Flexibility Reserve of Self-Consumption Optimized Energy Systems in the Household Sector

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Abstract: Energy generation and consumption in the power grid must be balanced at every single moment. Within the synchronous area of continental Europe, flexible generators and loads can provide Frequency Containment Reserve and Frequency Restoration Reserve marketed through the balancing markets. The Transmission System Operators use these flexibilities to maintain or restore the grid frequency when there are deviations. This paper shows the future flexibility potential of Germany’s household sector, in particular for single-family and twin homes in 2025 and 2030 with the assumption that households primarily optimize their self-consumption. The primary focus is directed to the flexibility potential of Electric Vehicles, Heat Pumps, Photovoltaics and Battery Storage Systems. A total of 10 different household system configurations were considered and combined in a weighted average based on the scenario framework of the German Grid Development Plan. The household generation, consumption and storage units were simulated in a mixed-integer linear programming model to create the time series for the self-consumption optimized households. This solved the unit commitment problem for each of the decentralized households in their individual configurations. Finally, the individual household flexibilities were evaluated and then aggregated to a Germany-wide flexibility profile for single-family and twin homes. The results indicate that the household sector can contribute significantly to system stabilization with an average potential of 30 GW negative and 3 GW positive flexibility in 2025. In 2030, the corresponding flexibilities potentially increase to 90 GW and 30 GW, respectively. This underlines that considerable flexibility reserves could be provided by single-family and twin homes in the future.

Keywords: flexibility provision; household sector; restoration reserve

1. Introduction

The transition of the energy and transportation sectors toward a higher share of renewable energies leads to a growing number of volatile electricity producers. This forces the Transmission System Operators (TSOs) to frequently make use of flexibility reserves. On the other hand, this also leads to an increasing number of flexible producers and consumers in the household sector (summarized under the term “microsystems”). The aim of this paper and the conducted study is to quantify the flexibility that the microsystems in single-family and twin homes could provide when participating in the German flexibility markets for Manual Frequency Restoration Reserve (mFRR) and Automatic Frequency Restoration Reserves (aFRR) in different scenarios for the years 2025 and 2030. For this purpose, the individual flexibility potentials of the microsystems Photovoltaic (PV), Battery Storage Systems (BSS), heat supply (Heat Pump (HP) and electrical heating elements) and Electric Vehicles (EVs) are identified and aggregated to average flexibility profiles, as described in Section 2. The same section details the methodology of the applied optimization...
model to simulated household configurations and behavior. The flexibility profiles are analogous to standard load profiles (SLPs) [1] and depend on the season and the day of the week.

The German Grid Development Plan 2030 [2] provides the framework for this paper. The same data and assumptions are used as those underlying the “B2025” and “C2030” scenarios. The B2025 scenario reflects a moderate expansion path in the near future. C2030 represents a progressive scenario with a high share of renewable energies and high degree of sector coupling [3].

Previous studies indicated a high importance of flexible electricity consumers and producers in the future balancing markets, but did not focus on the household sector and the scenarios of the German Grid Development Plan. Hahn et al. [4] investigated in detail the costs of providing flexibility through different technologies, in particular, Combined Heat and Power Plants (CHPs) and Energy Storage Systems (ESS), and You et al. [5] presented a novel approach to calculate flexibility offers for HPs and CHPs. Angenendt et al. [6] described in detail how BSS can participate in the Frequency Containment Reserve (FCR) market and its affect on economic efficiency and aging. Participation in the balancing market reduces the household’s self-consumption, and the battery experiences a higher load. Nevertheless, the economic efficiency of the system increases. An incentive system for flexibility provision and the estimated flexibility potential for the German state of Baden-Wuerttemberg was discussed by Liebe and Wissner [7]. For 2030, an EV-based maximum potential for negative flexibility of 400 MW and positive flexibility of 850 MW was shown. Schill et al. [8] determined the extent to which EVs can provide flexibility as a balancing reserve in 2035. Their results showed a positive flexibility of up to 1000 MW and a negative flexibility up to 1700 MW.

Elsner et al. [9] conducted a comprehensive evaluation of different technologies for flexibility provision. The flexibility provided through Demand Side Management (DSM) by German households was estimated to have a potential of $+/-65$ GW and 130 GWh in the year 2050. This includes household appliances, BSS and EVs. According to the results, the potential of PV, BSS and EVs significantly exceeds that of household appliances. Elsner et al. assumed that 70% of households will have an EV, and 20% of the EVs battery capacity will be available for grid control tasks (Vehicle-to-Grid). They also assumed that 80% of the houses with a maximum of two residential units have a BSS installed.

The present paper analyzes the potential that is technologically available for the provision of system services by households. The focus on single-family and twin homes is set, since those households are in control of all system components, can install PV and easily charge EVs in their driveway. Apartment and commercial buildings, as well as EVs, are not considered in this paper due to more complex regulations and energy management systems. Costs and benefits arising from flexibility provision are not the subject of this paper and have already been addressed in the publications mentioned beforehand.

