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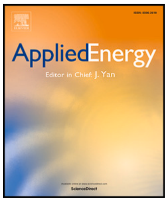

An analytical method for quantifying the flexibility potential of decentralised energy systems

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ABSTRACT

In this study, we developed a technology-independent method for quantifying the time-varying flexibility potential of different energy systems. As the flexibility of these systems was assumed to be an additional service, their primary application must not be undermined by flexibility provision; for example, providing flexibility from a heat pump must not threaten the space heating of a building. Therefore, the method developed for quantifying flexibility contains an estimation of the technology- and schedule-specific boundaries that consider the primary application of the energy systems. The time-varying flexibility potential of energy systems was proposed to be presented in a universal, two-dimensional, and technologically-agnostic form. It enabled to develop a method for aggregating the flexibility values from different energy systems. The developed methods were demonstrated on two case studies: the first included a calculation of the flexibility potential of a single battery storage (BS) system in a private household, and the second presented aggregation of the flexibility from multiple BS systems. The simulation proved that these BS systems could have provided flexibility additionally to their operation in compliance with the boundary values. In both case studies, the BS systems exhibited significant daily and seasonal variations in flexibility potential depending on the actual mode, operation in the following hours, local energy generation, and consumption. In general, the developed methods can be utilised to quantify and aggregate the time-varying flexibility potentials of energy systems, alongside their scheduled operation in the course of a single day as well as across seasons.

1. Introduction

1.1. General background

Increasing power generation from renewable energy systems is one of the key targets in the United Nations Sustainable Development Program and IPCC Climate Change Report and is intended to mitigate the negative impacts of the climate change [1,2]. In 2022, the installed capacity of wind power and photovoltaic (PV) systems increased by 266 GW in comparison to the previous year, and the total capacity of these volatile renewable energy systems reached 1.95 TW [3].

Besides that, energy consumption also increases and becomes more volatile, i.e. fluctuating, due to increasing amounts of electrical appliances (e.g. air conditioning, ventilation, and electronic devices) and decentralised integrated energy systems (e.g. electricity-based heating and water treatment systems and charging stations for electric vehicles).

The high share of volatile power generation from weather-dependent renewable energy systems, such as PV and wind power systems, together with fluctuating energy consumption, increase the level of variability and uncertainty [4]. In their turn, increasing variability and uncertainty intensify the need for flexibility in order to maintain the balance in supply and demand, i.e. every level of the power grid must become more flexible, [5,6].

In addition to the large-scale, centralised solutions existing nowadays, together with hydrogen-based back-ups, as well as reserves providing units and groups, the flexibility sources in the future will also include decentralised energy systems, such as power generation units, storage systems, integrated energy systems, so-called *prosumers*, and controllable loads in residential and commercial buildings, city districts, industrial estates, and other areas [7,8].

1.2. Related works

Through a literature review, we have identified different definitions of energy flexibility, diverse methods for quantifying the flexibility, as well as technical and economical metrics for evaluating the flexibility provision. The following subsections contain an overview about the qualitative (Section 1.2.1) and quantitative (Section 1.2.2) assessment

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Table 1

Short overview about individual methods for quantifying flexibility, as well as indicators and metrics for evaluating flexibility.

Ref.	Short description	Indicators, metrics, indices, etc.	Tech.-spec. investigated
[9]	Flexibility assessment tool to estimate the flexibility requirements and flexibility sources of a power system.	Technical flexibility and available capacity of flexible resources in MW, Flexibility Index	☐
[10]	Framework for quantifying and evaluating the operational flexibility of single power system units and combinations of them.	Power provision capacity (MW), power ramp rate capacity (MW/min), energy provision capacity (MWh), and ramp duration (min)	☐
[11]	Method for analysing the flexibility of building energy systems with thermal energy storage under consideration of different influencing factors.	Temporal flexibility, power flexibility and energy flexibility	☒
[12]	Bottom-up method to quantify the flexibility provided by the commercial buildings and introduction of a cost-curve to evaluate the flexibility provision.	Flexibility energy (kWh), corresponding costs for flexibility service (€)	☒
[13]	Investigation and evaluation of flexibility provided by the electricity and heat suppliers in the buildings connected to the district heating system.	Flexibility energy and flexibility hours	☒
[14]	Model to match the flexibility required by an aggregator with the flexibility provided by load shifting of devices in residential buildings.	Flexibility power and time period of flexibility request.	☒
[15]	Development of a model to quantify the energy flexibility potential of different buildings using a building model and uncertainty of buildings occupancy.	Energy flexibility potential (in kW)	☒
[16]	Five categories of building energy flexibility was proposed, and frameworks to quantify energy flexibility for all categories were developed.	Flexibility capacities (in kW or kWh) and flexibility ratios	☐
[17]	Computational model integrated in the energy management system (EMS) was developed to quantify the flexibility that can be offered by PV-BS systems.	Power, energy and duration of flexibility offer	☒
[18]	Model for the EMS to quantify the flexibility of distributed energy systems and to offer it on flexibility markets.	Power, energy, duration and price of flexibility	☒

of flexibility. As the main objective of this study is the quantification of flexibility potential, the existing qualitative definitions of flexibility are described shortly. Nevertheless, the overview about the definitions of energy flexibility contributes to deeper understanding of the quantification method developed in the current study.

1.2.1. Qualitative assessment of flexibility

A widespread definition of flexibility refers to the ability of a power system to respond rapidly to changes and fluctuations in energy generation and consumption, [4,19], or to the changes in net load, i.e. difference between load and power generated by variable renewable energy systems, [20,21]. In Ref. [22,23], the flexibility is defined as the ability of a system to modify power generation and consumption in response to external signals, e.g. price signals, activation signals, and others. Strbac et al. [24] inserted a consideration of system constraints into their definition of flexibility to ensure the secure and reliable operation of the system.

Li et al. [25] proposed to define energy flexibility as the ability of a building to adjust its energy generation and consumption in a flexible manner with respect to local circumstances (e.g. weather) in order to support the power grid, but without threatening the needs of the building's inhabitants (e.g. comfortable room temperature and sufficient lighting).

The flexibility is also defined as the technical capability of energy systems, such as heat pumps, gas boilers, PV and battery storage systems, to deviate from the reference or scheduled operation, [12,17]. More specifically, the technical capability of heat pumps to shift their operation to off-peak hours, [26], or to the time periods when the buildings are unoccupied, [15], can be also defined as flexibility.

Further existing definitions of flexibility, together with description of different flexibility sources on the supply and demand side, and methods for flexibility assessment are presented in the comprehensive review studies, such as Ref. [7,27].

1.2.2. Quantitative assessment of flexibility

Granado et al. [28] proposed to consider the following dimensions for quantitative characterising the energy flexibility: time (response time, ramp rate, time and duration of the availability of flexibility), spatiality (influence of flexible resource location on flexibility provision), resource type (demand-side, supply-side, grid-side, or storage technologies), and risk (defining by probability distribution of flexibility availability). In case of buildings, the existing quantification methods calculate the energy flexibility on the basis of the deviation from reference electricity consumption with consideration to either thermal comfort inside or electricity costs, [29].

Alongside the quantification methods, the metrics and indicators for evaluating the flexibility provision belong to the most significant parts of this research field. Li et al. [25] described a broad range of metrics for evaluating the flexibility provision resulted from different designs and operational strategies in the residential buildings, such as peak power reduction, self-consumption rate, energy savings due to demand responses, and others. Li et al. [30] proposed to categorise the key performance indicators (KPIs) for assessing the flexibility provided during operational phase of the buildings into baseline-required and baseline-free. The most frequently used baseline-required KPIs include the energy efficiency of demand response, the flexibility saving index, and peak power shedding. The leading baseline-free KPIs encompass the flexibility factor, energy shift flexibility factor, and load factor.

Table 1 presents a short overview about diverse individual methodologies and frameworks for quantifying flexibility of energy systems, as well as corresponding indicators, metrics or ratios for evaluating the flexibility. We propose to structure the references inside the table into two categories: general investigation and technology-specific investigation of the energy flexibility. The last investigated the term of energy flexibility based on a single or several specific technologies.

Based on the literature review, we could identify several gaps in the research field of energy flexibility. Though the consideration of needs, comfort and behaviour of buildings' occupants should be integrated in the method for quantifying flexibility, [25,31], a wide range of studies did not consider them. Besides that, the certain studies investigated the flexibility of a specific technology, what complicates the transfer to further energy systems. Only a few of studies proposed the approaches for aggregating flexibility values in addition to the method for quantifying the flexibility of individual decentralised energy systems. Although the quantification of flexibility must consider the dynamic nature of flexibility provided by decentralised energy systems, [32], a universal form for presenting the entire spectrum of time-varying flexibility potential is missing in the most of the studies. To summarise, a general method for quantifying the flexibility which combines the mentioned properties is still missing.

1.3. Overview and contribution

The main contribution of the current study is that we propose an analytical method for quantifying the time-varying flexibility potential that can be provided by energy systems. The developed method can be characterised by the following properties:

- considering primary application of energy systems and the needs of building occupants in the flexibility quantification by calculating the boundary values,
- presenting the time-varying flexibility potential in a universal, two-dimensional and technologically-agnostic form, and
- aggregating the flexibility values of different energy systems.

For demonstration purposes, the methods were applied to retrospective quantifying the flexibility potential of battery storage (BS) systems installed in private households, i.e. we calculated the flexibility potential that these BS systems could have provided in addition to their operation.

