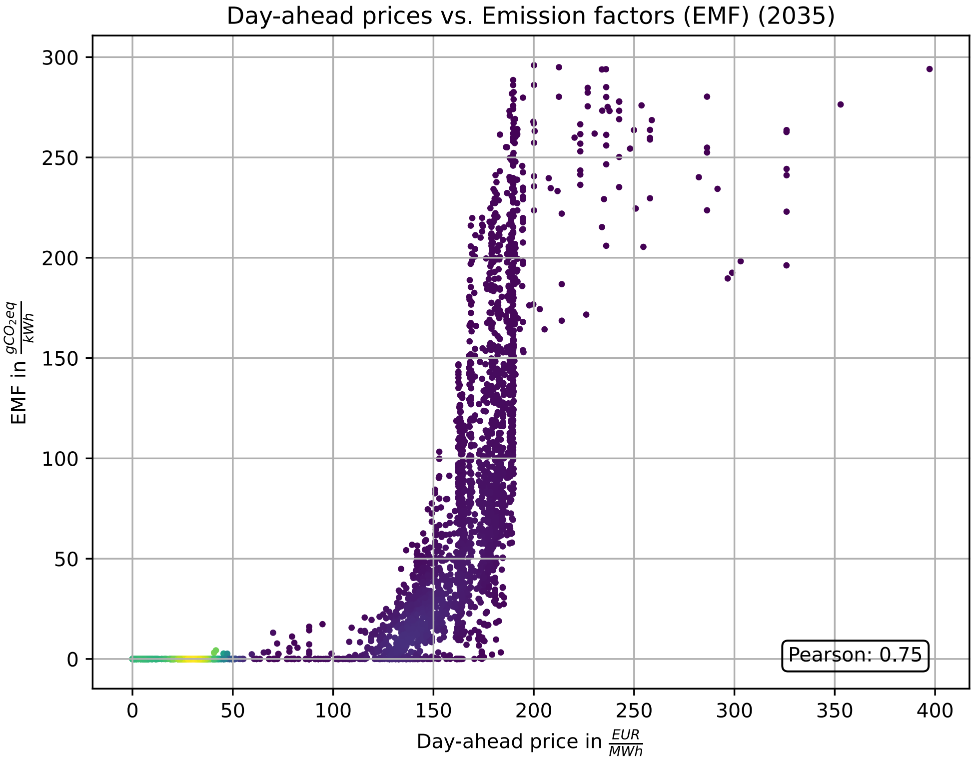

Figure 4: Future corelation between day-ahead prices and GHG emissions in Germany

Compared to Figure 3, the shape of the graph shows significant differences. Most of the tuples show almost zero specific emissions caused by almost exclusively renewable electricity generation in the corresponding hours. This is caused by the increased amount of installed renewable energy capacities in the year 2035 in the used scenario. Also, the maximum emissions caused by electricity generation are reduced by more than 50 percent. This is due to the shutdown of any coal-fired power plant. The power plants with the highest specific emissions in the scenario are gas-fired power plants. Like the specific emissions, also the day-ahead prices are reduced. Looking at the correlation between day-ahead prices and specific emissions, a Pearson correlation coefficient of 0.75 is observed. Therefore, assuming the future day-ahead prices and specific emissions, the correlation between prices and emissions is stronger in the scenario compared to the historic data.

3.2 Impact on the German electricity system

In this section the impact of additional flexibilities added by community battery storages on the German electricity system in 2035 is analysed. The impact can be measured by using two different indicators, namely costs or emissions. The additional flexibility provided by community battery storages create an impact on two sides. On the one hand the storages help reducing the costs and emissions caused by the purchase of electricity from the grid. On the other hand, the storages increase the revenue from selling the surpluses of electricity to the grid. It is assumed that the surpluses are absorbed by the non-modelled industrial sector. With regard to emissions, it is assumed that the renewable electricity fed into the grid reduces the use of fossil-fuel power plants and thereby displaces emissions. Again, it is assumed that the surplus electricity is absorbed by the non-modelled industrial sector.

3.2.1 Analysis of the impact measured by costs

The impact on the overall electricity system measured by costs is analysed in three steps. First the cost for purchasing electricity from the grid for each municipality are calculated individually and summed up afterwards. In this process, the levies consisting of concession fees are also considered, as they were, when optimizing the battery storages on single municipality level. In the reference system, costs totalling €7.3 billion are incurred for the purchase of electricity from the grid. To determine the cost reduction, this value is deducted from all other calculated costs. The result is shown in the figure. It can be seen that the cost of purchasing electricity from the grid is reduced for all storage use cases and regional storage distributions.

