

Integrated Assessment of Demand-Side Flexibility

Quantification, Aggregation, Variability Analysis, and Evaluation of Operational Impacts

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Abstract

The growing integration of weather-dependent renewable energy sources has significantly increased the need for flexibility in modern power systems. Small-scale integrated energy systems and storage technologies, such as battery storage systems, heat pumps, and electric vehicles, installed in buildings, quarters, and urban districts, offer considerable potential as sources of demand-side flexibility. However, a comprehensive framework for assessing the flexibility of these systems remains underdeveloped.

The thesis addresses this gap by investigating flexibility as an additional function of the energy systems, meaning that flexibility provision must not undermine their primary purposes and therefore must not negatively impact end-user energy needs. The thesis develops an integrated methodological framework for the comprehensive technical assessment of flexibility of the small-scale energy systems and storage installed in buildings and urban districts. This framework includes the quantification and aggregation of time-varying flexibility potential, explicit consideration of the primary applications of the energy systems, incorporation of variability and uncertainty, and evaluation of the impacts of flexibility provision.

The developed flexibility quantification method explicitly considers the primary operation of energy systems by defining power and energy boundaries, thereby ensuring that flexibility provision does not undermine the primary applications of the energy systems. Furthermore, the local flexibility needs arising from variability and uncertainty of photovoltaic systems are embedded into the calculation of these power and energy boundaries. To estimate these local flexibility needs, a novel methodology is developed for quantifying power and energy fluctuations of photovoltaic systems. The resulting flexibility is represented in a universal, two-dimensional, and technologically agnostic form, enabling consistent comparison and aggregation of flexibility values of diverse energy technologies. The proposed universal method for flexibility aggregation enables the determination of the most technically appropriate composition of flexibility values offered by multiple energy systems. Finally, the thesis introduces a novel concept of flexibility return to evaluate the impact of flexibility provision on the subsequent operation of energy systems and the power grid.

The developed methodology is demonstrated using empirical data and energy simulations of households equipped with photovoltaic-battery storage systems and heat pumps. This thesis establishes a foundation for the effective integration of demand-side flexibility into modern energy infrastructure, supporting the sustainable and resilient power system with a high share of renewable energy sources.

Kurzzusammenfassung

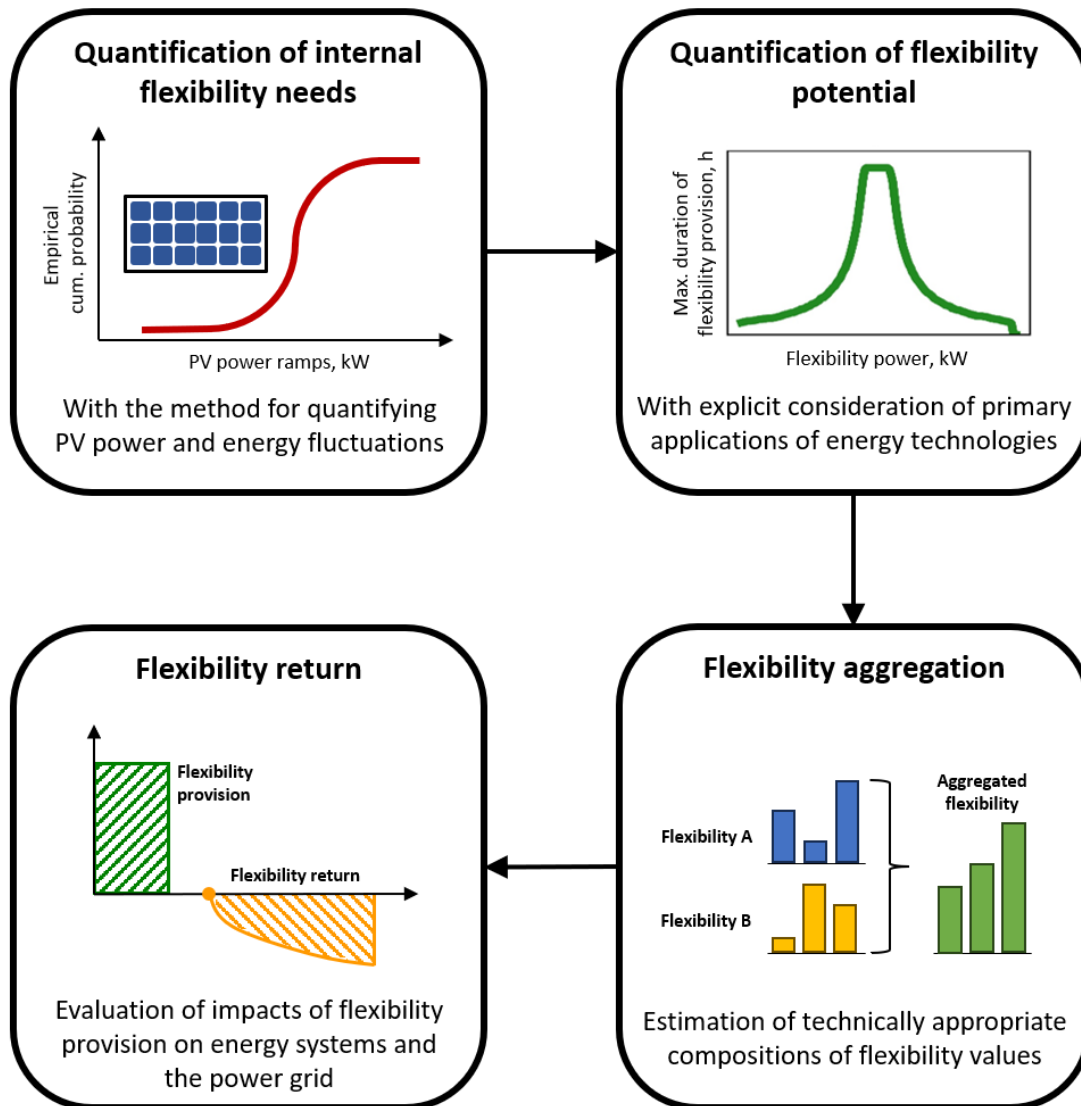
Die zunehmende Integration wetterabhängiger erneuerbarer Energien erfordert eine deutlich höhere Flexibilität des modernen Stromsystems. Dezentral installierte Energiesysteme und Speichertechnologien, wie Batteriespeicher, Wärmepumpen und Elektrofahrzeuge, bieten hierfür ein erhebliches Potenzial. Bislang fehlt jedoch eine umfassende Methodologie zur Quantifizierung und Bewertung dieser Flexibilitätspotenziale.

Die vorliegende Dissertation adressiert diese Forschungsfrage durch eine strukturierte Analyse der Flexibilität als Zusatzfunktion dezentraler Energiesysteme. Die Bereitstellung von Flexibilität darf den primären Einsatzzweck der Systeme nicht beeinträchtigen und keine negativen Auswirkungen auf die Bedürfnisse der Energieverbraucher zur Folge haben. Im Rahmen der Arbeit wird ein ganzheitlicher methodischer Ansatz zur technischen Quantifizierung und Bewertung der Flexibilitätspotenziale von kleinskaligen Energiesystemen und Speichern in Gebäuden und urbanen Räumen entwickelt. Die entwickelte Methodologie umfasst die Quantifizierung und Aggregation zeitlich variierender Flexibilität, die explizite Berücksichtigung der Hauptanwendungen der Systeme, die Einbindung von Variabilität und Unsicherheiten sowie die Bewertung der Auswirkungen von Flexibilitätsbereitstellung.

Die entwickelte Flexibilitätsquantifizierung erfolgt auf Grundlage definierter Leistungs- und Energiegrenzen, die sicherstellen, dass die primären Einsatzzwecke der Energiesysteme nicht beeinträchtigt werden. Zudem werden lokale Flexibilitätsbedarfe, die sich aus der Variabilität und Unsicherheit von Photovoltaikanlagen ergeben, direkt in die Berechnung dieser Grenzen integriert. Eine neuartige Methode zur Quantifizierung von Leistungs- und Energiefluktuationen von Photovoltaikanlagen wird hierfür entwickelt. Die resultierende Flexibilität wird in einer universellen, zweidimensionalen und technologieunabhängigen Form dargestellt, was eine vergleichbare Bewertung und Aggregation verschiedener Energietechnologien ermöglicht. Durch die vorgeschlagene Aggregationsmethode lassen sich technisch sinnvolle Kombinationen von Flexibilitätswerten unterschiedlicher Energiesysteme identifizieren. Abschließend wird ein neues Konzept des “flexibility return” eingeführt, um die Auswirkungen der Flexibilitätsbereitstellung auf den weiteren Betrieb der Energiesysteme und auf das Stromnetz zu bewerten.

Die entwickelten Methoden werden auf Basis empirischer Daten und Energiesimulationen von Haushalten mit Photovoltaikanlagen, Batteriespeichern und Wärmepumpen getestet. Damit leistet diese Dissertation einen grundlegenden Beitrag zur effektiven Integration nachfrageseitiger Flexibilität im zukunftsfähigen und resilienten Energiesystem mit hohem Anteil erneuerbarer Energien.

Graphical abstract



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Part I.

Preface

Chapter 1.

Introduction

The total installed capacity of renewable energy sources worldwide has reached 4,448 GW in recent decades, [1]. In the global electricity sector, renewable energy accounts for 30 % of total power generation, with expectations indicating an increase to 46 % by 2030, [2]. This growth will be primarily driven by wind and photovoltaic (PV) power systems, which are characterised by their weather-dependent, and therefore intermittent, energy generation. To maintain a stable and resilient energy supply despite this volatile generation, the energy system must significantly increase its flexibility, [3, 4, 5]. However, the increase in renewable energy sources arises in parallel with a decline in conventional flexibility resources, such as dispatchable fossil fuel power plants. Consequently, the existing flexibility portfolio must be expanded with further solutions, such as demand-side flexibility, energy storage systems, sector coupling, and grid flexibility, [6].

In addition to the growing share of renewables, an intensifying grade of decentralisation can be observed in the energy sector, as well as increasing electrification of heating and transportation sectors, [3]. This transition is characterised by the growing amount of small- and medium-scale distributed energy generators, storage systems, and integrated energy solutions (i.e. cross-sectoral energy systems), [7, 8], which are located closer to the direct point of consumption. These are referred to as *decentralised energy systems* in this work. The decentralised energy systems are typically installed for the specific purposes of end-users in their installation sites, for example, a battery storage installed in a single-family house to maximise the self-consumption of locally generated PV energy, a district heat pump installed in a urban district to provide space heating, or a charging infrastructure installed in a multi-tenant residential building for the electric vehicles of occupants. These purposes are referred to as *the primary applications* of decentralised energy systems in this work. In addition to their primary applications, these systems are technically capable to provide flexibility both within their installation sites, as well as on request to external signals, such as from the power grid, [3, 4, 9]. Moreover, the necessary technical requirements, such as smart meters, energy management systems, dynamic electricity pricing, and virtual power plants are already available in a mature form nowadays. [4, 10]

From a long-term perspective, the contribution of small-scale flexibility sources, such as electric vehicles, heat pumps, and home energy storage systems, to demand-side

flexibility is expected to grow significantly. Both electric vehicles and heat pumps are predicted to achieve flexibility potentials between 1 and 10 GW, while home energy storage systems are expected to exceed 10 GW. [11] By 2035, home battery storage systems, heat pumps, and electric vehicles are expected to provide an annual flexible capacity of 100 TWh for load shifting, [4]. However, despite their significant potential on the demand-side, small-scale flexibility options are currently underutilised due to a combination of deployment gap (e.g. limited deployment of digital infrastructure, such as smart meters), regulatory barriers (e.g. missing incentive systems), and socio-economic challenges (e.g. lack of user acceptance), [11]. Unlocking the flexibility potential of small-scale energy systems can significantly improve the efficiency, resilience, and cost-effectiveness of the power system. It enables better alignment between demand and volatile renewable energy generation, supports congestion management, and contributes to lower system costs by reducing peak loads and enhancing the utilisation of existing infrastructure. [11]

The flexibility provision must not threaten the primary application of decentralised energy systems; the needs and comfort of energy consumers must therefore remain ensured. For instance, a heat pump participating in flexibility provision must still deliver sufficient thermal energy to maintain a comfortable room temperature for the building occupants. The survey results in [12] indicate that the greater the loss of comfort associated with flexibility provision, the lower the likelihood that households will agree to offer flexibility. Since the flexibility potential of decentralised energy systems strongly depends on their primary applications and operational states at a given point in time, flexibility values are inherently **time-varying**, [13]. Beyond their primary applications, these systems, which belong to various technologies, can provide flexibility in different technological ways. For instance, heat pumps can offer flexibility by shifting their operation over time, i.e. load shifting. Flexibility provision is represented either by electricity consumed by heat pumps in times without heat demand or by reduction of electricity consumption during periods of heat demand. This additional electricity is stored as excess thermal energy in a buffer tank for later use, or the heat demand is met using the stored thermal energy, [14, 15, 16]. Battery storage can provide flexibility by adjusting their charging and discharging schedules, such as charging with grid electricity and discharging to the power grid when required, [17, 18, 19, 20]. As a result, the flexibility of decentralised energy systems is inherently **technology- and operation-dependent**, as well as time-varying. To effectively integrate these systems into the broader portfolio of flexibility sources and unlock their full flexibility potential, it is essential to develop a method for quantifying their available flexibility at any given time with consideration of their technology, operational schedules and primary applications.

Although existing scientific research has explored various forms and applications of demand-side flexibility, there remains a lack of a comprehensive and integrated framework for assessing the time-varying flexibility of decentralised energy systems. Numerous studies address flexibility quantification in isolation, without encompassing the full process, including quantification, aggregation, consideration of variability and uncertainty,

as well as investigation of consequences of flexibility provision. Existing quantification methods, for instance in [17, 21, 22], are often technology-specific which limits their generalisability. A wide range of studies disregards the operating mode, and therefore the primary application of decentralised energy systems, namely the needs and comfort of building occupants have not been addressed yet. However, these factors should be integrated into methods for quantifying flexibility of energy systems, as highlighted in [23, 24]. Moreover, the existing methods predominantly focus on calculating the flexibility potential, while neglecting the site-specific flexibility needs or requirements, such as those arising from the variability of on-site renewable energy generation. There is also a lack of evaluating the operational impact of providing flexibility, i.e. whether flexibility provision at given point in time leads to future energy surpluses or deficits. Although a broad range of metrics is proposed in [23] for evaluating the flexibility provision, a universal representation of time-dependent flexibility has not been established yet.

Building upon the identified research gap, the objective of this thesis is to develop a comprehensive framework for the integrated assessment of flexibility provided by decentralised energy systems installed in buildings and city districts. To verify the theoretical approach of this framework, this has to be demonstrated using historical power measurements of energy systems. The framework must encompass the following components and requirements:

- the investigation of flexibility as a secondary application,
- the representation of flexibility in a universal form for comparability and evaluability,
- the quantification of flexibility while considering the primary applications of the energy systems,
- the universal method for aggregating the flexibility of multiple decentralised energy resources,
- the incorporation of internal flexibility needs arising from the variability and uncertainty of local renewable energy generation, and,
- the quantification of consequences of flexibility provision on operation of decentralised energy systems and the power grid.

Before presenting the content and contributions of this thesis, it is essential to describe the concept of flexibility, as it is interpreted in various ways within the energy sector. This thesis defines flexibility as **the ability of a decentralised energy system, or a combination of systems, to be scheduled and operated in a flexible manner, while also being able to deviate from this planned operation for balancing local fluctuations in energy generation and consumption**. Flexibility provision is considered as an additional service and should not undermine primary application of energy systems, and therefore needs of building occupants.

Three levels of flexibility of decentralised energy systems are defined in Chapter 4. First, flexible scheduling refers to the technical ability of energy systems to be scheduled in a optimal and flexible way, e.g. considering dynamic electricity pricing. Second, short-term flexibility is required to compensate for unexpected local fluctuations, such as those caused by forecast uncertainties. Third, remaining flexibility can be offered in energy and flexibility markets for general balancing of energy generation and consumption.

In this thesis, the focus of flexibility usage is on balancing local energy generation and consumption to maintain the expected residual load, avoid additional costs and prevent overload on local energy infrastructure. The provision of grid services, such as frequency and voltage regulation, is not investigated in this study as purpose of flexibility provision, as flexibility is considered solely as an additional service of small-scale energy systems, and the necessary level of reliability can not be ensured. Furthermore, the time scale for flexibility provision is ranged from minutes to hours, with a maximum of intra-day balancing.

To address the identified research gap and achieve the defined objective, the thesis investigates the flexibility from two perspectives: flexibility sources and flexibility needs. The investigation of flexibility sources is presented in the publication entitled **“An analytical method for quantifying the flexibility potential of decentralised energy systems”** published in the Journal *Applied Energy*, [25]. This work develops a novel method to quantify the flexibility potential of decentralised energy systems. The principal advantage of the developed method over existing approaches is that it explicitly considers the operating modes of decentralised energy systems in the quantification of their flexibility potential, ensuring that flexibility provision does not undermine their primary applications. To address this requirement, power and energy boundaries are introduced, defining the extent to which an energy system can deviate from its operation for the purpose of flexibility provision without undermining its primary function. By incorporating these power and energy boundaries, the flexibility potential of a specific energy system can be quantified at any given point in time. This quantified flexibility is proposed to be represented in a universal, two-dimensional, and technologically agnostic form, specifically in terms of flexibility power and the maximum duration for which this power can be provided. Furthermore, a universal method for aggregating flexibility is developed, allowing for the estimation of the most technically appropriate composition of flexibility values offered by multiple energy systems. To summarise, the most valuable contributions of this study include the methods developed for quantifying and aggregating the time-varying flexibility values of diverse decentralised energy systems at any point in time, as well as a consistent representation of the calculated flexibility using universal parameters, regardless of the energy system technologies. The full version of this publication is presented in Chapter 4.

In the next publication, the flexibility is investigated from another perspective, focusing on flexibility needs arising from the variability and uncertainty of local renewable energy systems. This publication entitled **“Quantifying power and energy fluctuations**

of photovoltaic systems” is published in Journal *Energy Science & Engineering*, [26]. As PV is the most widely installed renewable energy technology in urban areas, [27], the power measurements of PV systems are utilised to quantify their variability and uncertainty. To achieve this, the research develops a novel method for quantifying power and energy fluctuations of PV systems. The first distinctive feature of the developed method is a computation of the empirical distributions of PV power fluctuations for three categories of days, classified according to the variability and daily output of PV generation. This allows for estimating the magnitudes of power fluctuations that arise most frequently in a given PV system and determining the probability of any power ramp. The second distinctive feature is a calculation of the daily energy fluctuations of PV systems for the defined classes and representation of these fluctuations using cumulative energy deviation curves. The quantified power and energy fluctuations can represent the internal flexibility needs arising from the variability and uncertainty of intermittent PV generation at a specific location. The study makes an assumption that these local flexibility needs must be balanced using available local flexibility sources. Therefore, the output of the developed method not only indicates the power and energy that need to be reserved or shifted locally for intra-day balancing, but also the required duration for this energy reserving or shifting. The entire scientific work is presented in Chapter 3.

The methodologies and findings from two previous studies are combined and extended in the publication entitled **“Investigating the Full Process of Flexibility Provision from Decentralised Energy Systems: From Quantification of Flexibility Potential to the Evaluation of Flexibility Provision Impacts”**, published in the Journal *energies*, [28]. This study presents a comprehensive framework that includes the quantification of flexibility potential, the consideration of local flexibility needs, the aggregation of multiple flexibility potential values, and the evaluation of the consequences of flexibility provision. The first essential contribution of this work is the introduction of a novel concept for integrating local variability and uncertainty into the developed flexibility quantification method. Specifically, the power and energy fluctuations of local PV systems, quantified using the method from Chapter 3, are incorporated into the calculation of power and energy boundaries before quantifying the flexibility potential of decentralised energy systems. None of the existing scientific methods have considered the variability and uncertainty of on-site renewable energy systems as local flexibility needs, nor have they integrated these values into the quantification of flexibility potential. As a second contribution, this research introduces a novel paradigm of flexibility return, which quantifies the consequences of flexibility provision on the subsequent operation of decentralised energy systems and the power grid. This concept addresses the issue that flexibility provision at a given point in time may cause a new flexibility need at a later time. To the best of the author’s knowledge, no existing methodology has investigated the influence of flexibility provision on the later operation of decentralised energy systems and the power grid. A full version of this study can be found in Chapter 5.

