Prosumer Integration in Flexibility Markets: A Bid Development and Pricing Model

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***Abstract*— The impact of renewable energies on the power grid is continuously increasing. Besides the emission-free power generation, the renewable energies often are the cause for congested grids, component failure and costly interventions by the distribution system operators (DSO) and transmission system operators (TSO) in order to maintain grid stability. The scientific community discusses in recent years the usability of distributed energy resources (DER) as flexible devices. However, no approach can be found that actually quantifies the potential flexibility and sets a price to it. The model presented in this paper optimizes the charging operation of an electric vehicle (EV) according to a price signal with a state of the art exhaustive search algorithm. Furthermore, this model offers all possible deviations from the optimal operation as flexibility to a corresponding market platform and sets a price to each offer, which is dependent on the future price level of the energy. With this model, it is possible to offer positive and negative prices for flexibility. The proposed model shows that an exhaustive enumeration algorithm is feasible to calculate flexibility offers, prices and applicable on currently discussed platform models. The example of an EV charging schedule is successfully modelled and described in this paper.**

Keywords—flexibility platform, distributed energy resources, home energy management system, operation planning, electric vehicles, smart grids

I. INTRODUCTION

The Union of the Electricity Industry (Eurelectric) describes flexibility as “the modification of the generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system. The parameters used to characterize flexibility include the amount of power modulation, the duration, the rate of change, the response time, the location, etc.” [1]

In accordance to the above mentioned definition, positive flexibility describes the consumption of energy or the postponement of feeding energy into the grid at times when it was initially scheduled. Negative flexibility means the exact opposite, i.e. to refrain from consuming energy or feeding energy into the grid at times when it was not scheduled.

On a large scale (> 1 MW) flexibility measures are already common practice to maintain grid frequency and avoid grid congestion. Concepts like ‘redispatch’ on the supply side, as well as demand-side-management in energy intensive industries are grid ancillary services applied by transmission system operators (TSO) and distribution system operators (DSO) today [2, 3, 4]. However, in addition to already available energy markets and regulatory mechanisms, the idea of a separate, flexibility platform or market arises and is proposed more frequently in academic and industrial research [5, 6, 7, 8, 9, 10]. Proposed platforms are meant to be accessible, not only by large industrial parties, but also by small DER, such as residential heat pumps (HP), combined-heat-and-power units (CHP), electric vehicles (EV) as well as photovoltaic (PV) and battery storage units. Such a platform would provide an alternative to grid expansion, modulation of large power plants and especially curtailing renewables and therefore allow the DSO and TSO to manage grid congestions in a more cost-effective and resource-efficient manner [11, 12]**.**

The paper at hand presents a novel home energy management system (HEMS) which provides the opportunity to participate in above mentioned flexibility market, as well as in a regular energy market. State-of-the-art HEMS are mostly known to determine the cost-optimal operation of energy generation and storage units within a household, mostly by utilizing mixed-integer-linear programming (MILP) or meta-heuristic search algorithms, such as genetic algorithm (GA) [13, 14, 15]**.** However, the proposed HEMS will - on top of finding the cost optimal operation strategy – find every deviation from this optimized schedule and post them as flexibility options on flexibility market platforms, by determining a price and considering user and unit specifications. This approach is considered an exhaustive enumeration method, which is often criticized for its high computational costs [16, 17]**.**

Flexibility market concepts for residential participants are designed and discussed in various different forms by current research projects, the most prominent ones in Germany/Europe being Invade H2020, Empower H2020, Flex4Energy, Enko, and SINTEG C/sells [18, 19, 20, 21, 22]**.** The main distinction between an existing energy market and a potential flexibility market is that power (kW) is traded, instead of energy (kWh). The demand is given by the congestion forecasts of DSOs and TSOs. A flexibility platform that is currently developed within the project C/sells is based on the following premises:

- Day-Ahead and congestion predictions are performed by DSO and TSO to generate flexibility demand