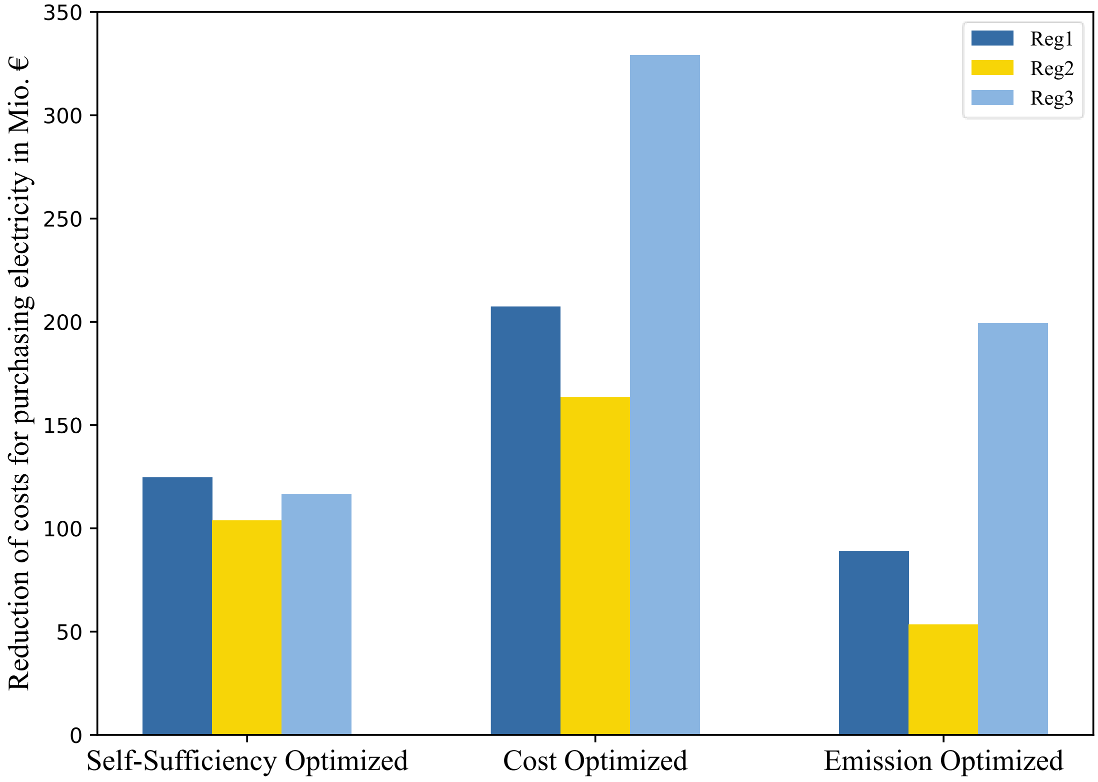

Figure 5: Absolute cost reduction for purchasing electricity depending on the use case and the regionalization method

In view of Figure 5, significant differences both among battery use cases and the regional distribution of storage are to be observed.

When comparing the use cases, the cost reduction for the emission optimized use case is the lowest in two out of three regionalization methods. This is the case when the storage is distributed based on installed capacity or renewable energy generation, as shown in Figure 2. Both regionalization methods exhibit a similar distribution of storage capacity. According to both heuristics, municipalities with high renewable energy generation are equipped with high storage capacity. This is even more pronounced in the case of Reg2, which is also the reason for the lower cost reduction due to additional storage. The emission optimized storage is operated to reduce the individual emissions of the municipalities. This can be achieved by increasing their electricity intake during periods of low emissions and reducing their electricity sales during periods of high emissions, provided that sufficient storage capacity is available. In the optimization conducted, the municipalities are able to reduce their individual emissions by feeding electricity to the grid. The reduction of emissions is calculated based on the amount of feed-in electricity and the specific grid emissions at the respective timestep. This logic leads to the fact, that even in the case of surplus, the storage is not charged with electricity from renewable energy sources of the municipalities but from the grid, when the specific emissions are low at that timestep. The electricity is discharged later when the specific grid emissions are high. As a result, more electricity is purchased from the grid with these regionalization methods, than in the other storage use cases, which causes a lower reduction in electricity purchasing costs. However, due to the correlation between prices and emissions, the emission optimized storage still manages to decrease electricity purchasing costs compared to the reference system where no additional community battery storages are available. For the storage distribution according to Reg3, the electricity purchasing costs can be reduced more significantly compared to the self-sufficiency optimized storage use case. Overall, there is a cost reduction of 2.7 % compared to the system without additional community battery storages. According to this logic, those municipalities are equipped with high storage capacity that have a high peak load and, consequently, high electricity intake. These are the municipalities that purchase electricity from the grid most of the time and inject only a small amount of renewable electricity. In this case, the emission optimized storage purchases electricity from the grid when the emissions are low. Due to the correlation between prices and emissions, these are usually the periods, when prices are low as well. The stored electricity is then used to reduce purchasing electricity at later timesteps, precisely when grid emissions and, consequently, electricity prices are high. This allows for the strongest reduction in electricity purchasing costs for this regionalization method in this use case.

In the comparison of use cases, the self-sufficiency optimized storage performs second best in two out of three regionalization methods. This is the case when the storage capacity is distributed based on installed capacity or renewable energy generation. In these cases, electricity purchasing costs can be reduced by 1.7 % and 1.4 %, respectively, compared to the reference case without community battery storages. When the storage is distributed according to Reg3, the cost reduction is the lowest at 1.6 % compared to the reference case, compared to the other two use cases. When comparing the cost reduction of the regionalization methods within the self-sufficiency optimized use case, Reg2 ranks last, as in all other use cases. Unlike the other two use cases, the self-sufficiency optimized use case achieves the greatest cost reduction when the storage is distributed according to installed capacity of renewable energy sources (Reg1). In this use case, the storage is operated to maximize the consumption of self-generated renewable electricity. The storage is charged whenever there is surplus in the respective municipality and discharged when there is a shortage. Electricity purchasing prices are not considered in this part of the analyses. Municipalities that provide a large amount of renewable energy not only have a high installed capacity of renewable energy sources but also high load factors. This means that most of the time, these municipalities can meet, or even exceed, their own electricity demand. A self-sufficiency optimized storage could therefore be charged at many timesteps. However, due to the low number of hours with electricity shortage, the storage can rarely be discharged. This results in storage capacity being tied to locations where it cannot be utilized according to the optimization logic. In other locations that have a balanced ratio of surplus and shortage hours, less storage capacity is available for reducing electricity procurement costs. A similar explanation applies to the results of Reg3. Here, municipalities with high peak loads and consequently high electricity demand, are equipped with high storage capacities. In these municipalities, electricity is purchased from the grid for most timesteps, which provides few opportunities for charging the storage with self-generated electricity. As a result, a significant amount of storage capacity remains unused, reducing the overall potential for lowering electricity purchasing costs. The regionalization based on installed capacity follows a similar logic to Reg 2, but it can achieve higher cost reductions. Unlike Reg2, Reg1 does not consider the load factors of renewable energy sources. Thus, municipalities with lower renewable energy generation are also equipped with higher storage capacities. These municipalities experience more timesteps of electricity shortage, allowing the storage to not only be adequately charged but also discharged more frequently. This enables better utilization of the distributed storage capacity and, consequently, greater reduction in electricity procurement and associated costs. In addition to better temporal utilization of the storage (i.e., number of equivalent full cycles), the better utilization of storage capacity also plays a role. Municipalities with the highest installed capacity often have the highest peak power generation. In the case of Reg2, precisely these communities, with the largest storage capacity, are also equipped with the highest storage power. This allows more energy to be stored from peak generation periods and later use this electricity to reduce purchasing of electricity.

