Smart Grid Power Management Interface for Use of short-term Flexibility

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***Abstract*—The high importance of Demand-Side-Management for the stability of future smart grids is consensus among a wide spectrum of energy market participants and within the research community. While it is accepted that Demand-Side-Management will yield positive contributions, it remains challenging to identify, access, and communicate available flexibilities to the flexibility managers in order to determine impacts and choose temporarily required demand-side flexibility to ensure system stability. In this paper we introduce a methodology to determine and communicate local flexibility potential of end-users to flexibility managers for short-term access. The presented approach achieves a reliable calculation of flexibility, a standardized low bandwidth data aggregation, and communication. With the integration into an existing system architecture the general applicability is outlined with a one end-user use case. The approach yields a transparent short-term flexibility potential within the flexibility manager system.**

***Index Terms*—Flexibility, Advanced Metering Infrastructure, Energy Management, Smart Meter Gateway, Electric Vehicle**

I. Introduction

Throughout the last years with the increasing share of Renewable Energy Sources (RES) the demand-side of the energy sector came into focus of research [2] - [8]. Whereas the production of energy was the main measure to strike a balance between generation and consumption, this solution is not longer the only solution [1]. The orientation on fulfilling high energy demands in times of low RES production leads to high reserve capacities and high costs for society. The integration of a rising share of Electric-Vehicles (EV) as time and location-independent loads adds an additional challenge for the energy infrastructure. Demand-Side-Management (DSM) offers a measure to archive a balance between generation and consumption without the need for additional investments in the energy generation infrastructure. Whereas the importance of DSM programs is a widely understood, the flexibility calculation and accessibility, as load deviation between current and possible power consumption, especially when concentrating on residential areas, is still a field of activity. The challenges can be summarized by the term *uncertainty*. When focusing on real-time applications uncertainty occurs through forecast errors of dynamic parameters and states of loads, user behaviour and ambient conditions, that influence load operations [2]. This work establishes a methodology as a Power Management System (PMS) extension that calculates a short-term reliable flexibility potential. Equation (1) shows the feasible power consumption space as the deviation between maximum and minimum possible power consumption for a specific discrete time step i. With the knowledge about the current power consumption the accessible system flexibility for DSM measures is identifiable. Due to short-term parameter states and end-user inputs into PMS interfaces for specific smart devices the flexibility can be calculated accurately and communicated to interested entities within the Wide Area Network (WAN).

$$P_{\mathrm{flex},i} = P_{\mathrm{max},i} - P_{\mathrm{min},i}; \forall i \in I \tag{1}$$

Those entities can utilize the communicated flexibility for short-term reactions to forecast errors or for short-term trading at the European Energy Exchange (EEX) or future flexibility markets, to maximize profit and the individual value for participating end-users. The scope of future work will be the integration of the presented model into large scale aggregator use cases. To summarize the contribution of this work, these are its main aspects:

- a new categorization of flexibility studies focusing on aggregator perspective
- end-user oriented PMS-input interface with detailed parameters under strict comfort consideration
- reliable flexibility calculation and data-parsimonious communication as real-time application
- approach to enable self-determined participation of a wide set of end-users on flexibility markets through aggregator entities
- integration of an abstraction layer for consideration of privacy and data security.

In Section II the analysed related works are presented and categorized, followed by the description of the PMS extension approach and two device examples in Section III. A use case showing the applicability of the approach is presented in Section IV. Section V implies the summary and the outlook for further investigations into flexibility methodology.

II. Flexibility studies overview

The calculation of the load potential of the demand-side for integrating RES or new appliances, considering changing end-user behaviour, is a highly relevant research topic in literature

[2] - [11]. Whereas different publications deal with the impact or potential of Demand-Side-Management (DSM) on aggregated demand [12] others try to cluster end-users, considering their ability to contribute to DSM mechanisms [9], [16]. The latter often evaluate measurements or statistical surveys for the clustering [8], [9]. The main similarity of all research is the existence of an entity that is responsible for scheduling the aggregated system for successful RES integration, cost reduction or peak-to-average ratio reduction. Whereas many publications focus on the above-mentioned research questions, only a few discuss categorization methodologies of flexibility and Demand Response (DR) studies to establish comparability and a wider understanding.

A. Categorization of flexibility studies

A rough categorization into *DR-based* and *DR-independent* flexibility studies is outlined in [4]. *DR-based* approaches are tailored to the underlying DSM mechanism. The main objective is the modeling of end-users' responsiveness to DR or Dynamic Pricing programs. In contrast the main goal of *DR-independent* approaches is to model the end-user's flexibility potential. These models can be used to evaluate the potential impact of DSM mechanisms on an end-user's power demand. Developing a new *DR-independent* model by evaluating open-source data for household appliances [4] presents a methodology for modeling consumer behaviour in the area of white goods, explicitly for washing machines, tumble dryers and dishwashers.

A second categorization of recent flexibility studies and research is performed by [10]. Four patterns for the communication and exploitation of flexibility are shown. A distinction between a) Physical Demand Response, b) Direct Market Demand Response, c) Indirect Market Demand Response and d) Decentralized Market Demand Response is presented. The categories a) and b) contain approaches that focus on direct load control signals for individual devices or whole systems, whereas c) focuses on power consumption adjustments by changing tariffs. Category d) is about local coordination of participants without a central coordination entity.