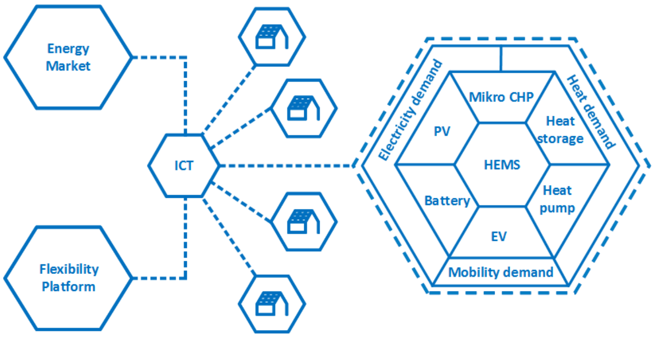

Fig. 1 Schematic of the HEMS and its connection to the energy market and to the flexibility platform

- Flexibility offers are posted for the next 24 hour in 15 minute intervals on the platform
- Every participant has direct access to the platform and can place offers
- Call and settlement will be communicated 15 minutes before delivery
- The efficiency of a flexibility measure on grid instances will be calculated by the platform itself and factored in to the given price
- A flexibility offer by a HEMS is defined by the following parameters: Time and date, negative/positive flexibility (power), available energy (negative/positive) and costs

In the following, a HEMS model for participation on a flexibility platform with above mentioned characteristics is proposed and described in detail.

II. METHOD

Fig. 1 visualizes the home energy management system (HEMS) as the central control unit of a property and the connected devices therein (e.g. electric vehicles (EV), heat pumps (HP), cogeneration units (CHP), heat storages and batteries). In Fig. 2 the functional overview of the HEMS is displayed. At the beginning of any optimization and calculation of flexibility offers the HEMS is supplied with input data. Afterwards, the optimization algorithm calculates an operating strategy for each device that minimizes energy costs. The coverage of the electricity, heat and mobility demand is the most important constraint and has to be fulfilled at any time. In accordance to the optimization result the HEMS will then buy or sell energy on the energy market for the operation of the connected distributed energy resources (DER). Deviations from the optimal solutions can further be offered as flexibility to a flexibility platform. The following subsections will describe the functionalities of the HEMS from Fig. 2 in detail.

A. *Input Data, Generation and Consumption Forecast*

In order to optimize the devices operation the HEMS depends on input data from multiple parties such as the user, weather stations, forecast provider or the DER itself. Device parameters are either set at the initial operation by setting for example an EV's battery capacity, maximum charging power etc. On the other hand, some parameters are continuously communicated when a new unit state occurs or for example certain boundaries such as the maximum SOC have been reached. The user provides general operational constraints. For example, the user sets the time when he needs to have a fully charged EV, what temperature level he would like to maintain inside his house, or at what time he might have scheduled to turn on his sauna. Besides those inputs from parties within the household the HEMS is fed with historical data and forecasts of the upcoming weather conditions and energy prices.

Based on all the described input data, the HEMS formulates constraints that limit the possibilities of the unit's operation. Below are the fundamental constraints of the model for the charging process of an EV listed.

$$t_{\text{operation}} \geq \frac{\left(SOC_{\text{Bat,desired}} - SOC_{\text{Bat}}(1)\right) \cdot E_{\text{Bat,cap}}}{P_{\text{Bat,charg,max}}} \quad (1)$$

$$P_{\text{Bat,charging}}(t) \leq P_{\text{Bat,charg,max}} \quad \forall t \in 1, \dots, end \quad (2)$$

$$SOC_{\text{Bat}}(t) \leq SOC_{\text{Bat,max}} \quad \forall t \in 1, \dots, end \quad (3)$$

$$SOC_{\text{Bat}}(t_{\text{end}}) = SOC_{\text{Bat,desired}} \quad (4)$$

The first constraint (1) covers that the operation time $t_{\text{operation}}$ is greater or equal than the time it takes to charge the battery with maximum charging power $P_{\text{Bat,charg,max}}$. $SOC_{\text{Bat,desired}}$ indicates the desired SOC of the user at the pick-up time, $SOC_{\text{Bat}}(1)$ the initial SOC and $E_{\text{Bat,cap}}$ the battery capacity in kWh. Constraints (2) and (3) limit the charging power and SOC during all time steps t. Equation (4) ensures that the desired SOC is reached at the last time step t_{end}. Non-negativity and further constraints are neglected within this brief summary.