Among all use cases, the cost optimized storage achieves the greatest reduction in electricity purchasing costs for all regionalization methods. Within the use case, the cost reduction for Reg2 is the lowest at 2.2% compared to the reference case. By distributing the storage capacity according to Reg1, electricity procurement costs can be reduced by 2.8 %. Reg 3 enables an even greater cost reduction of 4.5 %. The storage is operated to reduce costs for individual municipalities. They decrease purchasing of electricity when prices are high and increase feeding electricity into the grid when prices are high. In municipalities where electricity surplus occurs most of the time, they are utilized to charge the storage when electricity prices are low. When prices are higher, the storage is discharged to feed electricity into the grid, to generate profits. Storing electricity from the grid during periods of low prices rarely occurs in these municipalities because instances of electricity shortage are rare. Storing electricity from the grid to feed it back into the grid during periods of higher prices almost never occurs. This approach is not profitable due to the levies that must be paid for electricity from the grid, as the electricity prices must increase by at least the amount of the levies to generate profits. In the meantime, the storage cannot be used to store electricity from the municipalities, resulting in potential revenues not being captured, contradicting the optimization logic. As a result, in municipalities with high renewable energy generation, the reduction in purchasing electricity is only marginal, leading to lower cost reduction. In municipalities where electricity is mostly sourced from the grid, the behaviour of the storage is different. In these municipalities, more electricity is purchased from the grid when prices are low. It is later used to lower the electricity demand when prices are high. Thus, the amount of electricity purchased by the municipality changes only slightly. However, the associated costs can be significantly reduced. For this reason, the greatest reduction in electricity purchasing costs can be achieved with the storage distribution according to Reg3.

In the second step the revenues from selling electricity to the grid are calculated for each municipality by multiplying the amount of feed in electricity with the export price, which is analogue to the day-ahead price at the corresponding timestep. The reference system generated a total revenue of €7.9 billion from the sale of electricity. To quantify the absolute value added by the increase in revenue from electricity sold, the revenue from the reference system is deducted from all results. The increase of revenues for selling electricity to the grid is shown in Figure 6.

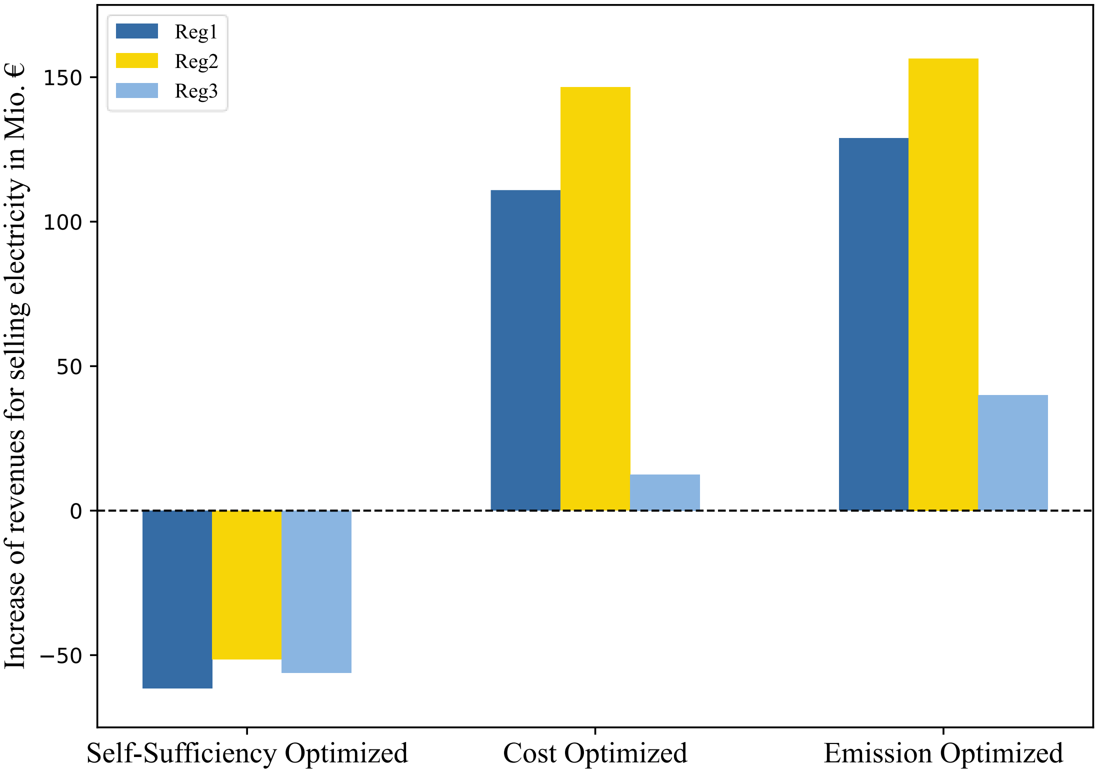

Figure 6: Absolute increase of revenue for selling electricity to the grid depending on the storage use case and regionalization