When participating in today's flexibility markets such as reserve capacity markets or intra-day trading platforms of energy, a central coordination entity is needed. This participation can increase the individual value of end-users, when flexibilizing their power consumption. The aggregation of end-users is an indispensable prerequisite because the trading volume is limited to minimal power and duration offers. However, how the aggregator reliable and timely receives or generates flexibility potential estimations is still a matter of concern. Focusing on the aggregator level as the central market participant enabling access of residential or small commercial end-users defines a new categorization of flexibility studies and thus embodies one contribution of this work.

B. Abstraction level of communication to aggregator back end

Fig. 1 shows the categorization through the abstraction level of the communication of flexibility or flexibility linked parameters to the aggregator level and from aggregator level to the aggregated system of end-users. Distinctions are drawn between:

- *Single Devices*
- *Clusters of devices or end-users* and
- *Total aggregation.*

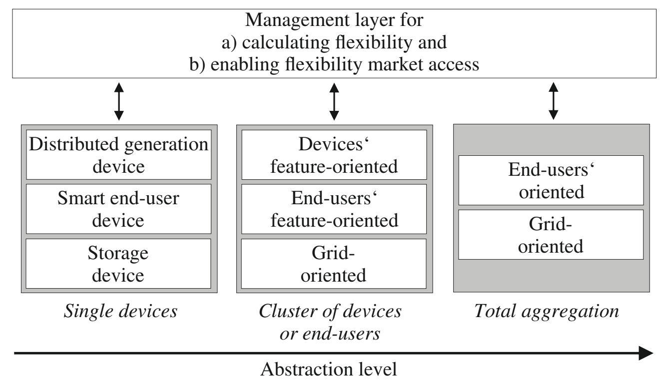


Fig. 1. Categorization of flexibility studies.

With *Single devices* approaches detailed information of a specific device is monitored and sent to the aggregator level. Through the evaluation of device or end-user features *Clusters of devices or end-users* are generated to reduce complexity and to rise reliability when focusing on behaviour and reactions within the clusters. The focus on very small grid areas is also possible within this categorization approach. When only working with *Total aggregation* whole distribution grids or all aggregator-connected end-users are abstracted to one entity. The categorization of the analysed works is shown in Table I.

A *Single devices* centred methodology for modeling costumer behaviour in the area of white goods is presented by [4]. There, flexibility is considered by three parameters, (a) the deferable energy, (b) the time of availability and (c) the deadline to exploit the offered flexibility for individual households. Another *Single device* approach is introduced by [13]. The predictive and agile balancing of a virtual power plant consisting of devices modeled as buckets, bakeries and batteries, reflecting their specific system behaviour is presented. By a centralized evaluation of the individual parameters, the system's agile balancing capabilities prioritize the tasks and achieve good results and short computation times.

An exemplary approach for the *Clusters of devices or end-users* is shown in [8]. Based on an end-user segmentation process, taking into account several end-user specific characteristics a flexibility forecast for the residential area is applied. The aggregator utilizes old measurements and feedbacks from recent realized DR events for the flexibility forecasting algorithm. [11] analyses the flexibility of thermostatically controlled devices through set point deviation set by the aggregator. The outlined approach does not communicate available flexibility. The developed Heating, Ventilation and Air Conditioning model (HVAC) is used to illustrate the behaviour of the aggregated HVAC systems to set point changes initiated by the aggregator.

Working with *Total aggregation*, [9] introduces a methodology for a day ahead reduction of the the power demand within specific intervals, by considering the sensitivities of residents to cost, environment and technology. The aggregator receives the aggregated load profile after the local optimization of each resident, following their specific sensitivity to reduce cost or increase the share of RES. The exact flexibility potential is not calculated, as only the original to the optimized load profile can be compared. [12] calculates the deployment of flexibility in the service sector using a model that optimizes the scheduling of flexible loads considering retail prices for electricity. The share of flexible loads and the total electricity consumption are the inputs for the optimal deployment. Due to high data security and privacy threats submitting device specific parameters to external entities is difficult to realize in the temporary regulation environment. In contrast to that the aggregation and clustering is linked to high uncertainties in realized and estimated flexibility.

TABLE I
LITERATURE CATEGORIZATION TO ABSTRACTION LEVEL TO AGGREGATOR BACK END.

Abstraction level	References
Single device	[4] [13] [14] [17]
Cluster of devices / end-users	[8] [11] [16] [2]
Total aggregation	[9] [12] [15]

The aim of the presented approach is the flexibility calculation of specific end-users without constrictive focus on possibly applied DSM mechanisms to gain full and reliable insides on connected aggregator flexibility. With the outlined method the communication of the maximum available and accessible flexibility is possible for a couple of hours into the future. Due to an end-user centred parameter input panel, the individual comfort requirements are taken into account, which is relevant for detailed flexibility calculation. Thus, the end-user inputs reflect their individual willingness to participate. To reduce privacy and data security threats an additional abstraction layer is implemented between the individual end-users and the flexibility aggregator. Fig. 2 shows this additional abstraction layer to decouple the controlled entities from the management area, following the architectural ideas from [5] and [6]. An additional advantage of the abstraction layer is the creation of a common understandable and generalized interface for the management layer regardless of implemented protocols or appliances. The function of the drivers is the conversion of a wide set of locally used protocols to an understandable protocol at the management layer. The approach of this work introduces a generalized flexibility value which can easily be aggregated by the abstraction layer without the need for protocol conversions.