2. Methodology and Flexibility Assessment

There are many different combinations of microsystems that can appear in households. In order to demonstrate and compare the impact of PV, BSS, HPs and EVs on the flexibility potential, all possible combinations are evaluated with the exception that BSSs are only considered in combination with PV, due to the lack of investment incentives for the household sector. This results in 10 possible microsystem combinations, which are shown in Table 1 with their frequency of occurrence in Germany, derived from the German Grid Development Plan [2].
Table 1. Different combinations of microsystems and their weighting according to the Grid Development Plan in *million units and percent.

| Scenario                                      | 2025 [M*] | 2025 [%] | 2030 [M*] | 2030 [%] |
|-----------------------------------------------|-----------|----------|-----------|----------|
| 1 PV only                                     | 2.88      | 52       | 2.22      | 22       |
| 2 Heat pump only                              | 0.88      | 16       | 1.70      | 17       |
| 3 Electric vehicle only                       | 0.28      | 5        | 1.50      | 15       |
| 4 Electric vehicle and heat pump              | 0.14      | 3        | 0.75      | 12       |
| 5 PV and battery system                       | 0.30      | 5        | 0.49      | 5        |
| 6 PV and electric vehicle                     | 0.21      | 4        | 1.12      | 11       |
| 7 PV and heat pump                            | 0.51      | 9        | 1.23      | 12       |
| 8 PV, battery system and electric vehicle     | 0.12      | 2        | 0.49      | 5        |
| 9 PV, battery system and heat pump            | 0.12      | 2        | 0.28      | 3        |
| 10 PV, battery system, heat pump and electric vehicle | 0.06      | 1        | 0.14      | 1        |

A total of 1200 time series were generated for the 10 combinations using the optimization system described in Section 2.2. For each combination, time series were generated for 120 households representing differing design parameters and operating conditions to obtain load flows and, if applicable, the State of Charge (SoC) of storages. The 120 simulations are the result of four different locations throughout Germany combined with three different orientations of the PV system per location. To also account for varying user behavior, these twelve combinations were then assigned to 10 randomly selected thermal load profiles, electrical load profiles and driving profiles. Finally, a mixed scenario was created that considers a weighted combination of the individual scenarios.

2.1. Parameters of the Microsystems and Their Flexibility Potentials

This section describes the input data for the time series generation and the flexibility potential of the microsystems. First, the data and parameters of the microsystems are explained, starting with PV in Section 2.1.1, followed by BSS in Section 2.1.2, EVs in Section 2.1.3 and the heating system in Section 2.1.5. Finally, the load profiles and the economic constraints are detailed.

2.1.1. Photovoltaic Systems

To determine the PV system performance, the simulation uses irradiation and ambient temperature data derived from the DWD COSMO-DE regional model [10] for the year 2012. The year 2012 is also used in the Grid Development Plan 2030 as a representative reference year. The data were obtained for four locations in Germany, with three different orientations (south, southeast, southwest). The roof pitch is assumed to be 37.5 degrees in all cases. The selected regions are shown in Figure 1, the reference location used for each segment is marked. The weighting of the regions is shown in Table 2, it is based on the PV capacity given in the Grid Development Plan [2]. Figure 2 shows the normalized generation of the PV system for the northeast location with a southern orientation as an example.

Table 2. Distribution of the installed Photovoltaic (PV) capacity amongst the four German regions.

| Region       | 2025 [%] | 2030 [%] |
|--------------|----------|----------|
| Northwest    | 27       | 30       |
| Northeast    | 21       | 20       |
| Southwest    | 26       | 26       |
| Southeast    | 27       | 24       |
Figure 1. Segmentation of Germany into the regions Northwest, Northeast, Southwest and Southeast with their respective reference locations.

Figure 2. Normalized generation of the PV system for the northeast location with southern orientation.

For a sample of 45,500 PV systems (see German market register [11]) with a maximum capacity of 10 kWp and a BSS, the south (45%), southwest (20%) and southeast (15%) orientations dominate. These percentages are used for the aggregation in Section 2.3.2 and are assumed to stay constant for the years 2025 and 2030. In the 120 simulated households, the PV system size ranged from 2 to 10 kWp with an average of 7 kWp.

The flexibility potential of PV depends on the output power at any given time. The output power can be reduced to provide negative flexibility. It is assumed that in normal operation, PV systems are always operated with their maximum possible output according to the irradiation. A preventive downregulation of PV to provide positive flexibility was not considered in this paper.

2.1.2. Battery Storage Systems

The German funding program for decentralized and stationary BSS [12] provides a detailed overview of the types and sizes of the storage systems used. The sizing of the BSS in this paper is based on the distribution found in the aforementioned publication, which correlates with the households’ electricity consumption. This results in BSS sizes ranging from 0.8 to 24 kWh with an average of 7.4 kWh for all 120 systems.

According to the Grid Development Plan [2], a ratio of battery capacity to charge/discharge power of 1 C is assumed. The C coefficient describes the charge and discharge process independent of its capacity. A discharge rate of 1 C indicates the storage can be
completely discharged or charged within one hour. However, the most frequently used hardware types typically have an inverter capacity of at least 2 kW and a maximum of 8 kW. These limits were assumed in this paper, resulting in an average power of 6 kW for all 120 systems.