Based on all the formulated constraints and input data the HEMS starts to forecast the energy consumption and generation of the entire household and the devices therein.

B. *Optimization Approach*

A fundamental difference between the approaches discussed in section I is the usage of an exhaustive search method to find the connected devices' optimal cost operation. Because only if all possibilities are available, the model offers the entire solution space as flexibility and likewise calculates its costs. The brute-force method is often criticized for its high computational cost [16, 17]. However, in the case of a HEMS the presented model finds the cheapest operation plan for the case of an EV charging optimization within less than 1 second on a state-of-the-art personal computer. Prerequisites are accurate thermal and electric demand forecasts, a temporal resolution of 15 minutes and that the number of possibilities is furtherly reduced by constraints. The model's temporal resolution is set in accordance to common forecasting and data acquisition models, the European energy market, and the flexibility platforms developed in current research projects [22]. Therefore, this method is used in this model to calculate the cheapest operation plan.

Once all constraints are formulated, all possible operation plans of the unit can be extracted. Operation plans that do not fulfill the aforementioned constraints are disregarded. The next step is to calculate the operation plan's cost by summing up the consumption at each time step and multiplying it by the energy prices which are given as a price forecast to the HEMS. Based on the calculated costs of each operation plan the cost optimal solution can be determined.

Finding the cost optimal solution for the charging process of an EV follows the above mentioned method. First, the necessary time to charge the EV with maximum power $t_{\text{min,Bat,charg}}$ is calculated in (5).

$$t_{\text{min,Bat,charg}} = \frac{\left(SOC_{\text{Bat,desired}} - SOC_{\text{Bat}}(t_1)\right)\cdot E_{\text{Bat,cap}}}{P_{\text{Bat,charg,max}}} \tag{5}$$

Equation (6) divides $t_{\text{min,Bat,charg}}$ by the HEMS' temporal resolution to calculate the necessary time steps $n_{\text{tSteps,min,Bat,charg}}$ for charging the EV.

$$n_{\text{tSteps,min,Bat,charg}} = \frac{t_{\text{min,Bat,charg}}}{n_{\text{minutes/timeslot}}} \tag{6}$$

Next, the model sorts the time table by price forecast in ascending order. The cost optimal charging plan is then, to charge the EV at the $n_{\text{tSteps,min,Bat,charg}}$ first time steps of the sorted price forecast with maximum power.

After determining the cost optimal solution of the DER the HEMS interacts with the day-ahead energy market, buys energy and communicates the charging plan to the unit control. The next subsection will discuss how the HEMS will determine the flexibility offers of the DER.

C. *Flexibility Offers*

The DSO is interested in the information of how much power the DER can offer as flexibility, for how long, at what location in the grid, and at what price. Therefore, a HEMS that offers flexibility must answer all of the mentioned characteristics. As described in section I, flexibility is defined as the "modification of generation injection and/or consumption" [1]. Hence, it is essential to analyze the 'normal', in the presented model the cost optimal, operation, in order to determine possible 'modifications' of the operation plan and offer those to a flexibility platform.

1) Location, Positive, and Negative Flexibility

The location of DER is a constant and therefore, can be set just once. For the German grid the description of the location can be described by the accounting grid, grid area and an identification number of the DER set by the DSO or TSO.

Positive flexibility in terms of consuming energy can be summarized as charging an EV, a battery or operating a HP. From the perspective of a CHP unit, positive flexibility can be offered by stopping the operation of the unit or feeding electrical energy into a local battery instead of the grid. Negative flexibility can be offered by the same DER by stopping the charging operation of an EV or the operation of a HP, starting to feed electrical energy into the grid with the CHP, PV unit or the battery. Therefore, with all above mentioned units positive and negative flexibility can be offered.