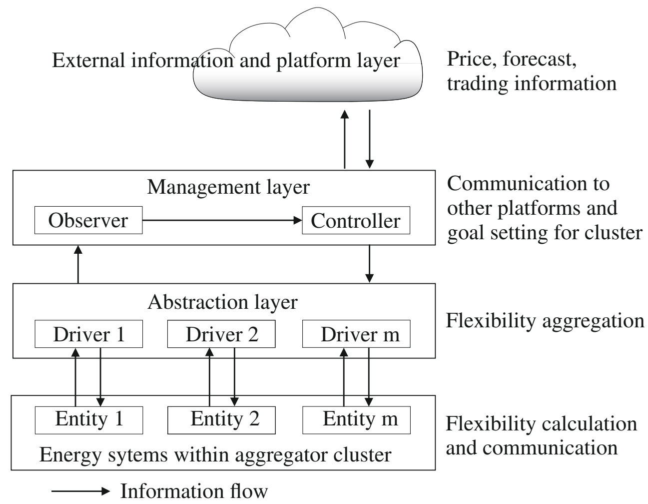


Fig. 2. General architecture of controlled entities, abstraction layer and management, based on [5].

C. Implementation into an existing framework

With the integration of an Advanced Metering Infrastructure (AMI) Germany facilitates the foundation for valuable additional services in the energy sector. The central and high-secure communication device, called Smart Meter Gateway (SMGw), enables communication and signal exchange between different entities surrounding the AMI. A detailed overview of the infrastructure and related requirements focusing on aspects of simulations can be found in [7]. The communication and data exchange is established between the Wide Area network (WAN), containing different External Market Participats (EMP), the Home Area Network (HAN) with end-user's smart devices and a visualization interface, and the Local Metrological Network (LMN) including metering devices for different energy sectors besides electric power. For the communication to smart devices, so-called Controllable Local Systems (CLS), the SMGw offers an additional communication channel for a limited and certified set of EMPs. This additional transparent data tunnel allows the direct communication and data exchange to end-user devices. For energy and power management purposes over a wide variety of different devices the connection to only one central management system is beneficial. The information allocated by the management system to EMPs is independent from device specific protocols within the HAN. Besides this harmonized information allocation, only one device, the management system, has to be configured as CLS within the SMGw. Other smart and controllable devices are only connected to the central management device. Fig. 3 shows the implementation of the presented approach into the SMGw architecture. Whereas non-CLS (nCLS) contributes to the overall power consumption, CLS, connected with the management system, are able to communicate state and parameter values. By adjusting the CLS operation specific goals can be met. The key parameter to be determined is the accessible amount of power that can be adjusted short-term.

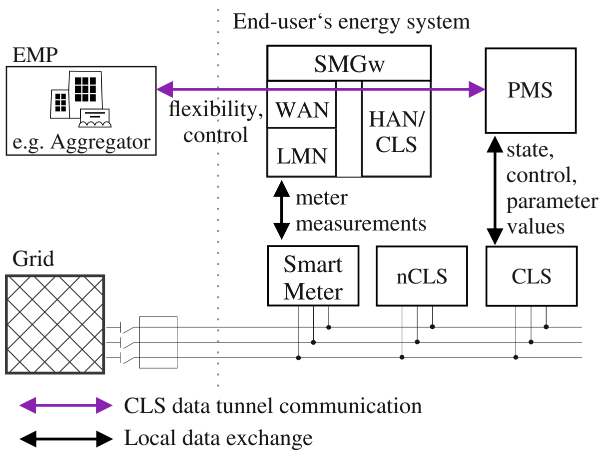


Fig. 3. Possible implementation of flexibility communication and control into existing architecture of Smart Meter Gateways (SMGw). The External Market Participant (EMP) receives flexibility information through the transparent data tunnel functionality of the SMGw, connecting the Wide Area Network and the Controllable Local Systems (CLS). The Power Management System (PMS) realizes the power consumption change, according to EMP's signals.

III. PMS EXTENSION MODULE FOR FLEXIBILITY COMMUNICATION

In order to develop a reliable and data parsimonious methodology for flexibility calculation and communication it is necessary to capture the current and short-term future states of relevant appliances and their state determining underlying parameters. Through the usage of an abstracted aggregated value, it is possible to communicate the flexibility potential of the associated devices, i.e. participating residential and commercial end-users. Applying this abstraction and aggregation layer within management applications a wide spectrum of DR programs can be realized. Fig. 4 shows the generalized approach using end-user inputs for setting the flexibility environment. The flexibility approach applied to this work focuses on maximum available power over time provided by a general set of 1) deferable, 2) interruptible and 3) flexible loads shown in Fig.4, taking into account the power consumption patterns of the devices, the current parameter states and end-user inputs for comfort purposes. The overview in Fig. 4 shows examples for device classes. However, the unique end-user inputs indicate a more complex contribution pattern of single devices when considering more degrees of freedom. Classic deferable devices can contribute as interruptible devices when considering short pauses in cycles. In terms of short-term flexibility, flexible and interruptible loads contribute to possible power consumption deviations.

A. Methodology description

With the time of the day represented by I intervals where $i \in \{1 : I\}$ and end-users given by $m \in \{1 : M\}$, where M is the number of participating end-users, the power consumption $P_{m,i}$ of an end-user in interval i can be calculated according to Equation (2). Whereas $P_{m,\text{nCLS},i}$ is the non-controllable part of the power consumption, $\sum_{d=1}^{D} P_{m,d,i}$ can be monitored and controlled for power reduction through signal exchanges between $d \in \{1 : D\}$ smart devices and an management system, using protocols like EEBUS or other protocols. However, $P_{m,d,i}$ is not addressable for the entire value, considering the specific appliance's state and the state determining underlying parameters.

$$P_{m,i} = P_{m,\text{nCLS},i} + \sum_{d=1}^{D} P_{m,d,i}; \forall i \in I, \forall d \in D \tag{2}$$