BSSs are used in households in combination with PV to maximize a household’s self-consumption and, thus, minimize the amount of electricity drawn from the grid. The charging and discharging behavior of a BSS is based on these requirements. Therefore, the BSS is fully charged when there is excess electricity from PV before electricity is fed into the grid. The flexibility potential of the BSS is calculated as the difference between the possible charging/discharging power and the actual power without flexibility provision. To provide negative flexibility, the discharging power can be reduced or the charging power can be increased. Conversely, positive flexibility results from an increase of the discharge rate or a decrease of the charging rate. In extreme cases, flexibility can be provided by switching from charging to discharging or vice versa, which can result in a flexibility twice as high as the maximal charging/discharging power. In addition to the charging and discharging power, the immediate flexibility potential is limited by the total capacity of the BSS and its current SoC. Negative flexibility can be provided up to a full charge, and positive flexibility up to a complete discharge.

The potential for a longer period of providing flexibility (provision period) is defined by the minimum immediate flexibility potential in the provision period. It is furthermore limited by the difference between the SoC and the minimum or maximum SoC. For example, for a 4 h provisioning period, the flexibility potential can reach a maximum of 0.25 C.

2.1.3. Electric Vehicles

The modeling of the EVs consists of the EV’s energy demand and battery storage. For the energy demand, we considered medium sized vehicles launched in the next two years. This resulted in an average electricity demand of 18 kWh/100 km.

An average storage capacity of 60 kWh was used for the EV’s storage. This was justified by the broad availability of public, high power charging capacities in 2030. This and the learning effect for vehicle owners made higher capacities unnecessary. The maximum power while charging at home was set to 11 kW using a simplified linear charging process.

The calculation of the flexibility potential of EVs is essentially the same as the flexibility calculation of the BSS. However, the following differences and additional restrictions have to be considered:

- The charging and discharging power is not necessarily limited by the battery of the EV, but by the maximum power rating of the wallbox (11 kW).
- For 2030 it is assumed that 50% of EVs will be able to charge bidirectionally.
- The EV has to reach a minimum SoC according to the user’s needs during charging. As a comfort feature, it is assumed that system services can only be provided if the SoC is above 70%. Below this level, the battery is recharged as fast as possible. Furthermore, the capacity for the next trip must also be available at the scheduled start of the trip. The trips and their electricity demand are defined according to the driving profiles described in Section 2.1.4.
- Flexibility can only be provided if the EV is plugged into the home wallbox. A possible provision of flexibility at public charging stations was not considered.

2.1.4. Driving Profiles

The simulation model integrates 120 different driving profiles. The profiles include the distance travelled and the current location. The energy demand results from the distance. The simulation model assumed that the EVs were only charged and available for system services when plugged in at home. Public charging points are included in the model, but due to the higher cost compared to home charging, they were only chosen when a distance traveled was further than battery capacity would have otherwise allowed. Charging options at the workplace were not taken into account. Due to tax advantages and flat rates,
charging at the workplace is often more attractive than charging at home. This implies that this share of EVs is rarely connected to the home grid and thus contributes only marginally to the flexibility potential of the household sector.

The profiles were created within the framework of the project “Charging Infrastructure 2.0” [13] using data from a nationwide survey “Mobility in Germany” (MiD) [14]. In this survey, 135,000 households were questioned about their everyday traffic behavior on behalf of the Federal Ministry of Transport and Digital Infrastructure (BMVI). Figure 3 shows the mean distance of all profiles and Figure 4 shows the mean presence of all EVs at home per type day and season. The annual mileage of the used driving profiles are between 7000 and 15,000 km, the average annual mileage is 11,236 km and the distances of the everyday trips are between 10 and 50 km.

![Figure 3. Average distance driven according to the driving profiles, based on [13].](image1)

![Figure 4. Mean presence of Electric Vehicles (EVs) at home parking lots, based on [13].](image2)

2.1.5. Heat Pumps and Auxiliary Heating Systems

If electricity is used to provide heat in a household, the heating system can also be used to provide flexibility in a power-to-heat context. Due to the high share of air-to-water heat pumps in Germany, we focus on this technology [15]. In addition to the heat pump, the heating system also includes an electrical auxiliary heating system (heating element), a domestic hot water storage, and a heating buffer storage. The design parameters of the heating system are determined based on the thermal load profiles described in Section 2.1.6:

- Heat pump with a thermal output of up to 14 kW;
• Electric auxiliary heater (heating element) with an electrical and thermal power of up to 9 kW;
• Hot water tank with a volume of 160 L;
• Heating buffer storage tank with a volume of 750 L.

The system’s flexibility results from the power reserve of the heating systems, the storage capacity of the domestic hot water tank, and the heating buffer storage. The following assumptions and specifications were made to determine flexibility potentials:
• The domestic hot water tank can be heated up to 80 °C for flexibility provision.
• The heating buffer storage tank is not used in the summer since there is typically no heating demand during this period.
• For the HP, the conversion rate between the electrical and thermal energy is defined by the Coefficient of Performance (CoP), while the heating element converts the electrical energy to thermal energy in a 1:1 ratio.

It can be beneficial to solely utilize the heating element providing negative flexibility over a longer period. We calculated the potential negative flexibility of each timestamp for (a) the heating element and (b) a combination of the heating element and the heat pump. The higher flexibility was then selected. The heating element is only used during normal operation, when there is an actual heat demand that cannot be covered by the heat pump alone. Thus, turning off the heating element or reducing its power results in a comfort loss, which is unacceptable for the provision of positive flexibility.