As the current study does not include the simulation of actual flexibility provision, the energy consumption of the investigated households was not changed. However, it is important to consider that the actual provision of flexibility means a deviation from optimised operation, and therefore it might increase the buildings' energy consumption, as well as their energy costs. Furthermore, an analysis of the flexibility reimbursement is also not included in the current study.

The paper is structured as follows: In Section 2, we describe a future concept of a flexibility management system, and present our understanding of the flexibility, as well as classification scheme for flexibility. Section 3 presents the characterisation of local flexibility needs and sources in detail. Section 4 describes the methodology developed for the quantification and aggregation of flexibility potential, as well as the universal presentation form of flexibility potential. Section 5 contains results and discussions of two case studies. In Section 6, we conclude the study and present an outlook for ongoing and future research works.

2. Energy flexibility

The future energy system will consist of interconnected sub-systems, which we denote below as *energy cells*. These energy cells could be, for instance, residential and non-residential buildings, quarters and city districts, commercial and industrial real estates, and other or even sub-systems of these. The main characteristic of the energy cells is that they can decide autonomously and within predefined boundaries regarding the operation of their internal energy systems and loads. Nevertheless, the energy cells are connected to the power grid for energy procurement and energy surplus feed-in. [33,34]

2.1. Concept of a flexibility management system

We assume that the EMS of the future energy cells has an additional function for flexibility management. The operating principle of this flexibility management system is described later in this Section.

First, the EMS of energy cell will enable the prediction of energy consumption and production from local renewable energy sources. Second, in terms of the predictions and dynamic electricity prices, the EMS will schedule the operation of energy cell components in a cost-optimal way. Besides the cost-optimisation, the EMS may have other primary or additional objectives that depend on the energy cells and their components, e.g. optimisation of self-consumption, peak reduction, etc. We refer to this ability of local components to be planned in an optimal manner as *flexible scheduling*. In the diverse reviewed research papers, as well as in the comprehensive review of [30] the flexibility provision was evaluated by comparing a reference operation of energy systems with their optimised operation. To summarise, a lot of existing studies investigated flexibility, which we define as the flexible scheduling. Third, the EMS will reserve or purchase the expected residual load (i.e. the net load remaining after the subtraction of local power generation) from the energy supplier. A penalty-aware controlling system might be integrated by the energy suppliers and grid operators in order to ensure that the energy cells strive to follow the reserved plan.

The tasks of flexibility management include the detection of unexpected local fluctuations in energy generation and consumption within the energy cell and the utilisation of local components to compensate for these internal fluctuations. The flexibility used to balance these unexpected fluctuations inside the energy cell will be referred to as *short-term flexibility*. If the possible local fluctuations can be forecast (for instance, using an uncertainty prediction), the flexibility management will reserve the expected amount of necessary short-term flexibility.

The flexibility that remains after scheduling and subtracting the short-term flexibility can be offered on a flexibility market platforms, e.g. to the neighbouring quarters, distribution grid and other balancing groups.

The vision of future flexibility management is displayed in Fig. 1. The figure shows a residential city district with three buildings, one of which (represented by a bold dashed line) includes BS and heat pump that provide flexibility (green curves) in addition to their primary applications. The flexibility management of the home EMS combines the flexibility potentials from these two components and provides the aggregated flexibility to the EMS of the residential city district. The district EMS aggregates the flexibility values from three buildings and offers this on a flexibility market.

The future flexibility management will support the EMS in optimising energy consumption from intermittent renewable sources in order to make the operation of energy cells more grid-friendly and to increase the utilisation rate of the power generation units, storage systems and flexible loads in the context of flexibility provision.

In the current paper, we confine the main application of flexibility to energy balancing (from 15 min to intraday), e.g. the mitigation of fluctuations in energy generation and consumption in order to maintain the reserved residual load of energy cells and to avoid additional costs. As the flexibility is considered as an additional service offered by energy cells, the necessary level of reliability required for grid services, such as frequency and voltage regulation, cannot be guaranteed. Therefore, these applications are not investigated in this study.

The described flexibility management system requires methods for quantifying and aggregating the flexibility of different energy systems, regardless of their specific technologies. These methods are developed and described within the scope of this work.

2.2. Definition and classification of flexibility

A generally accepted and standardised definition of energy flexibility is yet to be established [35]. Considering the existing definitions of flexibility presented in Section 1.2, we propose the following qualitative description of this term as an essential basis for the quantitative method developed in this study:

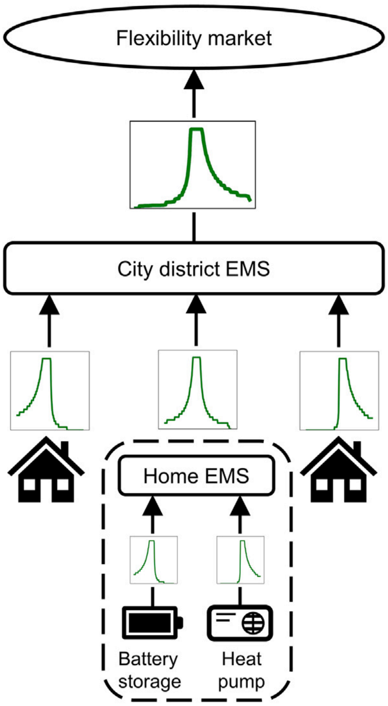


Fig. 1. Flexibility quantification and aggregation in a residential city district for offering on the flexibility market.

Definition. Flexibility is the ability of energy cells and their components (e.g. power generation units, storage systems, cross-sectoral integrated energy systems, and controllable loads) to deviate from optimally scheduled operation for balancing the fluctuations in energy generation and consumption without threatening the primary application of the components.

The flexibility can be provided as a reaction to internal (e.g. from building EMS), or external signals (e.g. from higher-level EMS or distribution grid operator).

Diverse studies proposed the classification of flexibility in positive and negative. In Ref. [12,23,36], the positive flexibility can be provided by increasing energy generation and feed-in or decreasing energy consumption, and, correspondingly, the provision of negative flexibility can be enabled by increasing energy consumption or decreasing energy production and feed-in. An opposing classification scheme for flexibility is proposed in Ref. [17,18]. Furthermore, the flexibility can be also classified in positive and negative in the context of energy generation and consumption of specific technologies, such as combined heat and power (CHP) systems and heat pumps, [11].

Similarly to [11,12,23,27,36], in this study the request for positive flexibility means a need for increase in energy generation and feed-in or decrease in energy consumption. The request for negative flexibility means a need for reduction in energy generation, feed-in energy curtailment, or increase of energy consumption. In this study, we present positive flexibility with positive power values (with a "+" sign) and negative flexibility with negative power values (with a "−" sign).

3. Local flexibility needs and sources

3.1. Local flexibility needs

The necessary amount of flexibility required by a power system can be estimated using some of the different calculation methods proposed in the scientific and engineering literature. For example, a flexibility chart presents the flexibility needs in terms of the penetration ratio of wind power, i.e. the capacity of installed wind power in MW divided by the peak load of the investigated area in MW, [37]. The flexibility needs in [9] consist of existing and additional flexibility requirements. The existing flexibility requirements include mainly variability and uncertainty of demand, whereas the additional requirements result from the variability and uncertainty of renewable energy output. Makarov et al. [38] calculated the amount of flexibility necessary for the California power grid using the values of forecast errors in demand and wind power predictions, as the forecast errors caused unexpected power ramps that must be balanced. In turn, Huber et al. [39] applied the power ramps in net load to measure the flexibility requirements of power systems

We make the following assumption in this study: Energy cells must balance their local flexibility needs with the available local flexibility resources, i.e. the EMS of energy cells should use local flexibility providers to mitigate local power and energy fluctuations with consideration to technical and economic constraints. The need for flexibility in energy cells arises from the power fluctuations caused by local weather-dependent renewable energy systems, load power fluctuations, forecast uncertainties, and unexpected failures.

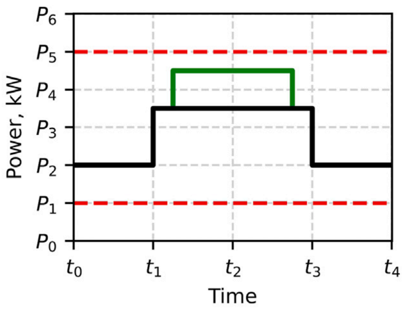
In general, the fluctuations that should be balanced can be described in terms of their power, energy and ramp rate. In [40], we proposed a method for quantifying the power and energy fluctuations of PV systems, as PV systems are the most popular choice for renewable energy sources in urban areas. The quantified power fluctuations (power ramps) can correspond to the necessary flexibility power values, namely the flexible power necessary to balance the fluctuations that arise. The calculated energy fluctuations (accumulated over a certain period of time) can be utilised to derive the required amount of energy for flexibility purposes. The ramp rate of the power fluctuations can also comply with the required reaction time and the ability of frequent power output change to mitigate the emergent fluctuations. This method can be applied to any PV system, and the results can be interpreted as part of the overall flexibility needs caused by the variable energy production of the PV system.