Figure 6 clearly shows that self-sufficiency optimized storage does not increase the revenues from electricity sold to the grid. On the contrary, the revenues are even reduced compared to the reference case. While in the case of a storage distribution according to Reg1, the electricity purchase costs could be reduced by 1.7 %, the revenues also decrease by 0.8 % in this storage distribution. With a storage distribution according to Reg3, the revenues are 0.7 % lower. If the storage capacities are distributed according to Reg2, the revenues are 0.6 % lower. This reverses the ranking of the regionalization's compared to the previously discussed cost reductions for the use case of self-sufficiency optimized storage. This also corresponds to the optimization logic of the storages. Simply optimizing self-sufficiency reduces the amount of electricity fed into the grid. This also means, that less revenue can be generated.

Looking at the increase of revenues, the emission optimized use case performs better than the cost optimized use case for all regionalization's. Here, too, the revenue increases in the individual regionalization's are exactly the opposite of the cost reductions. If the storage facilities are distributed according to Reg2, the revenues can be increased by 2 %. If they are distributed according to Reg1, revenues increase by 1.6%. A distribution of the storages according to Reg3 allows a revenue increase of only 0.5 %. The reason for the better performance of the emission optimized use case has already been explained above. In order to reduce emissions for each community, the storage facility purchases electricity from the grid more often, when emissions are low in order to sell it later when emissions are high. On the one hand, this leads to a lower cost reduction for the purchased electricity, but on the other hand, it also leads to higher revenues for the sold electricity.

In the use case of cost-optimized storage, the revenue from the electricity sold can be increased by up to 1.8% (Reg2). In the case of a storage distribution according to Reg1, the revenue increase is 1.4 %. In the case of a distribution according to Reg1, the increase in revenue potential is lowest at 0.2 %.

In the third step the costs for purchasing electricity from the grid are subtracted from the revenue, which is created by selling the surplus electricity. In total a revenue of 656 Mio. € could be generated in the reference system without storages. This revenue is subtracted from all the other results in order to quantify the value added measured by costs for the overall system. The absolute value added is shown in Figure 7.

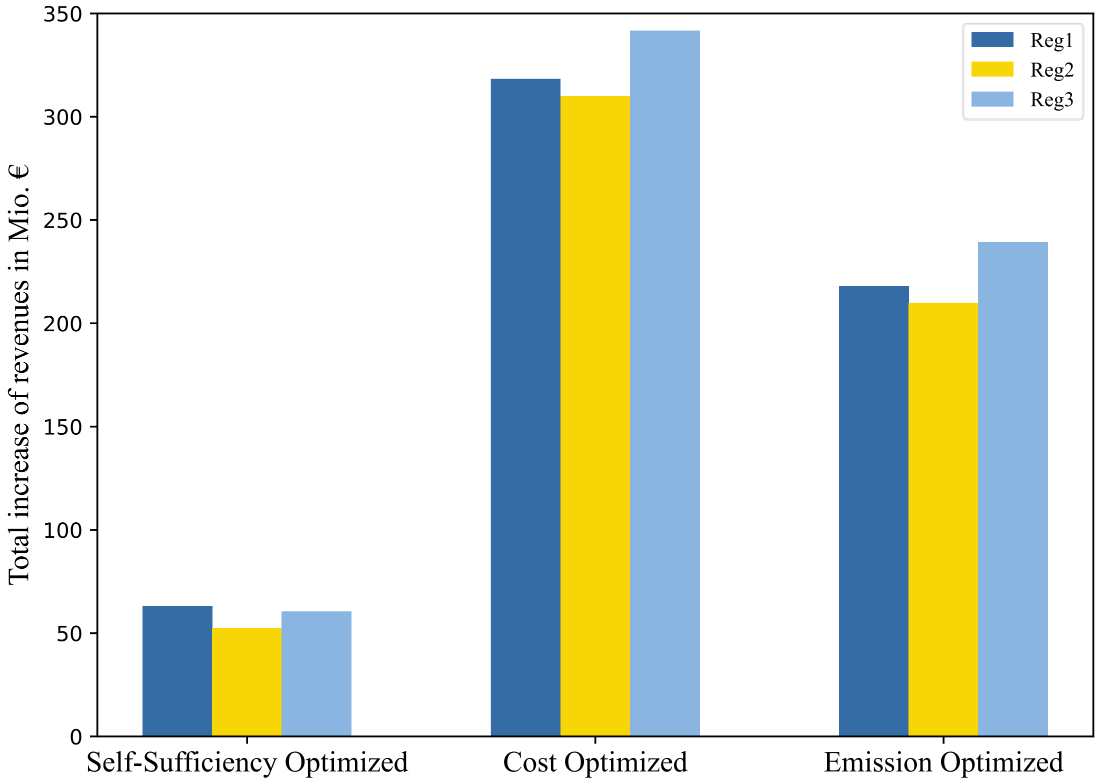

Figure 7: Overall added value quantified by costs

Compared to the reference system, all storage use cases and regionalization methods generate added value in terms of costs. The added value for the use case of self-sufficiency optimized storages is lowest at a maximum of 10 % with a storage distribution according to Reg1. A significantly higher added value can be achieved with emission optimized storages. This is due to the high correlation between electricity prices (day ahead prices) and specific emissions shown in Figure 3. In this case, a total added value of 38 % can be achieved for the entire system if the storage facilities are distributed according to the peak power of the municipalities (Reg3). Depending on the regional storage distribution, an added value of up to 54 % can be achieved with cost optimized storages. The performance of the individual storage use cases thus also corresponds to their optimization logics.