2.1.6. Thermal Load Profiles

The heat pump and the heating element have to cover the thermal load caused by heating and domestic hot water generation. For heating, an average specific heat demand of 80 kWh/m²a was assumed according to the scenario framework of the preliminary Grid Development Plan 2035 ([16], Table 15). The Grid Development Plan 2030 used in other parts of this paper did not provide any information on this.

The thermal load profile was determined from the outdoor temperature and solar radiation of the four reference locations. The heating calculation was based on a TRN-SYS heat demand model obtained from Fraunhofer IEE. Heat pump systems are usually combined with large-area heating units, such as underfloor heating systems. To simplify the model, no usage variations were assumed for the space heating, since the high inertia of the underfloor heating systems usually result in a constant room temperature even when residents are absent.

For the domestic hot water energy demand, tap profiles with stochastic variation were used [17]. These were weighted according to the population structure in Germany, taking into account the number of residents per household.

2.1.7. Electrical Load Profiles

The household’s electrical load of the simulated systems must be covered at each time interval. To properly represent the load profiles of German residential buildings, this simulation used the HTW-Berlin data set [18]. The essential characteristics of the load profiles are the following:
• Energy consumption between 1400 kWh/a and 9000 kWh/a;
• Average energy consumption: 5233 kWh/a;
• The household profiles do not include loads from heat pumps or EVs.

2.1.8. Economic Constraints

A market-driven electricity price was assumed based on the hourly prices of the day-ahead market. The time series of the day-ahead market was extrapolated using the SCOPE model [19,20]. A fixed price component was added, which includes grid charges, surcharges, and taxes. It was assumed that electricity generated by PV is less expensive than electricity purchased from the grid, and is preferentially used in household loads.
See Figure 5 for an overview of the average electricity price per type of day for the different seasons.

![Figure 5](image_url)  
**Figure 5.** Average electricity price per type of day and season.

### 2.2. Model Design

The households and their small-scale power units are regarded as self-demand optimized microsystems. The analysis of the flexibility potential is based on a mixed-integer linear program, which solves the unit commitment problem (UCP) for each of the decentralized household microsystems (i.e., the Home Energy Management System (HEMS)). The UCP considers the technical and economic restrictions of energy production, consumption and storage units. The objective function then maximizes the economic profits over the solution space. The major restrictions of this system and the objective function are defined below. The UCP is based on the Fraunhofer IEE optimization framework microSCOPE, whose optimization core, micro-core, was also applied in [21]. A table with a parameter and variable description is included in the Appendix A.

#### Equation System

The objective function maximizes the overall profits of the microsystems, which considers income from grid feed-in, costs of the operation of the energy units, and electricity taken from the grid, as seen below:

\[
\text{maximizing } \sum_{m \in M} \sum_{t \in T} \left( \pi_{\text{feed-in},t}^{(\text{grid})} \cdot \pi_{\text{feed-in},t} - \pi_{\text{cons},t}^{(\text{grid})} \cdot \pi_{\text{cons},t} \right) \cdot \Delta t, \tag{1}
\]

where \( \pi_{\text{feed-in},t}^{(\text{grid})} \) is the power flow going to the grid, \( \pi_{\text{cons},t}^{(\text{grid})} \) is the grid consumption power and \((\pi_{\text{feed-in},t}^{(\text{grid})}, \pi_{\text{cons},t}^{(\text{grid})})\) are the prices for electric energy fed into or taken from the grid, respectively.

The PV system is in each time step \( t \) constrained by a minimum generation of 0 kW and the forecasted generation \( P_{\text{fc},t}^{(\text{pv})} \) described in Section 2.1.1:

\[
0 \leq P_{\text{t},t}^{(\text{pv})} \leq P_{\text{fc},t}^{(\text{pv})}. \tag{2}
\]

The BSS operation is defined by the charging/discharging power and the SoC \( e_{\text{t}}^{(\text{bss})} \). The SoC is calculated by the previous period’s SoC minus the discharged energy plus the charged energy, which is taken from the grid or from the PV, such that:

\[
e_{\text{t}}^{(\text{bss})} = e_{\text{t-1}}^{(\text{bss})} \cdot (1 - \mu_{\text{time}}^{(\text{bss})} \cdot \Delta t) + \left( (1 - \mu_{\text{time}}^{(\text{bss})}) \cdot p_{\text{charge},t}^{(\text{bss})} + (1 - \mu_{\text{time}}^{(\text{bss})}) \cdot p_{\text{discharge},t}^{(\text{bss})} \right) \cdot \Delta t, \tag{3}
\]

where \( \mu_{\text{time}}^{(\text{bss})} \) defines the energy loss over time, while \( \mu_{\text{bss}}^{(\text{bss})} \) indicates the energy losses during charging and discharging.
The SoC is constrained by the minimum and maximum SoC of the storage system:

\[ e_{\text{min}} \leq e_t^{(bss)} \leq e_{\text{max}}. \]  

(4)

Charging and discharging rates are limited by the rated power, while either charging or discharging is allowed during one interval:

\[ p_{\text{charge},t}^{(bss)} \leq s_{\text{uni},t}^{(bss)} \cdot p_{\text{rated}}^{(bss)} \]  

(5)

\[ p_{\text{discharge},t}^{(bss)} \leq (1 - s_{\text{uni},t}^{(bss)}) \cdot p_{\text{rated}}^{(bss)}. \]  

(6)

In Equations (5) and (6), \( s_{\text{uni},t}^{(bss)} \in \{0, 1\} \) is a binary variable whose state equals 1 if the storage charges and 0 otherwise.