Chapter 1. Introduction

In summary, the thesis establishes a comprehensive framework for the technical assessment of the flexibility potential provided by small-scale decentralised energy systems installed in buildings and urban districts. This framework contains the following features:

- the understanding of flexibility in the context of decentralised energy systems,
- the quantification of local, time-varying flexibility potential, considering the primary applications of these systems to ensure that needs of energy consumers remain unaffected,
- the integration of internal flexibility needs caused by variability and uncertainty of local renewable energy generation into the procedure of flexibility quantification,
- the flexibility aggregation of multiple decentralised energy systems to identify the most technically appropriate composition of flexibility values,
- the analysis of the impact of flexibility provision on the subsequent operation of both decentralised energy systems and the power grid.

The functionality of the developed methods is demonstrated using energy simulations of households equipped with PV battery storage systems as well as heat pumps and heat storage systems.

The technical fundamentals and state of the art relevant to this thesis are presented in Chapter 2. This section covers key concepts related to decentralised energy systems, flexibility, and energy management systems, which are essential for understanding this thesis. Part II of this thesis comprises the scientific publications that constitute the core of the research. Chapter 3 includes the investigation of internal flexibility needs, Chapter 4 provides a comprehensive methodology for quantifying and aggregating the flexibility potential of small-scale energy systems, and Chapter 5 presents the complete process of flexibility provision. Chapter 6 concludes the thesis by summarising the main contributions and key findings of the research. Finally, Chapter 7 provides an outlook on future research directions and discusses various measures to enable flexibility provision of small-scale energy systems.

Chapter 2.

Scientific and Technical Background

On one hand, the increasing share of volatile renewable energy sources necessitates the integration of a broader range of flexible resources to enhance the overall flexibility of the energy system, [6, 10]. The concept of flexibility in the energy sector, along with its various sources and applications, is introduced in Section 2.1. On the other hand, the growing decentralisation of the energy system, combined with the ongoing electrification of the heating and transportation sectors, presents promising opportunities for enhancing flexibility, particularly through small-scale energy storage systems, demand-side measures and sector coupling, [4, 10]. In this context, the thesis focuses on the integrated assessment of flexibility of small-scale decentralised energy systems, which are primarily installed for energy supply in buildings, neighbourhoods, and urban districts. A detailed technical description of these systems is provided in Section 2.2. To efficiently unlock and integrate the flexibility potential of decentralised energy systems into the broader energy infrastructure, the deployment of smart energy management systems at the site level (e.g., in residential buildings) is essential. Accordingly, Section 2.3 outlines the definition, key components, and operating principles of a home energy management system.

2.1. Flexibility

Flexibility has always been an essential requirement in power systems. In the energy sector, flexibility is widely understood as the ability of a power system to manage variability and uncertainty in both supply and demand across multiple time scales, [29, 30]. This includes the capability to respond promptly and efficiently to fluctuations in energy generation and consumption. In conventional power systems, flexibility has predominantly been provided by supply-side energy assets, such as flexible fossil fuel-based thermal generators (e.g. open and combined cycle gas turbines), hydropower plants, and pumped hydro storage. These resources have traditionally been used to balance demand fluctuations, provide operational reserves, and ensure system stability and reliability. [6]

The flexibility requirements in the power system have changed in recent decades due to the decline of conventional power plants and the intensive integration of variable renew-

able energy systems, such as wind and solar power plants. Their output depends strongly on weather conditions which feature strong daily and seasonal variations, making power generation inherently intermittent. As a result, flexibility provision to maintain a stable and reliable energy supply can no longer rely solely on supply-side energy assets, as in conventional systems. The energy transition has emphasised the growing need for additional sources of flexibility, including energy storage, sector coupling and demand-side flexibility. To activate these additional sources, various operational solutions and incentive models should be implemented, such as dynamic electricity pricing for end-users, widespread distribution of smart meters, advanced forecasting of renewable energy generation, and others. To summarise, the provision of flexibility in the future energy system should be a holistic framework that encompasses diverse technologies, operational strategies, and market mechanisms to effectively manage the variability and uncertainty of renewable energy sources and ensure system stability and reliability. [6, 31]

The Ref. [6] categorises the flexibility by source into supply-side, demand-side, energy storage, sector coupling and grid flexibility. In comparison to supply-side flexibility shortly described above, the demand-side flexibility refers to the ability of energy consumers, including industrial, commercial, and residential, to adjust their consumption in response to external signals for better matching the energy generation of renewable energy sources. The flexibility of energy storage includes various storage technologies like batteries, pumped hydro, thermal, and hydrogen storage, which can decouple energy generation and consumption in time. To balance supply and demand across large areas, the power system needs grid flexibility which relates to the robust transmission and distribution networks with advanced controls and communication systems, i.e. smart grids. [6]

Based on different purposes for which flexibility is used in the energy system, the flexibility use can be categorised in self-utilised, grid-oriented and system-oriented, [5]. Self-utilised flexibility use refers to the use of flexibility by the owner or operator of flexibility source to achieve internal objectives, which may be technical, procedural, or economic. This type of flexibility use is not driven by external signals. Examples include maximising self-consumption of locally generated electricity, optimising industrial processes, or enhancing comfort for private consumers. Self-utilised flexibility use should align with, or at least not hinder, grid and system-oriented flexibility use, nor increase the need for them. [5] The definition of self-utilised flexibility use overlaps with the understanding of *flexible scheduling* proposed in this thesis (s. Chapter 1).

Grid-oriented flexibility use is necessary to directly influence the state of the power grid, such as maintaining voltage stability and reducing overloads on lines and transformers. It is primarily applied in congestion management or in providing non-frequency ancillary services, such as reactive power support. A key characteristic is the location-dependent impact of flexibility provision on the grid, making it a crucial tool for system operators. [5]

System-oriented flexibility use refers to methods for maintaining the balance between energy generation and consumption within a particular area or bidding zone in the electricity market. This includes energy trading across various time frames (e.g., forward and spot markets) and the provision of frequency control services. The location of flexibility source for this type of flexibility use is not critical for the balancing purpose. The objective of system-oriented use is to ensure overall system equilibrium. [5]

A comprehensive literature review on existing definitions of flexibility and various methods for flexibility quantification and assessment, as well as technical descriptions of flexibility needs and sources are presented in Chapter 4.

2.2. Decentralised energy systems

Decentralised energy systems are small-scale power generators and storage systems located close to the points of direct energy consumption, and are connected to the distribution power grid, [3]. This thesis focuses on the grid-connected decentralised energy systems installed in buildings, neighbourhoods, living quarters, and city districts that are further connected to the stable power grid. The decentralised energy systems in these locations are primarily installed to meet the occupants needs, such as space heating, domestic hot water, cooling, electricity supply, increasing self-consumption of local renewable energy systems, and others. The most widely applied decentralised energy systems at building level include rooftop PV system, battery storage, heat hump, combined heat and power (CHP) system, electric vehicle and corresponding charging infrastructure, [7].

Rooftop photovoltaic (PV) systems, which convert solar radiation into electrical power, belong to the most widely installed renewable power generations in urban areas, [27]. The main components of these systems include PV modules, inverter, smart meter and ancillary components such as mounting structures and cables. The inverter converts the direct current generated by the PV modules into alternating current by employing high-frequency switching power electronics. Additionally, the inverter optimises power extraction through maximum power point tracking (MPPT), ensures grid compliance by regulating voltage, frequency, and phase, and includes protective features for system and grid safety. [32, 33] The primary objectives of integrating PV systems into buildings are to reduce grid electricity costs, provide a sustainable local power supply, and decarbonise on-site energy consumption.

An increasing number of residential buildings integrate battery storage systems alongside rooftop PV systems to maximise self-consumption of locally generated electricity, reduce energy costs, and increase energy autonomy. In 2024, the installed capacity of residential battery storage systems in Germany reached 15.4 GWh [34]. A typical battery storage system consists of the battery module, battery management system, power conversion system, and, depending on the application and installation site, additional components,

[35]. The battery module consists of battery cells arranged in series and/or parallel to store electrical energy in the form of chemical energy. The battery management system is a crucial component, responsible for functions such as cell monitoring, power management, temperature management, charging and discharging operations, health status monitoring, cell protection, and lifespan estimation, [36]. The power conversion system, or hybrid inverter, performs the same function as the inverter in a PV system, i.e. converting direct current from the battery to alternating current, making it compatible with electrical appliances and the power grid.

Currently, battery storage systems are primarily operated to maximise self-consumption of locally generated PV energy. However, these systems can also provide flexibility by changing from this widely applied self-consumption optimisation to a system- and grid-oriented operation. To achieve this, charging and discharging schedules must consider not only PV power forecasts but also dynamic electricity pricing and the real-time state of the power grid. Battery storage systems can be charged with PV electricity during periods of high PV generation or with grid electricity when its prices are low. Conversely, discharging may be scheduled during periods of low PV output and/or high grid electricity prices. Additionally, battery storage systems can adjust their operation in response to local signals from the system operators to prevent or mitigate local grid overloads. These strategies for charging (and in the near future also for discharging) can be applied to battery electric vehicles. Currently, charging of electric vehicles typically begins immediately after connection to a charging station, without considering electricity prices and real-time state of the power grid. However, these systems can also provide flexibility by transitioning to a system- and grid-oriented operation. [13]

In the European Union, 63.5 % of final energy consumption in the residential sector accounts for heating purposes, [37]. According to Building Energy Act in Germany, heating systems installed in new buildings within new construction areas must use at least 65 % renewable energy, and in 2045 all heating systems in buildings must be fully operated with renewable energy, [38]. The heating systems powered by renewable energy include heat pumps, solar thermal systems, biomass and wood heating systems, CHP systems powered by biogas, as well as district heating networks.

The heat pump is a thermodynamic device to transfer heat from a lower-temperature source, such as outside air, ground, water and waste heat, to a higher-temperature sink using a refrigerant as the working fluid and external energy, mostly electricity. The main components of a heat pump include heat exchanger, compressor, expansion valve, and evaporator. Additionally, the system can be equipped with a buffer tank, which serves as a hydraulic decoupling component to optimise heat distribution, enhance system efficiency, and increase operational stability and longevity by minimising compressor cycling. The building envelope also provides passive thermal buffering through its thermal mass and insulation. However, it cannot fully replace the function of a buffer tank. In a building where the heat pumps are also used for domestic hot water supply, a thermal storage, mostly hot water tank, is required. In such cases, heat pump systems may

2.2. Decentralised energy systems

include an electric heating element or operate in combination with a gas boiler, which can also serve as a backup heating source during extremely cold weather. [39]

Currently, heat pumps are operated in a demand-driven mode, meaning their operation is based on immediate heating requirements. However, they can also provide flexibility by transitioning to a system-oriented operation that considers dynamic electricity pricing. In this approach, heat pump operation is scheduled during periods of low electricity prices. It is necessary to store the excess thermal energy in a buffer or hot water tank for later use. Additionally, real-time conditions of the power grid can also be integrated into the scheduling process to provide grid-supportive operation. In Germany, distribution system operators are already allowed to temporarily reduce the power consumption of heat pumps to prevent or mitigate local grid overloads. [13, 40]

A small scale combined heat and power (CHP) system, which simultaneously generates electricity and utilises the waste heat for space heating or domestic hot water, can also contribute to flexibility provision if they are installed together with battery and thermal storage systems (see the description of the flexibility provision of battery storage and heat pumps above). This configuration enables that electricity surplus can be stored in batteries and excess thermal energy in hot water tanks.

Some described technologies, such as CHP, heat pump and electric vehicle with the necessary charging infrastructure, belong to integrated energy systems, or cross-sectoral energy systems. These systems enable the interconnection of traditionally separate sectors (electricity, heating, transportation, and gas supply) to improve efficiency, flexibility, resilience and sustainability. These integrated energy systems are particularly crucial in power systems with a high share of weather-dependent renewable energy sources, as they enhance the utilisation of fluctuating generation, reduces curtailment and stabilise the entire energy system. By leveraging integrated energy systems, surplus electricity from local renewable sources can be effectively utilised at the points of direct energy consumption for heating, cooling, and transportation purposes. Integrated energy systems can be classified based on the type of end-use energy conversion, including power-to-heat (PtH), power-to-gas (PtG), power-to-mobility (PtM) and further types of interconnection such as power-to-hydrogen and vehicle-to-grid, [41]. PtH and PtM technologies are already widely implemented in buildings, neighbourhoods, and urban districts. Their deployment is expected to expand further, as can be derived from the survey results in [42], i.e. more than 90 % of distribution grid operators participated in the survey expect a strong to very strong change in load profile due to heat pumps and electric vehicles.

As mentioned above, the decentralised energy systems are installed in buildings, quarters, and city districts for different primary applications, such as electricity supply, heating, cooling, and other. However, these technologies are technically capable of providing flexibility by deviating from their typical or scheduled operation. The Chapter 4 describes the technical requirements for decentralised energy systems in order to utilise them for flexibility provision additionally to their primary applications: capability to

flexibly modify the operating power on request, availability of energy buffer, and connection to advanced information and communication infrastructure. Besides that, this thesis proposed to describe the flexibility potential of any decentralised energy system with a flexibility power and maximal duration of flexibility provision at any given point in time.

2.3. Home energy management system

The *home energy management system* (HEMS) is a combination of hardware and software solutions to enable real-time monitoring of energy generation, consumption and storage, as well as to automatically manage and optimise the energy flows with minimal human interference to achieve a given objective, such as maximisation of self-sufficiency and minimisation of energy costs, [43, 44]. As HEMS continue to evolve, their architecture, functionality, and operational strategies are being continuously expanded through the integration of advanced hardware solutions and the development of enhanced optimisation algorithms.

The core of the HEMS software architecture is a control and optimisation unit. This unit encompasses algorithms to determine the optimal operational schedule for achieving the defined objectives. Then it sends corresponding control signals to connected energy systems, storage and controllable loads. The optimisation unit commonly uses one of the following methods: mathematical methods (e.g. linear, non-linear, and dynamic programming), model predictive control, meta-heuristic methods (e.g. genetic algorithm and particle swarm optimisation), or advanced machine learning algorithms. The HEMS software can also contain the advanced functions, such as unit for data processing and analysis and forecasting module. The processing and analysis unit is responsible for analysing the data collected by sensors and smart meters to transfer insights into energy usage patterns for making informed decisions. The forecasting module contains algorithms for forecasting of energy consumption and renewable energy generation, mainly PV systems. [43, 45, 46]

The hardware part of HEMS can include various components for monitoring and data collection, as well as communication and user interfaces. The components for monitoring and data collection are crucial for collecting real-time data of energy generation, consumption and storage within the building. They often involve smart meters, sensors and smart plugs. The communication interface is necessary for the communication between HEMS and different units, such as energy systems and controllable devices. The modern advanced versions of HEMS can also communicate with electricity markets, and the power grid. In comparison to that, the user interface provides end users with personalised monitoring and control of their home energy consumption directly from mobile and web applications. [43, 45, 46]

2.3. Home energy management system

The survey of 2,000 German households shows that the main objectives for installing HEMS in residential buildings include saving the energy costs, maximising the self-consumption of locally generated PV energy, and increasing the independence from energy markets, [44]. Mascherbauer et. al. [47] calculated that smart HEMS can reduce grid-electricity consumption of a well-insulated single-family house in Austria with PV and heat pump by up to 40.7 %. The Ref. [44] calculated that a three-person German household that switches to a renewable energy system combining with a HEMS solution can reduce its entire energy costs by approximately 50 %. Besides savings the operational costs, the HEMS can also prevent the installation of the oversized energy-intensive equipment in a long term, such as district heat pump and HVAC in large residential buildings or modern living quarters, as well as ensure the efficient operation of this equipment there. [48].

Alongside the reduction of household energy costs, the HEMS combining with dynamic electricity prices and local signals, such as time- and regionally differentiated grid charges proposed in [49], can also reduce the system costs encompassing generation cost and transmission/distribution cost. The system-oriented operation of heat pumps, meaning with consideration of dynamic electricity prices and local signals, can reduce the system cost by 24 % in comparison to a typical demand-driven operation. The reduction of system cost resulting from system-oriented charging of electric vehicles can even reach 70 % in comparison to simple immediate charging. [13] In addition, the intelligent operation of small-scale flexibility sources can reduce costly and emission-intensive electricity generation from gas and coal-fired power plants, [13], thereby contributing to lower CO₂ emissions.

The operating principle of HEMS varies based on predefined objectives, the availability of energy systems, controllable loads, and system architecture. Its functionality is described below on example of a household equipped with a PV system, battery storage, heat pump, electric vehicle, and HEMS with advanced software and hardware solutions. HEMS continuously collects real-time data from smart meters, sensors, energy systems, and external sources, such as weather forecasts and electricity pricing. Then, it processes this data to predict energy generation and consumption of the household considering user requirements, weather and price forecasts. Based on these predictions combining with actual electricity pricing, the HEMS makes optimal operational schedules for the integrated energy systems, storage and flexible loads. For example, HEMS schedules the charging and discharging of battery storage based on load and PV power forecast, and electricity prices, as well as it adjusts the battery storage operation in case of PV forecast error. Another example, on days with very low PV generation, HEMS schedules the heat pump operation and electric vehicle charging based on user requirements and electricity prices, shifting the load to off-peak hours for minimising energy costs. Afterwards, HEMS sends control signals to manage the operation of energy systems, storage and controllable appliances. At each point in time, the HEMS can automatically adjust the operation in case of user requirement changes, electricity pricing signals, power grid signals, forecast uncertainties and further deviations. Furthermore, HEMS can identify

different faults, activate the alarm system, and transmit relevant fault information. An essential function of future HEMS should be the capability to respond to the local signals in the event of local grid overload. Specifically, system operators should be able to transmit a signal to HEMS, requesting to adjust the operation of connected energy systems to support grid stability.

Already nowadays, the smart HEMS can automatically adjust energy usage in response to grid electricity pricing. As described in Section 2.2, the small-scale decentralised energy systems in buildings and city districts can technically provide flexibility. Through HEMS, the decentralised energy systems in multiple households can be combined into a virtual power plant for participating in energy and flexibility markets. Therefore, HEMS provides the essential automation, intelligence, coordination, and communication necessary for households to be a meaningful and reliable source of flexibility in the modern energy infrastructure.

Part II.

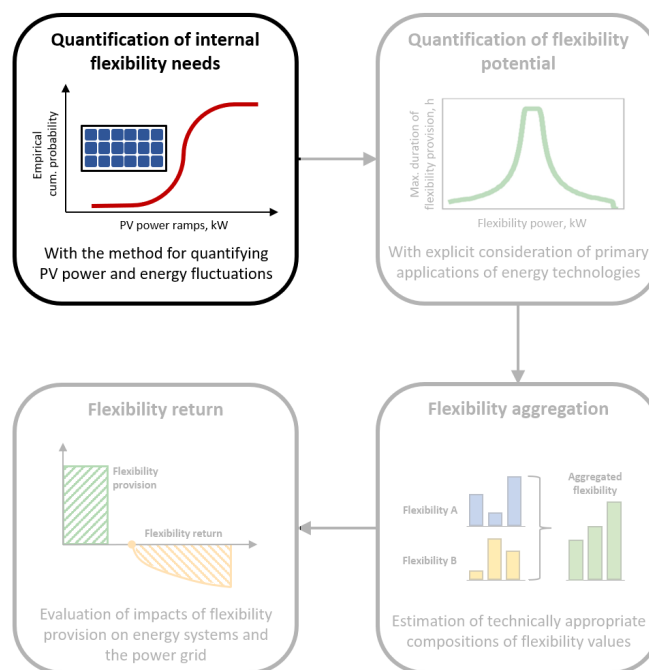
Publications

Chapter 3.

Quantification of internal flexibility needs

The work is published as open access article

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Specific contributions of N. Maitanova: Investigation; development of methodology; time series analysis of photovoltaic systems; photovoltaic system modelling; energy simulations; forecasting of photovoltaic power output; evaluation and visualisation of results; writing of the original manuscript.