As an example we consider a water boiler with an attached reservoir. In order to meet the user's comfort level, the water temperature must not fall below a pre-defined threshold value. The modus operandi is such that the water boiler will usually be turned on for a couple of minutes in order to bring the water temperature in the "comfort zone". A switch off signal will lead to a cut in power for only a short time interval as the temperature must be held within a certain range. Our methodology takes into account not only the current state of the boiler but also the state determining parameters such as the water and inner room temperature. A similar example can be outlined by imagining the usage of a dish washer. The possibility to pause the operation of the appliance introduces the variable $t_{\text{dw,pause}}$, which defines the maximum time duration the operation of the dish washer can be paused for. This is why the end-user specific inputs (see Fig. 4) for pause time $t_{\text{dw,pause}}$ and end time $t_{\text{dw,end}}$ have to be considered for the time length of flexibility. Following these statements, the controllable part of Equation (2) can be formulated as Equation (3), considering the flexibility's availability for, in the energy sector, relevant interval time length of $t_{\text{es}} = 15\text{min}$. Equation (3) shows the separation of CLS into two bins for accessibility greater and smaller ($\underline{D}$) t_{es}. Only CLS belonging to the bin $\bar{D}$ contribute to flexibility events, as the others change their ON/ OFF status before the event can takes place.

$$\sum^{D} P_{m,d,i} = \sum^{\underline{D}} P_{m,d,i} + \sum^{\bar{D}} P_{m,d,i}; \forall i \in I, \underline{D} \cup \bar{D} = D \tag{3}$$

Assuming that the power consumption fraction changes over time, we can write $\mathbf{P}_{m,\text{flex},i}$ as the flexibility matrix containing information about accessible power, duration and possible start times of flexibility events for end-user m, communicated at interval i, shown in Equations (4) and (5). Row $n \in \{1 : N\}$ of $\mathbf{P}_{m,\text{flex},i}$ corresponds to the beginning of the time window during which flexibility is available. It has to be stressed that the matrix elements refer to the outlined relevant time t_{es} on a 15 min time basis. So the first possible allocation of the flexibility appears in t_{es} min taking into account the lack of immediate communication and reaction. Column $j \in \{1 : J\}$ contains the possible duration of the flexibility event.
Using Equation (6) the exemplary value $P_{2,8,i}$, sent at 4 pm for $I = 1440$ intervals, shows a possible flexibility event starting at ($t_{\text{flex,start}} = (960/t_{\text{es}} + 2) \cdot t_{\text{es}} = 66 \cdot t_{\text{es}}$ min) 4:30 pm. With

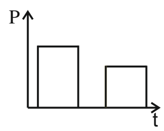
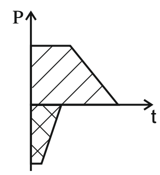
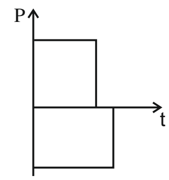
Device class	Deferable	Flexible	Interruptible
Class example	Washing maschine Cloth dryer Dishwasher	Battery Storage Electric Vehicle	Thermal storage systems
Unique end-user inputs	n_d: number of pauses in cycle $t_{d,\,pause}$: pause duration	$E_{d,\,bat}$: energy capacity $P_{r,\,d}$: rated charging power	building dimensions building age $n_{persons}$: number of persons $V_{storage}$: storage tank capacity $\Theta_{storage,flex,min/max}$: flex event setpoints
Operation-oriented end-user inputs	$t_{d,\,end}$: end time of cycle	$t_{EV,\,end}$: end time of cycle	
Accessible flexibility considering end-user inputs			

Fig. 4. Applied flexibility definition and end-user inputs for PMS initialisation for several devices.

the help of Equation (7) the duration $t_{\text{flex,dur}} = 8 \cdot t_{\text{es}} = 120$ min can be calculated. By transmitting the flexibility matrix in a constant frequency of t_{es} the accessible system flexibility can be updated for further consideration. The further reduction of rows is possible. The information flow is shown in Fig. 5. Starting with the CLS itself, the PMS calculates the flexibility potential to fill the flexibility matrices. Possible dimensions of $\mathbf{P}$ are N = 4 and J = 5. In the next step the flexibility matrices, consisting of power, duration and possible start time of the event, are sent to the abstraction layer. By aggregating all associated entities in the aggregator system the overall system flexibility can be provided to the management layer operated in the aggregator backend. The detailed knowledge of accessible flexibility in the aggregator system leads to reliable and exact flexibility offers in markets such as the intra-day spot market.

$$\mathbf{P}_{m,\text{flex},i} = \begin{bmatrix} P_{1,1,i} & P_{1,2,i} & \cdots & P_{1,J,i} \\ P_{2,1,i} & P_{2,2,i} & \cdots & P_{2,J,i} \\ \vdots & \vdots & \ddots & \vdots \\ P_{N,1,i} & P_{N,2,i} & \cdots & P_{N,J,i} \end{bmatrix} \forall m \in M, \forall i \in I \tag{4}$$

where

$$P_{n,j,i} = \sum^{\bar{D}} P_{d,n,j,i} \tag{5}$$

$$t_{\text{flex,start}} = \left(\left\lfloor \frac{i}{t_{\text{es}}} \right\rfloor + n \right) \cdot t_{\text{es}} \tag{6}$$

$$t_{\text{flex,dur}} = j \cdot t_{\text{es}} \tag{7}$$

Equations (2) to (5) describe a situation where only turn-off appliances as generation substitute are considered. When implementing appliances with an automated switching functionality, e.g. thermal or electric storage devices shown in 4,