3.2. Local flexibility sources

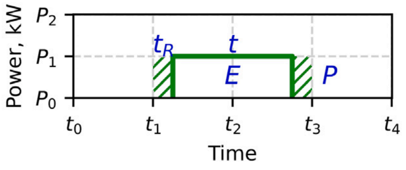
The energy systems, such as energy generation units, storage systems, cross-sectoral integrated energy systems, and controllable loads, are installed in the energy cells to meet the occupants' needs, such as space heating, domestic hot water treatment, cooling, increasing self-consumption from local renewable energy systems, peak shaving, and others. In addition to these primary purposes, these components of the energy cells can be supplementary applied for flexibility provision, as already investigated in [17,23,32,33,41,42]. In this study, these components of the energy cells are called *flexibility providers* or *flexibility sources*.

We propose three requirements for the components of energy cells in order to be technically able to utilise them for flexibility provision:

1. A component of energy cells can provide flexibility if it can modify its actual operating power on request (within given technical and economic boundaries).
2. The flexibility provider must have a buffer that allows for deviation from the schedule for a period of time (e.g. for 30 min.). The buffer corresponds to the ability to store energy in physical form (e.g. battery or heat storage) or virtual form (e.g. postponement of energy consumption).
3. The energy cells must be linked to a modern information and communication infrastructure for measuring, monitoring, communicating, and controlling the components, for the components to make flexibility requests, to receive flexibility values calculated by these components, and to send flexibility offers to the flexibility market.



(a) Flexibility provision (green) in addition to the scheduled operation (black)



(b) Flexibility box

Fig. 2. Abstract schematic presentation of flexibility provision in addition to the scheduled operation (a); schematic presentation of the main parameters of the flexibility box (b).

3.2.1. *Flexibility box*

Derived from the definition in Section 2.2, the flexibility potential can be presented as an addition to the scheduled operation, as is shown in Fig. 2(a). We propose ***a flexibility box*** for the abstract description and presentation of flexibility potential of any decentralised energy system (the green box in Fig. 2(b)). The flexibility box can be characterised mainly by the power and energy values.

P **Flexibility power**: Additional power offered by the flexibility provider and bounded by the nominal power of the technology.

E **Flexibility energy**: Amount of energy provided as flexibility; bounded by the nominal capacity of the technology buffer. In case of multiple cycles, the total amount of flexible energy is represented by the sum of areas of the multiple boxes.

However, for the technical provision of flexibility, we propose two additional properties, which describe technical limitations of the given technology: minimal duty cycle and reaction time.

t **Minimal duty cycle**: Minimal period of time between the sequential power changes of a flexibility provider to avoid technical damages.

t_R **Reaction time**: Time period from the flexibility request to the start of the provision of the requested power [43].

The universality of the flexibility box allows different flexibility providers to be combined for aggregated flexibility. Fig. 3 displays an abstract graphical presentation of flexibility need and the aggregated flexibility potential from two different sources.

The red line presents an unexpected power fluctuation that should be balanced by the flexibility sources. We assume that flexibility source A has a slow reaction time, but that it can offer more energy for flexibility provision. We also assume that flexibility source B has a fast reaction time and short minimal duty cycle, but a small capacity. Neither flexibility source A nor B can fulfil the requested flexibility demand on its own. Therefore, the flexibility values from these providers are combined. In this example, we utilise the fast reaction time and short minimal duty cycle of flexibility provider B, as well as much of the energy of flexibility provider A.

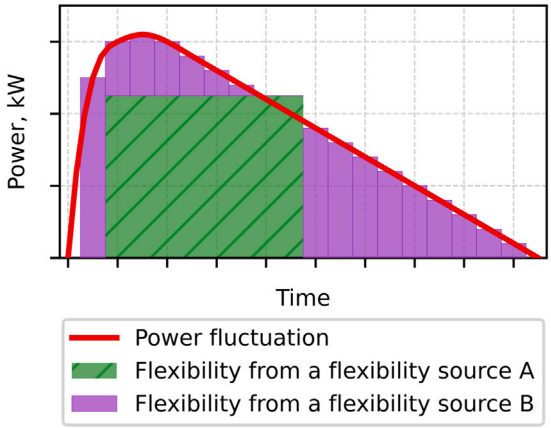


Fig. 3. Schematic presentation of flexibility needs and provision from two flexibility resources.

In general, the optimal combination of flexibility resources depends on their technology-specific characteristics, such as power (parameter P), capacity (parameter E), minimal duty cycle (parameter t), and reaction time (parameter t_R).

3.2.2. *General description*

The actual provision of flexibility (even from a single flexibility provider) can be limited by different factors, such as the primary purposes of the energy cells components, their scheduled operation, technology-specific parameters, and comfort conditions for building occupants. For example, El Geneidy and Howard [44] found out that outdoor air temperature, heat pump base load, and constraints for comfortable indoor temperatures can limit the amount of flexibility offered by heat pumps or even fully preclude the flexibility provision. As the energy cell components can offer flexibility solely as an additional service, the provision of flexibility must not threaten the primary purposes of these components. In other words, the primary purposes must always be prioritised over flexibility provision.

The energy cell components belong to different technologies with their specific characteristics, such as nominal power and capacity, way of providing flexibility, response time, minimal duty cycle, and others. The technology-specific characteristics of the energy cell components must be considered during estimation of flexibility potential in order to avoid negative influences, such as device damage and the lifetime shortening of the components. Despite the diversity of the technologies that make up the energy cells' components, the flexibility from these different technologies must be presented and described in a universal and technology-agnostic way.

In this study, we propose a general tabular form for the description and characterisation of different energy cell components in the context of flexibility provision. This tabular form contains a description of the primary application purposes, requirements, flexibility box assignment, and limitations of the energy cells components mentioned above. Table 2 presents a description of typical flexibility provision from BS and heat pumps, together with heat storage.

The row “Primary application” describes the primary applications of the observed flexibility provider, i.e. the main reasons for the installation of this device in the energy cells. The row “Flexibility box” includes the technology-specific parameters to assign the flexibility box for the flexibility potential. The rows “Positive flexibility provision” and “Negative flexibility provision” contain the technology-specific description for providing positive and negative flexibility by means of the flexibility provider. The “Boundaries” row contains the calculated technology-specific characteristics of the flexibility provider that limit

Table 2

Description of a typical BS and heat pump with heat storage in the context of flexibility provision.

	Li-ion BS system	Heat pump (HP) with heat storage (HS)
GENERAL INFORMATION		
Primary application	Increase of self-consumption, reduction of peak load, etc.	Heating, cooling, hot water treatment
FLEXIBILITY BOX		
Power P	Charge and discharge power	Nominal electrical power of HP compressor
Min. duty cycle t	Equal to reaction time	Equal to min. running time, e.g. 6 min. in [45]
Energy E	Usable BS capacity	Thermal capacity of HS
Reaction time t_R	Very fast, in ms, [46]	Fast, in s, [47]
TECHNOLOGY-SPECIFIC INFORMATION AND LIMITATIONS		
Positive flexibility provision	Increase in discharging power. Decrease in charging power.	Decrease in the electrical power of HP. Heat demand is covered by HS.
Negative flexibility provision	Increase in charging power. Decrease in discharging power.	Increase in the electrical power of HP. Heat surplus is stored in HS.
Boundaries	Power boundaries: nominal charging and discharging power. Energy boundaries: min. and max. energy must be stored in BS to fulfil the primary application.	Power boundaries: nominal electrical power of HP. Energy boundaries: min. and max. energy must be stored in HS to fulfil the primary application.
Further limitations	BS cycle lifetime, etc.	Room air temperature, reduction of HP efficiency caused by modulation, etc.

or prohibit the flexibility provision. Further internal and external factors that limit or prohibit the flexibility provision are given in the row “Further limitations”.

In this study, we propose to characterise the flexibility potential mainly in terms of flexibility power (parameter P) and maximal duration of providing the given flexibility power (derived using parameters E and P). The procedure for calculating these values is comprehensively described in Section 4.

4. Methodology

The flexibility assessment of any flexibility provider consists of two main parts: initialisation and quantification. The initialisation segment must be implemented once following installation of a new energy cell component that is intended to be utilised for flexibility provision, in addition to its primary application. This part can be repeated after a relevant change or modification of the flexibility provider, e.g. expanding of the energy system, replacement of a component, etc. The initialisation consists of the following main steps: identifying the energy cell component that can provide flexibility additionally to its primary application, and making an overall description in the context of flexibility provision according to Table 2 (return to Section 3.2 for more information).

Compared to initialisation, the quantification of flexibility potential must be conducted on a regular basis (e.g. each hour), as long as the energy cell component is applied for flexibility provision alongside its operation. The developed method can be observed as a framework for quantifying time-varying flexibility potential from any flexibility provider. The output of the method is an abstract flexibility potential that the energy units and systems can theoretically provide in addition to their operation.

4.1. Quantification of flexibility from a single energy cell component

Using the developed method, we quantified the flexibility potential at each point in a predefined *planning time*, i.e. a time interval for which the operation of the energy cell components was scheduled to fulfil the primary application.

We propose describing the flexibility potential from the energy cell component in relation to the duration of providing power supplementary to the scheduled operation without threatening the primary application of the energy cell component, i.e. the method strives to estimate the following function:

$$\mathrm{dur}: \mathbf{Power} \rightarrow \mathbf{Time} \tag{1}$$

where the flexibility power value is assigned to the maximal time this power can be provided alongside original schedule of the energy cell component.

In the following subsections, we describe three general calculation steps for the flexibility quantification method that can be applied to any flexibility provider. For a better understanding of the developed method, we describe the calculation steps more specifically on the example of quantifying the flexibility potential for BS.