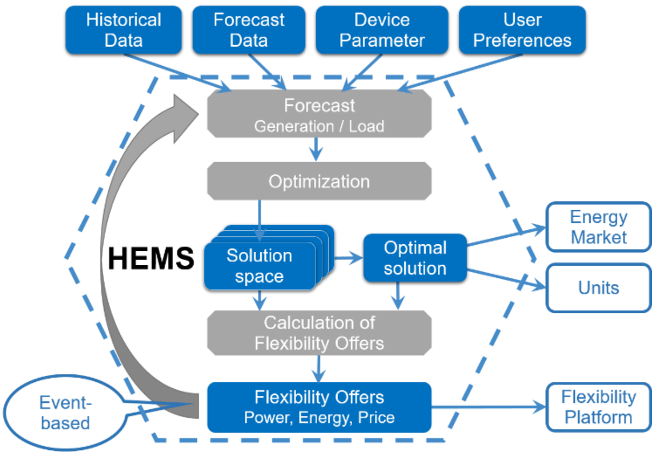

Fig. 2 Functional overview of the HEMS

For the example of an EV, the decision whether it can offer positive or negative flexibility is dependent on the charging plan. Is the EV currently not charging and not fully charged, positive flexibility can be offered. On the other hand if the EV is scheduled to be charged, negative flexibility can be offered.

After determining the direction of the flexibility and at which location it can be offered it is important to quantify the power and energy to be offered.

2) Power, Duration and Energy

The DER's operating power is mostly limited by design and only in a few cases dependent on the unit's current state. Therefore, the presented model uses the maximum power as the power with which it can offer flexibility. In the case of a HP and positive flexibility it is the maximum operating power or in the case of negative flexibility the planned operating power.

The duration for which the flexibility $t_{\text{Flex,offer}}$ can be offered is calculated in (7). $E_{\text{Flex,offer}}$ sets the amount of energy $E_{\text{Flex,offer}}$ that can be consumed, restrained or generated and the offered power $P_{\text{Flex,offer}}$ is set as above mentioned.

$$E_{\text{Flex,offer}} = P_{\text{Flex,offer}} \cdot t_{\text{Flex,offer}} \tag{7}$$

The amount of energy is always dependent on the unit's current state. Using the example of a battery storage the flexibility that can be offered depends on its SOC. Similarly, the CHP and HP's flexibility depends on the SOC of the heat storages that are connected to them and the load that is consuming energy. If no heat storages are installed the flexible energy will depend on the heat storage capacity of the supplied building and its current state.

Coming back to the example of an EV, the offered flexible power is equal to the maximum charging power as positive flexibility and the planned charging power as negative flexibility. In the case of an initial SOC of 50 % and a battery capacity of 80 kWh the flexible energy can be ±40 kWh.

3) Price of the flexibility

After determining all technical characteristics of a flexibility offer, the final step is to calculate a reasonable price that ensures the reimbursement of additional effort, considers a financial risk on the energy market, and creates a high probability of being called. In order to fulfill those requirements (8) to (10) were developed.

In (9) the cost for a kWh of positive flexibility is calculated. Meaning, the unit's offered flexibility price when the HEMS already bought the energy on the day-ahead market for a later operation but it is being called up for operation ahead of time. Hence, when a flexibility call occurs, the HEMS can sell the pre-bought energy on the intra-day market and even offer negative prices for positive flexibility. Negative prices mean that the HEMS pays money to be called up for flexibility. Similar to (7), (8) calculates the number of offered flexibility time steps $n_{\text{off,Flex,tSteps}}$ by dividing the offered energy by the power at time step i and the number of time steps per hour $n_{\mathrm{tSteps/hour}}$. In (9) the average of the $n_{\mathrm{off,Flex,tSteps}}$ minimal prices is multiplied by a factor consisting of the risk margin R_{margin} from which minus 1 is subtracted. The risk margin can be in the range of 0 to 1. Zero indicating a very low risk and the expectancy to sell energy at the buy-in price and one expecting high fluctuations on the intra-day market.