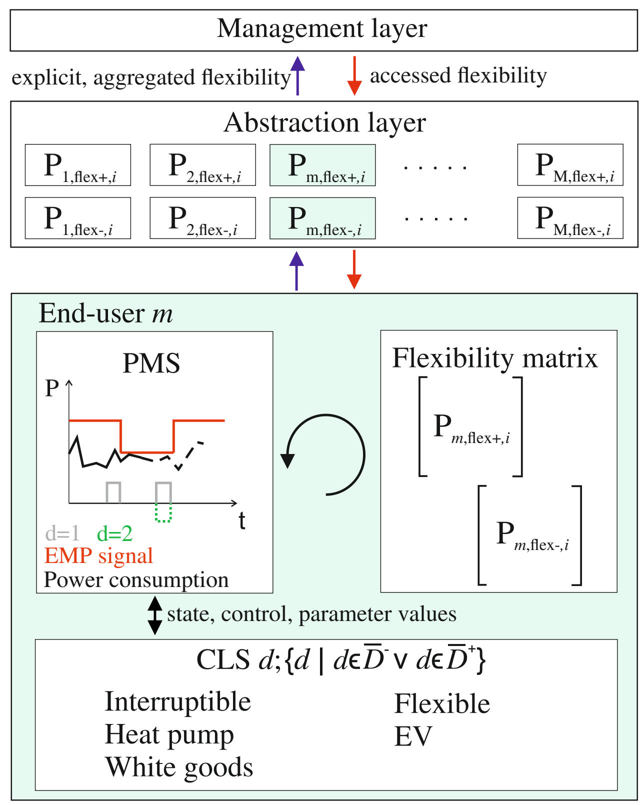


Fig. 5. Information flow in the presented methodology from CLS to management layer.

Equation (8) shows the additional load capacity. Considering the residual time of device d to maintain the current ON or OFF state, it can either belong to bin D^+ for a turn off flexibility and temporal on state or to D^- for turn on flexibility and temporal OFF state. Following the same suggestions as for

Equation (3) only the flexibility, which is still accessible in t_{es} min or later are relevant for communication. These devices belong to $\bar{D^-}$. The matrix from Equation (4) can either be formulated for a positive or negative flexibility potential of the end-user. As described above, $P_{m,\text{flex}+,i}$ shows the generation equivalent, whereas $P_{m,\text{flex}-,i}$ shows the higher load potential, both describing end-user m. The overall flexibility potential within the aggregator area is then $\sum_{m=1}^{M} P_{m,\text{flex}+,i}$ for generation and $\sum_{m=1}^{M} P_{m,\text{flex}-,i}$ for additional power demand. Whereas several device classes and their contribution to flexibility realization were mentioned in Fig. 4, only interruptible and interruptible-flexible devices are relevant for the flexibility matrices. This is because the flexibility matrices show the maximum possible deviation from the current power consumption

$$\sum^{D^-} P_{m,d,i} = \sum^{\underline{D^-}} P_{m,d,i} + \sum^{\bar{D^-}} P_{m,d,i}; \quad \forall i \in I, \forall d \in D^-, \underline{D^-} \cup \bar{D^-} = D^- \tag{8}$$

B. Single device flexibility calculation

Following the description of the general method for flexibility aggregation developed in this paper the focus lies upon the single device flexibility calculation leading to $\sum_{m=1}^{M} P_{m,\text{flex}+,i}$ and $\sum_{m=1}^{M} P_{m,\text{flex}-,i}$. Fig. 4 shows the end-user's unique and operation-oriented inputs for determining the flexibility for the real devices. Through the implementation of knowledge-based models of single devices into PMS, the behaviour of devices that interact with the status determining and monitored parameters can be locally evaluated and used to fill the flexibility matrices. The single device's contribution to short-term flexibility communicated with the flexibility matrices, are limited to the device classes interruptible and flexible. In the following section the approach is presented with two devices: Electric heater systems or heat pumps and EVs, as exemplary interruptible and interruptible-flexible devices. Additionally, the PMS end-user inputs for white goods such as dishwashers and washing machines also contribute to the flexibility matrices as interruptible loads, if considered.

1) Electric heater system: The thermal dynamic of buildings, following the same number of interval I, can be calculated through Equations (9) and (10) for the next step's inner temperature $\theta_{\text{in},i+1}$ and the water storage temperature $\theta_{\text{storage},i+1}$, applied in [7]. The additional parameters stated are the heat gain through windows $\dot{Q}_{\text{sol},i}$, the heat gain arising from the heat flow from the hot water storage tank $\dot{Q}_{\text{heat}}, i$, which is positive for Equation (9) and negative for Equation (10) and the heat gain from present persons $\dot{Q}_{\text{pers},i}$. The values $\dot{Q}_{\text{x,xchg},i}$ and $\dot{Q}_{\text{axchg},i}$ contain the thermal exchanges with the surrounding air caused by transmission and direct ventilation. The hot water usage is covered by $\dot{Q}_{\text{hw},i}$, whereas $\dot{Q}_{\text{eheat},i}$ represents the electrical heater heat gain. The implementation of efficiencies is possible and can cover conversion and transportation losses.

$$\theta_{\text{in},i+1} = \theta_{\text{in},i} + \frac{\Delta t}{C_{\text{in}}} \Big(\dot{Q}_{\text{sol},i} + \dot{Q}_{\text{heat},i} + \dot{Q}_{\text{pers},i} + \dot{Q}_{\text{in,xchg},i} + \dot{Q}_{\text{axchg},i} \Big) \tag{9}$$

$$\theta_{\text{storage},i+1} = \theta_{\text{storage},i} + \frac{\Delta t}{C_{\text{storage}}} \Big(\dot{Q}_{\text{heat},i} + \dot{Q}_{\text{eheat},i} + \dot{Q}_{\text{storage,xchg},i} + \dot{Q}_{\text{hw},i} \Big) \tag{10}$$