4.1.1. Step 1: Schedule

General case. Make an optimal operational schedule of the flexibility provider or use the existing schedule to fulfil the primary application within technical and economical boundaries for the planning period of time.

Example of BS. Create the operational schedule with electrical power values $P_{\text{sched}}(t)$ with $t \in [0, T]$, where T denotes the length of the planning period. $P_{\text{sched}}(t)$ refers to the optimally scheduled charging and discharging power values of the BS.

$P_{\text{sched}}(t)$, the current state of charge, and the efficiency of BS are used to derive the planned storage capacity $E_{\text{sched}}(t)$, i.e. the amount of energy stored in the BS at point in time t.

4.1.2. Step 2: Calculation of boundaries

General case. Calculate the boundary values that describe the ability of the flexibility provider to deviate from operation in terms of power and energy for the purpose of flexibility provision without threatening the primary application.

The primary application can be also understood that energy systems meet the needs of building’s occupants, such as space heating, mobility, or other services. Since the boundary values are calculated with regard to the scheduled operation, the needs of building occupants are considered in the flexibility quantification. In its turn, as long as the boundary values are complied with, the flexibility provider can offer flexibility in addition to the scheduled operation. The boundary values set restrictions for the modification of the actual power of the flexibility provider and for the state of its buffer (the meaning of the buffer term is explained in Section 3.2) during the planning period of time.

Example of BS. We propose two boundary types for the BS. First, boundaries for power, i.e. the minimal $P_{\min}$ (maximal discharging power) and maximal $P_{\max}$ (maximal charging power of the BS) electrical power. For the BS the following usually holds:

$$|P_{\max}| = |P_{\min}| = P_{\text{nom}}, \tag{2}$$

where P_{nom} is the nominal power of the BS.

Second, the boundaries for the amount of energy stored in the BS, i.e. the minimal $E_{\min}(t)$ and maximal $E_{\max}(t)$ amount of energy should or allowed to be stored in the BS at point in time t, such that the BS can be operated as scheduled during the remaining portion of the planning period.

The boundaries for the amount of energy stored in the BS at point in time t can be calculated as follows:

$$E_{\max}(t) = E_{\mathrm{sched}}(t) + \left(Q_{\mathrm{nom}} - \max_{\tau\in[t,T]} E_{\mathrm{sched}}(\tau)\right) \tag{3}$$

and

$$E_{\min}(t) = E_{\mathrm{sched}}(t) - \min_{\tau\in[t,T]} E_{\mathrm{sched}}(\tau) \tag{4}$$

where Q_{nom} is the usable capacity of the BS.

4.1.3. Step 3: Flexibility duration

General case. Calculate the maximal duration $\mathrm{dur}(P_{\mathrm{flex}})$ for providing the requested flexibility power P_{flex} according to the estimated boundary values of the flexibility provider.

Example of BS. The maximal duration of the flexibility provision $\mathrm{dur}(P_{\mathrm{flex}})$ from the BS is equal to the time period in which a sum of the scheduled operational power P_{sched} and flexibility power P_{flex} lies within the estimated power boundaries. Additionally, the scheduled capacity E_{sched} of the BS, together with additional capacity E_{flex} for flexibility provision must be inside the energy boundaries during this time period. The additional capacity for flexibility provision E_{flex} is calculated with:

$$E_{\mathrm{flex}} = P_{\mathrm{flex}} \cdot \tau \tag{5}$$

The maximal duration of the flexibility provision $\mathrm{dur}(P_{\mathrm{flex}})$ is given by:

$$\begin{aligned} \max \quad & t \in [0,T] \\ \text{s.t.} \quad & \forall \tau \in [0,t] : P_{min} \le P_{\mathrm{sched}}(\tau) + P_{\mathrm{flex}} \le P_{\max} \\ & \forall \tau \in [0,t] : E_{min}(\tau) \le E_{\mathrm{sched}}(\tau) + E_{\mathrm{flex}}(\tau) \le E_{\max}(\tau) \end{aligned} \tag{6}$$

4.1.4. Output of the method

Steps 1 and 2 can be also considered as preparation steps for flexibility calculation. These steps are independent of the requested flexibility power P_{flex}. The boundary values, estimated in these steps, depend solely on the technical parameters of the flexibility provider, its actual mode and scheduled operation for the planning time. As step 3 offers a function for calculating the maximal duration $\mathrm{dur}(P_{\mathrm{flex}})$ for flexibility provision, this step can be repeated for different flexibility power values P_{flex}, both positive and negative, i.e. for different flexibility power requests.

Therefore, the numerical results of the flexibility quantification method consist of two dimensions: the flexibility power values P_{flex} in kW and maximal duration $\mathrm{dur}(P_{\mathrm{flex}})$ in hours for which the flexibility power values can be provided alongside the scheduled operation. This universal two-dimensional form of describing the calculated flexibility potential can be applied for different energy cell components independently of their technologies, primary purposes, operating schedules, and other technical characteristics.

The numerical results of flexibility quantification (power and maximal duration values) can be presented graphically in the form of *a flexibility potential curve*. This curve is proposed in this study as a universal graphical depiction of entire flexibility potential, i.e. the maximal duration of flexibility provision for the range of defined, selected or requested flexibility power values. Fig. 4 presents a simplified flexibility potential curve using the example of the BS system.

The vertical axis of the flexibility potential curve displays the duration of flexibility provision from zero to the maximal planning period of time, e.g. six hours. The horizontal axis presents the flexibility power values. As the BS can technically provide both positive and negative flexibility, the area on the horizontal axis below 0 W presents negative flexibility power values, and above 0 W positive ones. The zero value of flexibility power corresponds to no flexibility provision, and it is given for the purpose of joint graphical presentation of positive and negative flexibility power values.

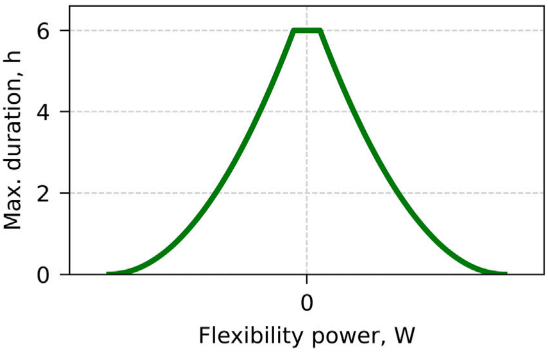


Fig. 4. Presentation of an exemplary flexibility potential curve.

Every single point on the flexibility potential curve can be transformed into a single flexibility box. A power value of the flexibility potential curve complies with parameter P of the flexibility box, and the corresponding duration value complies with parameter E divided by the P. The form of flexibility potential curve can vary depending on the technology used for flexibility provision, ability of this technology to provide both positive and negative flexibility, day and time of flexibility requests, etc.

The proposed procedure for flexibility potential quantification can be repeated for each point in time and for every component of the energy cells that is intended to be applied for flexibility provision.

4.2. Aggregation of flexibility values

Energy components inside the energy cells, such as power generation units, storage systems, and controllable loads, can be combined with each other to provide higher degrees of flexibility for longer periods of time, i.e. in response to requests for higher flexibility power. As the energy cell components belong to different technologies with specific technical characteristics, primary applications and individual operational schedules, these components can provide different values of flexibility, i.e. different flexibility power values for different time periods. In order to orchestrate numerous different energy generation units, storage systems and controllable loads with the purpose of flexibility provision, we propose the following method for aggregating the flexibility values from multiple components. The main aim of the proposed method of flexibility aggregation is to estimate the most technically appropriate compositions of flexibility values offered by the energy systems for providing the aggregated flexibility.

The input data of the developed method for flexibility aggregation includes flexibility power and duration values of any number of flexibility providers, that are combined for the aggregated flexibility provision. These flexibility power and duration values are calculated separately for each flexibility provider using the method for quantifying flexibility described in the previous subsections.

For the purpose of explanation, we consider a combination of flexibility providers that are orchestrated for the purpose of providing aggregated flexibility. The aggregated flexibility power of the combination P_{agg} is the sum of flexibility power values of the flexibility providers included in this combination.

$$P_{\mathrm{agg}} = \sum_{i=1}^{n} P_i \tag{7}$$

where P_i is a flexibility power value of ith flexibility provider in the combination of n components.

The maximum of aggregated flexibility power, i.e. the maximal positive flexibility, is equal to the sum of the maximal power values of all flexibility providers in the combination. The similar condition can be defined for the minimal aggregated flexibility, i.e. the maximal negative flexibility.

$$P_{\text{agg}}^{\max} = \sum_{i=1}^{n} P_i^{\max} \qquad P_{\text{agg}}^{\min} = \sum_{i=1}^{n} P_i^{\min} \tag{8}$$

The flexibility power values of each flexibility provider in the combination must satisfy the following conditions, i.e. they must lie between the following limit values:

$$P_i^{\min} \le P_i \le P_i^{\max} \tag{9}$$

Aside maximal and minimal values, the flexibility providers can offer different values of flexibility power for different duration of flexibility provision (see a range of flexibility power and duration values presented by the *flexibility potential curve* in Section 4.1.4). Therefore, the same aggregated flexibility power might be provided by different compositions of the power values of the flexibility providers. For example:

$$P_{\text{agg}} = P_1 + P_2 + \dots + P_n = \tilde{P}_1 + \tilde{P}_2 + \dots + \tilde{P}_n \tag{10}$$

where P_i and $\tilde{P}_i$ present different power values that ith flexibility provider can offer as a flexibility additionally to its operation.