The EV can be modeled similarly using a variation of Equations (3)–(6), where \( p_t^{(ev)} \) corresponds to the consumption profile:

\[ p_{\text{discharge},t}^{(bss, ev)} = p_t^{(ev)}. \]  

(7)

Each HP has an efficiency rate given by the CoP, which relates the heat supplied to the electrical energy consumed such that:

\[ p_t^{(hp)} \cdot \text{COP} = q_t^{(hp)}. \]  

(8)

The energy sources are used to supply energy to the simulation system. While the energy yield of the PV system is covered by Equation (2), the electricity consumed from the grid is flexible and is dependent on the self-generated electricity, storage discharging and household load. No additional constraints are therefore required.

The energy balance in the equation system is ensured by two central energy balance equations. One for the electricity balance of the household, and one for the thermal demand (Figure 6). The balance equation of the electrical energy defines the relationship between the parameter for the household’s electricity baseload (\( P_{\text{el}} \)) and the power variables of the energy generation and consumption units, including the BSS:

\[ p_t^{(pv)} + p_{\text{discharge},t}^{(bss)} + p_{\text{cons},t}^{(grid)} = p_{\text{charge},t}^{(bss, ev)} + p_t^{(hp)} + p_t^{(he)} + p_t^{(bss)} + p_{\text{charge},t}^{(bss)} + p_{\text{feed-in},t}^{(grid)}. \]  

(9)

Figure 6. Visualization of the modelled microsystem with all possible power units.
The thermal energy balance is defined similarly, where $Q_{th}^h$ corresponds to the thermal demand of the household, $q_{th}^{(hp)}$ and $q_{th}^{(he)}$ are the thermal generations of heat pump and heating element, respectively, and $q_{tss}^{(tss)}$ are variables for charging and discharging the thermal storage system:

$$q_{th}^{(hp)} + q_{th}^{(he)} + q_{tss}^{(tss)} = Q_{th}^h + q_{tss}^{(tss)}.$$  \hspace{1cm} (10)

2.3. Flexibility Assessment

Flexibility is determined by modeling and simulating the households’ system behavior during normal operation. HEMSs are operated with the aim of maximizing profits while minimizing costs, and they do not explicitly consider flexibility provision in their operating strategy. The determined flexibility potentials are, therefore, an additional benefit without restrictions or disadvantages for the household occupants.

The following provision periods are taken into account when determining flexibility:

- Immediate flexibility;
- Provision over at least 15 min;
- Provision for at least 1 h;
- Provision over at least 4 h.

Apart from the provision periods mentioned above, it is assumed that the system is unaffected by any previously provided flexibility.

2.3.1. Household Flexibility

Depending on the microsystem configuration, a household can provide both positive and negative flexibility. Positive flexibility is provided if a household increases its feed-in to the grid or if it reduces its electricity consumption. Negative flexibility is provided by reducing the amount of electricity fed into the grid or by increasing the amount of electricity consumed. The load and consequently flexibility of a household results from the sum of the changes in the input or output of the individual producers or consumers, as seen in Equation (11):

$$P_{th}^{bh} = P_{el}^i + P_{ev}^{(ev)} + P_{bs}^{(bs)} + P_{ev}^{(ev)} + P_{th}^{(hp)}.$$  \hspace{1cm} (11)

To determine the flexibility, the individual sub-systems are first considered independently and then combined. The basic household consumption without EV or HP ($P_{el}^i$), was not altered in this paper. Potential flexible consumers, such as smart appliances, were not considered, since they are not expected to be mainstream in the near future.

2.3.2. Aggregation and Extrapolation

A simulation system was set up for each of the 10 system combinations (see Table 1). Each system was simulated 120 times with varying input parameters. The 120 simulations resulted from the combination of the four locations (Figure 1) with the three different roof orientations (Section 2.1.1). For each of these combinations, 10 different household load profiles were randomly assigned, resulting in 120 time series per system combination.

The individual flexibility profiles were aggregated into an average, German-wide household profile. The aggregation was performed in three consecutive steps:

1. Aggregation to the location and orientation level: The 10 flexibility time series for each location and orientation were aggregated into an average profile with evenly weighted inputs.
2. Aggregation to the location level: Twelve average profiles remained with three per location, which were aggregated into one profile per location. The individual profiles were weighted according to the orientation proportions in Section 2.1.1.
3. Standardized German household flexibility: The results of the four locations were aggregated to a standardized German household flexibility profile using the weights presented in Table 2.

The flexibility profiles of standardized German households are available for each of the scenario/system combinations as presented in Table 1. For further evaluation, these standardized household profiles can be mixed and extrapolated to evaluate various scenario designs as discussed in Section 2. This approach allows for a simple adjustment of the scaling factors to evaluate alternative expansion scenarios.