Applying the flexibility methodology and end-user inputs from Fig. 4 to the above mentioned electric heater element the remaining time until the storage tank and the inner temperature reach the lower set-points can be used as positive flexibility or generation equivalent, when ON. By calculating the energy difference between the current storage tank temperature $\theta_{\text{storage},i}$ and the lower temperature $\theta_{\text{storage,set}} - \delta_{storage}/2$ the remaining time can be estimated. The parameter $\delta_{storage}$ shows the width of the allowed storage temperature range and indicates the lower and upper allowed temperatures for heating operations. Relevant parameters for the estimation of flexibility are the assumed hot water usage for the next intervals and the heat transmission through the building components. The hot water usage profile is closely linked to the number of end-users in the building. By setting the number of persons as PMS end-user input, one of three smoothed hot water usage profiles applied in [7] are implemented as hot water usage forecast $\dot{Q}_{\text{hw,fc}}$. Fig. 6 shows the original hot water usage profile L from [19] and the applied smoothed profile for PMS calculation with an end-user input for 3 persons. The additional end-user inputs containing building age and building dimensions influence the thermal transmission through the building $\dot{Q}_{\text{in,xchg}}$ or storage tank envelope $\dot{Q}_{\text{st,xchg}}$. By setting PMS inputs for building age a generalized k-value k_{wall} is applied for thermal transmission. In [18] the evolved building standards and corresponding k-values in Germany were outlined. These values for four different building standards are implemented in the real time simulation. On the one hand for the electric heater and the thermal building model, by adjusting the averaged k-values normally distributed around the mean value and on the other hand by the implementation of the averaged value into PMS functionality.

When using Equation (11) and (12) the remaining time $t_{\text{eheat,pos},i}$ for interval i until the lower energy level is reached can be calculated. When turned off the remaining time $t_{\text{eheat,neg},i}$ until the upper energy level of the storage tank can be calculated with Equations (13) and (14), using the rated heat power from the electric heater system. Following the same idea for inner room temperature the remaining time until the inner room temperature reaches the lower or higher set-point can be estimated.

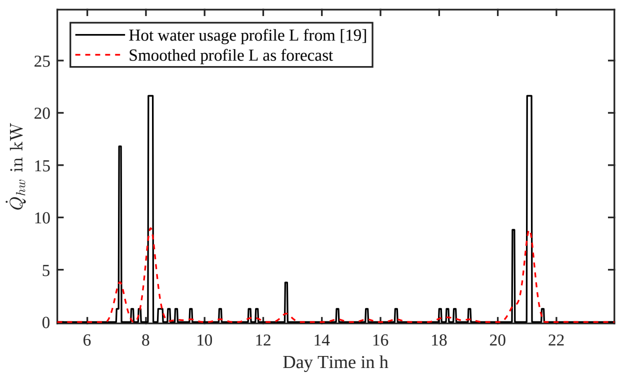


Fig. 6. Original hot water usage profile L and smoothed profile for PMS applications with an energy demand of 11.655 kWh per day [19].

$$E_{\text{storage},i} - E_{\text{storage,min}} + \sum_{p=i}^{P} \left[\dot{Q}_{\text{hw,fc},p} + \dot{Q}_{\text{in,xchg},p}(k_{\text{wall}})\right] \cdot \Delta t = 0 \tag{11}$$

$$t_{\text{eheat,pos},i} = P - i \tag{12}$$

$$E_{\text{storage,max}} - E_{\text{storage},i} + \sum_{n=i}^{N} \left[\dot{Q}_{\text{hw,fc},n} + \dot{Q}_{\text{st,xchg},n}(k_{\text{wall}}) + \dot{Q}_{\text{eheat},i}\right] \cdot \Delta t = 0 \tag{13}$$

$$t_{\text{eheat,neg},i} = N - i \tag{14}$$

With the two calculated time values $t_{\text{eheat,pos},i}$ and $t_{\text{eheat,neg},i}$, the flexibility matrix of Equation (4) can be filled. It is important to emphasize that the possible starting time of the flexibility event is depended on $t_{\text{eheat,pos},i}$ and $t_{\text{eheat,neg},i}$, for the former when ON and OFF, respectively. The same issue is relevant for the duration of the flexibility event but in the opposite way. So the matrices can be filled by taking into account only two parameters. By adding additional temperature set points for flexibility events the possible duration of the event can be extended.

2) Electric Vehicle: Applying the flexibility methodology and end-user inputs from Fig. 4 to the EV charging process, the remaining time until the charging process has to start, is the maximum duration of the flexibility availability $t_{\text{EV,pos},i}$. Equation 15 shows the calculation of the possible flexibility event duration. The relevant parameters for calculating the duration of the charging $t_{\text{EV,charge}}$ are the battery capacity $E_{\text{EV,bat}}$ and the rated charging power of the charging infrastructure $P_{\text{r,EV}}$. The general charging of EVs is represented by a constant power and a constant voltage phase, which goes in tandem with a falling power consumption from nearly 80 % State-of-Charge (SOC) to fully charged, based on battery management. Equation (16) shows the charging power for different SOC.