$$n_{\mathrm{off,Flex,tSteps}} = \frac{E_{\mathrm{Flex,offer}}(i) \cdot n_{\mathrm{tSteps/hour}}}{P_{\mathrm{Flex,offer}}(i)} \tag{8}$$

$$c_{\mathrm{pos.,Flex}} = mean\left(mink\left(c_{Forecast}(i{:}\,i_{\mathrm{end}}), n_{\mathrm{off,Flex,tSteps}}\right)\right) \cdot \left(R_{\mathrm{margin}} - 1\right) \tag{9}$$

The cost for negative flexibility can be calculated by assuming the scenario of a HEMS that has pre-bought energy on the day-ahead market for charging an EV at a certain point in time. Negative flexibility for this exact moment is being called, meaning that the HEMS will send appropriate signals to the charging station to stop the charging process of an EV. In this scenario the refrained energy must be caught up at a later point in time. The HEMS must therefore buy the energy on the intra-day market, which can result in much higher prices than the pre-bought energy. Therefore the prices will be positive, indicating that the HEMS will receive money for offering negative flexibility.

In (10) the average of the $n_{\mathrm{off,Flex,tSteps}}$ minimal prices in which no operation was initially scheduled $i_{non-operational}$ by the HEMS and past the flex offer is multiplied with a factor consisting of a risk margin to which 1 is added to.

$$c_{\mathrm{neg.,Flex}} = mean\left(mink\left(c_{Forecast}\left(i + i_{non-operational}{:}\, end\right), n_{\mathrm{off,Flex,tSteps}}\right)\right) \cdot \left(R_{\mathrm{margin}} + 1\right) \tag{10}$$

The accumulation of the aforementioned characteristics of flexibility offers are then communicated as a table to a flexibility platform. In the event of a forecasting error, new input data, a flexibility call, or an unexpected user behavior the HEMS restarts the optimization process.

III. RESULTS

Within this section the results of the above described model for offering flexibility with an EV that requires a total energy of 80 kWh, can be charged with a maximum power of 20 kW and is available for operation in the time period from 04:30 to 18:30 are presented. Fig. 3 shows the cost optimal charging plan (black line), all placed flexibility offers (color map, from orange to purple), a simulated flexibility call (red line) and the new optimization results (grey line) after a flexibility call. The x-axis shows the time of a day and the y-axis the cumulated energy. The calculated cost optimal operation shows multiple charging periods over the period of the day. When the EV is not available for operation, the HEMS cannot offer any flexibility and therefore, shows only dots in the period from 00:00 until 4:00 and in the late evening. Once the EV is available for operation the flexibility offers are visible as colored lines, that start on the line of the cost optimal operation plan, either start to rise with a constant gradient and end at a certain energy level. The starting point of each flexibility line is equal to the time step at which the flexibility is offered. The gradient of the offers is dependent on the offered power. In the case of positive flexibility the gradient will be proportional to the charging power of 20 kW and for negative flexibility equal to zero, since the HEMS will refrain from charging the EV in those time steps. The offered flexible energy is for positive flexibility the difference between the energy levels (from starting to end point) of each flexibility offer. Is negative flexibility offered, the energy is equal to the difference between the end point of the flexibility offer and the energy level of the cost optimal operation plan at the same time step.

At time step 10:00 Fig. 3 shows the simulated call for positive flexibility. The total offered flexibility at this time is according to Table 1 40 kWh but only 25 kWh are called, indicated by the red line. The power of the flexibility offer is completely retrieved, indicated by the congruence of the flexibility retrieval with the offer. After the flexibility retrieval ends the HEMS calculates a new cost optimal operation plan for the remaining energy. Because in the presented model the price forecast was not altered between the initial optimization and the simulated flexibility retrieval the new optimal operating strategy is only slightly different than the initial strategy.