3.2.1. Analysis of the impact measured by emissions

Since the analysis of the impact measured in terms of costs has already dealt in detail with the storage behaviour of the different use cases in different municipality types (many surpluses from renewable energies, high electricity purchases from the grid), this is no longer discussed here. For this reason, a separate analysis of the emissions caused by electricity purchases and the displaced emissions achieved by electricity sales is omitted. Instead, the added value to the overall system achieved by community storages is shown directly, measured in terms of emissions. To do this, the emissions caused at the municipality level by the electricity purchased from the grid are first calculated and summed up. Then, the emissions displaced by renewable energy generation in each community are calculated. Finally, the emissions caused are subtracted directly from the displaced emissions. This shows that already in the reference system without additional storage capacities, more emissions are displaced in total by the household sector and the other renewable energy generation considered than are caused by electricity purchases. The result for the reference case is 815 kt CO2equ of displaces emissions. Figure 8 shows the added value that additional storages can achieve, depending on their use case and regional distribution.

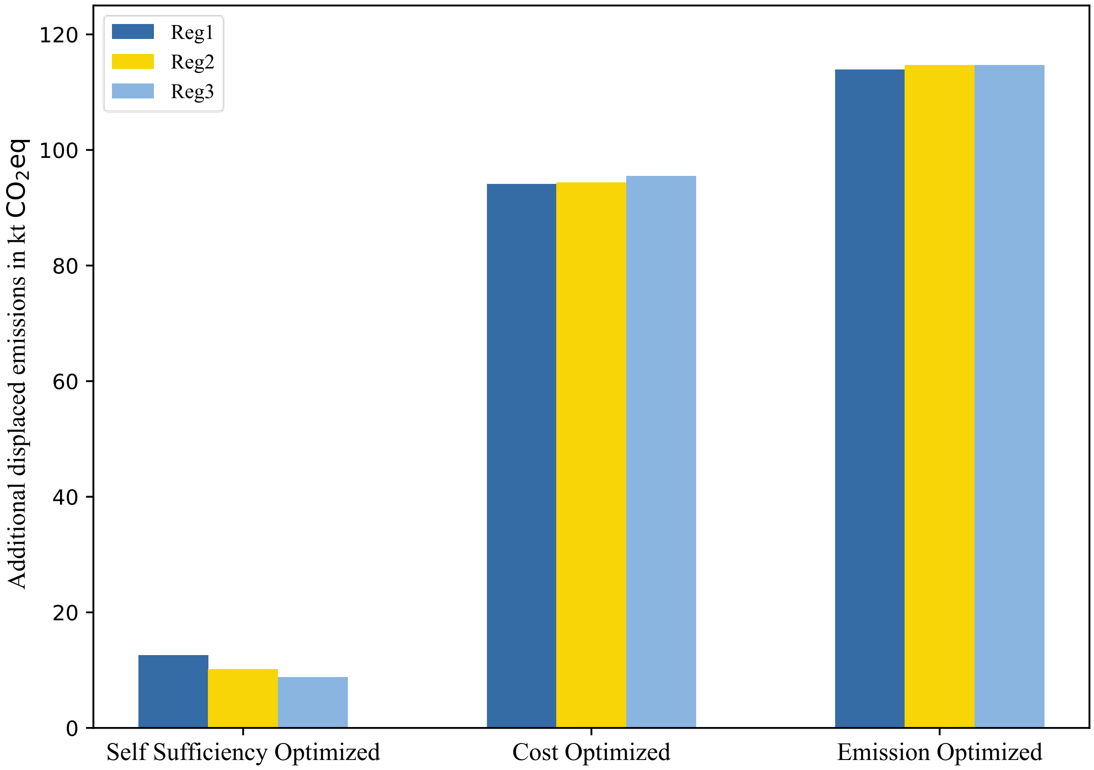

Figure 8: Overall added value quantified by emissions

Similar to the cost analysis (see Figure 7), the self-sufficiency optimized storage (cf. Figure 8) also performs worst in the emissions analysis. Within the use case, the greatest added value can also be achieved by a storage distribution according to Reg1. This amounts to 1.5 % compared to the reference system. In contrast to the costs, the lowest added value in terms of emissions can be achieved by distributing the storage according to Reg3 with 1 %. A storage distribution according to Reg2 achieves an added value of 1.2 %. The reason for the poorer performance of the Reg2 and Reg3 storage distributions has already been explained in the previous subsection. Both regionalization's mainly provide the municipalities with a high storage capacity where it cannot be used fully. In Reg2, these are the municipalities that predominantly sell electricity to the grid due to high renewable generation. Thus, there are many timesteps in which the storages can be charged, but only few time steps in which the storages can be discharged. In Reg3, it is exactly the opposite. Here, municipalities with a high peak load and thus also with a high power consumption are equipped with storage. As a result, there are only a few possibilities for the self-sufficiency optimized storages to store electricity from their own generation.