ORIGINAL ARTICLE



Quantifying power and energy fluctuations of photovoltaic systems

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Abstract

The high share of power generation based on fluctuating renewable energy sources, especially wind and solar, has increased the levels of variability and uncertainty in power systems. The aim of this study is to develop a method for quantifying the variability of photovoltaic (PV) systems. The developed method investigates the power measurements of a PV system and quantifies its power and energy fluctuations in three steps. The first includes a classification of days into three classes according to the variability and power output of the PV system. The second consists of computing the empirical cumulative distribution functions of PV power ramps for the given classes. The third calculates the PV daily energy fluctuations based on predicted PV power output. This method of PV variability quantification was then applied to seven rooftop PV systems in different locations that feature different installed capacities, years of installation, orientations and solar cell types. The testing of this method indicates that it can be used to quantify the power and energy fluctuations of different PV systems, independent of their locations and technical characteristics. The proposed method was developed as part of a general approach for quantifying the flexibility potential of buildings and city districts with PV systems.

KEYWORDS

energy fluctuations, photovoltaic variability, power fluctuations, power ramps

1 | INTRODUCTION

The use of fluctuating renewable energy sources, such as wind and solar radiation, for generating power has increased in recent decades; in 2019, the total installed capacity of renewable energy worldwide reached 2537 GW.¹ The inherently fluctuating nature of renewable energy has escalated the level of variability and

uncertainty in power systems, and therefore the need for flexibility has increased.^{2,3} Furthermore, the increasing decentralisation of the energy system requires greater flexibility at the distribution grid level, for example, stronger load balancing.⁴ Such flexibility in the distribution grid can be initially offered by the decentralised energy units and prosumers in buildings and city districts, such as heat pumps, heat storage, photovoltaic

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(PV) battery systems, charging stations for electric vehicles and so forth.^{4–7} Moreover, the small decentralised energy units can be pooled together to provide a higher amount of flexibility. However, the energy units in buildings are not installed to provide flexibility, but for other purposes, such as heating, hot water treatment and increasing self-consumption. The flexibility provision can constitute an additional service that must not threaten the main purposes of the energy units. This priority must be considered obligatory to estimate the flexibility potential of the buildings and city districts. Another challenge in quantifying flexibility in buildings lies in diversity, that is, the decentralised units in the buildings belong to different technologies with their specific technical characteristics, such as their way of providing flexibility, response time and others. However, the flexibility potential from different energy units with diverse main purposes must be quantified in a general way to provide flexibility from single units or to orchestrate them for combined flexibility provision. The present study arose during the development of a general method for the assessment and quantification of flexibility in buildings and city districts. Although flexibility has become an important concern in research and energy industry, a general method for quantification of flexibility still does not exist.

According to the definitions of flexibility proposed by the International Energy Agency and different authors,^{8–12} the need for flexibility arises due to power fluctuations in energy generation and consumption. In other words, the need for flexibility depends on the magnitude, frequency, point in time and duration of power fluctuations. Power fluctuations occur as a result of the variability and uncertainty of power demand and power output from fluctuating renewable energy sources. Therefore, the investigation of power fluctuations is a significant basis for quantifying the flexibility needs of power systems.

Solar PV power generation constitutes the second-highest generation growth rate among all renewable energy technologies,¹³ and PV systems are the most popular choice for renewable energy sources in urban areas.¹⁴ However, the fluctuating power generated by grid-connected PV systems can have a negative impact on voltage and power quality in low-voltage electricity grids.^{15–19} PV power fluctuations and their negative effects on the power grid can be mitigated by different methods, such as the use of storage solutions, demand-side management and the curtailment of PV output.^{16,18,20,21} Although the mentioned studies proposed different methods for mitigating the power fluctuations from PV systems, they did not

conduct detailed investigations and quantifications of PV power fluctuations.

Despite the proven negative impacts of PV fluctuations on the power grid, the investigation of the fluctuations from PV systems is still not an obvious part of PV system operation analysis. Nowadays, the analysis of PV system operation and performance includes different procedures, such as evaluation of data quality, correction of data quality issues, calculation of the energy performance index, performance rate and performance loss rate, calculation and comparison between predicted, expected and measured energy values, the calculation of self-consumption rate and so forth.^{22–26} Moreover, the future power system with high shares of fluctuating renewable energy sources must take into account the magnitudes and frequencies of power fluctuations from these sources. The overall investigation of PV systems in the future can be supplemented with the analysis and quantification of fluctuations in PV power outputs. This supplemented procedure can be performed with the help of the method introduced in this study.

The primary reason for the fluctuations of the power generated by PV systems lies in the fluctuating nature of solar radiation. Therefore, numerous studies have investigated the variability of solar irradiance on the horizontal surface.²⁷ Others have proposed the classification of days according to the variability of solar radiation,^{28,29} or according to the clearness or cloudiness of the sky.^{30–33} The researchers behind the studies^{34–36} investigated all PV power fluctuations that arose without using classification schemes. The main aim of the current study is to propose a comprehensive method for investigating PV power and energy fluctuations that combines an appropriate classification of days according to PV variability with the quantification of PV fluctuations. The present study seeks to answer the following research question: Do PV systems feature characteristic distributions, magnitudes or frequencies of power and energy fluctuations according to the level of variability of the PV power output? As a result, a method for quantifying the power and energy fluctuations of PV systems was developed and is introduced below. The developed method distinguishes between power and energy fluctuations of PV systems. The quantification of the power fluctuations only requires technical characteristics and time series with the measured power values of the PV systems. The estimation of the energy fluctuations is based on the day-ahead prediction of PV power output, that is, the PV power curve must be predicted for the next 24 h, and the measured and predicted daily energy values are applied for the quantification of the PV energy fluctuations.

On the assumption that the power and energy fluctuations of a local PV system are known, this information can be applied to compensate for the emerging fluctuations locally, for example, within a building in which the given PV system is installed. Energy-generating units, storages and flexible loads in the buildings can compensate for the power fluctuations of local PV systems. In other words, these units can provide flexibility within buildings and city districts. Moreover, the compensation of power fluctuations increases the self-consumption of PV systems and minimises possible negative impacts on the distribution grid. The calculated values of the power and energy fluctuations of PV systems can correspond to the power and capacity of the flexibility providers necessary for balancing fluctuations in energy generation and consumption. These results can be applied in the planning and dimensioning of decentralised energy units (e.g., power and capacity of battery storage) in buildings with PV systems. Therefore, the method proposed in this study can form a part of a future general method for quantifying flexibility. The general method for flexibility quantification can build the foundation of future business models, markets and incentive systems for the provision of flexibility from buildings and city districts, initially for themselves but also to the distribution grid.

This paper is structured as follows. Section 2 presents the developed methodology for quantifying the power and energy fluctuations of PV systems. For validation purposes, this method was applied to seven PV systems in northern and southern Germany. The description of the observed PV systems and reports regarding input data quality are included in the first part of Section 3. The subsequent parts contain the results of the quantification of the power and energy fluctuations of the investigated PV systems and a description of potential applications of the developed method. Finally, Section 4 concludes the paper and presents an outlook on the relevance, utilisation options and possible directions that future works could take.

2 | METHODOLOGY

This study introduces a method for investigating and quantifying the power and energy fluctuations of PV systems, or, in other words, the method quantifies the variability of PV systems. The variability of fluctuating renewable energy technologies, such as wind and PV systems, has been assessed in numerous studies by investigating their power ramps. A power ramp is defined as the difference in power values between two successive points in time. This parameter belongs to the

most important factors for investigating the variability of fluctuating PV and wind power generation, as highlighted by Huber et al.³ Power ramp magnitudes in kW, power ramp rates in kW/min, ramp duration in min and flexible energy capacity in kWh were utilised together or separately for the quantification of needed and available flexibility,^{37–39} for the estimation of ramping requirements,⁴⁰ or for the investigation of the flexibility options of building energy systems.^{41–43} The method for quantifying power fluctuations in the present study is also based on analyses of the power ramps of PV systems. Aside from the investigation of power ramps, the developed method includes other familiar methods from the literature, for example, a variability index (VI),²⁹ a clear-sky index (CSI)⁴⁴ and an empirical cumulative distribution functions (eCDFs) of power ramps.³⁴ The developed method for quantifying the power and energy fluctuations of PV systems consists of three steps:

Step 1: Classification of days. Classification of the days with PV generation in the ‘low variability’ and ‘high variability’.

Step 2: PV power ramp analysis. Computation of the distribution of PV power ramps for each class from Step 1.

Step 3: PV daily energy fluctuations. Calculation of PV energy fluctuations for each class from Step 1.

2.1 | Step 1: Classification of days

The first step includes a classification of days in ‘low variability’ and ‘high variability’ according to power fluctuations of PV systems. This step is based on the VI and CSI. The VI was introduced by Stein et al.²⁹ for quantifying the variability of solar radiation. This approach was also mentioned in the literature review of Lohmann²⁷ as a method for evaluating solar radiation variability and was applied by Kreuwel et al.²⁸ to analyse PV power output fluctuations. The VI from Stein et al.²⁹ evaluates the variability of solar radiation by comparing measured global horizontal irradiance (GHI) with the calculated GHI under clear, that is, cloudless, sky conditions. The ground measurements of solar radiation for higher temporal resolutions are only available for a limited number of locations because solar radiation measurements have remained complex and challenging, and therefore, expensive.⁴⁵ On the other hand, the inverters of PV systems can provide measurements of PV power with acceptable temporal resolutions.^{46,47} The variability of PV power results not only from the variability of solar irradiance but also from the technical parameters of observed PV systems, such as temperature coefficients and degradation of solar cells, as well as from

the local conditions, such as periodical shading and reflections caused by trees, chimneys and neighbouring buildings, as well as from the surrounding ground (albedo effect). The influence of these factors on the PV power output can be derived solely from PV power measurements, but certainly not from GHI measurements. In addition to the higher availability, the use of the PV power measurements instead of GHI ones offers a much higher level of direct applicability in the field of energy management in buildings and city districts. The energy management systems can directly utilise the measured power values of the PV systems for various applications, such as the control and scheduling of the storage systems and flexible loads inside the buildings based on PV power output. The measured power values are directly available from the inverters of the PV systems without the need for additional measurement equipment, which is necessary for receiving the measured GHI values. These were the main reasons behind the modification of the VI outlined by Stein et al.²⁹ for the quantification of PV power fluctuations. The proposed modification is to substitute the GHI values by measured and calculated PV power under clear sky conditions, as is presented in Equation (1):

$$VI_{PV} = \frac{\sum_{k=2}^n \sqrt{(P_{meas,k} - P_{meas,k-1})^2 + \Delta t^2}}{\sum_{k=2}^n \sqrt{(P_{CS,k} - P_{CS,k-1})^2 + \Delta t^2}}, \quad (1)$$

where $P_{meas,k} - P_{meas,k-1}$ is the power ramp between the measured PV power values of points in time k and $k-1$, $P_{CS,k} - P_{CS,k-1}$ is the power ramp between the calculated PV power values under clear sky conditions during the same points in time and Δt the time interval.

(especially with different installed capacities), the calculated values of VI_{PV} were normalised with the highest observed value of VI, as proposed by Kreuvel et al.²⁸

The PV systems with frequent and large power ramps feature high values of VI_{PV} . On the other hand, on days with stable solar radiation (i.e., steadily sunny or steadily overcast), PV systems have lower VI_{PV} values. With the help of VI_{PV} , it is possible to separate days with highly fluctuating PV power from those with steady PV power. However, the VI_{PV} does not distinguish days with high PV output from days with low output, as these days feature small and infrequent fluctuations, and therefore, low values of VI_{PV} . For the purpose of making this distinction, Stein et al.²⁹ applied the daily clearness index, which also requires the GHI measured values. Due to the aforementioned higher availability of PV power measurements, the CSI from Engerer and Mills⁴⁴ is proposed to distinguish days with a high PV output from those with a low output as follows:

$$K_{PV} = \frac{E_{PV,meas}}{E_{PV,CLR}}, \quad (2)$$

where $E_{PV,meas}$ is the measured daily energy output of a PV system and $E_{PV,CLR}$ the calculated daily energy output of a PV system under clear sky conditions. Clear days with high PV generation levels have larger values of K_{PV} in comparison to overcast days with low PV outputs.

Based on the estimated values of VI_{PV} and K_{PV} , the following classification of days is proposed within the developed method for quantifying PV power fluctuations. The thresholds for the VI_{PV} are based on VI values from Kreuvel et al.²⁸ and those for the K_{PV} are derived from Alves et al. and colleagues^{30–32}:

- | | | |
|--|---------------------------------------|---------|
| • Days with low and infrequent power fluctuations, that is, low variability and: | | L days |
| ○ With high PV power output | $VI_{PV} < 0.2$ and $K_{PV} \geq 0.7$ | LH days |
| ○ With low PV power output | $VI_{PV} < 0.2$ and $K_{PV} \leq 0.3$ | LL days |
| • Days with large and frequent power fluctuations, that is, high variability, and various PV power outputs | Rest values | H days |

The PV power under clear sky conditions for a given PV system is calculated by utilising the open source Python framework, pvlib.⁴⁸ To apply the VI_{PV} to comparing the variability of different PV systems

The first letter in these class names corresponds to the variability of PV power, that is, to the magnitude and frequency of PV power fluctuations ('L' stands for low variability and 'H' for high variability). The second letter

corresponds to the generated PV daily energy ('L' for low PV daily output and 'H' for high output). If the class name contains only one letter, then this single letter is taken to describe the variability level and the PV output is thus neglected. The first step of the proposed methodology results in clearly classified days in LH, LL and H days, with the amount or percentage of days belonging to each class.

2.2 | Step 2: PV power ramp analysis

The second step includes computing the eCDF of PV power ramps. Mazumdar et al.³⁴ introduced the investigation of PV power fluctuation by building the distribution of all arising PV power ramps. Herein, we propose the application of this method to the three classes defined in Step 1 (LH, LL and H days) to investigate the individual eCDF of the power ramps for each class.

The proposed approach estimates the frequency of PV power ramps under a specific threshold (in kW), that is, it specifies that the power ramps under a particular threshold σ (in kW) arise with a definite frequency.³⁴ The eCDF of PV power ramps can be built by applying Equation (3),⁴⁹ as given below:

$$F(\sigma) = \frac{1}{n} \sum_{i=1}^n I(Y_i \leq \sigma). \quad (3)$$

$F(\sigma)$ is considered as the empirical distribution function of the observed power ramps $Y_i = P_{meas,k} - P_{meas,k-1}$. The empirical probability that the power ramps lie below a given threshold σ can be calculated with the following two steps. The first step includes counting the number of power ramps less or equal to the given threshold σ , that is, indicator I is assumed to be 1 for power ramps equal to or less than σ and 0 otherwise. In the next step, the value computed in the first must be divided by the total number of PV power ramps n .

The measured PV power values (in W) are normalised by the installed capacity of the PV system (in kWp). Hence, the power ramps are presented in normalised form (in W/kWp). If σ_1 and σ_2 are the lower and upper thresholds, respectively, the empirical probability that the arisen PV power ramp lies in this interval can be calculated as $F(\sigma_2) - F(\sigma_1)$.³⁴

2.3 | Step 3: PV daily energy fluctuations

The third step of the method investigates fluctuations in daily energy produced by the PV systems. We understand the PV daily energy fluctuation to be the difference

between the predicted and measured values of PV daily energy. The calculation of the PV energy fluctuations is performed as follows: first, the power curve of the given PV system for the next 24 h is predicted; second, predicted daily energy is determined; and third, a comparison is made for the predicted daily energy to the measured daily energy of the given PV system. It was decided that the developed method does not strictly prescribe, which approach should be applied to predict the PV power output, as there are numerous different predictive methods, for example, persistence, physical models, machine learning algorithms and so forth.⁵⁰ The most relevant takeaway from Step 3 is that the prediction of the PV power for the next 24 h is necessary for quantifying the PV energy fluctuations.

The PV energy fluctuations are represented by uniform forecast errors, namely, the mean absolute error (MAE) and root mean square error (RMSE) for three defined classes, LL, LH and H days:

$$MAE = \frac{1}{N} \sum_{i=1}^N |E_{daily,pred} - E_{daily,meas}|, \quad (4)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^n (E_{daily,pred} - E_{daily,meas})^2}. \quad (5)$$

The energy fluctuation for a particular day is represented graphically by calculating the cumulative energy of the PV system for that day, both measured and predicted. The distance between the measured and predicted cumulative curves corresponds to the PV energy fluctuation of the observed day. The third step in the developed approach results in MAE and RMSE values of PV energy fluctuations for three classes and a graphical representation of the energy fluctuations for each day of the observed period.

The proposed method for quantifying the PV power and energy fluctuations was applied to seven different PV systems. The major requirement for the PV power measurements was that the measured power values of all investigated PV systems have identical temporal resolutions, thus enabling the power fluctuations of different PV systems to be compared with each other.

3 | CASE STUDY

3.1 | Data description

The developed method for quantifying PV variability was applied to seven roof-mounted PV systems at different locations in Germany with different installed capacities, years of installation, orientations and solar cell types.

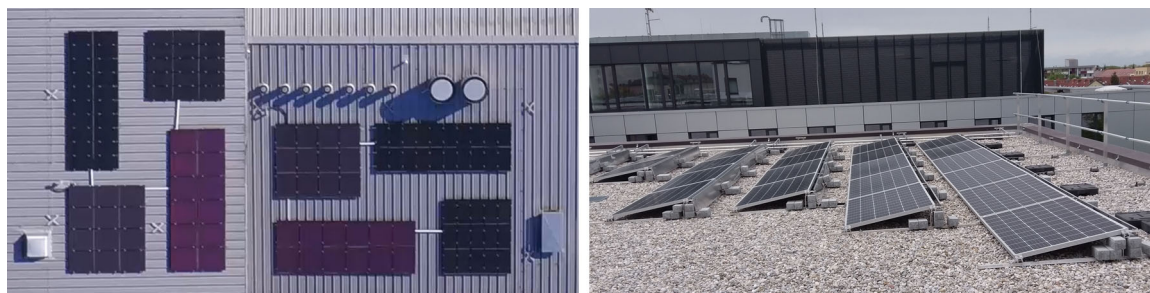


FIGURE 1 Photovoltaic (PV) systems in Oldenburg (left) and a PV system in Munich (right). *Source:* ©DLR

Eight PV systems are installed on the roof of the DLR Institute of Networked Energy Systems in Oldenburg in northern Germany (Figure 1, left). However, the power measurements of two PV systems with copper indium gallium selenide solar cells were not applied in this investigation, as the solar cells of these two PV systems have been subject to extremely high levels of degradation. The installed capacities of the six remaining PV systems are between 1125 and 1200 W_p; each PV system has a separate inverter with a nominal power of 1100 W.⁵¹ The seventh investigated PV system, with an installed capacity of 99.9 kW_p, is located on the roof of a real estate building in Munich in southern Germany (Figure 1, right). This PV system consists of five inverters with a nominal power of 20 kW per unit.⁵² The capacities of the inverters are almost equal to the total capacities of the modules amongst all of the investigated PV systems. These and further technical characteristics of the investigated PV systems are displayed in Table 1.

To become acquainted with and understand PV power measurements, an intensive data analysis was conducted, and a data quality report was created according to Kelleher et al.⁵³ The data quality report controls for the data availability, calculates the descriptive statistics (mean, maximum, minimum, standard deviation, etc.) and detects data quality issues, such as outliers and missing values. The power measurements of the six investigated PV systems in Oldenburg are available for the time period from 2011 to 2021, and those of the PV systems in Munich are available for the years 2019 and 2020. These data sets with PV power measurements do not feature outliers in either city, that is, there are no measured power values greater than the installed capacities of the PV systems, and there are no recorded negative power values. Because the monitoring of the PV systems in Oldenburg from April 2019 to June 2020 failed, the power measurements for this period of time are missing. Moreover, the power measurements are also missing for July to October 2021. The total proportion of the missing values in the data set of the PV systems in Oldenburg accounts for 15% for the period

of time from 2011 to 2021. The proportion of missing values in the data set of the PV system in Munich accounts for 7% in the time period from 2019 to 2020. According to the rule of thumb proposed by Kelleher et al.,⁵³ the proportion of missing values of all investigated PV systems can be described as uncritical. The quality of PV power measurements was evaluated as satisfactory for quantifying power and energy fluctuations using the method developed in this study. In the previous chapter, it was noted that the measured power values of the observed PV systems must have identical temporal resolutions. Correspondingly, all of the PV power measurements investigated herein featured a constant temporal resolution of five minutes.

3.2 | Results and discussions

In the first step of the method for quantifying PV power and energy fluctuations, we calculated the VI_{PV} and K_{PV} for all of the investigated PV systems. Based on the calculated values, the days were classified as LH, LL and H days.

The scatter plots shown in Figure 2 represent the calculated values of VI_{PV} and K_{PV} of all investigated PV systems in Oldenburg (top and middle plots) and Munich (bottom plot).