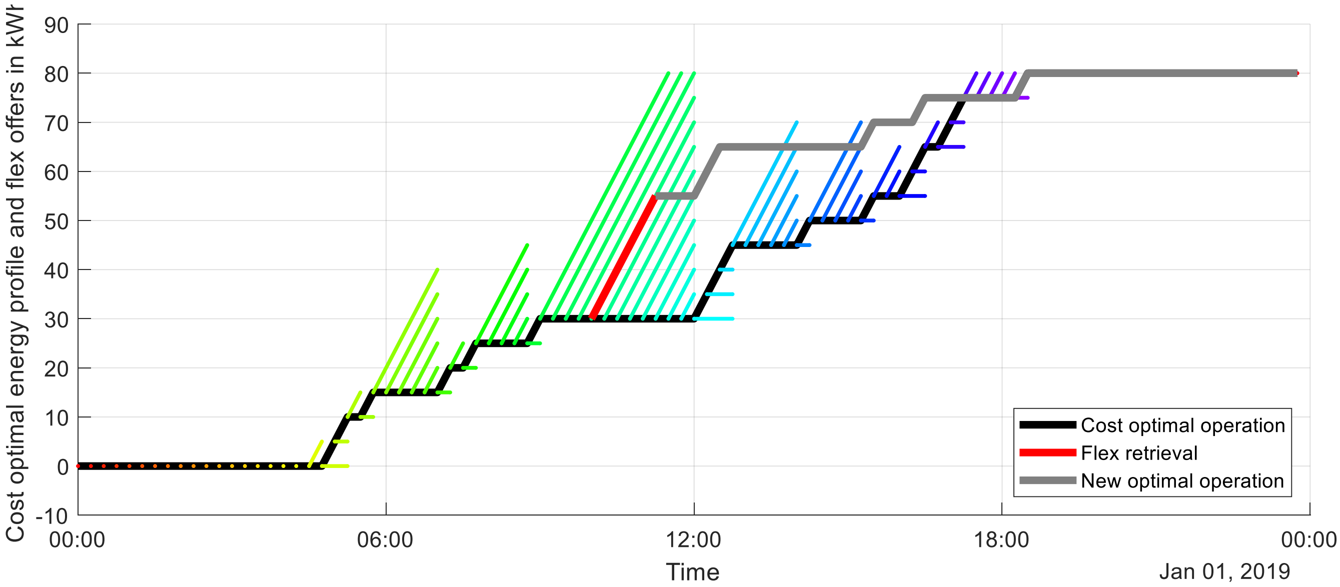

Fig. 3 Flexibility model of an EV with, cost optimal operation plan, simulated flexibility call and re-optimization results

Table 1 Flexibility offers from 9:45 to 12:45 with the scheduled power, negative and positive power, energy, and prices

Time	Scheduled Power in kW	Neg. Power in kW	Pos. Power in kW	Neg. Energy in kWh	Pos. Energy in kWh	Neg. Price in €/kWh	Pos. Price in €/kWh
01.01.2019 09:45	0	0	20	0	45	0,000	-0,182
01.01.2019 10:00	0	0	20	0	40	0,000	-0,181
01.01.2019 10:15	0	0	20	0	35	0,000	-0,180
01.01.2019 10:30	0	0	20	0	30	0,000	-0,180
01.01.2019 10:45	0	0	20	0	25	0,000	-0,179
01.01.2019 11:00	0	0	20	0	20	0,000	-0,178
01.01.2019 11:15	0	0	20	0	15	0,000	-0,177
01.01.2019 11:30	0	0	20	0	10	0,000	-0,177
01.01.2019 11:45	0	0	20	0	5	0,000	-0,176
01.01.2019 12:00	20	-20	0	-15	0	0,379	0,000
01.01.2019 12:15	20	-20	0	-10	0	0,375	0,000
01.01.2019 12:30	20	-20	0	-5	0	0,366	0,000
01.01.2019 12:45	0	0	20	0	25	0,000	-0,180

After discussing the technical characteristics of the flexibility offers, Table 1 is an excerpt of the flexibility offers in a tabular form and Fig. 4 shows the offered flexibility prices and the power over one day. The flexibility power is constant at a level of ± 20 kW for either positive or negative flexibility and corresponds to the maximum charging power of the EV. The subplot below, shows the offered flexibility prices in €/kWh. The HEMS calculates for positive flexibility negative prices and for negative flexibility positive prices.