3. Results

The presented results are based on the weighted and extrapolated scenario as described in Section 2.3.2. The average positive and negative household flexibilities were derived through a weighted aggregation of system combinations, load profiles, and locations. They were then scaled to a single nationwide flexibility profile (time series) for Germany using the numbers provided in Table 1. Detailed results of the single system combinations are available and can be requested from the authors.

All results are visualized in the style of residential SLPs as described by [1]. This visualization style allows for easy differentiation between seasons as well as between workdays and weekends. The flexibility results of all days belonging to a certain period (seasons, workday vs. Saturday and Sunday) were aggregated (mean, interquartile range, min/max) and visualized in different combinations. The following subsections provide an overview of the flexibility potential in 2025 and 2030, discuss the impact of different product lengths when trading the flexibility, and highlight the daily variation within specific seasons.

The subsequently used seasons are defined as follows:

- Winter: First Monday of December until the first Monday of April of the following year;
- Transitional season: First Monday of April until first Monday of June, and first Monday of October until first Monday of December;
- Summer: First Monday of June until first Monday of October.

3.1. Comparison of the Potential Flexibility in 2025 and 2030

3.1.1. Immediately Available Negative Flexibility

Figure 7 shows the immediately available negative flexibility for the mixed scenario for 2025 (Figure 7a) and 2030 (Figure 7b). The average daily flexibility profile is depicted for the categories workday, Saturday and Sunday and the previously defined seasons winter, transitional season and summer. Public holidays as well as school holidays are likely to affect the results but have not been accounted for due to the varying definitions of the German states.

The substantial increase of the available flexibility from approximately 30 GW in 2025 to 80 GW in 2030 is mainly caused by the much higher number of the considered households and the higher market penetration of BSS and EVs. The shifting shares for the different system combinations from 2025 to 2030 also affect the flexibility profile’s shape throughout the day. While the negative flexibility available by shutting down PV systems is still evident through the peak around 12 a.m. in 2025, other systems dominate the flexibility provision in 2030.

The workday available flexibility in 2030 drops during the daytime, which is mainly linked to EVs being used during that time, making them unavailable for flexibility provision. Furthermore, BSSs reach their maximum SoC and cannot provide negative flexibility as soon as they are fully charged. In both years, the available flexibility during the winter and transitional season is slightly higher than during the summer. This difference is caused by the heating systems, which, with the exception of water heating, are not used during the summer and some periods of the transitional season. The decrease of the average flexibility throughout the weekend is caused by EVs reaching a high SoC.
3.1.2. Immediately Available Positive Flexibility

While the daily profiles of the immediately available positive flexibility shown in Figure 8 appear different from the negative flexibility presented beforehand, the affecting principles are very similar. Since fewer system components can provide positive flexibility, the positive flexibility is significantly lower than the negative flexibility. The positive flexibility in 2025 is mainly characterized by the BSS and indirectly caused by the PV system. Since the BSS can switch from charging to discharging, the immediately available positive flexibility peaks whenever the PV system reaches its maximum power. The two drops in the morning (around 6 a.m.) and in the evening (around 9 p.m.) are likely caused by an increase in household electricity consumption supplied by the BSS.

The dramatic increase in the immediately available positive flexibility from about 2 GW in 2025 to about 28 GW in 2030 is caused by EVs. While in 2025 all EVs and wall-boxes are still considered to operate unidirectionally and thus cannot contribute to the provision of positive flexibility, the share of EVs and wall-boxes capable of bidirectional charging is considered to be 50% in 2030. In addition, the number of expected EVs is sixfold from 2025 to 2030. While the number of BSSs also increases, EVs dominate the flexibility in 2030. This is particularly due to their high charging and discharging power of up to 11 kW. Similar to the provision of negative flexibility, the drop during working hours in 2030 is caused by EVs in use or parked elsewhere. Based on the used driving profiles, weekends are hardly affected by EVs unavailability.
In both years, the available positive flexibility during the summer and the transitional seasons is higher than during the winter. This can be attributed to the PV system and BSS, since the BSS is charged at a higher power during summer days. In addition, the households' electricity demand during summer nights is lower compared to winter nights. The heating system is insignificant since the heat storage is not proactively charged anticipating an upcoming flexibility demand.

3.2. Daily Variation in the Available Flexibility

The results presented in Section 3.1 show the negative and positive flexibility available on an average day. This implies a higher and lower flexibility potential during single days of the presented categories. While an average value is a good indicator for the general flexibility potential, it is crucial to provide a certain flexibility with a high likelihood as soon as households are utilized for flexibility provision.

Figures 9 and 10 show the variation of the available negative and positive flexibility for 2030. The depiction is inspired by a boxplot and presents the average availability (dark blue line), the flexibility range (light blue band), and the minimal and maximal available flexibility (red lines) of the considered days. Figure 9 compares the variability of the negative flexibility in the summer and winter of 2030. The average flexibility is slightly higher in the winter months than the summer, as also presented in Section 3.1.1. This is
caused by the higher capacity of the heating system during winter months, which also causes a higher variation recognizable in Figure 9b.