Each dot indicates the calculated values of VI_{PV} and K_{PV} of the specific PV system for one day. The plots of the PV systems in Oldenburg contain more dots because the measurements of these PV systems are available for longer periods of time than those of the PV system in Munich. The scatter plots of all of the investigated PV systems feature similar triangular forms, despite different installed capacities, solar cell types, orientations and locations of the installations. Based on the estimated values of VI_{PV} and K_{PV} , the days were classified as LH, LL and H days and the numbers of days in each class were calculated.

As is presented in Table 2, about 60% of the days in the observed period were classified as H days for all PV

TABLE 1 Main technical characteristics of the investigated photovoltaic systems

Label of PV system	Location	Installed capacity (kWp) ^a	Inverter capacity (kW)	Orientation	Azimuth	Inclination	Solar cell type	Data available
O-SW-mimo	Oldenburg	1.20	1.10	Southwest	237°	7°	Micromorph (a-Si and μ c-Si)	2011–2021
O-SW-aSi		1.14	1.10				Amorphous silicon	
O-SW-CIS		1.125	1.10				Copper indium selenide	
O-SE-mimo	Oldenburg	1.20	1.10	Southeast	147°	7°	Micromorph (a-Si and μ c-Si)	2011–2021
O-SE-aSi		1.14	1.10				Amorphous silicon	
O-SE-CIS		1.125	1.10				Copper indium selenide	
M-S-moSi	Munich	99.90	100.0	South	177.5°	10°	Monocrystalline silicon	2019–2020

Abbreviation: PV, photovoltaic.

^aInstalled capacity is equal to the total capacity of the PV modules.

systems, that is, high and frequent PV power fluctuations arose in 60% of the days during the observed period. The percentages of LH and LL days were almost identical to each other for the PV system in Munich. However, the PV systems in Oldenburg had 6–12 percentage points more LL days than LH days, that is, those in Oldenburg had more days with lower PV outputs during the observed period. This observation can possibly be explained by the location. As Munich is located farther south than Oldenburg, the annual solar radiation levels in Munich are higher, with the average annual GHI in the time period from 1981 to 2010 having been 1161–1180 kWh/m² in Munich compared to 981–1000 kWh/m² in Oldenburg.⁵⁴

The estimated values of VI_{PV} and K_{PV} and the classification of days according to the PV variability do not yield further information regarding the extent or magnitude of the observed PV power fluctuations (in W). For this reason, the second step of the developed method for quantifying PV power fluctuations includes computing the distribution of the PV power ramps of three classes. Figure 3 depicts the eCDFs of normalised power ramps for six PV systems in Oldenburg and one in Munich. The coloured curves represent the three classes defined in Step 1 (yellow—LH days, blue—LL days and green—H days). The vertical axes of the diagrams represent the empirical probability of power ramps and the horizontal axes the normalised values of PV power ramps with a 5 min temporal resolution. Each eCDF-plot contains an embedded plot that embodies the probability density functions (PDFs) of power ramps for this PV system.

As can be seen in Figure 3, the green curves lie noticeably above (on the negative X -axis scale) and below (on the positive X -axis scale) the yellow and blue curves. This can be interpreted by the fact that the H days have larger PV power ramps, whereas the L days have a greater number of low-power ramps. For instance, the empirical probability that the power ramp of the PV system O-SW-aSi lies in the range [−50 W, 50 W] is 98% on LL days, 97% on LH days and 77% on H days. However, the empirical probability that the power ramp of this PV system lies in the range [50 W, 200 W] is about 1% on L days and almost 9% on H days. The resulting eCDF curves can be applied for estimating the empirical probability of any power ramp ranges for all of the observed PV systems.

The eCDF curves of the power ramps on L days (blue and yellow curves) are practically identical in form and gradient. However, the PDF curves differ in terms of PV power ramp densities these days, as can be seen in the embedded plots presented in Figure 3. The LL days feature the highest density of small power ramps

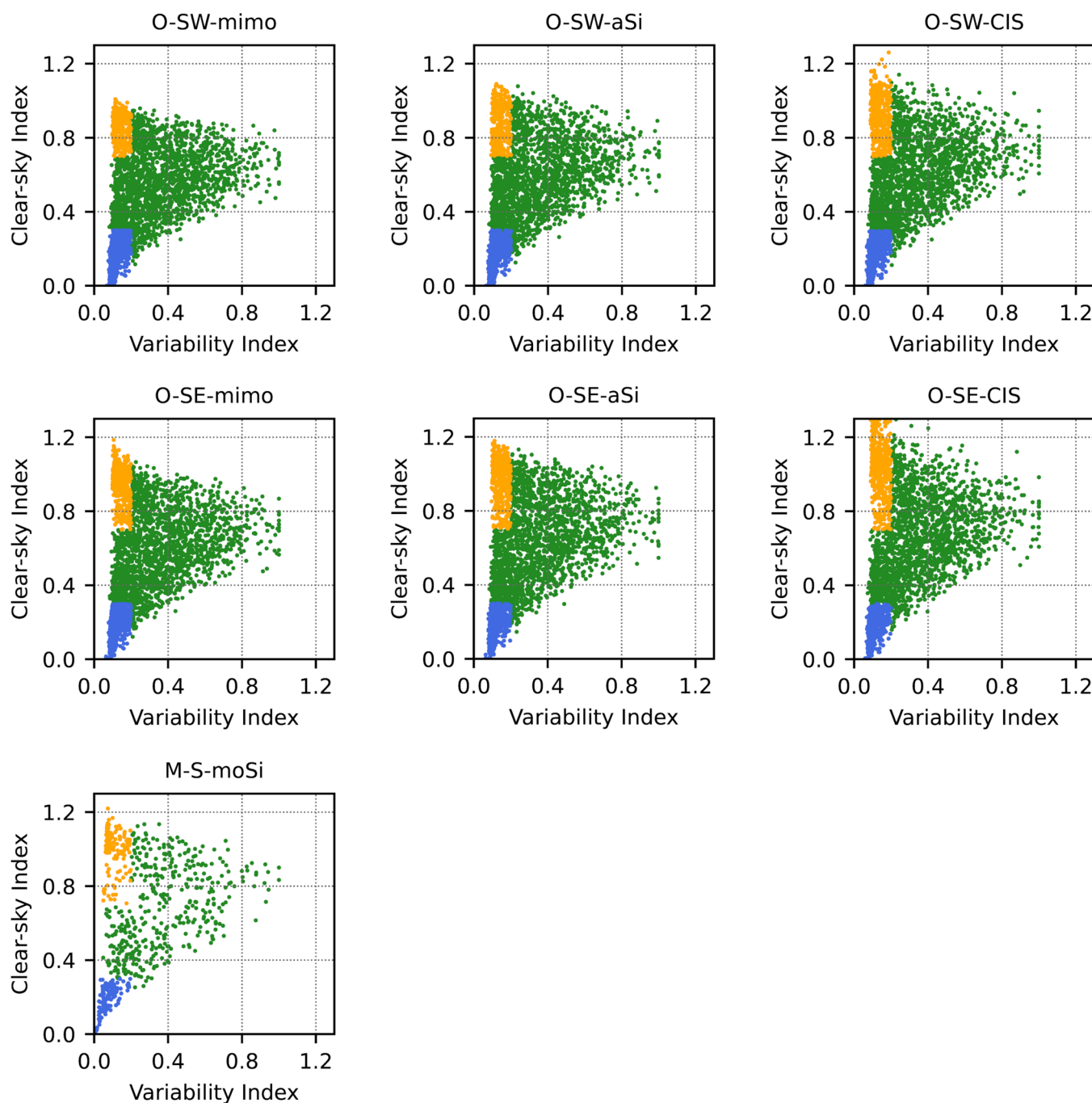


FIGURE 2 Scatter plots with VI_{PV} versus K_{PV} of the observed photovoltaic (PV) systems in Oldenburg (top and middle) and Munich (bottom). The coloured dots represent three classes corresponding to the variability and daily output of the PV systems: yellow—LH days; blue—LL days; and green—H days.

(s. peaks of blue curves on embedded plots in the area between -10 and 10 W/kWp). The LH days have a higher density of power ramps in the ranges $[-25, -10)$ and $[10, 25)$, that is, the yellow PDF curves are located slightly above the blue and green curves in the observed ranges.

The PV systems in Oldenburg have similar installed capacities and durations of operation, but different orientations and solar cell types. However, the eCDFs

and PDFs of power ramps with 5 min temporal resolutions in Oldenburg PV systems look extremely similar, as illustrated in Figure 3. To numerically compare the eCDF curves of the different PV systems with each other, the nonparametric, two-sample Kolmogorov–Smirnov (K–S) test was used. This test compares the cumulative distributions of two data sets and is based on the maximum distance between the given eCDF curves. If

TABLE 2 Percentage of LH, LL and H days over the time period under consideration for the investigated photovoltaic systems

PV system	LH days (%)	LL days (%)	H days (%)
O-SW-mimo	13.81	25.06	61.13
O-SW-aSi	12.68	24.40	62.92
O-SW-CIS	13.81	25.06	61.13
O-SE-mimo	13.89	23.97	62.14
O-SE-aSi	15.07	21.55	63.38
O-SE-CIS	15.45	23.75	60.80
M-S-moSi	19.44	18.83	61.73

Abbreviation: PV, photovoltaic.

the resulting K–S test statistic is small, then the null hypothesis cannot be rejected. The null hypothesis of the present study is that the distributions of power ramps of two given PV systems of the specific day class are identical.^{55,56}

Figure 4 displays the K–S test statistics for the investigated PV systems. The null hypothesis cannot be rejected for the PV systems in Oldenburg, as these PV systems can have identical distributions of power ramps at 5% significance levels despite their different solar cell technologies and orientations. The location of the PV systems and duration of the observed period of time demonstrate the most significant influence on the K–S test statistics, which was as expected, because GHI fluctuations are the primary driver for PV power fluctuations, especially for PV systems in the same location, as this study demonstrates. The null hypothesis can therefore be rejected for the PV systems in the different locations (Oldenburg vs. Munich) on LH and LL days.

The first and second steps of the developed method contain the investigation of power fluctuations. The third step deals with the analysis of PV energy fluctuations. As was explained in the previous chapter, the fluctuation of PV energy constitutes the difference between the measured and predicted energy output of the PV system. To predict the PV power for a particular PV system, the solar radiation forecasts from the Open Data Server of the German Meteorological Service (Open DWD)⁵⁴ for the locations of the observed PV systems were utilised. The solar radiation forecasts contain predictions of direct normal irradiance, diffuse horizontal irradiance and GHI, with a temporal resolution of 1 h. The hourly resolved values of the solar radiation forecasts were interpolated to the 5 min resolved values, following the second approach for temporal interpolation proposed by Lorenz et al.⁵⁸ These 5 min resolved solar radiation

predictions and technical parameters of the PV systems (PV module type, inverter type, number of modules per string, number of strings per inverter, location, azimuthal angle and inclination angle) were inserted into the Python framework pvlib⁴⁸ to predict PV power curve for the subsequent 24 h.

Based on the given technical characteristics of the PV modules, the pvlib model first computes the direct current (DC) power of one PV module under given meteorological conditions. Then, the model computes the DC behaviour of the PV modules combined in the arrays considering wiring losses and mismatch effects. The next modelling step includes the conversion of the DC power to alternating current (AC) power in consideration of the prevailing results and technical characteristics of the inverter. The output of the model is the AC power of the observed PV system before the electricity meter, that is, the AC power generated by the PV system before local consumption or feeding into the power grid.^{48,59}

The solar radiation forecasts from OpenDWD were collected for a period of time that is shorter than the operating period of the PV systems. Nevertheless, the PV power of the selected PV system O-SW-aSi was predicted for one entire year, from 1 July 2020 to 30 June 2021. Then, the cumulative energy—predicted and measured—was calculated for each day of this investigated time period. The predicted cumulative energy was then compared to the measured cumulative energy of the same day. Figure 5 illustrates the measured and predicted cumulative energy of the selected PV system O-SW-aSi for three randomly selected days (upper plots) and the difference between the measured and predicted cumulative energy values of this PV system for all days in the observed period from 1 July 2020 to 30 June 2021 (bottom plots). Three randomly selected days in the upper plots represent the three defined classes: 5 August 2020 was classified as the LH day, 9 September 2020 as the LL day and 4 August 2020 as the H day.

The difference between the measured and predictive energy levels in the bottom plots takes both positive and negative values because the predictive model can both over- and underestimate. Figure 5 illustrates that the energy fluctuations are smaller on days with lower variability in comparison to those with higher variability. Approximately 90% of all grey curves representing the cumulative energy difference on the LH and LL days lie between -750 and 250 Wh. The cumulative energy difference on the H days is considerably higher and the majority of curves lie between -2000 and 1000 Wh. The difference between the measured and predicted curves is the forecast error, which derives from the uncertainties of the

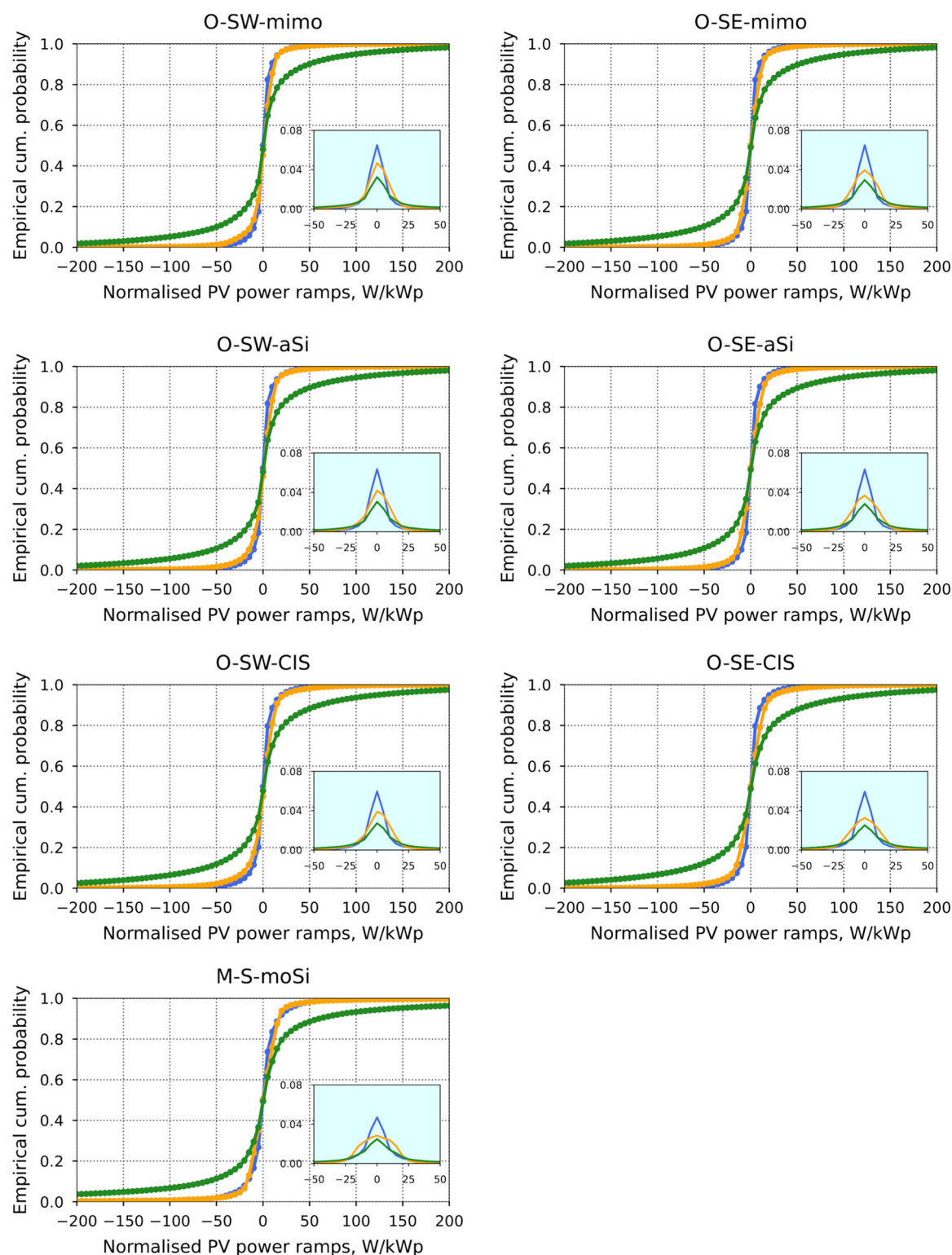


FIGURE 3 Empirical cumulative distribution function (large plots) and probability density function (embedded plots) of normalised photovoltaic (PV) power ramps with a 5-min temporal resolution. Each plot corresponds to the definite PV system. The three coloured curves represent the three categories based on the variability of PV power: yellow—LH days; blue—LL days; green—H days.

weather predictions. Moreover, the developed predictive model cannot consider all of the specific technical characteristics of the investigated PV system and the specific local conditions, which can also influence

forecast accuracy. Aside from the graphical representation, the PV energy fluctuations can also be demonstrated in numerical form by the forecast errors MAE and RMSE, which are displayed in Table 3.

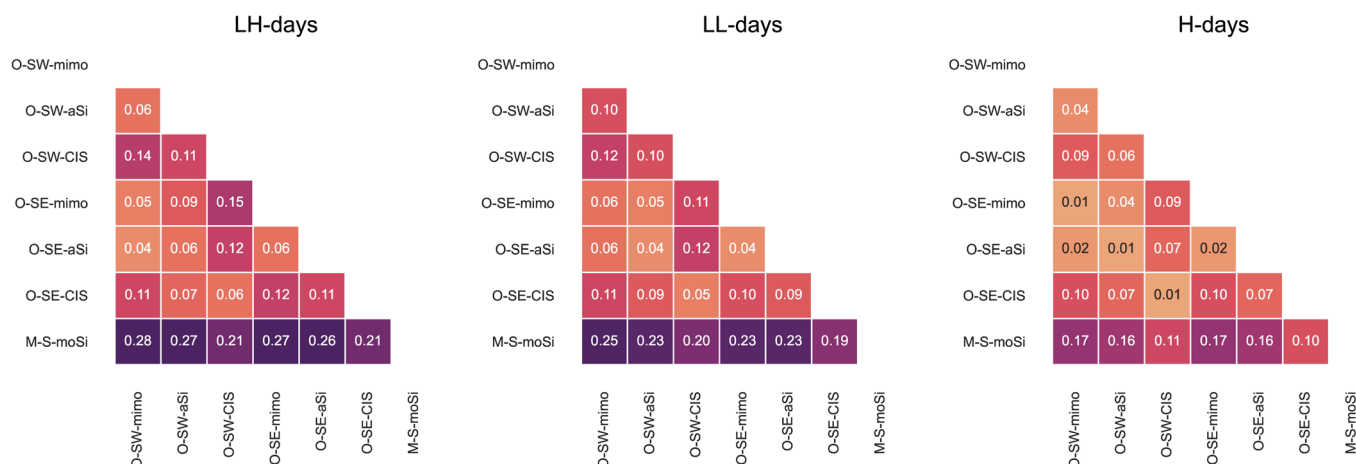


FIGURE 4 Result statistics of the two-sample Kolmogorov-Smirnov test for the investigated photovoltaic systems. The critical value is 0.21 at a 5% significance level (calculated using critical values for the two-sample Kolmogorov-Smirnov test (two-sided)⁵⁷).