$$t_{\text{EV,pos},i} = t_{\text{EV,end},i} - t_{\text{EV,charge},i} - t_i \tag{15}$$

$$P_{\text{EV},i} = \begin{cases} \frac{P_{\text{r,EV}}}{(1-0.8)} \cdot \left(1 - \frac{SOC_{\text{EV},i}}{100}\right) & \text{SOC}_{\text{EV},i} \geq 80 \\ P_{\text{r,EV}} & \text{else} \end{cases} \tag{16}$$

When estimating possible power reductions to fill the flexibility matrices, the associated power consumption by the current SOC needs to be known. Then, a matrix **SP** can be calculated containing a pre-calculated minute-based charging process. For each minute from start to fully charged the SOC and associated power consumption are defined as first and second dimension, respectively. Fig. 7 shows a pre-calculated charging process for the end-user inputs $E_{\text{EV,bat}} = 58$ kWh and $P_{\text{r,EV}} = 11$ kW.

$$\mathbf{SP} = \begin{bmatrix} \underline{\text{SOC}}_1 & \underline{\text{SOC}}_q & \cdots & \underline{\text{SOC}}_Q \\ P_{\text{EV},1} & P_{\text{EV},q} & \cdots & P_{\text{EV},Q} \end{bmatrix} \tag{17}$$

The $\underline{\text{SOC}}_q$ is presented as the difference between the current and the SOC for a fully charge battery. The pre-calculated charging from 1 to 99.5 % SOC takes $Q = 479$ min for the modeled battery. The SOC curve shows that the constant voltage phase, from 80 % SOC to fully charged EV, takes nearly one third of the whole charging process. It has to be stressed that constant power assumptions for charging processes lead to huge deviations in the time needed for charging. Applying the information from Fig. 7 to a newly arrived EV, the remaining time $t_{\text{EV,charge},i}$ until the EV is fully charged can be calculated with:

$$t_{\text{EV,charge},i} = Q - q \tag{18}$$

where

$$\underline{\text{SOC}}_q = 100 - \text{SOC}_{\text{EV},i} \tag{19}$$

With the knowledge about the current SOC and the position q within the matrix **SP** all future minute-based power consumption can be extracted. The single EV battery model is integrated as presented in [20] with Equations (21) for Open-Circuit-Voltage (OCV) calculation, considering the SOC, and (20) for SOC calculation through time integration of the battery current. The parameter values for the fitted OCV model is shown in Table II. Fig. 8 shows the OCV for the battery model apllied to the EV.

$$SOC_{\text{EV},i} = SOC_{\text{EV},i-1} + \frac{i_{\text{EV},i} \cdot \Delta t}{C_{nom}} \tag{20}$$

$$OCV(SOC_{\text{EV},i}) = N_{\text{series}} \cdot \left(p_1 e^{(\alpha_1 SOC)} + p_2 e^{(\alpha_2 SOC)} + p_3 e^{SOC^2}\right) \tag{21}$$

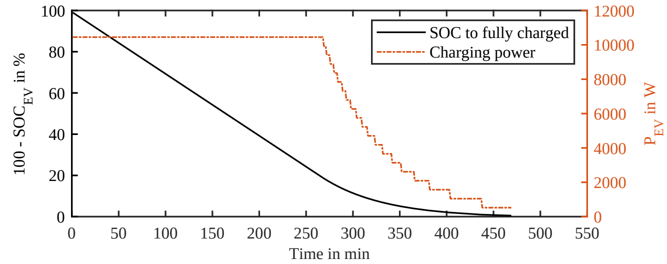


Fig. 7. The pre-calculated minute-based charging process for $P_{\mathrm{r,EV}} = 11\mathrm{kW}$, $E_{\mathrm{EV,bat}} = 58\mathrm{kWh}$ and a fixed inverter efficiency $\eta_{\mathrm{inv}} = 0.95$. The SOC is shown as deviation from current to full charged SOC.

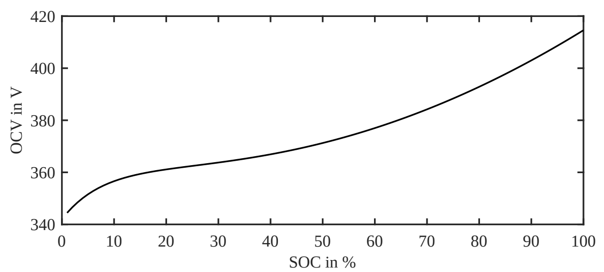


Fig. 8. OCV of the applied battery model to different SOC states for reference device EV.

TABLE II
PARAMETERS FOR APPLIED OCV MODEL.

Parameter	Value
p_1	3.649
p_2	-0.229
p_3	7.3e-5
α_1	-0.00066
α_2	-0.1239
C_{nom} in Ah	20
N_{series}	100
N_{parallel}	7

IV. USE CASE

As exemplary use case the above explained methodology was implemented into the set-up presented in [7]. The detailed Simulink device models for an EV, a heat pump system, a washing machine and a dishwasher were used as reference devices with associated specific operation and state conditions. The end-user inputs for the exemplary use case are given in Table III. These end-user inputs were applied to the PMS functionality for calculating short-term flexibility. Additionally, the operation-orientated parameters set by end-users and the underlying state determining parameters are submitted by protocols like EEBUS or OpenADR.

The calculated flexibility values were modified following the outlined methodology in Section III-B to fill the flexibility matrices from Equation (4). Utilizing the CLS data tunnel offered by the SMGw infrastructure the flexibility matrices were allocated to interested EMPs within the WAN. The EMP

TABLE III
UNIQUE END-USER INPUTS FOR PMS EXTENSION OPERATION.