![Statistics of the negative flexibility: summer](image)

![Statistics of the negative flexibility: winter](image)

**Figure 9.** Daily variation in the immediately available negative flexibility in the (a) summer and (b) winter of the year 2030.

The potential positive flexibility depicted in Figure 10 appears to be less volatile for both summer and winter months. At the same time, the spikes of the maximal flexibility stand out. The presented min. and max. values are the combined min. and max. values of all considered days. Spikes can be caused by low prices and/or weather events of single days. Zig-zag behavior as seen in Figure 10b is usually the result of spikes during multiple days. They occur in the early morning workdays, and they occur on weekends in the morning and around noon. Those spikes can be mainly explained by low electricity prices; due to an independent charging management, the EVs utilize this in their optimized charging schedule and start to charge with high power at the same time. Many cars drop out shortly after due to fully charged batteries. Stopping the charging process (unidirectional) or even discharging the battery to provide positive flexibility leads to the spikes present in both seasons. The spikes are less evident during the summer months since the EVs are optimized to charge using PV power, thus, drawing less power from the grid.
The flexibility statistics show that the utilizable values can be significantly lower if high likelihoods are required. Forecasts are likely to account for most of the variability, and Virtual Power Plants (VPPs) can make this variability manageable. Still, when discussing future flexibility options and capacities, average values can be misleading.

3.3. Impact of Different Product Lengths

The previously discussed instantaneous flexibility had no requirement for a continuous provision. When tendering mFRR and mFRR, the requested product length requires the providers to maintain the flexibility for an extended period.

Figures 11 and 12 compare the instantaneously available positive and negative flexibilities to those provided for 15 min, 1 h, and 4 h. The BSS is an easy example of the impact of an extended provision period. If the BSS has a charging/discharging power of 5 kW and a capacity of 5 kWh, it can provide negative flexibility of 5 kW for one hour. If the provision period is extended to four hours, the negative flexibility drops to 1.25 kW. This basic principle is valid for all energy storage. Of course, the CoP has to be taken into account for the heat pump. For the PV system, the negative flexibility for a longer period is defined by the lowest potential production.
Figure 11. Impact of different product lengths (minimal provision period) on the available negative flexibility in the (a) summer and (b) winter of the year 2030.

Negative and positive flexibility potentials are significantly reduced if extended provision periods are required. Furthermore, the flexibility profile levels out as the provision period is prolonged. The presented results are based on single households optimized for minimal self-consumption costs without any superior energy management (VPP), forecasts, or an adjusted schedule to increase the household’s flexibility. An integrated optimization and scheduling approach is likely to increase the flexibility potential for even longer provision periods.
4. Discussion

Between 2012 and 2020 TSOs tendered a maximum capacity of 5.5 GW positive and 5.7 GW [22] negative flexibility for aFRR and mFRR together. A maximum of 620 MW [23] was tendered for FCR within the same period.

In the present paper, the ability of households (single-family and twin homes) to contribute to the flexibility reserve without receiving a specific signal was investigated. The operating strategies of the system components are driven by a household-specific behavior optimizing monetary and comfort requirements. This consideration has not been investigated in previous publications.

Based on the German Grid Development Plan’s expansion path, average negative flexibilities of 21–37 GW (depending on the season and time of day) in 2025 and 59–101 GW in 2030 are potentially available in the specified mixed scenario of the household segment. The potential for average positive flexibilities is between 0.8 and 4.9 GW in 2025 and between 14.8 and 32 GW in 2030.

This shows that considerable flexibility reserves could be provided by households in the future. The integration of EVs leads to a significant increase in flexibility potentials due to their high charging power and battery capacity. For the provision of positive flexibility, the wide availability of bidirectional charging is imperative.

Figure 12. Impact of different product lengths (minimal provision period) on the available positive flexibility in the (a) summer and (b) winter of the year 2030.
The integration of heating systems (power-to-heat) in terms of heat pumps, the heating elements, and heat storage significantly increases the flexibility potential. The heating element is crucial due to its high nominal power and fast modulation capability. However, due to its poor efficiency, this flexibility option should be of lower priority. For the heat pump to be considered, it must be able to operate with modulated power to adapt its schedule. Neither of the latter is common for current heat pumps.

A comparison of the results with existing scientific publications is difficult, since previous studies have evaluated the flexibility of individual technologies using different time horizons and sectors. Future research is warranted to investigate operating strategies for optimized flexibility provisions. This should lead to higher flexibilities over longer provision periods. Utilizing forecasts is an essential component in this context. An integration to a superior system (e.g., VPP) is important since the individual household optimization does not necessarily serve the energy system best and should be coordinated with other systems. Furthermore, additional flexibility provision of EVs while parked and plugged in at work could smooth the flexibility potential during workdays and should be part of further research. EVs could be used for company internal flexibility provision (e.g., peak shaving). Apartment buildings and cars parked in their parking garages are an additional possible source for flexibility provision and should also be investigated.

**Author Contributions:** E.D.: conceptualization of the study, development of the simulation cases, extension of the optimization model to feature EV and HP components, execution of simulations and analysis. S.P.: flexibility calculation based on the simulated results. Aggregation, extrapolation and visualization for the scenarios of the German supply system. A.D.: development of the underlying optimization model microSCOPE/|E|nergyPilot-micro and mathematical representation of the equation system relevant for the simulation. P.G.: adaption of the optimization model and development of the simulation cases. S.H. and K.W.: discussion and input to the regulatory framework and requirements as well as support in the development of the model assumptions. All authors have read and agreed to the published version of the manuscript.