If the emissions are used as the basis for quantifying the added value for the overall system, the emission optimized use case performs best. In contrast to the costs, the regional distribution of the storage capacities has only a very small influence on the emissions. From a systemic point of view, under the assumption of an ideal network, it does not matter how the storage capacities are distributed. In all cases, the added value achieved approx. 14 % compared to the reference system.

The difference between the storage distributions considered is also only slight in the case of cost optimized storage. In all cases, an added approx. 11 % can be achieved compared to the reference system.

3.3 Local impact on municipalities

After the influence of additional flexibility through community battery storages was analysed in the previous chapter the influence on the individual municipalities will be investigated in this chapter. Similar to the previous chapter, the impact on the costs and emissions will be analysed. As in the previous chapter, it is assumed that surplus electricity from municipalities is absorbed by the industrial sector, which is not modelled. Therefore, the analysis of the value added by community battery storage at the municipal level also takes into account the revenues and displaced emissions from feeding electricity into the grid, in addition to the costs and emissions caused by electricity purchases.

Local added value considering costs

When determining the local added value measured in terms of costs, only the storage distribution according to Reg1 is considered, since this has the highest influence measured in terms of the overall system. For this purpose, the costs incurred for electricity purchases are calculated for each individual municipality. In addition to the costs, the revenues from the feed-in of electricity to the grid are also calculated on a municipality-specific basis. The calculated costs are then subtracted from the revenues for each municipality. The result is a balance sheet for each municipality for the reference system without storage, the use case of self-sufficiency optimized storage and the cost optimized storage. To determine the local added value, the balances of the two storage use cases are set in relation to the reference balance. The result can be seen in Figure 9 as the relative added value for each municipality.

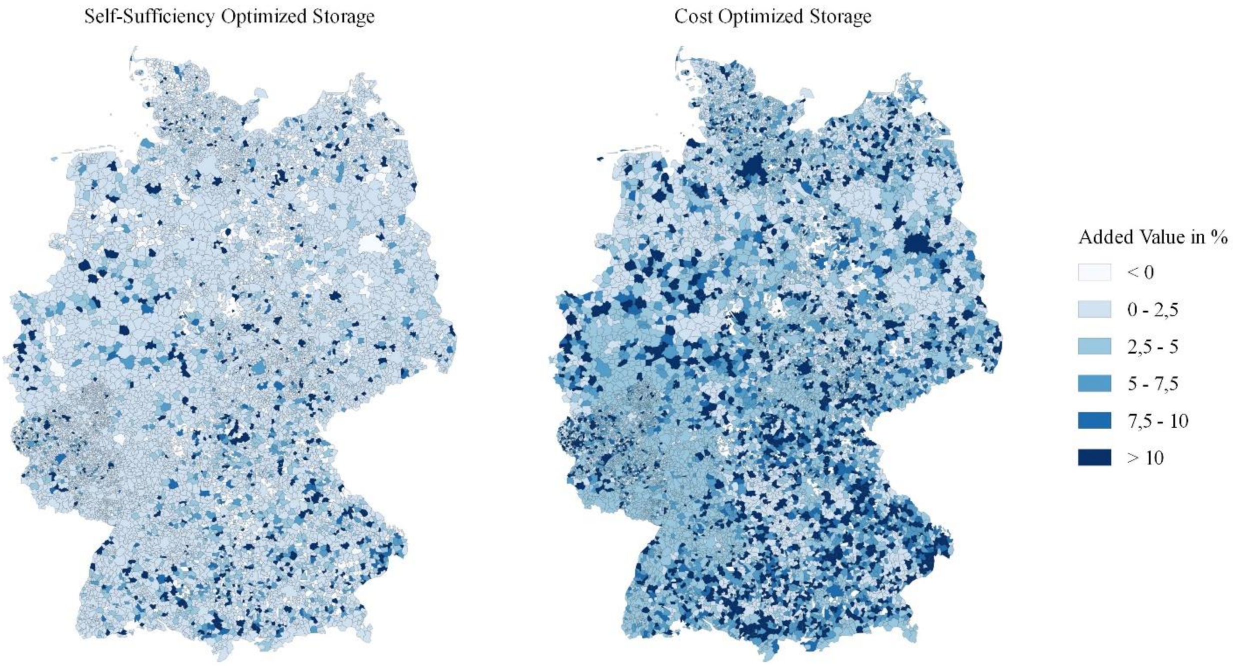

Figure 9: Relative added value quantified by costs using Reg 1

Figure 9 shows the relative added value that can be generated by additional flexibility in the form of community battery storages at the municipality level. Municipalities coloured in dark blue have a relative added value of more than 10 % compared to the reference case without storage. In municipalities marked in white, no added value can be generated by the additional flexibility.

On the left side, where the relative added value generated by the self-sufficiency optimized storage is shown, an even picture can be seen with only a few positive and negative outliers. In most municipalities, the additional storage can generate an added value between 0 % and 2.5 %. The negative outliers are municipalities in which no added value can be generated. These municipalities are either very large cities like Berlin or very small municipalities. In this large cities, there is no single time step over the entire year in which a surplus of renewable energy generation prevails. Consequently, the self-sufficiency optimized storages cannot store any surpluses here and thus remain unused. The small municipalities, in which no added value can be achieved, are municipalities that provide a surplus of renewable electricity at any time. As a result, the storage facility cannot store any electricity there and also remains unused. The positive outliers are also mostly small communities, in which an added value of more than 10% can be achieved through the additional storage capacity. In these municipalities, there is a good ratio of surpluses to shortages, so that the storage facilities can store and withdraw electricity throughout the year.