In order to estimate the duration of aggregated flexibility for a specific composition of power values, we select the minimum of the flexibility provision duration values, as the duration of the aggregated flexibility provision is as long as the shortest duration of flexibility provision amongst all providers:

$$\text{dur}\left(P_1, P_2, \dots, P_n\right) := \min\left\{\text{dur}(P_1), \text{dur}(P_2), \dots, \text{dur}(P_n)\right\} \tag{11}$$

where $\text{dur}(P_i)$ is the maximal duration, for which ith unit of the combination can provide the flexibility power P_i.

In cases when the aggregated flexibility power can be provided by multiple compositions of flexibility power values for different periods of time, we select the maximal duration value, i.e. the longest duration of aggregated flexibility provision $\text{dur}(P_{agg})$ of the combination.

$$\text{dur}(P_{\text{agg}}) := \max\left\{\text{dur}(P_1, P_2, \dots, P_n) \,\middle|\, P_{\text{agg}} = P_1 + \dots + P_n\right\} \tag{12}$$

In this study we choose the longest duration of aggregated flexibility provision as a decision key parameter for selecting the optimal combination. However, the decision regarding the optimum can differ according to the different purposes, limitations, preferences and further characteristics of the investigated energy cell.

The proposed flexibility potential curve is also suitable to display the aggregated flexibility potential from the combination of different flexibility providers.

4.3. Overview

Fig. 5 presents graphically the overall functional principles of the flexibility quantification and aggregation methods developed in this study. The technical characteristics and optimal operational schedules of the flexibility providers, as well as the relevant requirements and limitations, are used as input data for the developed flexibility quantification method. This technology- and schedule-specific input data is required for the initial calculation steps (green) in order to define and calculate the boundaries of the investigated flexibility providers. The technology and schedule-specific boundaries are used in the following technology-agnostic calculation steps (blue) to estimate the values of the flexibility power (in kW) and those of the flexibility provision duration (in h). As the results of the flexibility quantification are presented in a universal and technologically-agnostic form, the different flexibility providers can be compared with each other and even their flexibility values can be aggregated in order to respond to the higher flexibility requests.

5. Results and discussion

The developed method for quantifying flexibility potential was demonstrated on example of a private household equipped with a PV and BS system — first case study. The flexibility aggregation was demonstrated on two private households with PV and BS systems with different operations of the latter — second case study. Although the case studies include residential buildings with BS systems, the methods were developed in such a way that they can be applied to any energy cell and for any flexibility provider (e.g. BS, heat pump, heat storage, system for heating, ventilation, air conditioning, etc.).

The case studies are presented to demonstrate the operating principle of the developed methods. The flexibility potential in the case studies was retrospectively quantified, i.e. we quantified the theoretically possible flexibility that the BS systems could have provided in addition to their operation. Therefore, the actual flexibility provision and its impact on the subsequent operation (after flexibility provision) were not investigated and evaluated in this paper.

For the retrospective quantification of flexibility at the given point in time, we used the historical power measurements of the BS systems and the historical energy demand of private households over the following six hours. This time interval was set as the planning time period, and is a free variable that can be selected according to user needs.

5.1. Data

We decided to use real power measurements for quantifying the flexibility potential, as this type of data have unexpected power fluctuations caused by the variability and uncertainty of load and volatile renewable energy systems, energy system failures, etc. Because of this aim, the measured energy data EMSIG [48] recorded by the open source EMS OpenEMS was applied in both case studies for the flexibility potential quantification and aggregation. The applied open access dataset contains the measurements of eleven private households in the DACH region (which comprises Germany, Austria, and Switzerland) from 01/10/2017 to 31/12/2020 with a time resolution of 15 min. The following measured values are included in the dataset:

- Active power generated by the PV system;
- Fed in and drawn active power of the grid meter;
- Charged and discharged active power of the BS;
- State of charge of the BS; and
- Consumed active power from all loads [48].

The energy operation of the households in the period from 01/01/2019 to 31/12/2019 was selected for both case studies. The main reason for this decision was a small amount of missing values in the dataset for the year 2019.

The household with ID number “EMS-5” was selected for the first case study, i.e. for testing the flexibility quantification method, whereas the households with ID numbers “EMS-1” and “EMS-5” were selected for the second case study, i.e. for the testing of the flexibility aggregation method. The relevant information about the power generation and consumption of the selected households is summarised in Table 3.

We opted to compose these two households because of their different power generation and consumption profiles. In 2019, the “EMS-1” household consumed 2632.24 kWh and the “EMS-5” 8292.95 kWh of electrical energy. “EMS-1” consumed an almost equal amount of energy per month during the entire year, i.e. its average energy consumption was 219 kWh per month with a standard deviation of 39 kWh. The average energy consumption of the “EMS-5” household was 692 kWh per month, with a standard deviation 274 kWh. We assume that “EMS-5” has an electricity-based space heating system, as its energy consumption during the colder months (averaged by month) was two times higher than in the warmer ones (averaged by month). We derived the installed capacity of the PV systems from the maximal recorded power of the PV systems (see “Max. PV power” in Table 3), as the original

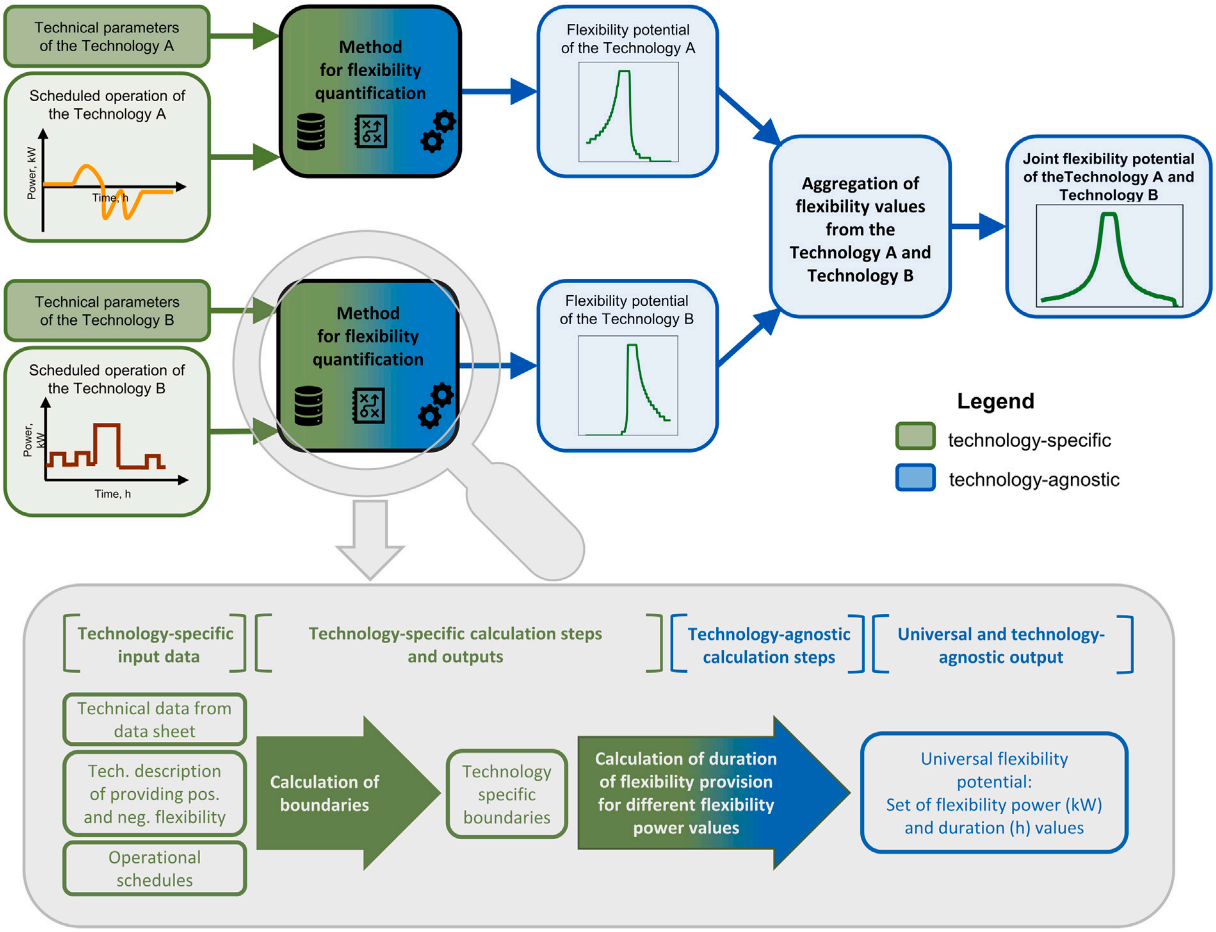


Fig. 5. Functional principle of the methods developed for flexibility quantification and aggregation.

Table 3
Short description of the selected private households, their PV and BS systems.

	EMS-1	EMS-5
Household		
Annual consumption	2 632 kWh	8 293 kWh
Max. power	10 kW	9 kW
Photovoltaic system		
Annual generation	6 918 kWh	13 022 kWh
Max. power	7.3 kW	11.6 kW
Battery storage		
Max. discharge power	8.2 kW	5.4 kW
Max. charge power	7.1 kW	7.9 kW

dataset does not contain these values. The investigated households have the same BS systems with a nominal power of 9 kW and usable capacity of 12 kWh. Further information about the dataset can be found in [48].