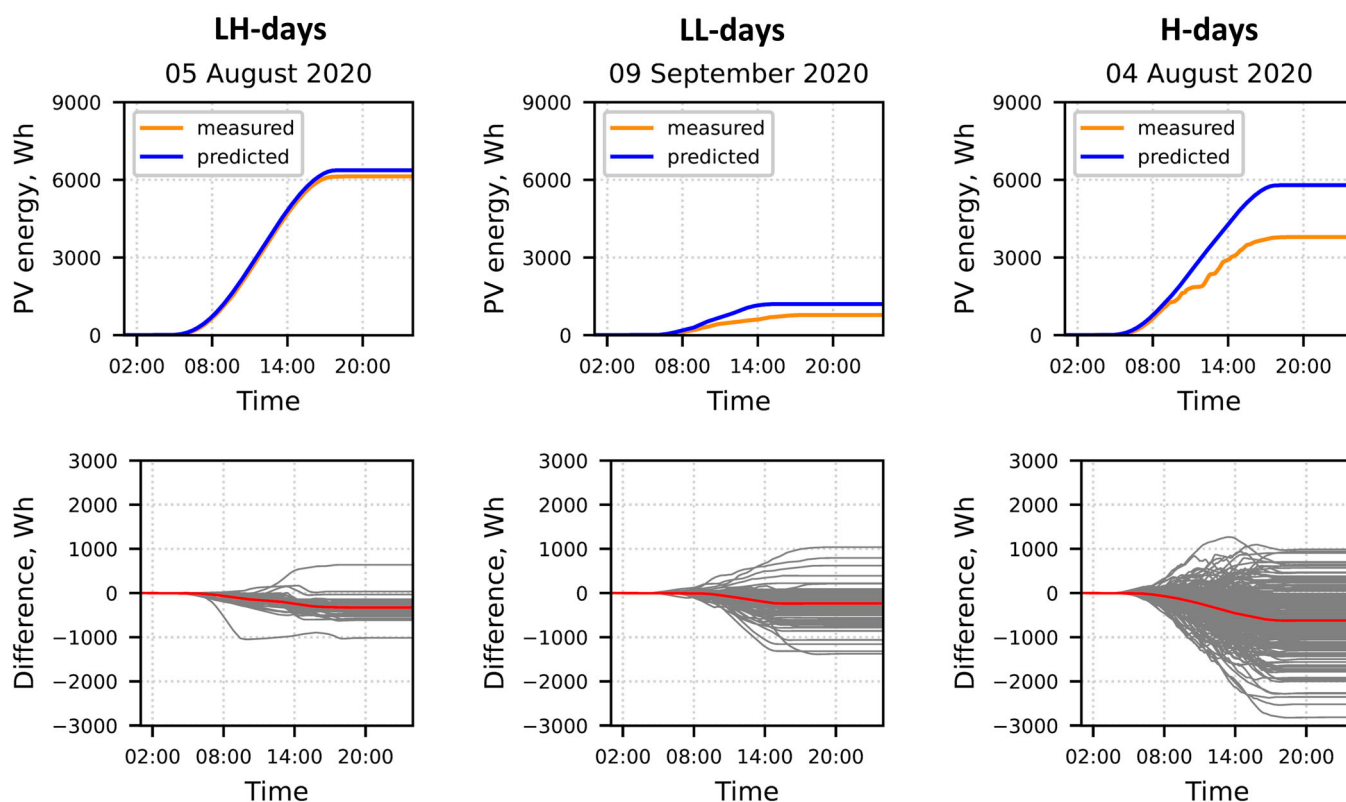


FIGURE 5 The upper plots display the measured and predicted cumulative energy of the photovoltaic system O-SW-aSi with an installed capacity of 1.14 kWp for 3 days in 2020. Each day represents the definite class from Step 1. The bottom plots display the difference between the values of measured and predicted cumulative energy levels for all days of the definite class. The red curves represent the mean values.

The MAE and RSME of the PV daily energy on H days were approximately twice as high as the MAE and RMSE values on the LH and LL days. The calculated values of the MAE and RMSE can indicate that PV variability increases the forecast errors of PV energy

prediction. In general, the days with high variability feature significantly higher PV energy fluctuations than days with low variability. It is also evident that the energy generation of the PV system on LL days is considerably lower than on LH days, but the MAE and RMSE of these

TABLE 3 MAE and RMSE of the predicted daily energy of the photovoltaic system O-SW-aSi for three defined classes for the time period under consideration

	MAE (Wh)	RMSE (Wh)
LH days	360.13	404.62
LL days	326.10	455.06
H days	696.19	877.89

Abbreviations: MAE, mean absolute error; RMSE, root mean square error.

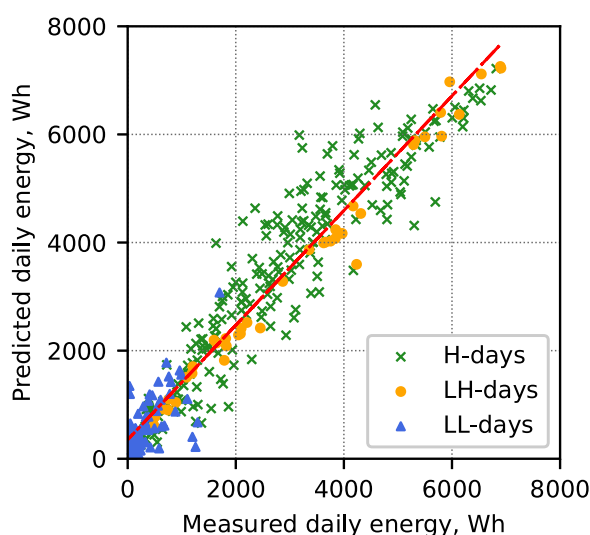


FIGURE 6 Scatter plot of the measured and predicted daily energy of the photovoltaic system O-SW-aSi for the three classes. The red line represents the trend line.

two classes are noticeably similar. Based on these results, it can be concluded that the PV variability has more of an influence on the PV energy forecast error than the PV daily output.

Figure 6 contains a scatter plot in which the measured daily energy values are plotted against the predicted daily energy values of the PV system O-SW-aSi.

The blue triangles are located in the area of low energy output, up to approximately 2000 Wh. This location of the blue triangles corresponds to their category because this category of days has a lower PV power output, that is, the PV system generated a small amount of electrical energy on these days. The yellow dots are located significantly closer to the trend line than the blue and green ones. These dots belong to the LH days with high PV power output and low variability. For this class, the PV power can be more accurately predicted than for the days with high variability. The green crosses are located along the entire trend line, which means that days with highly fluctuating PV production (H days) occur throughout the entire year, that is, highly fluctuating PV production can occur on both days with low and high PV energy outputs.

The developed predictive model tends to overestimate the power of the observed PV systems for the next 24 h. However, the model's quality is beyond the scope of this study. The possible reasons for this overestimation and the model's optimisation are not addressed and discussed, as the particular reasons for this prediction uncertainty cannot be accurately determined. These factors may include different influences, such as assumptions made in the pvlib model, bias in the OpenDWD weather predictions and local circumstances that can be included in neither the simulation model nor in the weather prediction, such as shadowing or soiling of the PV modules.

The proposed methodology for quantifying PV energy fluctuations can be applied to any PV system if solar radiation predictions for its particular location and technical parameters are available. Moreover, other predictive models and approaches, such as machine learning algorithms, can also be applied to the prediction of PV power, and this prediction can then be used to quantify PV energy fluctuations. If precise weather forecasts are available, it may be possible to make precise predictions of PV power. Based on such more precise PV power predictions, it could then be possible to classify days in advance. If the class of the coming day, the distributions of the PV power fluctuations and the PV energy fluctuation for the said day are known, available flexibility technologies can be prepared and scheduled to mitigate possible power and energy fluctuations in PV systems. The other side of the coin is that small energy management systems must often be operated at low-cost levels, and therefore, they cannot afford to perform cost-intensive PV power predictions, for example, as described by Maitanova et al.⁶⁰ and Hanke et al.⁶¹ In this case, the proposed method for calculating PV energy fluctuations is a tool that can utilise low-cost PV power predictions with satisfactory accuracy in energy management systems.

3.3 | Potential applications

As noted in the introduction, the developed method for quantifying power and energy fluctuations can supplement the existing overall analysis of PV system operation and performance. This supplemental investigation is relevant for future power systems with high shares of fluctuating renewable energy sources and decentralised energy units, for example, for city districts with PV systems and integrated energy systems, such as heat pumps, energy storages and electric vehicles.

The results of the developed method for quantifying the power and energy fluctuations of a given PV system

include the distribution of PV power fluctuations (characteristic magnitude and frequency of the power ramps) and daily energy fluctuations. These results can be utilised in a future general method for the assessment and quantification of flexibility in a building with a PV system. Assuming that the fluctuations of the local PV system are balanced by the available local flexibility providers, the computed PV power fluctuations may correspond to the power of these flexibility providers (in kW), for example, storage systems, energy generating units and controllable loads. The quantified PV energy fluctuations can coincide with the necessary capacity of the flexibility sources (in kWh) to balance fluctuations. As the method developed in this study directly utilises PV power values (not the GHI values that require additional measurement equipment), the required size of the local flexibility sources for mitigating the fluctuations of local PV systems can be derived directly from the results of the proposed method for quantifying power and energy fluctuations of the PV systems.

The calculation of the power fluctuations using the developed method is based on the power ramps at each point in time, but the energy fluctuations are computed on a daily basis. This difference in temporal resolution can also be explained by the different utilisation of the results of the developed method. The power fluctuations are computed for each point in time to determine that the available local flexibility sources provide enough nominal power to mitigate the power ramp arising at the given point in time. Because the PV power prediction uncertainties are summed over the day, the computed daily energy fluctuations can be compared to the capacity of the local flexibility sources to estimate whether the available flexibility sources have a sufficient amount of energy to balance the daily energy fluctuations.

The developed method for quantifying the power and energy fluctuations of the PV systems can be applied when planning the energy supply of buildings. At this stage, the results of the proposed method can support adequate dimensioning of the energy units, which can also be utilised as a flexibility source. Furthermore, the proposed method can be integrated into the energy management system for scheduling the operation of local energy units in buildings for the next day, considering not only local weather patterns but also influences from infrastructure components, such as chimneys and trees. This field of utilisation can be described as follows. First, the next day can be classified into LH, LL or H days based on the low-cost and publicly available weather prediction for the next day (first step of the proposed method). Second, the assigned class and corresponding eCDF of power ramps of the given PV systems can be utilised to estimate the most likely values of power

fluctuations for the next day (second step). Third, the probable value of energy fluctuation can also be determined based on the assigned class, that is, the estimated value of an energy fluctuation corresponds to the amount of energy that must be reserved or shifted locally to compensate for the fluctuations in energy generated by the PV systems (third step). This amount of energy can be derived from the suggested representation of PV daily energy fluctuation, namely, from the height of the cumulative deviation of the forecasted daily energy of PV systems. Furthermore, the cumulative curve can also indicate the required duration of energy reserving or shifting, that is, how long the required amount of energy should be reserved for balancing purposes. The operation of local decentralised energy units, that is, flexibility providers, can be scheduled in such a way that the arising power and energy fluctuations can be balanced by the local energy units. On the days with expected high energy fluctuations and insufficient capacity of the local units, that is, H days, the building energy management systems can purchase the additional amount of energy during times with lower electricity prices and store it within buildings for balancing the daily energy fluctuations. Conversely, on the days with expected low fluctuations, the available flexibility can be offered to the distribution grid.

The results of the K-S test showed that the neighbouring PV systems can have the same distributions of power ramps. This insight underlies the next possible application of the developed method. The manufacturers of the inverters can offer a new service to PV systems operators, that is, the expected characteristic power fluctuations of a new PV system can be derived from the PV power fluctuations of neighbouring systems calculated with the help of the method proposed in this study.

4 | CONCLUSIONS

This study proposes a new, three-step method for quantifying the variability of PV systems. The first step includes a classification of days with PV generation into LH, LL and H days according to the calculated values of a modified VI and CSI. The second step consists of building the eCDF of PV power ramps for three given classes. The final step entails the calculation of fluctuations in daily energy generated by the PV systems. The developed method for quantifying the power and energy fluctuations of PV systems combines familiar technical approaches with certain novelties proposed in this study. The first of these novelties is to compute the distributions of PV power ramps for three given classes, whereby the

power ramp distributions are investigated according to different variability levels of PV power output. This investigation demonstrates that days with high variability (H days) and those with low variability (L-days) feature characteristic distributions of PV power ramps. The computed distributions of the power ramps enable the magnitudes of power fluctuations that arise most frequently in a given PV system to be estimated. In other words, based on the computed distributions, the probability of any power ramp of any PV system can be determined for the given variability class. The second novelty of this study is the proposal to investigate the daily energy fluctuations of PV systems for the defined classes, and to represent these fluctuations with the help of cumulative energy deviation curves. This type of representation provides not only the amount of energy that must be reserved or shifted locally for balancing purposes within a day but also the necessary duration of energy reserving or shifting.

For validation purposes, the developed method was applied to seven rooftop PV systems. The method performed well, although the investigated systems were characterised by different installed capacities, orientations, solar cell types, years of installation and durations of operation. The PV systems from the same location had an almost equal percentage of days in the given classes. Moreover, the results of a K-S test indicated that the PV systems from the same location could have similar distributions of power ramps. However, all of the investigated PV systems are located in Germany in western Europe. It may be academically interesting to apply the developed method to PV systems in other locations with apparently differing climate and weather conditions. Moreover, future research could include the adaptation of the developed method to quantify the variability of other fluctuating renewable energy technologies and load fluctuations.

As previously noted, the method proposed in this study can be part of the future general method for quantifying flexibility in buildings and city districts with PV systems. Future research works can test the application of the results of the developed method for evaluating and dimensioning flexibility providers, as well as for scheduling their operations. Thereby, the usefulness of this method for assessing the flexibility potential of buildings and city districts can be evaluated.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data sets with PV power measurements were used for validation purposes. The data of the PV systems in Oldenburg, Germany, are available on request from the authors. The data of the PV system in Munich, Germany, are not available due to privacy restrictions of the PV system owner.

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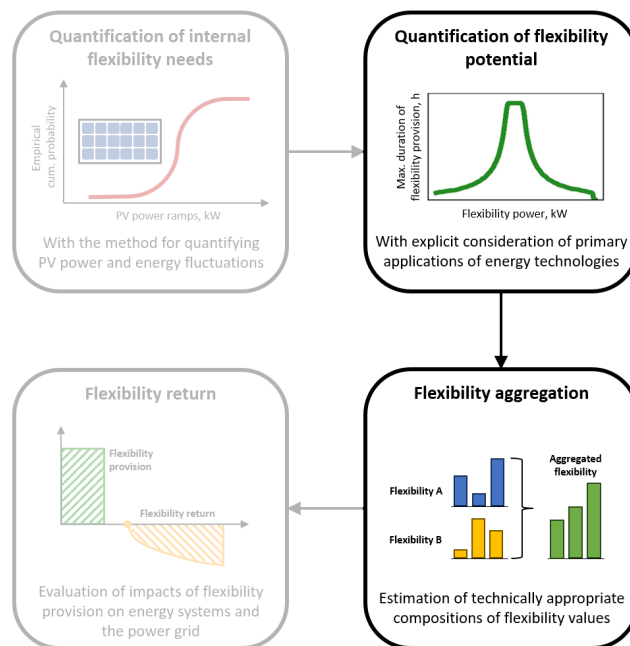
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Chapter 4.

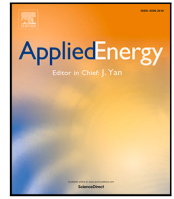
Quantification and aggregation of flexibility potential

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Specific contributions of N. Maitanova: Investigation; development of methodology; data analysis of households, photovoltaic, and battery storage systems; modelling of a battery storage system; energy simulations; evaluation and visualisation of results; writing of the original manuscript.



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:

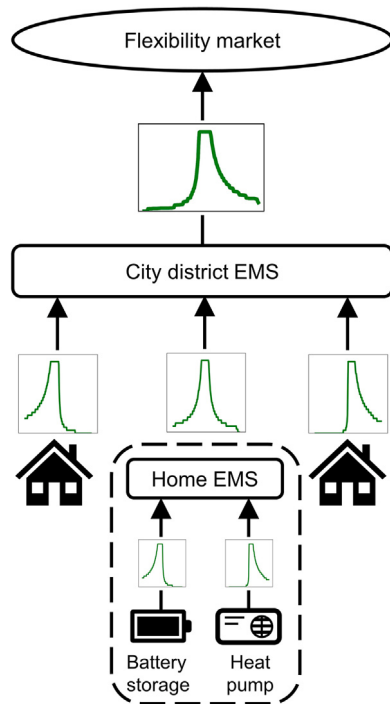


Fig. 1. Flexibility quantification and aggregation in a residential city district for offering on the flexibility market.

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.

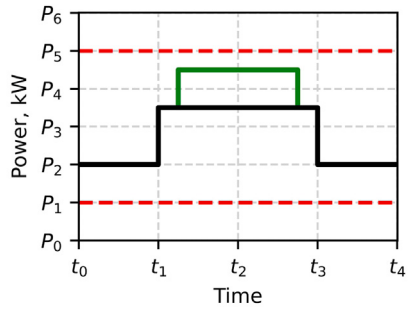
In general, the fluctuations that should be balanced can be described in terms of their power, energy and ramp rate. In [40], we proposed a method for quantifying the power and energy fluctuations of PV systems, as PV systems are the most popular choice for renewable energy sources in urban areas. The 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

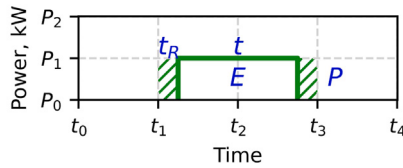
The energy systems, such as energy generation units, storage systems, cross-sectoral integrated energy systems, and controllable loads, are installed in the energy cells to meet the occupants’ needs, such as space heating, domestic hot water treatment, cooling, increasing self-consumption from local 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.

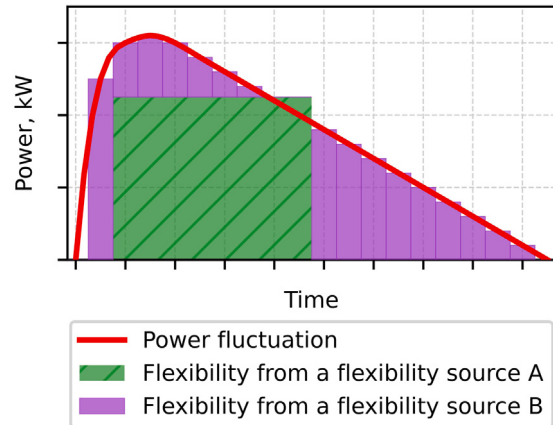


Fig. 3. Schematic presentation of flexibility needs and provision from two flexibility resources.

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:

$$\text{dur} : \text{Power} \rightarrow \text{Time} \quad (1)$$

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:

$$|P_{\text{max}}| = |P_{\text{min}}| = P_{\text{nom}}, \quad (2)$$

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 $E_{\text{min}}(t)$ and maximal $E_{\text{max}}(t)$ 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:

$$E_{\max}(t) = E_{\text{sched}}(t) + (Q_{\text{nom}} - \max_{\tau \in [t, T]} E_{\text{sched}}(\tau)) \quad (3)$$

and

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

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

4.1.3. Step 3: Flexibility duration

General case. Calculate the maximal duration $\text{dur}(P_{\text{flex}})$ 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 $\text{dur}(P_{\text{flex}})$ 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:

$$E_{\text{flex}} = P_{\text{flex}} \cdot \tau \quad (5)$$

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

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

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 $\text{dur}(P_{\text{flex}})$ 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 $\text{dur}(P_{\text{flex}})$ 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

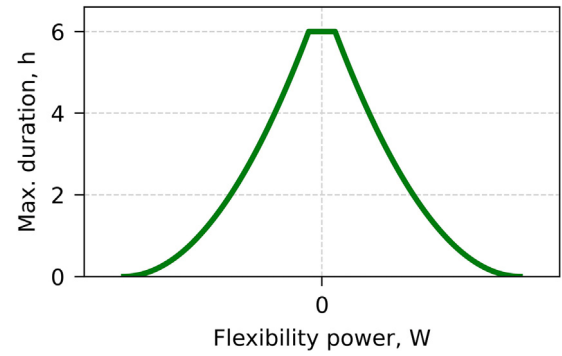


Fig. 4. Presentation of an exemplary flexibility potential curve.

for the purpose of joint graphical presentation of positive and negative flexibility power values.