Compared to the left side, the right side, which shows the added value of cost optimized storages, shows a more uneven picture. While there are some municipalities in Northern Germany and at the border of Bavaria and Baden Wuerttemberg where an added value of less than 2.5 % can be generated by the additional storages, it is significantly higher in the other parts of Germany. This becomes particularly clear when looking at the major German cities such as Berlin and Hamburg, where the added value is mostly above 10 %.

Comparing the local distribution of the added value achieved in Figure 9 with the distribution of the storage capacity in Figure 2, major differences can be observed. In Figure 2, four main clusters could be identified for Reg 3. The first cluster is located in North Rhine-Westphalia and the northern part of Lower Saxony. The second cluster is located in

Saarland. The third cluster extends over parts of the states of Rhineland-Palatinate, Hesse and Baden Wuerttemberg. The fourth cluster is located in Berlin and its suburbs. In addition, smaller clusters are identified in and around the largest German cities. This cluster distribution no longer applies to the distribution of added value from Figure 9. The changes in the northern part of Lower Saxony in particular are clear. Here, larger storage capacities are located according to the regionalization logic Reg 3. However, the storage capacities are not big enough to store major parts of the surpluses in order to maximize the income from selling electricity to the grid. Therefore the absolute added Value is not big enough compared to the incomes generated within the reference system. The remaining part of the cluster merges with the cluster in Saarland and large clusters in Rhineland-Palatinate, Hesse and Baden-Wuerttemberg to form a cluster. In this cluster, renewable energy generation is not too large and frequent. As a result, added value can be generated by the storages located here. A new cluster is formed in the eastern part of Bavaria and in Thuringia. In the case of cost optimized storage, the largest cities also remain as clusters. Due to the high energy procurement, large added values can be achieved here through the storages. This is somewhat less the case for the suburbs.

Local added value considering emissions

When determining the local added value measured in terms of emissions, only the storage distribution according to Reg1 is considered, since it has the highest influence measured in terms of the overall system. For this purpose, the emissions for electricity purchases are calculated for each individual municipality. In addition to the emissions, caused by the purchase of electricity, displaced emissions from the feed-in of electricity resulting from the optimization of the individual municipalities are also calculated on a municipality-specific basis. These displaced emissions are based on the approach that by feeding renewable electricity into the grid, less electricity has to be provided by the grid and the partly fossil-fuel power plant park behind it. The result is an emission balance for each municipality for the reference system without storage, the use case of self-sufficiency optimized storage and the emission optimized storage. To determine the local added value, the balances of the two storage use cases are set in relation to the reference balance. The result can be seen in Figure 10 as the relative added value for each municipality.

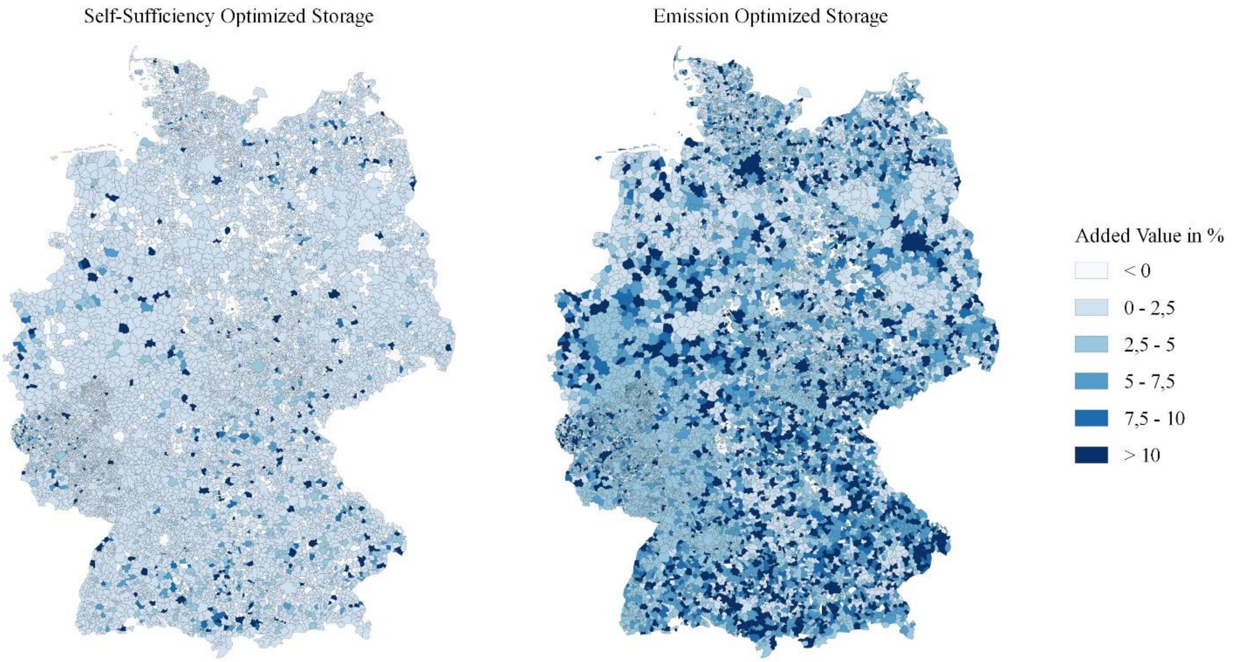

Figure 10: Relative added value quantified by emissions

Comparing the regional distribution of added value measured by emissions in Figure 10 with the distribution of added value measured by costs in Figure 9, similar patterns can be observed. This is due to the high correlation of prices and emissions shown in Figure 4.