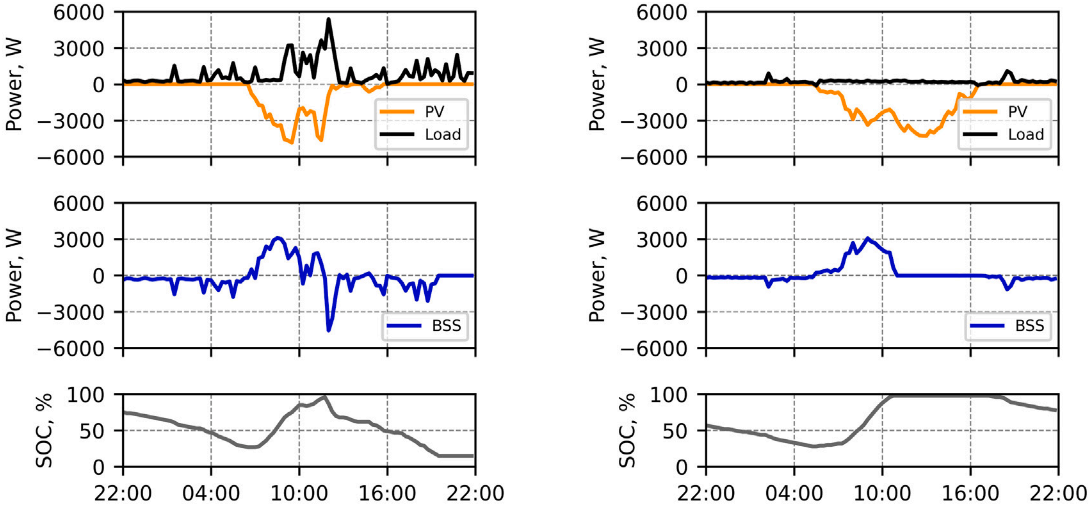
5.2. Flexibility potential of a single BS

As the primary application of the BS is not explained in [48], we assume that it was installed to optimise the self-consumption rate of energy produced by the local PV system. In addition to this primary application, the BS can theoretically provide positive flexibility by increasing the discharging power or decreasing the charging power, and the negative flexibility by increasing the charging power and decreasing the discharging power. The flexibility potential of the BS in “EMS-5” was calculated with the help of the developed procedure presented in Sections 4.1.1–4.1.3.

Step 1 of the developed method prescribes obtaining the operational schedule of the flexibility provider in order to fulfil the primary application. In this study, the flexibility potential was quantified retrospectively using historical power measurements, and therefore the measured charging and discharging power values of the BS were assumed to be its scheduled operation. Fig. 6(a) displays the load, PV and BS of the household “EMS-5” on April 3rd, 2019, with the top sub-figure presenting the power curves of the load (black) and PV system (orange), the middle sub-figure showing the power curve of the BS operation, and the bottom one displaying the state of charge (SOC) values of the BS in percent.

For the purpose of better presentation, the supply power values (PV and BS discharging) are given with negative signs and the consumption power values (load and BS charging) with positive ones. As is apparent in Fig. 6(a), the BS was charged when the PV power exceeded the load and the BS discharged when the PV output was below the load.

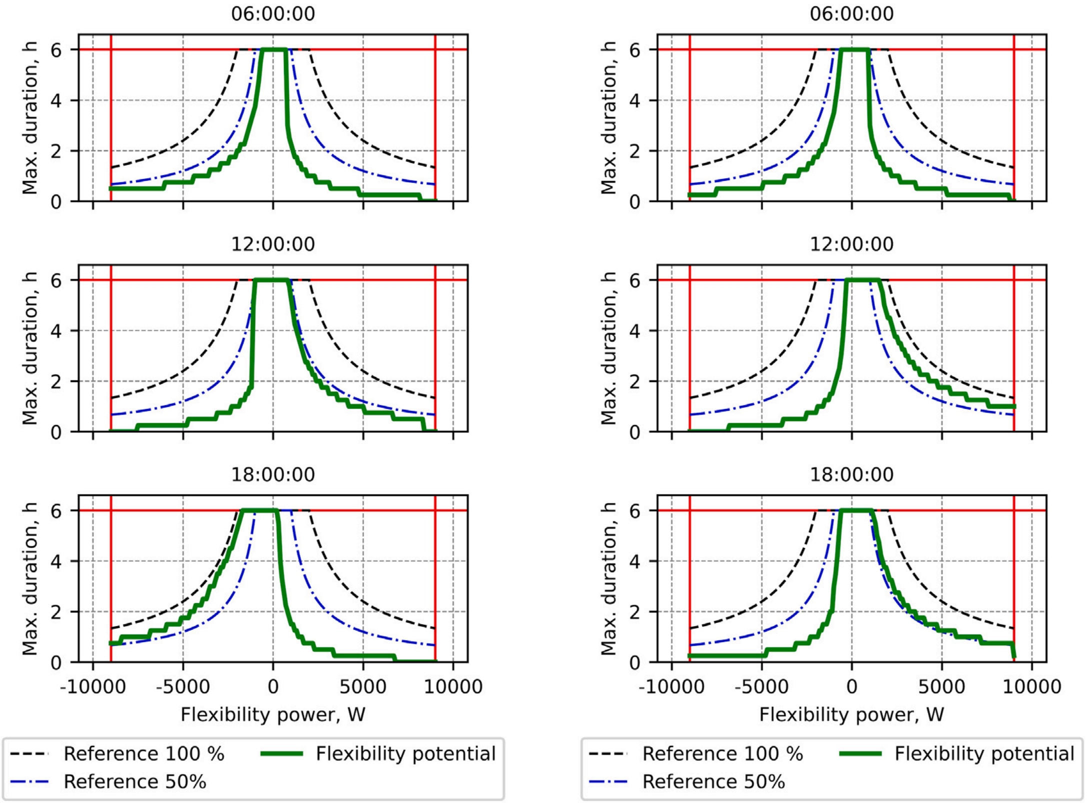
Step 2 includes the calculation of the boundary values. As noted in Section 4.1.2 we defined two types of boundary for the BS, i.e. for power and for energy stored in it. The lower and upper power boundaries were taken from the technical data sheet of the BS. Because the BS charging is presented with positive values and the BS discharging with negative ones, the lower power boundary is the maximal discharging power or the nominal power of the BS with the “−” sign, and the upper power boundary is the maximal charging power of the BS or the nominal power with the “+” sign. The lower and upper power boundaries of the BS remain stable during the entire quantification of the flexibility potential. In contrast to this, the lower and upper energy boundaries must be estimated for each point in time, and these values depend on the actual SOC and BS operation in the following hours (see Eqs. (3) and (4)).



(a) EMS-5

(b) EMS-1

Fig. 6. Historical power measurements of two households “EMS-5” and “EMS-1”, their PV and BS systems on April 3rd, 2019, [48].



(a) EMS-5

(b) EMS-1

Fig. 7. Duration of different positive and negative flexibility power values in “EMS-5” and “EMS-1”, i.e. flexibility potential curves, at 06:00, 12:00, and 18:00 on April 3rd, 2019.

In order to investigate flexibility potential of the BS for different flexibility power values P_{flex}, we defined a range of positive and negative flexibility power values. In this study, the following range was applied $P_{\text{flex}} \in [-9000, 9000]$, where −9000 W is the maximal negative flexibility power and lower power boundary and 9000 W the maximal positive flexibility power and upper power boundary of the BS.

In **Step 3**, we estimated the maximal duration of the flexibility provision for each flexibility power value from the defined power range. First, we calculated the new power values of the BS and new values of energy stored in the BS in case of deviation from the operation for the purpose of flexibility provision. Second, we checked that these new power and energy values lie between the lower and upper boundaries at each point in time over the next six hours (planning time period). Otherwise, the flexibility cannot be provided from this point in time.

A graphical presentation of applying power and energy boundaries for quantifying the maximal duration of the flexibility provision is presented in Fig. 8. The blue curve in the upper sub-figure presents the measured power of the BS from 12:00 to 18:00 on April 3rd,

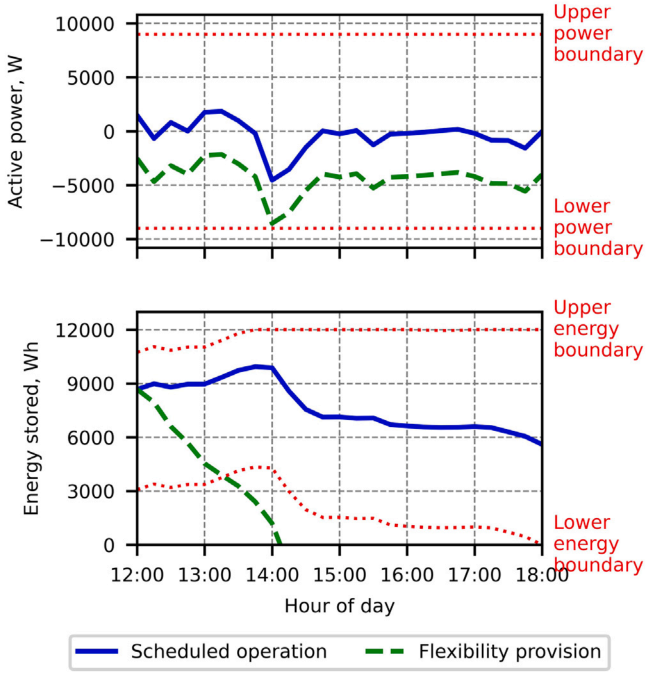


Fig. 8. Graphical presentation of the utilisation of power and energy boundaries for calculating the maximal duration for providing 4000 W of positive flexibility by the BS at 12:00 on April 3rd, 2019. The measured power values of the BS (blue curves) are taken from [48].