The prices for negative flexibility rise towards the end of the day because the energy must be caught up at a later point in time and the number of possible operation time steps decreases. The prices at 12:00 temporarily decrease for negative flexibility due to the fact, that the offered energy is decreasing over time and therefore more options to catch up the energy are available. The prices for positive flexibility slightly decrease with the amount of offered energy. Only at the last block of positive offers the costs stay constant. This behavior of the model can be explained with (9) in which the average of the minimum prices for the required energy is calculated. When the amount of offered energy is high, more time steps must be considered, indicating a higher risk on the energy market and therefore resulting in a higher energy price. The constant prices for the last block of negative prices (time period 17:15 to 18:00) is caused by the constant amount of offered energy of 5 kWh (see Fig. 3).

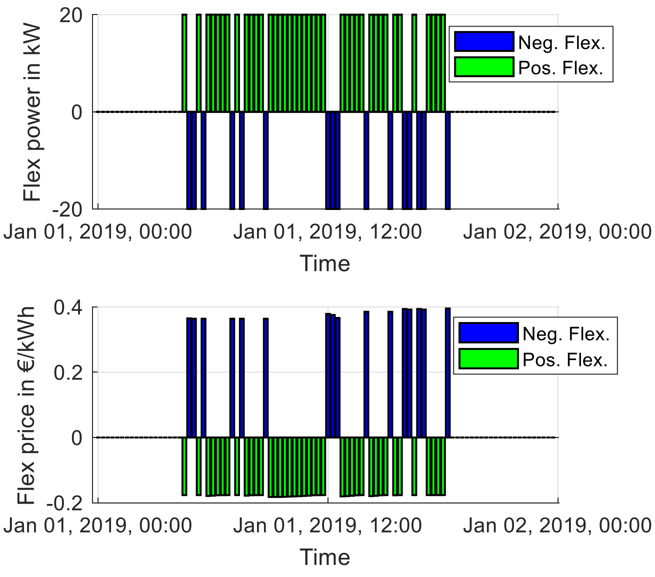

Fig. 4 Offered flexible power and prices for flexibility in €/kWh

The presented results verify the models structure described in section II. The next section will summarize the possible applications and limitations of the presented model.

IV. DISCUSSION

The model presented in this paper is capable of processing user preferences, historical data, unit parameters, energy price and weather forecasts, calculating cost optimal operating strategies and flexibility offers. The results of the model show the compatibility to flexibility platforms described in section I and developed in current research projects [22]. A simulation of a unidirectional EV model verified the functionalities of the proposed HEMS. The implementation of HEMS models for further DER shall verify the applicability of the presented method to HP, CHP, PV units and connected battery and heat storages.

The general criticism regarding exhaustive enumeration methods of consuming too much computational costs [16, 17] could not be confirmed by the results of the presented model. The model shows rather that for a discrete model with a time horizon of 24 h and a temporal resolution of 15 minutes, the exhaustive enumeration approach can calculate an optimal operating strategy and the respective flexibility offers in less than 1 second on a personal state-of-the-art computer. Moreover, this technique offered a simple approach to investigate all possible deviations from the cost optimal operating strategy, hence laid the foundation of the flexibility calculations.

V. CONCLUSION AND OUTLOOK

Within this paper, a novel HEMS model is presented, which processes input data from multiple parties, optimizes the DER's operation strategy and calculates offers for a flexibility market platform. The results of the EV simulation are presented in this paper. It is verified that the proposed model shows the expected functionality and enhances the economic opportunities for DER’s and prosumers, by participating on a flexibility platform. The quantification of the offerable flexibility by DER and their pricing, which so far cannot be found in the literature, represents a novelty to the scientific community.

In future research, the transferability to other DER units will be demonstrated and more complex systems of multiple market participants will be investigated. Within the scope of the SINTEG project c/sells, where more than 50 partners from German academic and industrial research institutions, including multiple DSOs and TSOs participate in discussions and the development of different local flexibility platforms, the opportunity for in-depth analysis and validation of the concept is given. The next step will be the application of the presented method to a PV and battery storage combination and HP/CHP unit and heat storage combination. Laboratory testing in a Hardware-in-the-Loop environment as well as testing in the field will be conducted in near future. Another field of research is the investigation of alternative cost functions, such as minimizing CO_2-emmissions or maximizing the level of autarky.

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