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**Abbreviations**
The following abbreviations are used in this manuscript:

- aFRR: Automatic Frequency Restoration Reserves
- BSS: Battery Storage System
- CoP: Coefficient of Performance
- CHP: Combined Heat and Power Plant
- DSM: Demand Side Management
- ESS: Energy Storage System
- EV: Electric Vehicle
- FCR: Frequency Containment Reserve
- BMVI: Federal Ministry of Transport and Digital Infrastructure
- HP: Heat Pump
- mFRR: Manual Frequency Restoration Reserve
- PV: Photovoltaic
- SLP: Standard Load Profile
- SoC: State of Charge
- TSO: Transmission System Operator
- VPP: Virtual Power Plant
- UCP: unit commitment problem
- HEMS: Home Energy Management System
## Appendix A

### Table A1. Parameters.

| Parameter          | Description                                      | Unit | Domain |
|--------------------|--------------------------------------------------|------|--------|
| $\Delta t$         | Time interval in hours for the given $T$         | h    | [0.25, 1] |
| $P_{\text{feed-in},t}$ | Price for the electricity fed into the grid     | Euro | $\mathbb{R}$ |
| $P_{\text{cons},t}$  | Price for the electricity consumption from the grid | Euro | $\mathbb{R}$ |

**Energy Sources and Sinks**

| Parameter          | Description                                      | Unit | Domain |
|--------------------|--------------------------------------------------|------|--------|
| $P_{\text{pv}}(t)$ | PV forecast for timestep $t$                      | kW   | $\mathbb{R}_0^+$ |
| $P_{\text{el},t}$  | Electrical and thermal baseloads to be covered    | kW   | $\mathbb{R}_0^-$ |

**Storages**

| Parameter          | Description                                      | Unit | Domain |
|--------------------|--------------------------------------------------|------|--------|
| $\mu_{\text{time}}$ | Storage loss per hour                            | percent | [0, 1] |
| $\mu_{\text{bs}}$   | Transmission loss for charging and discharging  | percent | [0, 1] |
| $P_{\text{rated}}$  | Rated power limiting charging and discharging    | kW   | $\mathbb{R}_0^+$ |

**Electric Vehicle and Heat Pump**

| Parameter          | Description                                      | Unit | Domain |
|--------------------|--------------------------------------------------|------|--------|
| $P_{\text{ev}}(t)$ | Rated power limiting charging and discharging    | kW   | $\mathbb{R}_0^+$ |
| COP                | Coefficient of Performance of HP                 |      | $\mathbb{R}_0^+$ |

### Table A2. Variables.

| Variable          | Description                                      | Unit | Domain |
|-------------------|--------------------------------------------------|------|--------|
| $P_{\text{grid}}$ | Power of the grid feed-in                       | kW   | $\mathbb{R}_0^+$ |
| $P_{\text{grid},t}$ | Power of the grid consumption                   | kW   | $\mathbb{R}_0^+$ |
| $P_{\text{pv},t}$  | Power output of the PV plant                     | kW   | $\mathbb{R}_0^+$ |
| $P_{\text{input sink}}$ | Grid feed-in / schedule to be traded     | kW   | $\mathbb{R}_0^+$ |
| $P_{\text{discharge},t}$, $P_{\text{charge},t}$ | Charging and discharging power               | kW   | $\mathbb{R}_0^+$ |
| $s_{\text{uni},t}$ | Binary variable for charging direction (simultaneous charging and discharging not allowed). |        | {0, 1} |
| $e_{t}$            | Stored energy at time $t$                        | kWh  | $\mathbb{R}_0^+$ |
| $e_{\text{min}}, e_{\text{max}}$ | Minimum and maximum possible state of charge | kWh  | $\mathbb{R}_0^+$ |

**Electric Vehicle**

| Parameter          | Description                                      | Unit | Domain |
|--------------------|--------------------------------------------------|------|--------|
| $P_{\text{ev},t}$  | Electric power of EV (dis-)charging              | kW   | $\mathbb{R}_0^+$ |

**Heat Pump System**

| Parameter          | Description                                      | Unit | Domain |
|--------------------|--------------------------------------------------|------|--------|
| $P_{\text{hp}}$    | Electric power input of the heat pump            | kW   | $\mathbb{R}_0^+$ |
| $Q_{\text{hp},t}$  | Thermal power output of the heat pump            | kW   | $\mathbb{R}_0^+$ |
| $P_{\text{he},t}$  | Electric power input of the heating element      | kW   | $\mathbb{R}_0^+$ |
| $Q_{\text{he},t}$  | Thermal power output of the heating element      | kW   | $\mathbb{R}_0^+$ |
| $Q_{\text{tss, out},t}$ | Thermal power output of thermal storage system | kW   | $\mathbb{R}_0^+$ |
| $Q_{\text{tss, in},t}$ | Thermal power input of thermal storage system   | kW   | $\mathbb{R}_0^+$ |
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