2019. The blue curve in the bottom sub-figure indicates the amount of energy stored in the BS during the planning time period. The green dashed curve presents the provision of the 4000 W positive flexibility by the BS. The red dotted curves correspond to the power and energy boundaries calculated in the previous step. The BS can provide positive flexibility by decreasing its charging power and increasing its discharging power. If we consider both the power and energy boundaries, the BS could have provided 4000 W of positive flexibility for a maximum of 1.25 h. The provision of this flexibility power for longer periods of time might have led to an undermining the lower energy boundary, i.e. the BS could have no longer fulfilled its operation in the remaining planning time if it were to continue to provide positive flexibility after 1.25 h. Therefore, the provision of 4000 W of positive flexibility must have terminated after 1.25 h and the BS must have returned to its scheduled operation.

The complete flexibility potential of the BS in “EMS-5” is presented in Fig. 7(a) by the flexibility potential curves (green curves) for three different points in time 06:00, 12:00 and 18:00 on April 3rd, 2019. These points in time are referred to as “times of flexibility requests”. The horizontal axis displays the power values that the BS can provide as the flexibility in W, whereas the range between −9000 W and 0 W corresponds to the negative flexibility, and that between 0 W and 9000 W to the positive flexibility. The vertical axis represents the duration of flexibility provision in hours. The vertical red curves correspond to the lower and upper power boundaries of the BS and the horizontal red curves to the maximal planning time, namely six hours.

The black dashed line presents the reference case, *Reference 100%*, in which the BS is assumed to be either fully discharged or charged, and the entire BS capacity to be solely used for the provision of negative or positive flexibility, respectively. The flexibility potential curve of the BS (green) always lies below this reference case curve. The second reference case, *Reference 50%*, is represented by the blue dot-dashed line and corresponds to the BS with an SOC of 50%, which is also utilised solely for the flexibility provision. In both reference cases, the primary purpose of the BS and scheduled operation were not considered.

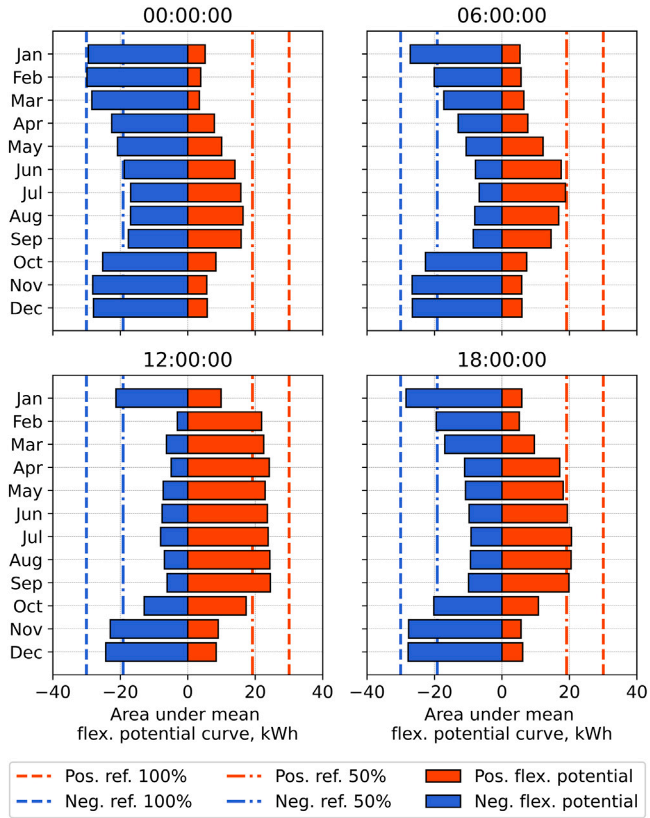
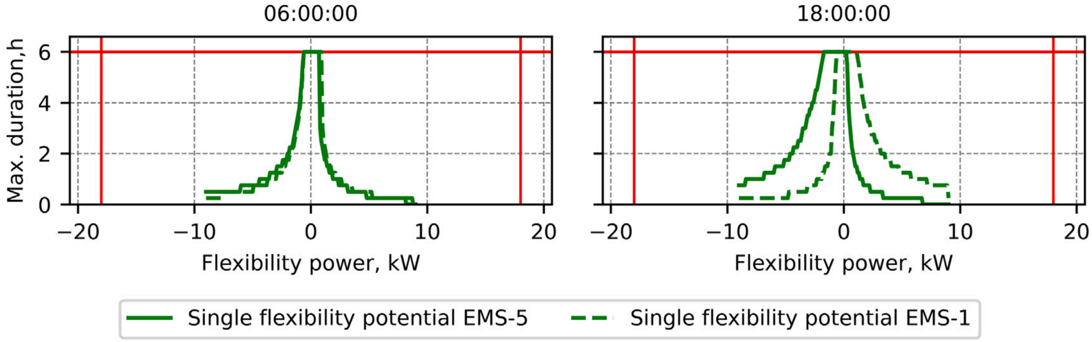


Fig. 9. Area under the monthly mean flexibility potential curves of the BS in “EMS-5” calculated at the time points of 00:00, 06:00, 12:00, and 18:00 for 2019.

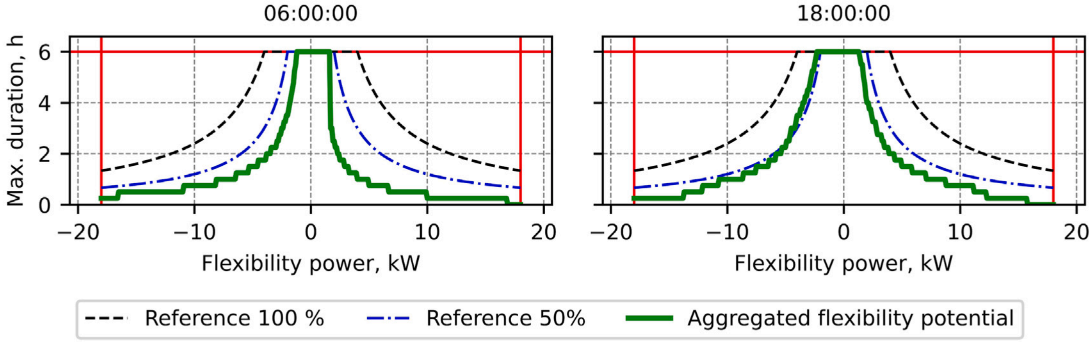
As can be gleaned from Fig. 7(a), the flexibility potential of the BS varied during the day, in that it saw significant daily variation in its flexibility potential. The main reasons for this variation lie in the different SOC values of the BS at the time of the flexibility request, as well as the operation of the BS for the next six hours. At 12:00 (noon), the positive flexibility potential of the BS was much higher than its negative flexibility potential. At this point in time, the BS was almost completely charged and the additional charging for the purpose of negative flexibility provision would have been possible to a limited extent. On the other hand, the almost-fully-charged BS would have been additionally discharged for the purpose of positive flexibility provision. The opposite situation can be observed in the evening (18:00), when the negative flexibility potential of the BS exceeded its positive flexibility potential. As the BS reached the minimum SOC at the end of the day, the BS could have been charged to provide the negative flexibility. More intensive discharging of the BS would not have been possible, as the power and energy boundaries would have been undermined and so the BS would not have been able to fulfil its primary application in such a case.

The BS not only features daily variations in flexibility potential but also seasonal ones. The flexibility potential of the BS in the selected household was estimated for each point in time in the year 2019. The bar charts in Fig. 9 display the values of areas under monthly mean flexibility potential curves of positive (red) and negative (blue) flexibility for four points in time: 00:00, 06:00, 12:00, and 18:00. The area values under the flexibility potential curves were calculated separately for positive and negative flexibility using the trapezoidal rule. The dashed vertical lines correspond to the *Reference 100%* case, and the dot–dash vertical lines to the *Reference 50%* one.

At four displayed points in time, we can observe that the blue bars are higher than the red bars during the colder months, meaning that the BS of the selected household had much higher negative flexibility



(a) Flexibility potentials of the single BS systems “EMS-5” and “EMS-1” calculated separately from each other.



(b) Aggregated flexibility potential from the combination of the BS systems “EMS-5” and “EMS-1”.

Fig. 10. Flexibility potentials of the BS systems “EMS-5” and “EMS-1” calculated separately from each other (a); and the aggregated flexibility potential that can be provided by both BS systems (b) at points in time 06:00 and 18:00 on April 3rd, 2019.

potential during this time. In the warmer months, the BS could theoretically have provided more positive flexibility (see the higher red bars on the charts for 06:00, 12:00, and 18:00), or the positive and negative flexibility potentials be almost equal to each other (see the bar chart for 00:00).