PMS-input	Value	Unit
$P_{\mathrm{r,EV}}$	11	kW
$E_{\mathrm{EV,bat}}$	58	kWh
n_{persons}	2	-
V_{storage}	200	l
$P_{\mathrm{r,hp}}$	1.8	kW
COP_{hp}	3.5	-
building age	2013	years
building dimensions	10, 10, 2.5	m

is able to access the flexibility potential for short-term forecast errors or trading at intra-day exchange markets. In Fig. 9 a flexibility event was chosen by the EMP. The corresponding flexibility matrix for generation substitute is presented in Equation (22), depicting the positive flexibility matrix for a weekend day. The flexibility matrix was sent at $i = 1245$ min, which corresponds to 20:45 h. Because of a high market price at the energy exchange the flexibility potential for 21:00 h was selected for the maximum available time of 30 min. Looking at the end-user devices, the EV contributes with a power reduction of 11 kW, whereas the heat pump system adds 1.8 kW. The overall estimated possible power reduction for 30 min was achieved. In Fig. 9 the potential flexibility event duration is shown for the EV. The red-dotted area is the flexibility event set by the EMP. Whereas the possible flexibility duration increases during the event it stays at nearly the same value until the EV is fully charged. The slight decrease after the flexibility event occurs because of the simplified pre-calculated charging process. The simplification does not exactly capture the charging behaviour from 80 % to 100 %.
The impact on heat pump behaviour with the flexibility event realization is shown in Fig. 10. The contribution to a possible flexibility event is dependent on the negative flexibility time value higher than 15 min, because the heat pump system's flexibility is accessible only with a charging time greater then 15 min until the storage tank and the inner room are at the upper limit of the temperature deadband. Whereas the heat pump system is switched to OFF and the storage and inner room temperature slightly change during the flexibility event, the positive flexibility time value rise. This occurs because of the additional implemented hot water usage profile forecast, which changes to zero within this exemplary time interval.
This exemplary use case outlines the presented process from local flexibility calculation to the communication and short-term access through EMP choise, reacting to price signals or energy system imbalances.

$$\mathbf{P}_{m,\mathrm{flex+},1245} = \begin{bmatrix} 12.80 & 12.80 & 11.00 & 11.00 & 11.00 \\ 12.24 & 12.24 & 10.45 & 10.45 & 10.45 \\ 10 & 10 & 8.2 & 8.2 & 8.2 \\ 6.6 & 6.6 & 6.6 & 6.6 & 6.6 \end{bmatrix} \quad (22)$$

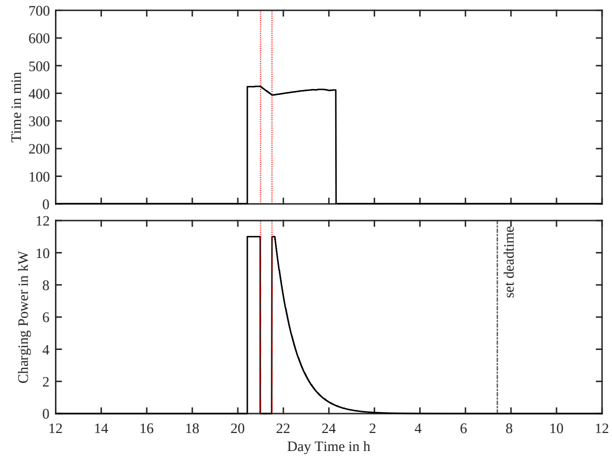


Fig. 9. Development of the possible flexibility event duration for the charging process of an EV (top) and power consumption during the charging process (bottom) with EMP-controlled flexibility event in the red-dotted area and set deadtime by end-user.

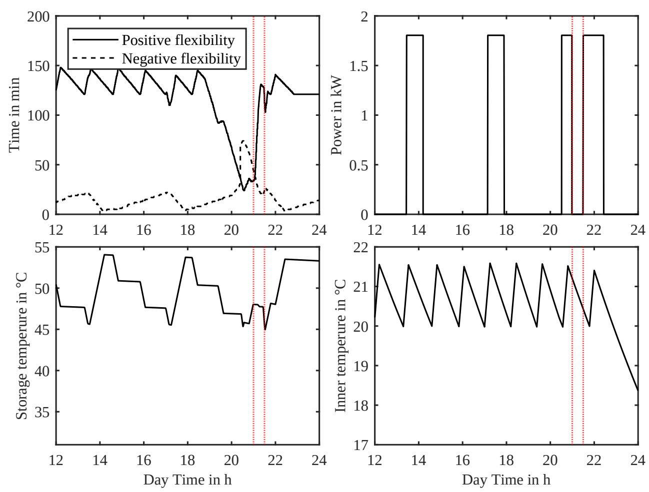


Fig. 10. Positive and negative flexibility time values for estimating possible start time of event and possible duration (top left), power consumption (top right), storage tank temperature (bottom left) and room temperature (bottom right) of modeled heat pump system during the flexibility event in the red-dotted area.

V. Conclusion

In this work an approach was presented that achieves detailed insights in short-term flexibility potential in aggregator systems. By the implementation in the existing SMGw infrastructure the individual and common concerns for privacy and data integrity are ensured. End-user specific PMS-inputs create the boundaries for local flexibility calculation, following the comfort needs of the end-user. The simulation results show the work flow of the approach and the applicability for accessing the communicated short-term flexibility. Further work will concentrate on an expansion to more devices, considering generation equivalent and additional load potential in a wider perspective. The implementation of the approach into more end-user energy systems will proof the large-scale applicability and the impact on grid stability or short-term profit maximization for EMPs and participating end-users.

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