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.

$$P_{\text{agg}} = \sum_{i=1}^n P_i \quad (7)$$

where P_i is a flexibility power value of i th 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.

$$\begin{aligned} P_{\text{agg}}^{\text{max}} &= \sum_{i=1}^n P_i^{\text{max}} \\ P_{\text{agg}}^{\text{min}} &= \sum_{i=1}^n P_i^{\text{min}} \end{aligned} \quad (8)$$

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:

$$P_i^{\text{min}} \leq P_i \leq P_i^{\text{max}} \quad (9)$$

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:

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

where P_i and $\tilde{P}_i$ present different power values that i th 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:

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

where $\text{dur}(P_i)$ is the maximal duration, for which i th 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 $\text{dur}(P_{\text{agg}})$ of the combination.

$$\text{dur}(P_{\text{agg}}) := \max\{\text{dur}(P_1, P_2, \dots, P_n) \mid P_{\text{agg}} = P_1 + \dots + P_n\} \quad (12)$$

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

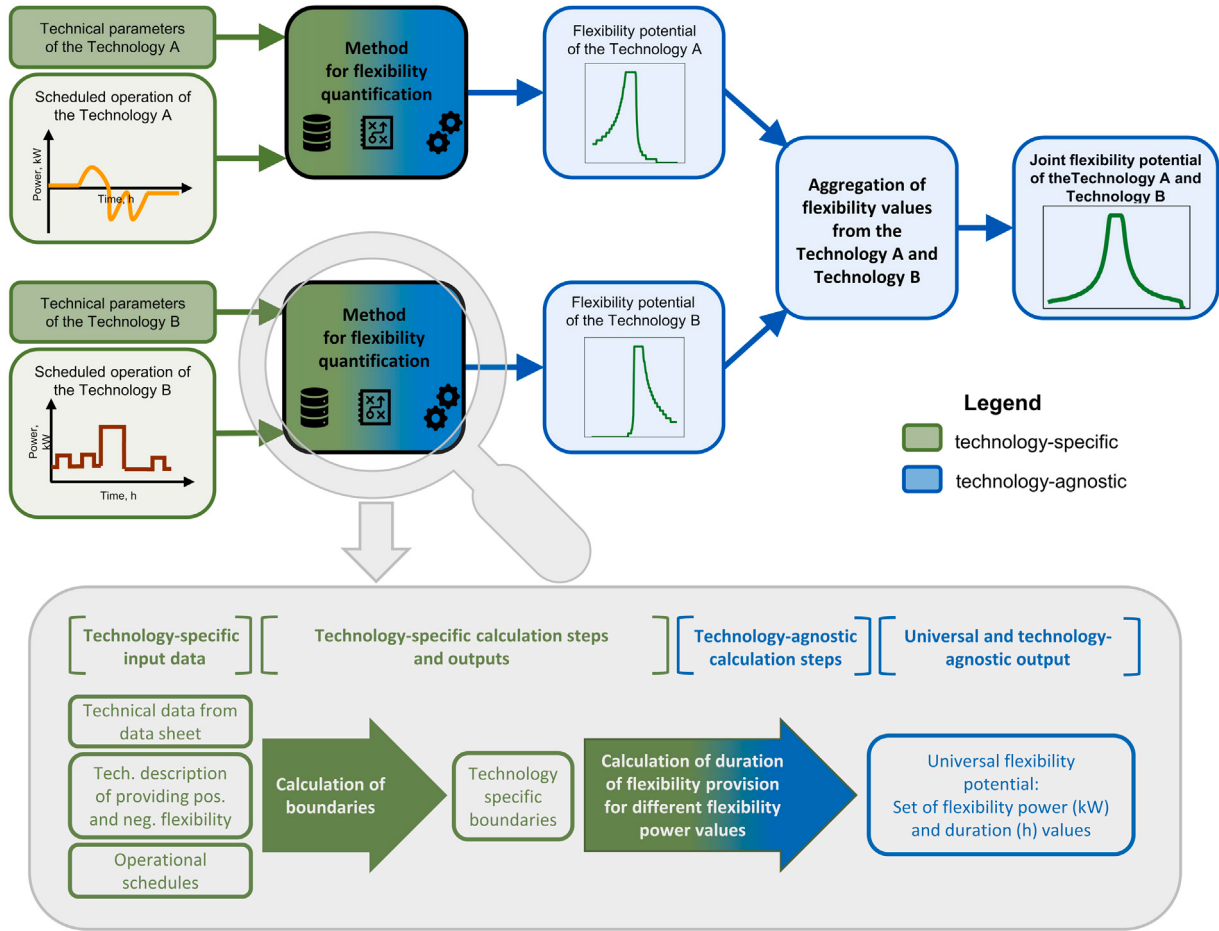


Fig. 5. Functional principle of the methods developed for flexibility quantification and aggregation.

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)).

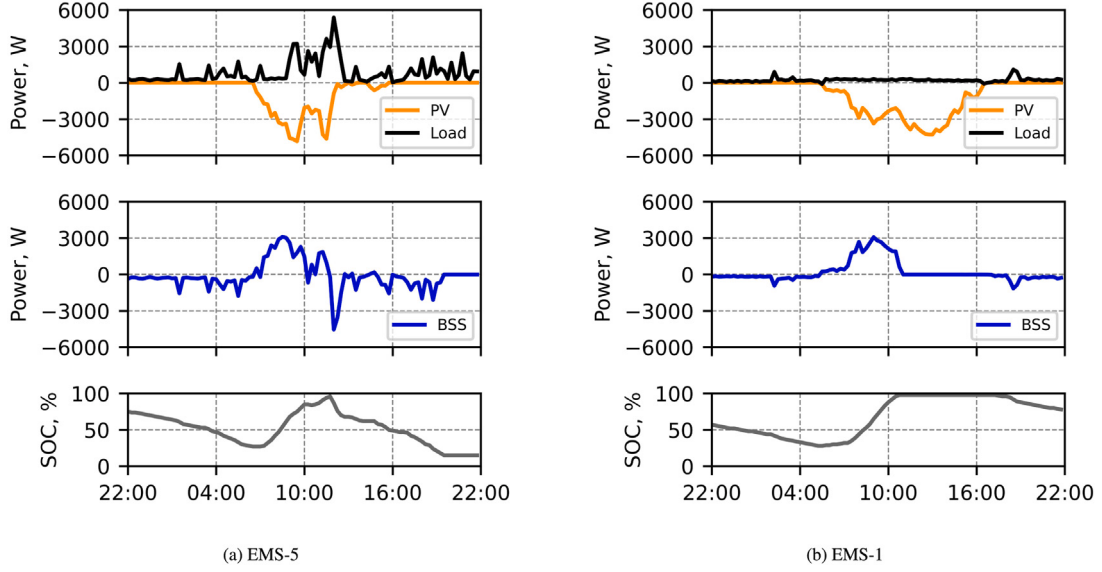


Fig. 6. Historical power measurements of two households “EMS-5” and “EMS-1”, their PV and BS systems on April 3rd, 2019, [48].

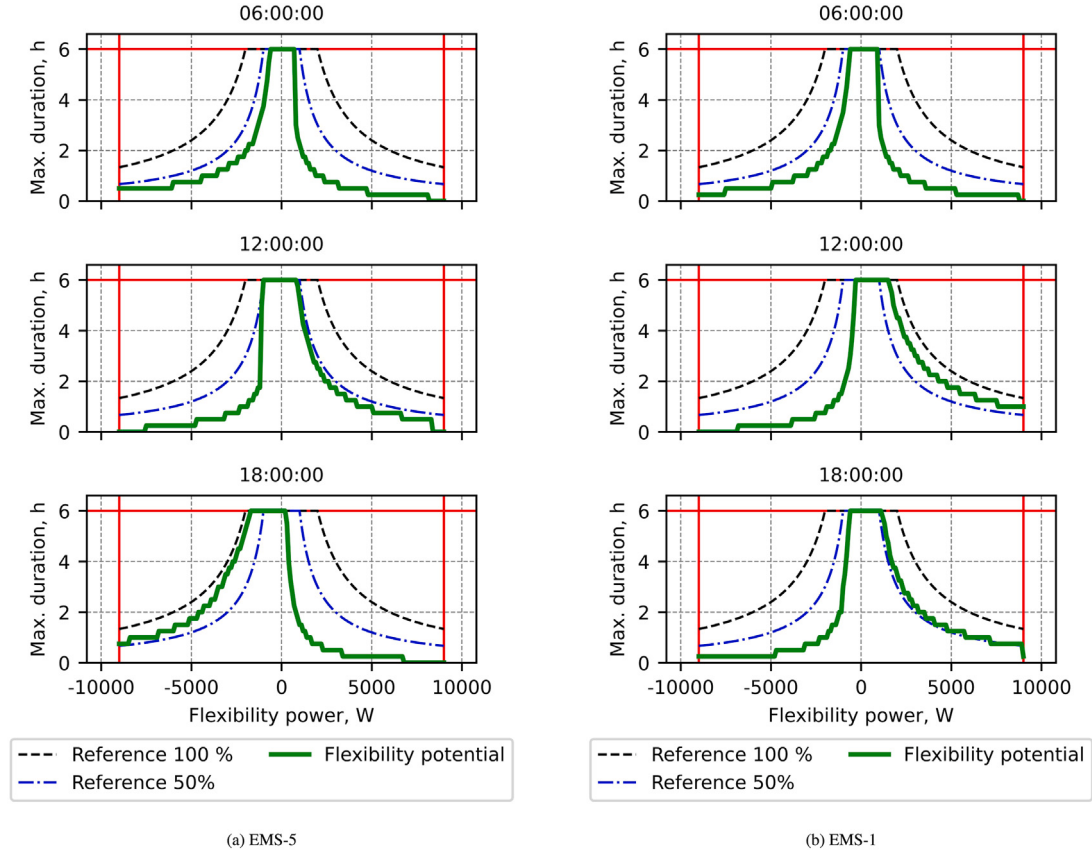


Fig. 7. Duration of different positive and negative flexibility power values in “EMS-5” and “EMS-1”, i.e. flexibility potential curves, at 06:00, 12:00, and 18:00 on April 3rd, 2019.

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 $P_{flex} \in [-9000, 9000]$, 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,

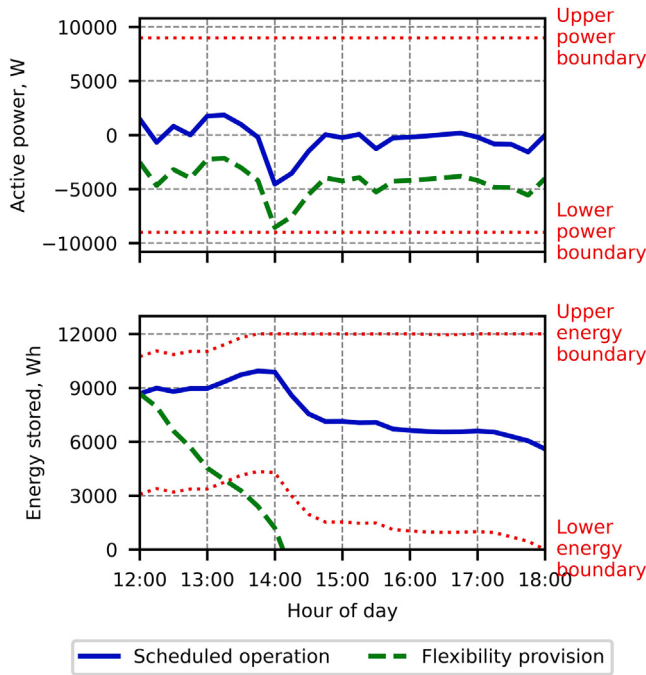


Fig. 8. Graphical presentation of the utilisation of power and energy boundaries for calculating the maximal duration for providing 4000 W of positive flexibility by the BS at 12:00 on April 3rd, 2019. The measured power values of the BS (blue curves) are taken from [48].

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.

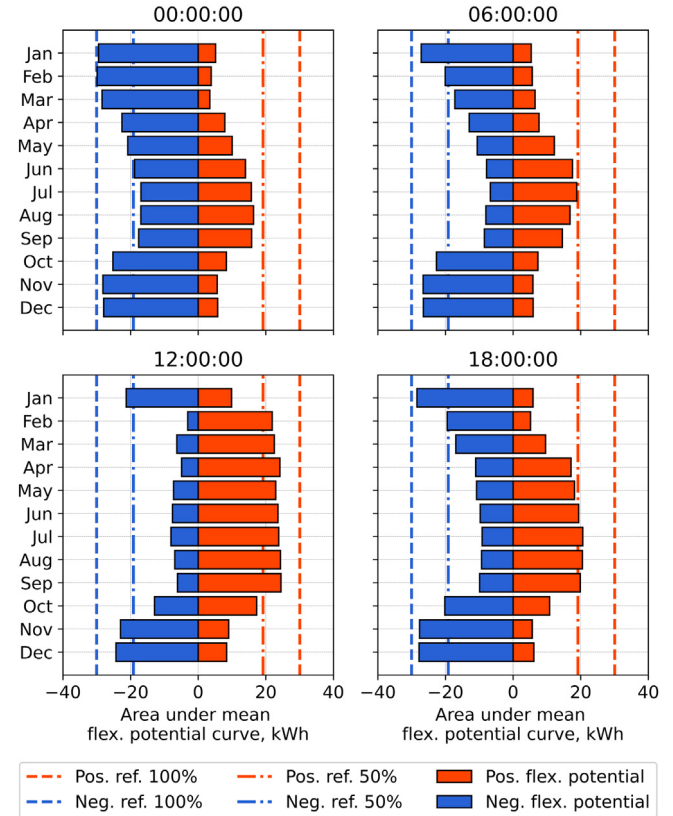


Fig. 9. Area under the monthly mean flexibility potential curves of the BS in “EMS-5” calculated at the time points of 00:00, 06:00, 12:00, and 18:00 for 2019.

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

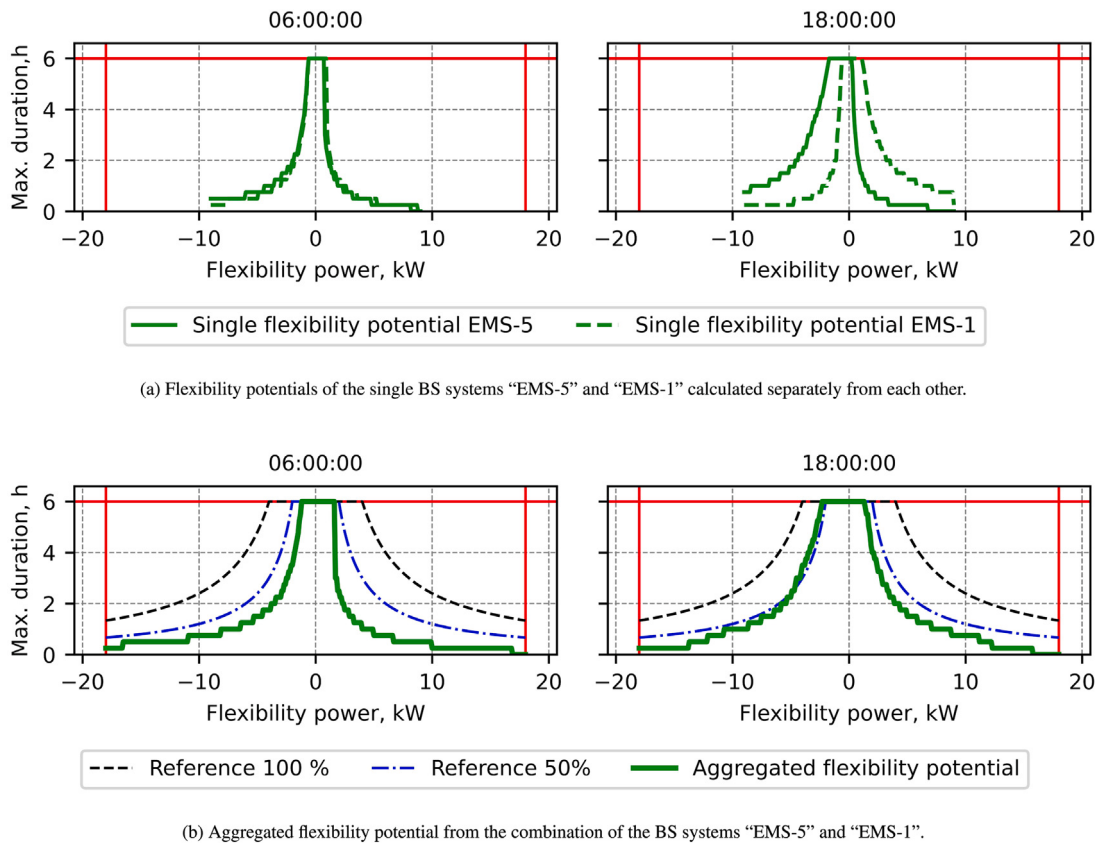


Fig. 10. Flexibility potentials of the BS systems “EMS-5” and “EMS-1” calculated separately from each other (a); and the aggregated flexibility potential that can be provided by both BS systems (b) at points in time 06:00 and 18:00 on April 3rd, 2019.

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 potential 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

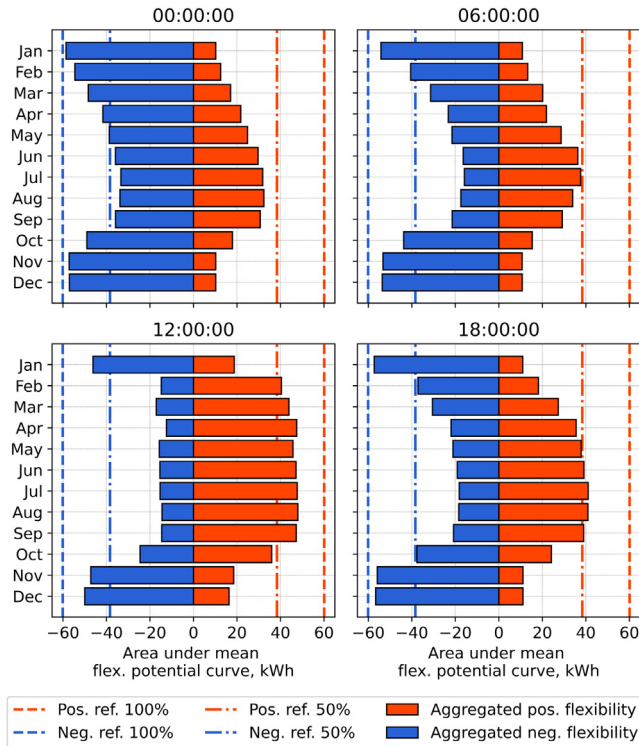


Fig. 11. Calculated area values under the aggregated mean flexibility potential curves of the combination consisting of the two BS systems, “EMS-1” and “EMS-5” in 2019.

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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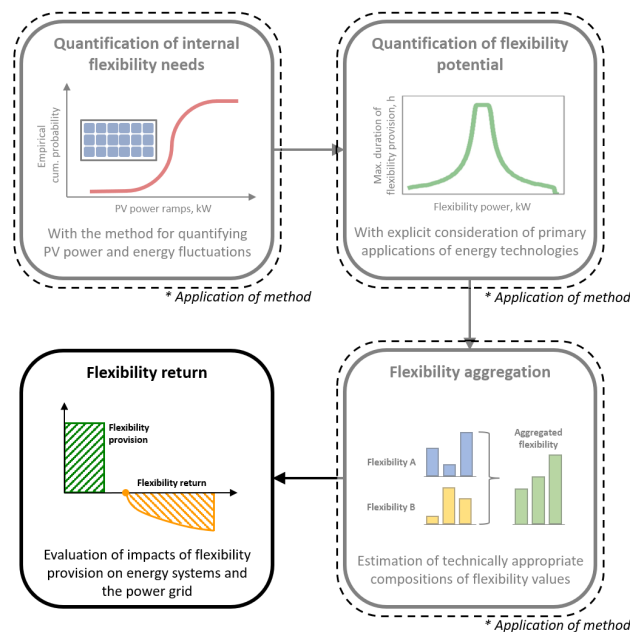
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Chapter 5.

Investigation of full process of flexibility provision

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Specific contributions of N. Maitanova: Investigation; methodology; conceptualisation of flexibility return; data analysis of households, heat pumps, and balancing energy; energy simulations; evaluation and visualisation of results; original manuscript writing.

Article

Investigating the Full Process of Flexibility Provision from Decentralised Energy Systems: From Quantification of Flexibility Potential to the Evaluation of Flexibility Provision Impacts

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Abstract: Although they are primarily installed for specific applications, decentralised energy systems, storage systems, and controllable loads can provide flexibility. However, this varies over time. This study investigates the fundamentals of flexibility provision, including quantification, aggregation, simulation, and impact on energy systems and the power grid. We extended our methods by integrating adjustments to calculate the flexibility potential of heat pumps (HPs) and heat storage (HS) systems, as well as by incorporating variability and uncertainty. The simulations revealed the relevance of energy systems operation to flexibility, e.g., 2 K deviation in HS temperature increased theoretical coverage by 16 percentage points. The results also proved that aggregating multiple systems could obviously enhance their flexibility potential, e.g., six investigated battery storage (BS) systems could have covered up to 20 percentage points more external flexibility requests than any individual unit. The provision of flexibility by decentralised energy systems can lead to energy surpluses or deficits. Such imbalances could have been fully balanced in a system- and grid-oriented manner in 44% of BS simulations and in 32% of HP-HS ones. Overall, the findings highlight the importance of the system- and grid-oriented operation of decentralised energy systems, alongside local optimisation, for a future energy infrastructure.