We can also notice the following patterns for all months. From midnight until noon, the negative flexibility potential of the BS decreased and the positive flexibility potential increased. And from noon until evening, we could observe the opposite pattern: the positive flexibility potential became smaller and the negative flexibility potential higher. Comparing to the reference cases, we can notice that the BS at midnight and in the evenings of the colder months remained almost fully discharged and could theoretically have offered negative flexibility. And at noon and in the afternoons of the warmer months, the BS had at least a 50% SOC (on average) and could theoretically have been used for the positive flexibility provision.

The daily and seasonal variations of the BS can partially be explained by the energy generation of the local PV system. In times of higher PV generation (around noon and during the summer months), the BS can provide higher values of positive flexibility, i.e. the BS had higher SOC values during these times and therefore it could also have been discharged for the purpose of positive flexibility provision. In times with zero or low PV generation (during the nights and the colder months), the negative flexibility potential of the BS was in general higher than its positive flexibility potential. Because of less charging of the BS and the resulting lower SOC values during these times, the BS could have been additionally charged more often for the purpose of negative flexibility provision.

Although the primary application of the BS in the selected household was not flexibility provision, it could theoretically provide flexibility as an additional service. Because of the observed daily and seasonal variation in the flexibility potential, it is necessary to quantify and update the flexibility potential of the BS at regular time intervals and also after any change in the operation.

5.3. Flexibility aggregation

The developed method for flexibility aggregation was tested on the BS systems installed in two private households, “EMS-1” and “EMS-5”. The calculation results of the flexibility aggregation are presented for one day – April 3rd, 2019 – as well as for the entire year of 2019.

As can be seen in Fig. 6, the households “EMS-5” and “EMS-1” had commonalities and differences in their load and PV power profiles on April 3rd, 2019. The energy consumption of the households and power generation from the PV systems influenced the operation of the BS systems. In its turn, the operation influences the flexibility potential.

As can be seen in Figs. 7(a) and 7(b), the BS systems in the households “EMS-5” and “EMS-1” had similar operation and similar SOC values at 06:00, i.e. both BS systems were charged from 06:00 to 12:00. Therefore, both BS systems had similar flexibility potential curves at this point in time (see the overlapping flexibility potential curves of these in Fig. 10(a)). The flexibility potential curves of the BS systems calculated separately from each other show that both BS systems could have provided some more negative flexibility than positive. The aggregated flexibility potential curve at 06:00 has higher flexibility power values, but approximately similar form to the separate flexibility potential curves of the BS systems “EMS-5” and “EMS-1” (see the left-hand side of Fig. 10(b)).

At 18:00, we can observe the opposite situation, in that the BS systems in “EMS-5” and “EMS-1” had different operations and SOC values (see Figs. 7(a) and 7(b)). Therefore, the flexibility potential curves of the BS systems have very different forms at this point in

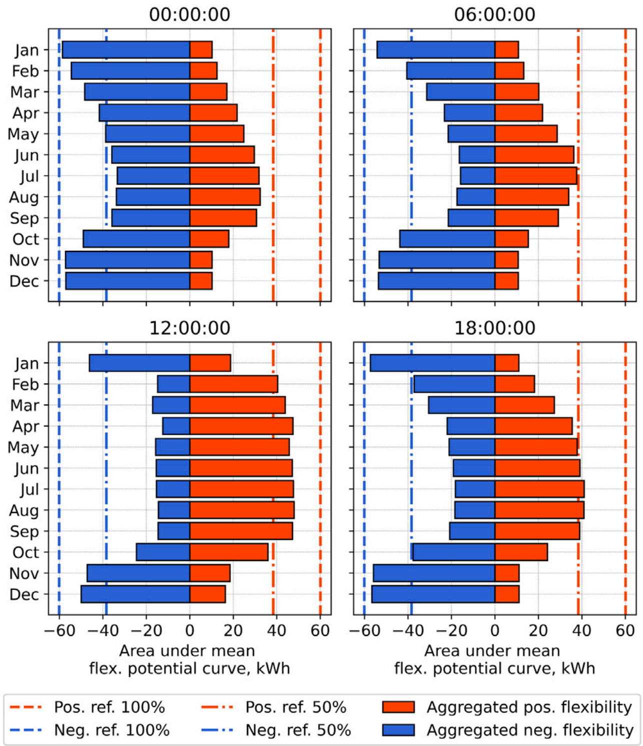


Fig. 11. Calculated area values under the aggregated mean flexibility potential curves of the combination consisting of the two BS systems, "EMS-1" and "EMS-5" in 2019.

time, as can be seen in Fig. 10(a). The flexibility potential curve of the BS in "EMS-5" (solid green line) is shifted predominantly to the negative flexibility area, and the flexibility curve of the BS in "EMS-1" (dashed green line), predominantly to the positive flexibility one. It can be understood that the BS in "EMS-1" could have provided more positive flexibility and the BS in "EMS-5" more negative flexibility at this point in time. Nevertheless, the resulting aggregated flexibility potential curve from two selected households became symmetrical, i.e. the aggregation of the flexibility values from two different BS systems resulted in approximately equal aggregated positive and negative flexibility potentials at 18:00 (see Fig. 10(b)).

Fig. 11 presents the area values under the aggregated mean flexibility potential curves from the combination of two BS systems in "EMS-5" and "EMS-1". In order to obtain these values, we first calculated the mean aggregated flexibility potential curves for every month of 2019. Secondly, we estimated the area under the mean flexibility potential curves separately for positive and negative flexibility using the trapezoid rule.

The area under the aggregated mean flexibility potential curve is equal to or smaller than the simple sum of the areas under the separate mean flexibility potential curves of the flexibility providers. The main reason for this difference is that the maximum duration of the aggregated flexibility provision is equal to the minimum duration from the combination of the flexibility providers, in that, from the maximum duration values of the flexibility providers, the minimum value must be chosen. This condition means that the complete flexibility potential of a single flexibility provider may not be included in the aggregated flexibility potential. In the presented aggregation case study, the deviation values are not significantly high because of the small amount of flexibility providers in the combination and their use of the same technology. However, this deviation may vary significantly depending on the amount of flexibility providers in the combination and technology types of the flexibility providers.

6. Conclusions and outlook

6.1. Conclusions

In this study, we investigated the energy flexibility, developed the analytical methods for quantifying and aggregating the flexibility of energy systems, as well as proposed the universal and technologically-agnostic form for presenting the flexibility.

The developed method for flexibility quantification requires technologically and operationally-specific input data for calculating the boundary values. These boundary values consider the technical characteristics and primary application of the energy systems, and set limitations and restrictions on flexibility provision. The flexibility of energy systems can then be quantified in compliance with these boundaries. The output of the method consists of two universal values: flexibility power and maximal duration of flexibility provision. This numerical result can be presented graphically by the flexibility potential curve. Due to the proposed technologically-agnostic form, the flexibility values of different energy systems can be aggregated using the aggregation method developed in this study.

The flexibility quantification and aggregation were demonstrated by simulations of private households equipped with PV and BS systems. The results of the case studies indicated that the flexibility of the BS was varied over the day, as well as over the year. The time-varying flexibility of the BS depends strongly on its actual mode, actual SOC, operation in the following hours, time of the day, and season. We observed that the negative flexibility potential of the BS was higher during nights and in the colder months, whereas the positive flexibility potential was higher during daylight hours and in the warmer months.

The distribution of aggregated flexibility values and the shape of aggregated flexibility potential curve were similar to the distributions and shapes of the flexibility of the single BS systems if they had similar SOC values and similar operations during the investigated period of time. In the opposite cases, the aggregated flexibility could have contained advantages and disadvantages of the single components. Furthermore, we observed that in few cases the aggregated flexibility potential differed insignificantly from the simple sum of the separate flexibility potentials of the two BS systems. This can be explained by the fact that the maximal duration of aggregated flexibility provision is equal to the flexibility provision of the component with the shortest duration.

The developed methods, as well as the proposed form of presenting flexibility can be applied to quantify, aggregate and evaluate the time-varying flexibility potentials of different energy systems installed in the energy cells.

6.2. Outlook

As this study outlines the means to analytically quantify flexibility potential, we intend to combine the developed methods with the quantification of flexibility needs, to simulate the actual flexibility provision and flexibility reimbursement, and to investigate the impacts of flexibility provision on the operation of energy systems in our upcoming study. In this case, we can use the majority of technical KPIs from [30] to evaluate the flexibility provision, as the calculated flexibility potential consists of such universal values as power and duration; time series with power values of demand and energy systems are also available as input data.

Within this study, the flexibility potential was calculated using the historical measured values. As the future applications could entail quantifying the flexibility using forecast-based schedules, we plan to consider the uncertainty in the flexibility quantification in our upcoming study.

The methods proposed in this study can be applied to quantify the flexibility of large-scale energy cells (e.g. big city district) including flexibility providers of different technologies. Hence, the influence of different technologies with their specific characteristics, operating schedules and limitations on flexibility provision can be investigated. Furthermore, the developed methods can be combined with the economic incentive models that should support and motivate energy cells to offer flexibility as an additional service. In addition to the economic aspect, future studies should also include the development, investigation and integration of the communication protocols and standards to efficiently provide flexibility from energy cells on flexibility markets.

CRediT authorship contribution statement

Nailya Maitanova: Writing – original draft, Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Visualization. **Sunke Schlüters:** Writing – review & editing, Supervision, Project administration, Conceptualization, Methodology. **Benedikt Hanke:** Writing – review & editing, Conceptualization, Supervision, Funding acquisition. **Karsten von Maydell:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is provided by the open-access database EMSIG, s. Ref [48].

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