Conclusion

In the course of the expansion of renewable energies with the goal of providing a climate-neutral energy supply, the need for additional flexibilities within the power system will also increase. A part of this flexibility demand (6 GW in 2035) will be provided by large-scale battery storage in the future [5]. In this paper, a simple approach was used to investigate the added value that these storages can generate if they are operated as community battery storages. For this purpose, load profiles for all individual municipalities in Germany were used [1,2]. These consist of the energy consumption of the household sector and the local electricity generation from renewable energies. Within the household sector, additional flexibilities from home battery storages and have already been considered. Since the simulation considered each municipality individually, the impact of additional local storage capacity on electricity prices and emissions within the grid was neglected. This led to a bias in the results, which is why overall system modelling must take place in the next step. The findings from this paper can be used as a basis for this.

The added value that can be generated by the additional flexibilities in the form of community energy storage was analysed on two levels. First, the sum of all municipalities was analysed as an overall system. A distinction was made between three different storage operation strategies (use cases) and three different logics for the regional distribution of storage capacities. If the added value was quantified on the basis of costs, it was shown that cost optimized storages primarily reduce electricity purchasing costs, whereas emission optimized storages increase revenues from sales. Overall, however, the cost optimized storages performed better than the emission optimized storages, which also corresponds to the optimization logic. In a comparison of the different regional storage distributions, the greatest added value was achieved with a distribution according to peak load. When quantifying the added value in terms of emissions, the results were similar. In accordance with the optimization logic, the greatest added value was achieved through emission optimized storage. In contrast to the quantification of the added value in terms of costs, the regional distribution of the storage facilities has a smaller influence here. Regardless of whether the added value was quantified by costs or emissions, it was lowest for the self-sufficiency optimized storages. The reason for this is the poor utilization of the storage capacities. This became particularly clear when evaluating the individual municipalities.
In addition to quantifying the added value for the overall system, the effects on the individual municipalities were also examined. For this purpose, the added value measured in terms of costs and emissions was calculated for each individual municipality and shown in the form of a map of Germany. A similar regional distribution of the added value for the cost optimized and emission optimized storage systems was found, which was positive for all municipalities. However, there were some deviations from the regional distribution of storage. In the case of self-sufficiency optimized storage, there were some municipalities in which the additional storage capacity did not generate any added value. This is due to the fact that, according to the optimization logic, the storage facilities in these municipalities could not be fully utilized.

In the next step, an overall system modelling must be carried out in which the industrial sector, which has so far been a passive electricity consumer, is also taken into account. Furthermore, the repercussions of the behaviour of the additional storage facilities on hourly electricity prices and grid emissions must be taken into account. Based on the findings of this paper, an investigation of the self-sufficiency use case can be dispensed with, since it has already proven to be only partially effective here. Instead, it is proposed to investigate an additional regionalization based on the ratio of generation and load within a municipality (supply-demand-ratio, SDR). In this case municipalities with a SDR near one (i.e. roughly equal supply and demand) are to be equipped with high storage capacities, since a balanced SDR allows for the most efficient usage of storages.

References

[1] Bogensprenger, Alexander Johannes: Assessing the Potential of Multiple Use Cases for German Energy Communities via Integration of Machine Learning in the Energy-Economic Modeling Process. Dissertation. Herausgegeben durch Technische Universität München - TUM School of Engineering and Design der Technischen Universität München: München, 2023.

[2] Bogensperger, Alexander et al.: Comparison of Pricing Mechanisms in Peer-to-Peer Energy Communities. In: 12. Internationale Energiewirtschaftstagung (IEWT) 2021. Wien: Technische Universität Wien, 2021.

[3] Corradini, Roger; Konetschny, Claudia; Schmid, Tobias– FREM - Ein regionalisiertes Energiesystemmodell –n: et - Energiewirtschaftliche Tagesfragen Heft 1/2 2017. München: Forschungsstelle für Energiewirtschaft, 2017

[4] Staatlich veranlasste Strompreisbestandteile. In https://www.bmwk.de/Redaktion/DE/Textsammlungen/Energie/strompreise.html. (Abruf am 2023-06-30); Berlin: Bundesministerium für Wirtschaft und Klimaschutz (BMWK), 2022.

[5] Klimaneutrales Stromsystem 2035. Wie der deutsche Stromsektor bis zum Jahr 2035 klimaneutral werden kann. Berlin: Agora Energiewende, Prognos, Consentec, 2022.

[6] ENTSO-E: Transparency Plattform. In https://transparency.entsoe.eu. (Abruf am 2023-03-27); Brüssel: ENTSO-E, 2023.

[7] The ecoinvent Database, Version 3.6: www.ecoinvent.org; Zürich: ecoinvent, 2019.

[8] Ganz, Kirstin: Wie funktioniert die Merit Order?. In https://www.ffe.de/veroeffentlichungen/infografik-wie-funktioniert-die-merit-order/. (Abruf am 2023-06-30); München: Forschungsgesellschaft für Energiewirtschaft mbH, 2022.

[9] Honghui, Xu: Dependent Evidence Combination Based on Shearman Coefficient and Pearson Coefficient. In: IEEE Access 06/2917. Chengdu, China: University of Electronic Science and Technology of China, 2017. DOI: 10.1109/ACCESS.2017.2783320.