Keywords: flexibility of heat pumps; integration of uncertainty into flexibility quantification; flexibility provision simulation



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1. Introduction

The transition towards a decarbonised energy supply means a higher penetration of renewable energy systems that entail volatile electricity generation, such as wind turbines and photovoltaic (PV) systems, as well as an increasing ratio of electrification in the heating, cooling, and transportation sectors [1,2]. Nevertheless, the power grid must ensure a reliable and stable energy supply at each point in time despite the fluctuating nature of power generation by volatile renewable energy systems. Therefore, the grid must enhance flexibility by extending the existing portfolio with decentralised flexibility sources, such as integrated energy systems, storage systems, the solutions of demand side management and response, as well as power-to-X-to-power technologies [3,4].

Efforts in pursuit of this objective can already be observed nowadays. Mlecnik et al. [5], for instance, investigated market development in seven European countries and found that the business solutions for providing flexibility from buildings had mostly been developed by the retail industry, energy facilities companies, and aggregators. Since the beginning of 2024, distribution grid operators in Germany have been allowed to temporarily reduce the energy consumption of decentralised energy systems with installed capacities over 4.2 kW in the case of potential grid overloads, as prescribed in §14a of the German Energy Industry Act [6]. Wanapinit et al. [7] estimated that the system-oriented operation

(e.g., based on dynamic electricity prices) of battery storage (BS) systems installed in residential buildings could reduce electricity generation costs by 6% in comparison to operation for self-consumption optimisation. Adding the regional peak reduction as a secondary objective could also improve the loading of infrastructure in both the distribution and transmission grids.

As assumed in [8,9], the future power system may consist of multiple energy cells that can decide autonomously and within specified conditions about the operation of their local energy generators, storage systems, and loads. These energy cells could encompass, for example, residential, commercial and industrial buildings, quarters, city districts, and others, or even components or joined clusters of these. Different energy systems can be installed in energy cells, such as PV-BS systems, heat pumps (HPs), heat storage (HS) systems, combined heat and power (CHP) generators, charging stations for electric vehicles, systems for heating, ventilation and air conditioning, and other units. These systems have concrete primary applications, e.g., energy supply, optimisation of self-consumption, space heating, cooling, water heating, and further needs of energy cell occupants. However, they are technically able to provide flexibility inside and outside their energy cells by changing their initial or scheduled operation. Therefore, these technologies are referred to as *flexibility providers* in this paper.

In our previous study [10], we defined *flexibility* as the ability of energy cells and their components (e.g., power generators, storage systems, cross-sectoral integrated energy systems, and controllable loads) to deviate from optimally scheduled operations for balancing the fluctuations in energy generation and consumption without undermining the primary application of the components. As the overall capabilities of these energy systems are most of the time not fully exploited for their primary applications, we investigate the flexibility that remains after the operation of the energy systems has already been optimised to ensure their primary applications. For example, the operation of HP-HS systems must primarily be scheduled to provide the necessary amount of thermal energy for space and water heating. Then, the remaining capacity of this system to balance further deviations can be offered as flexibility inside or outside of the energy cells. The similar understanding of flexibility as the additional service was described and calculated using the example of BS systems by Tiemann et al. [11]. As the deviations can be presented by both power ramp ups and ramp downs, the flexibility can be distinguished as positive and negative. The need for positive flexibility requires an increase in energy generation or decrease in energy consumption, and the need for negative flexibility can be covered by the opposing actions [10].

The studies [3,12–16] have presented extensive literature reviews regarding energy flexibility, existing methods of flexibility quantification, as well as evaluation metrics. In our previous work [10], we also conducted a literature review concerning existing definitions of flexibility, methods for quantifying and assessing flexibility for general cases, various building types, and different energy technologies. Although the provision of flexibility belongs to the highly researched topics in recent decades, only a few studies have investigated the entire process of flexibility provision, including quantification, aggregation, the simulation of flexibility requests, the consideration of uncertainty, and other procedures. Danner et al. [17] proposed modelling the flexibility power of decentralised energy systems based on PV and load predictions and then aggregating the flexibility power boundaries of all investigated components in the pool. Afterwards, a flexibility request was disaggregated via the iterative assignment of flexibility portions to the most suitable components of the pool. Agbonaye et al. [18] developed and combined two methodologies: one for calculating the flexibility potential of decentralised energy systems and another for estimating flexibility needs from the congestion of transformers, ancillary services, and the dispatch of wind power systems. Furthermore, the authors assessed whether the calculated available flexibility potential coincided spatially and temporally with the estimated flexibility needs of the power grid. Früh et al. [19] investigated an entire process for the coordinated, vertical provision of flexibility from decentralised energy systems connected to distribution grids under consideration of grid constraints. First, they quantified and aggregated the flexibility

potential of the energy systems from the bottom up. Second, they applied a top-down concept to disaggregate the flexibility requests that could be provided by a single energy system. To the best of the authors' knowledge, no methodology has been developed for investigating the influence of flexibility provision on the further operation of decentralised energy systems and power grids if the flexibility is provided as the additional service, i.e., flexibility provision is a secondary (and not mandatory) application of the energy systems.

This study makes the following contributions to the energy flexibility research field: Its first contribution involves integrating specific calculation steps into the existing flexibility quantification method (developed in our previous work [10]) to quantify the flexibility of HP-HS technologies. Its second contribution is the development of an approach for integrating variability and uncertainty into the flexibility quantification method. And the third contribution involves analysing the impact of flexibility provision on the operation of energy cells and the power grid evaluated through the concept of *flexibility return*. To summarise, this study contributes to the research field by providing a comprehensive investigation, quantification, and evaluation of the entire process of flexibility provision based on the example of energy system simulations. To demonstrate the functionality of the developed methods, we calculated the theoretical flexibility potential of multiple decentralised energy systems belonging to diverse technologies and having different applications.

The current study is structured as follows: Section 2 contains the methodology, namely the fundamentals of the flexibility provision process. In Section 3, we present and discuss the results of the case studies to demonstrate the functioning of the proposed methodologies. Section 4 concludes the study and also presents an outlook for future research.

2. Methodology

In this Section, we present the theoretical basics for the entire process of providing flexibility by means of decentralised energy systems installed in energy cells for specific primary applications. This implies that flexibility provision is the secondary (non-mandatory) application of these energy cells components. The complete process of flexibility provision consists of the following procedures: (1) quantifying and aggregating the flexibility potential of different flexibility providers with consideration of local uncertainties, (2) providing the requested amount of flexibility and re-scheduling the operation of energy systems, and (3) calculating the impact of the flexibility provision for future operation of the local energy system and the power grid.

2.1. Quantifying the Flexibility Potential

In our previous work [10], we developed a method for quantifying the flexibility potential of decentralised energy systems that consists of three main calculation steps. These steps were explained in [10] for a general case as well as for a BS. As the heating sector has great potential for providing flexibility to the power grid, numerous studies have proposed frameworks for quantifying and evaluating the flexibility of electricity-based heating systems, e.g., [20–22]. In this study, we extend the existing method of our previous work [10] to quantify the flexibility potential of HP-HS systems. The technology-specific, as well as operational schedule specific steps, for quantifying the flexibility potential of these technologies are explained in the following.

Step 1: Schedule. The operation of HP-HS systems is scheduled to produce the necessary amount of thermal energy, e.g., in a cost-optimal way, in order to ensure comfortable room temperature as well as sufficient hot water volume for building occupants. The input data contain time series with heat demand, scheduled HP electrical power consumption $P_{\text{sched}}(t)$, and energy amount stored in the HS according to the schedule $E_{\text{sched}}(t)$. In addition to that, the technical information of the energy systems is also taken into account, such as the nominal power and coefficient of performance (COP) of the HP, as well as the nominal volume of the HS.

Step 2: Calculation of boundaries. In this step, we propose defining and calculating the boundary values. By *boundary values* we are referring to the ability of the HP-HS

system to deviate from typical or scheduled operation in terms of power and energy for the purpose of flexibility provision without undermining its primary application, namely space and water heating. The boundary for power depends on the nominal electrical power of the HP compressor $P_{HP,nom}$. Therefore, the lower P_{min} and upper P_{max} power boundaries are defined as follows:

$$P_{min} = 0 \quad P_{max} = P_{HP,nom} \quad (1)$$

The boundary for energy consists of the minimal $E_{min}(t)$ and maximal $E_{max}(t)$ amount of energy that must be stored in the HS at time t , so that the heating system can be operated as scheduled until the end of the planning time. Here, planning time refers to a time interval for which the operation of the HP-HS system is scheduled to cover the heat demand. As the flexibility potential is quantified based on whether the heating system can both provide flexibility and cover the heat demand from the given point in time until the end of the planning period, the duration of this period must be defined beforehand.

$$E_{min}(t) = E_{sched}(t) - \min_{\tau \in [t, T]} E_{sched}(\tau) \quad (2)$$

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

where $E_{sched}(t)$ is the scheduled energy amount stored in the HS at time t and Q_{nom} is the usable capacity of the HS.

Similar to our flexibility quantification method, the studies summarised by Wagner et al. [23] also proposed integrating the operational boundaries, amongst other values, in order to mathematically represent the behaviour of energy systems for investigating their optimised operation and flexibility provision.

Step 3: Calculation of the flexibility power and duration. The maximal duration of the flexibility provision dur (P_{flex}) from the HP-HS is equal to the time period in which the new operating power of the HP (the operating power P_{sched} changed according to the flexibility power (P_{flex}) lies within the estimated power boundaries. Additionally, the scheduled capacity $E_{sched}(\tau)$ of the HS, together with additional capacity $E_{flex}(\tau) = \int_0^\tau P_{flex}(t)dt$ for the flexibility provision, must be inside the energy boundaries during this time period. Therefore, the maximal duration of the flexibility provision dur (P_{flex}) is given by

$$\begin{aligned} \max \quad & t \in [0, T] \\ \text{s.t.} \quad & \forall \tau \in [0, t] : P_{min} \leq P_{sched}(\tau) - P_{flex} \leq P_{max} \\ & \forall \tau \in [0, t] : E_{min}(\tau) \leq E_{sched}(\tau) - E_{flex}(\tau) \leq E_{max}(\tau) \end{aligned} \quad (4)$$

The output of the flexibility quantification method consists of two universal dimensions: the flexibility power P_{flex} in kW and the maximal duration dur (P_{flex}) in hours for which this flexibility power can be provided alongside the scheduled operation. The universality of the output enables the application of different metrics to evaluate the flexibility of various energy systems, regardless of their technologies or primary purposes, as well as to compare and aggregate their flexibility values.

2.2. Aggregating the Flexibility Values of Different Technologies

The orchestration of multiple decentralised energy systems for the purpose of combined flexibility provision increases the extent of flexibility potential, i.e., the combination can offer more flexibility in comparison to any single unit within it. The aggregated flexibility potential contains higher flexibility power values for longer periods of time. Moreover, aggregation can smoothen the flexibility potential of multiple energy systems.

In [10], we proposed a method for aggregating the flexibility values of the different energy systems. The main goal of this method was to estimate an optimal combination of energy systems to provide the requested flexibility power for the longest time considering

the technological and schedule-specific characteristics of the energy systems in the combination. The input data include the flexibility power P_{flex} and duration dur (P_{flex}) values of any number of flexibility providers, which are combined for the aggregated flexibility provision. These values are quantified independently for each flexibility provider in the combination using the flexibility quantification method described in the previous subsection.

The output of the flexibility aggregation method consists of aggregated flexibility power and duration, as well as flexibility power values that the components in the combination contributed to the aggregated flexibility. The optimal combination of flexibility values was determined on the condition that the aggregated flexibility power can be provided as long as possible. A detailed explanation of the method for aggregating flexibility values, together with the necessary equations, is provided in our previous study [10].

2.3. Consideration of Local Flexibility Needs

In the current study, we assume that the energy cells reserve their residual load beforehand and strive to follow it. However, the deviations from this residual load occur because of variability in local energy consumption, the volatility of energy generated by the local weather-dependent renewable energy systems, energy forecast uncertainty, the failure of energy systems, etc. We assume that local flexibility providers, such as BS, HP-HS, controllable loads, and others, should strive to balance these local deviations. Therefore, the deviation in the internal power and energy consumption of the energy cell can be understood as *local flexibility needs*.

In general, the local flexibility needs can be presented with power and energy values, as we described in [24]. We propose considering the local flexibility needs by addition/subtraction of their power and energy values from the power and energy boundaries of the flexibility providers estimated in Step 2 of the flexibility quantification method (see Section 2.1). Therefore, the definite amount of power and energy is *reserved* for the case that the energy cells must mitigate their internal unexpected fluctuations, i.e., local flexibility needs.

$$\tilde{P}_{\min}(t) = P_{\min}(t) + |P_{\text{flex.needs}}| \quad \tilde{P}_{\max}(t) = P_{\max}(t) - |P_{\text{flex.needs}}| \quad (5)$$

$$\tilde{E}_{\min}(t) = E_{\min}(t) + |E_{\text{flex.needs}}| \quad \tilde{E}_{\max}(t) = E_{\max}(t) - |E_{\text{flex.needs}}| \quad (6)$$

where $\tilde{P}_{\min}$, $\tilde{P}_{\max}$ present the lower and upper power boundaries, respectively, and $\tilde{E}_{\min}$, $\tilde{E}_{\max}$ the lower and upper energy boundaries with consideration of local flexibility needs. $P_{\text{flex.needs}}$ and $E_{\text{flex.needs}}$ are reserved for balancing the unexpected local fluctuations in power and energy within the energy cells.

As the consideration of the local flexibility needs reduces the distance between lower and upper boundaries, the flexibility potential is quantified within the narrower range of power and energy. Therefore, the integration of the local flexibility needs into the flexibility quantification will cause a decrease in the theoretical flexibility potential that can be offered outside the energy cells.

2.4. Flexibility Provision and Flexibility Return

The flexibility provision of decentralised energy systems may cause energy surpluses or deficits at later points in time. Therefore, the energy systems inside energy cells may not be capable of following their initially scheduled operations and satisfying the needs of the building occupants. In other words, the flexibility provision may bring about negative impacts on energy cells and the power grid, e.g., a lack of thermal energy for space heating in buildings or additional power consumption during times of power grid overload. In order to prevent or minimise these negative impacts on both the local energy system and the power grid, the energy provided as flexibility should theoretically be returned. For instance, after providing negative flexibility by increased power consumption, this additionally consumed energy should be fed back into the power grid and vice versa.

To assess possible strategies for energy return, we propose the following method. The flexibility provision changes the amount of energy stored in the flexibility providers in

comparison to the scheduled operation, e.g., a lower water temperature in HS in the case of positive flexibility provision or a higher water temperature in HS in the case of negative flexibility provision. Therefore, the new values of energy stored in the flexibility provider $E_{\text{new}}(t)$ at time point t can be estimated as follows:

$$E_{\text{new}}(t) = E_{\text{sched}}(t) - E_{\text{flex}}(t). \quad (7)$$

The developed method for flexibility quantification ensures that the operation of the energy systems, together with the flexibility provision, does not undermine the technical and schedule-specific boundaries within the planning time period. For instance, the power and state of charge of the BS must stay within the lower and upper boundaries during the entire planning time period. However, after this time period, the energy amount $E_{\text{new}}(t)$ might undermine the technical boundaries (e.g., nominal capacity of the BS systems) if the operation is not adjusted properly until a certain point in time. Therefore, we define the following:

$$R^-(t) = \text{cummin}\{E_{\text{new}}(t) - E_{\text{min}}, 0\} \quad (8)$$

and

$$R^+(t) = \text{cummax}\{E_{\text{new}}(t) - E_{\text{max}}, 0\}, \quad (9)$$

where $R^-(t)$ denotes the cumulative amount of energy missing at time t in the case of a positive flexibility provision and $R^+(t)$ the cumulative amount of energy exceeding in the case of negative flexibility provision. We term this function the *flexibility return curve*, as it describes the amount of energy that was previously provided as flexibility and should theoretically be returned to or removed from the flexibility provider. Compensating for the energy surpluses or deficits caused by flexibility provision ensures that flexibility providers operate within their technical boundaries, energy cells retain their initially scheduled operations, and additional overloading of the power grid is avoided.

As long as $R^-(t)$ and $R^+(t)$ are equal to zero, the energy deficit or surplus created by the flexibility provision do not negatively impact the operation of flexibility providers. Therefore, the flexibility return is still not mandatory, but possible. If the values of $R^-(t)$ and $R^+(t)$ drop below or rise above zero, the prior flexibility provision starts to bring about an energy deficit or surplus, respectively.

Figure 1 displays the schematic understanding of the flexibility return curve for the example of $R^-(t)$. The top plot presents the amount of energy stored in a flexibility provider during the initially scheduled operation (grey curve) and after the positive flexibility provision (red dashed curve). The middle plot depicts the extent to which the amount of energy in the storage falls below the lower energy boundary caused by the flexibility provision. Moreover, the bottom plot shows the cumulative energy deficit, i.e., the flexibility return curve. According to this figure, all of the energy provided as flexibility should theoretically be returned to the flexibility provider by 18:45.

To clarify, *flexibility return* does not refer to the obligatory physical reversal or withdrawal of the energy previously supplied as flexibility. This is an attempt to investigate and quantify the impact of flexibility provision on the further operation of decentralised energy systems, as well as to illuminate the necessary information for minimising negative impacts on the energy cells and the power grid.

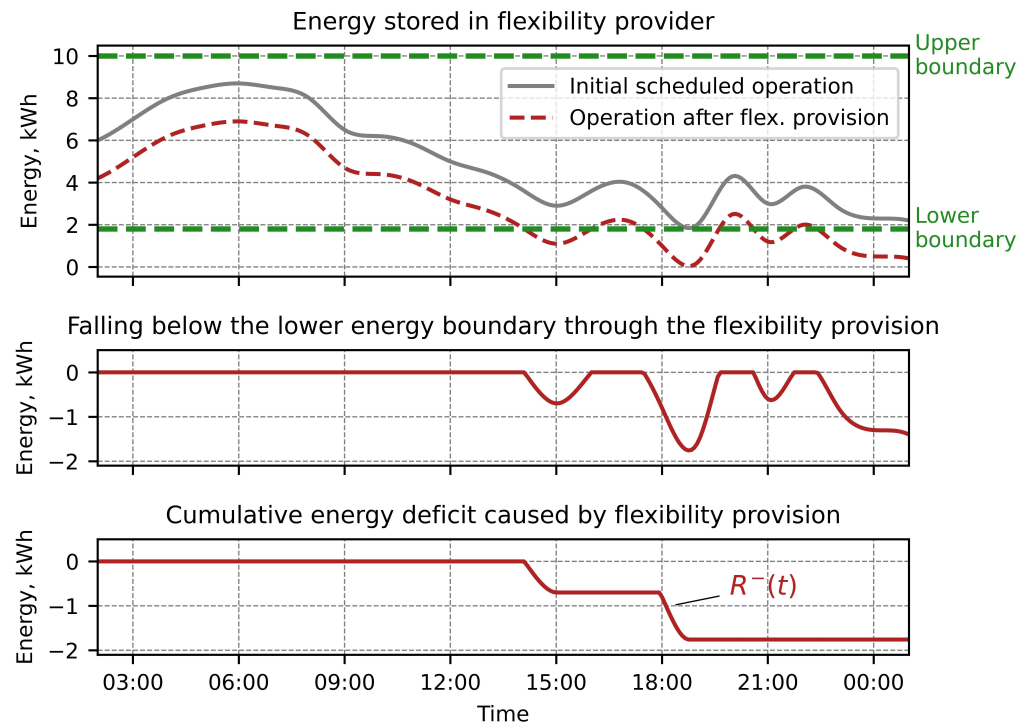


Figure 1. Schematic presentation of the flexibility return curve for the example of $R^-(t)$.

3. Results and Discussion

The functional principle of all procedures within the flexibility provision, together with additional necessary calculations, are demonstrated in the example of HP-HS and PV-BS systems in residential buildings, as well as combinations of these technologies.

3.1. Data

This section describes the input data applied to quantify and aggregate the flexibility potential, as well as to simulate the flexibility provision and flexibility return.

3.1.1. Battery Storage Systems

The open access dataset EMSIG [25] contains the power measurements of eleven households in the DACH region (Germany, Austria, and Switzerland) recorded by home energy management systems from 1 October 2017 to 31 December 2020 with a time resolution of 15 min. The following measured values are included in the dataset: active power output of the PV system, load active power, fed in and drawn active power at the grid meter, charged and discharged active power of the BS, and the state of charge (SOC) of the BS.

All households have an identical BS system, *Fenecon Pro 9–12*, which features a nominal power of 9 kW and usable capacity of 12 kWh to maximise the self-consumption rate of local PV systems. As [25] does not provide the installed capacity of PV systems in the households, we derived these values from the highest measured PV power in the dataset. This value is well-suited for application in the modelling of PV system operation, as well as for making PV predictions, as presented in [26].

For our investigation, we selected six households from the EMSIG dataset in the period from 1 January 2019 to 31 December 2019. One of the main reasons for choosing these households was their negligibly small number of missing values in 2019. The key information about these households is summarised in Table 1. A more detailed description of the dataset can be found in [25].

Table 1. Main information regarding the investigated households with the PV-BS systems in 2019 [25].

	EMS-1	EMS-2	EMS-3	EMS-4	EMS-5	EMS-9
HOUSEHOLD						
Annual energy consumption, MWh	2.63	8.66	5.85	2.95	8.29	13.35
Monthly energy consumption						
- averaged by month, kWh	219.0	721.4	487.6	245.5	691.1	1112.9
- standard deviation, kWh	38.7	154.0	98.7	30.7	273.9	133.3
PHOTOVOLTAIC SYSTEM						
Max. measured power, kW	7.27	13.70	11.69	9.77	11.56	10.64
Annual energy production, MWh	6.92	16.33	13.47	12.11	13.02	12.26

3.1.2. Heat Pumps and Thermal Storage Systems

The historical electrical power consumption of the HPs installed in 38 single-family houses (SFHs) in Northern Germany is collected in a publicly available dataset WPuQ [27]. For our investigations, we selected the measured data of six households with an available time resolution of 15 min. The main reasons for this were that the selected households do not have PV systems and their heat demands were mainly covered by the HP-HS systems, i.e., the HPs provided the required amount of thermal energy either without heating rods or the operation of the heating rods was negligibly low. Another relevant reason was that the measured time series of the selected households only had small amounts of missing values in 2019. Table 2 presents an overview of the annual energy consumption of the households, along with the annual and monthly energy consumption of their heat pumps. Further information about the dataset, as well as descriptions of data acquisition and its validation can be found in [27].

Table 2. Main information regarding the investigated households with the HP-HS systems in 2019 [27].

	SFH-3	SFH-8	SFH-9	SFH-12	SFH-18	SFH-19
HOUSEHOLD						
Annual energy consumption, MWh	2.04	3.21	4.68	2.89	2.95	3.43
HEAT PUMP						
Energy consumption						
- Annual, MWh	2.46	5.46	7.07	2.77	1.97	2.13
- Monthly mean, kWh	204.7	455.1	588.8	231.1	164.5	177.4

3.1.3. Balancing Energy

We use the publicly available statistical data [28,29] and historical values of balancing energy for the year 2019 [30] to estimate the time and power that a single household can theoretically provide as flexibility to the power grid. The balancing energy is distinguished into (+) and (−). The “Balancing energy volume (+)” displays the necessary amount of energy (in MWh) to physically balance the energy deficit in the German transmission system within every 15 min. For instance, in the case of overestimation of the energy feed-in at a given time, the power grid requires more energy feed-in or less energy consumption. The opposite case is the energy surplus in the German transmission system presented by “Balancing energy volume (−)”. For example, in the case of underestimation at the given time interval, the power grid needs less energy feed-in or higher energy consumption [31].

The Federal Statistical Office of Germany counted 40.9 million households in 2019 [28]. According to [29], in 2019 approximately 21% of the households in Germany had at least one of the following flexibility technologies: PV, BS, HP, CHP, solar thermal systems, wood

pellet heating systems, or electric vehicles. In accordance with this information, we assume for our simulations that 21% of German households could theoretically have provided energy flexibility to the power grid in 2019. Drawing on this assumption, together with the historical values of balancing energy, we calculated the flexibility power $P_{\text{flex,household}}$ and energy $E_{\text{flex,household}}$ requested from a single household, i.e., how much flexibility one household could theoretically have provided to cover the needs of balancing energy in 2019:

$$E_{\text{flex,household}}(t) = \frac{E_{\text{balancing}}(t)}{N_{\text{households}} \cdot \%n_{\text{flex.households}}} \quad (10)$$

$$P_{\text{flex,household}}(t) = \frac{E_{\text{flex,household}}(t)}{\Delta t} \quad (11)$$

where $E_{\text{balancing}}(t)$ presents the total balancing energy at the point in time t (from [30]), $N_{\text{households}}$ is the total amount of households, and $\%n_{\text{flex.households}}$ is the share of the households utilising at least one flexibility technology. The total annual sum of the balancing energy, as well as the mean energy per household with at least one flexibility technology are presented in Table 3.

Table 3. Main information regarding the balancing energy in 2019.

	Balancing Energy Volume (+)	Balancing Energy Volume (-)
Total annual sum, MWh	2,077,714	−1,572,785
Mean per household with flexibility technology per year, kWh	241.9	−183.1

Figure 2 displays the calculated balancing power values per household in Germany per 15 min. In Figure 2 we do not recognise any pattern, such as the daily or seasonal dependency of the balancing power per household calculated using the historical measured values. The calculated balancing power per household, both (+) and (−), is in the range between −300 W and 300 W, apart from three outlier days in June 2019 when the values reached almost 900 W. In order to avoid possible confusion in understanding of the figure, we confirm that the balancing power (+) and balancing power (−) did not occur at the same time. Each time point contained either a single value of balancing power ((+) or (−)) or no value (no balancing energy was required). To demonstrate that, we inserted the bottom sub-plot in Figure 2, which displays the balancing power per household on a single day, 15 March 2019.

The historical balancing energy was chosen for the calculation of the balancing power per household because these values present the actual physical imbalance caused by the overestimation or underestimation of energy generation and consumption in the German power grid. As these amounts of energy were actually missed or exceeded, they had to be balanced by the available flexibility sources.

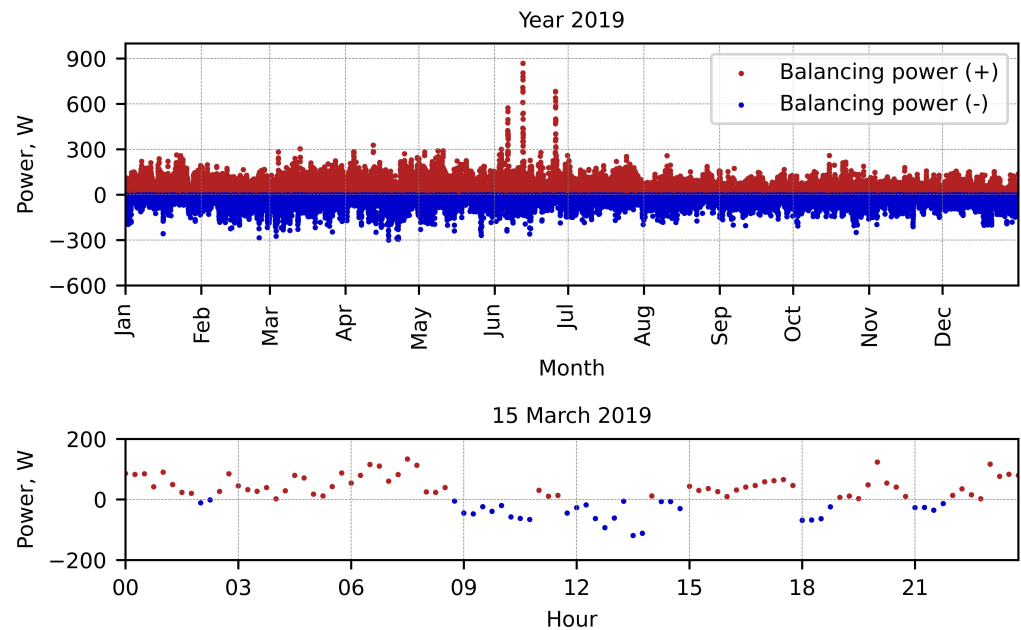


Figure 2. Balancing power (+) and (−) per single household with at least one flexibility technology for the entire year of 2019 (top sub-plot), and for one day 15 March 2019 (bottom sub-plot). All values were calculated using the historical balancing energy for the year 2019 [30].

3.2. Flexibility Quantification

In our previous work [10] we demonstrated the developed method for quantifying flexibility in residential buildings with PV-BS systems. In this study, we applied the developed method to quantify the flexibility potential of HP-HS-systems in selected households that could also have provided it additionally to their operations in 2019.

The **first step** in the proposed flexibility quantification method prescribes scheduling the operation of the decentralised energy systems to cover the needs of building occupants. The original time-series with electrical power consumption of the HPs from [27] were used to derive the time-series with thermal power required for heat demand of the selected households (see Table 2). As the historical power measurements reflect the operational fluctuations of the heat pumps under real-world conditions, we assume that the derived heat demand also includes the corresponding kind of variability. This generated heat demand data were then applied to simulate the optimal operation of the HP-HS systems in the selected households using a generic MTRESS model [32,33].

These newly generated data contain time-series of the household heat demand, operating electrical power of the HPs, thermal power flow between HP and HS, as well as the amount of thermal energy stored in the HS systems at each point in time. The thermal energy stored in the HS was calculated using the difference between the flow and return temperatures. In the simulations of the scheduled operation (without flexibility provision), we defined that the nominal difference between the flow and return temperatures in the HS must not exceed 10 K, i.e., during the operation without flexibility provision the maximal nominal flow temperature was set to 40 °C and the return temperature to 30 °C.

In the **second step** of the method for quantifying flexibility, we defined and calculated the power and energy boundaries of the HP-HS systems. The lower power boundary of these systems is equal to zero and the upper power boundary to 4.5 kW_{el} (set nominal power of the HP compressor). These power boundaries remain stable during the quantification of the flexibility potential of the HP-HS systems for the entire year of 2019. In comparison to that, the lower and upper energy boundaries should be calculated anew at all points in time for the planning period, the duration of which was set to six hours. However, this value is a free variable and can be changed according to the users of the flexibility quantification method.

In order to enable the simulation of the flexibility provision, we assumed that the HS was allowed to deviate by up to 5 K from its nominal temperature levels. In this case, the flow

temperature in the HS could reach a maximal value of 45 °C during the provision of negative flexibility, and the return temperature was allowed to cool down to 25 °C during the provision of positive flexibility. The additional energy corresponding to the allowed temperature deviation in the HS was considered in the calculation of the energy boundaries, as well as in that of the amount of energy stored in the HS during and after the flexibility provision.

In the **third step** of the flexibility quantification method, we calculated the maximal duration for providing the flexibility power values. In order to investigate the entire flexibility potential of the HP-HS, we defined a range of positive and negative flexibility power values. The following range was defined $P_{\text{flex}} \in [-4500, 4500]$ with a step of 100 W, where -4500 W was the maximal negative flexibility power and 4500 W the maximal positive flexibility power. We estimated the maximal duration of the flexibility provision for each flexibility power value in this range. Firstly, we calculated the new power values of the HP and new value of energy stored in the HS in case of deviation from the operation for the purpose of flexibility provision. Secondly, we determined that these new power and energy values lay between the lower and upper boundaries at each point in time over the subsequent six hours. Otherwise, the flexibility could not be provided. The flexibility potential was calculated for every 15 min time interval independently of each other.

To highlight, the primary objective of power and energy boundaries is to ensure the secure operation of energy systems, thereby meeting the needs of building occupants. As long as the flexibility potential is calculated within these boundaries, occupants will not experience any negative impact from flexibility provisions. In case of undermining the boundaries, the flexibility potential at that point in time is considered to be zero.

As the decentralised energy systems have different primary applications and can provide flexibility solely as an additional service, these systems feature a time-varying flexibility potential. In Figure 3, the daily variations in flexibility potential are presented for the example of the HP-HS system in “SFH-19” for two different times, 00:00 and 10:00, on 24 January 2019.

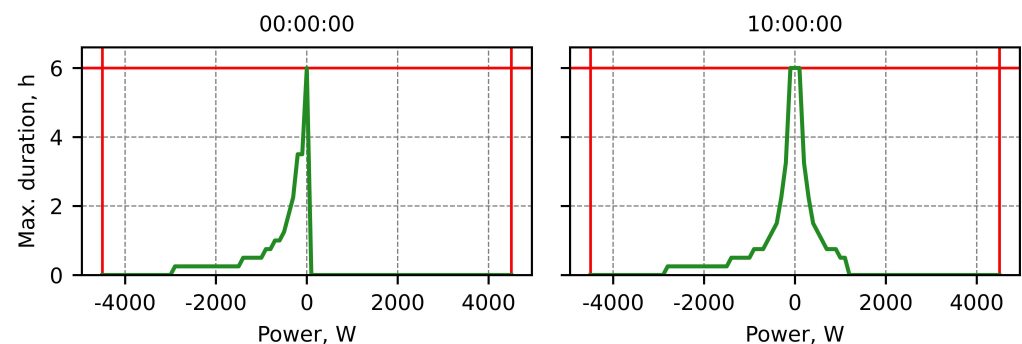


Figure 3. Duration of different positive and negative flexibility power values in “SFH-19”, i.e., flexibility potential curves, at 00:00 and 10:00 on 24 January 2019.

The green curves in Figure 3 represent the flexibility potential for the entire flexibility power range at the given points in time. The vertical red lines correspond to the power boundaries, and the horizontal red line depicts the planning time of 6 h. At midnight on 24 January 2019, the HP-HS system in “SFH-19” could have almost solely provided the negative flexibility by additional increase of the HP electrical power. At 10:00 on the same day, this HP-HS system could have provided approximately similar amounts of positive and negative flexibility. The current operating mode of the HPs and energy amount stored in the HS systems have a strong influence on the flexibility potential.

In addition to daily variations, the HP-HS systems in the observed households also have seasonal variations in their flexibility potential. Figure 4 presents the maximal flexibility power that the HP-HS system in “SFH-19” could have provided as flexibility at each time point in 2019 for the maximal duration of 15 min.

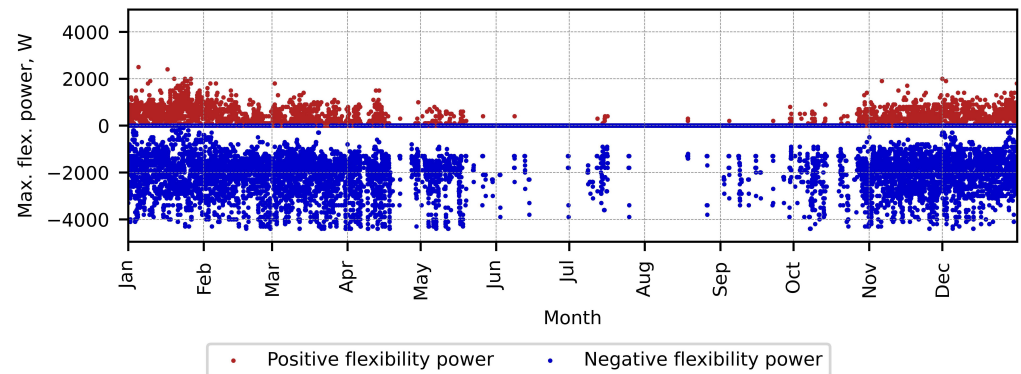


Figure 4. Maximal flexibility power values that the HP-HS in “SFH-19” could have provided for the maximal duration of 15 min at each time point in 2019.

Each point in time in Figure 4 has two values indicated by two dots: the red dots correspond to the maximum positive flexibility potential, whereas the blue ones represent the maximum negative flexibility potential for the 15 min period. However, the flexibility potential also includes the intermediate power values between zero and the calculated maximum. For example, the calculated maximal power of the positive flexibility at 1000 W can be interpreted as the HP-HS system having theoretically reduced its power consumption by a value between 0 W and 1000 W for the purpose of positive flexibility provision.

The annual mean of all maximal positive flexibility power values during the heating period (from January to April and from October to December) was equal to 150 W for the maximal duration of 15 min. Over the same period of time, the annual mean of all maximal negative flexibility power values was much higher, at 1800 W. Thus, the HP-HS system in the selected household had much higher negative flexibility potential than positive. In other words, the flexibility potential could have been provided more frequently by switching on the HP.

Based on the flexibility potential curves for each point in time of the year 2019, we calculated the monthly mean flexibility potential curves for the selected points in time (00:00, 06:00, 12:00, and 18:00) independently from each other. The area under these monthly curves was then calculated using the trapezoidal rule (see Figure 5). The values of the area under the monthly mean flexibility potential curves demonstrate both the daily and seasonal variations in the flexibility potentials.

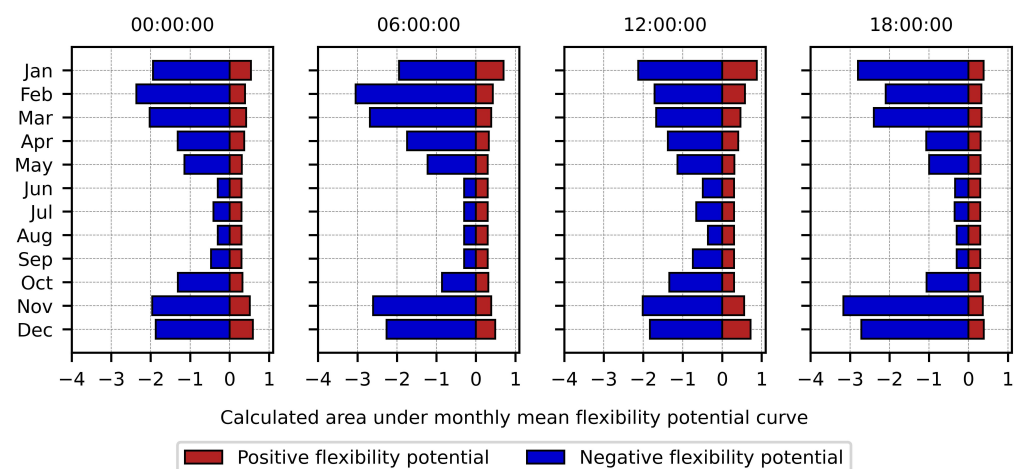


Figure 5. Area under the monthly mean flexibility potential curves of the HP & HS in “SFH-19” calculated at the time points of 00:00, 06:00, 12:00, and 18:00 for 2019.

Similarly to Figure 4, the calculated area values under the mean flexibility potential curves demonstrate that the HP-HS system in “SFH-19” could have provided more negative

flexibility than positive in 2019. Furthermore, the calculated flexibility potential in the colder months is higher than in warm ones, as the HP-HS systems were operated more frequently and intensively in the months with lower outside air temperatures to generate a sufficient amount of thermal energy for comfortable room temperature. As the investigated household had almost no heat demand in the warmer months, the HP-HS system was operated very rarely. In this regard, the flexibility potential during this time period was much lower. The HP-HS systems with another operational mode, such as for the provision of space and water heating as well as cooling, could have been operated during the entire year. Therefore, these systems could have had higher flexibility potential during the warm season.

3.3. Flexibility Aggregation

In this section, we demonstrate the flexibility aggregation method and describe the results of aggregating the flexibility potential values from two different technologies: BS and HP-HS. For this purpose, we selected a household “EMS-1” with a PV-BS system from [25] and a household “SFH-19” with an HP-HS system from [27]. These two households were selected for the flexibility aggregation case study, because based on data analysis we assumed that “EMS-1” did not have an electricity-based heating system, and that HP-HS system in “SFH-19” was operated primarily during the cold season. These two decentralised energy systems were therefore taken to belong to different technology categories, and to have different primary applications, technical characteristics, and operational schedules.

For the annual evaluation of the aggregated flexibility potential, we calculated the maximal aggregated flexibility power that the BS in “EMS-1” and HP-HS system in “SFH-19” could have provided together at each point in time for the maximal duration of 15 min in 2019. Figure 6 presents the mean weekly percentage contributions of the BS and the HP-HS system (top and bottom sub-plots) to the aggregated flexibility, as well as the maximal aggregated flexibility power that this combination could have provided at each point in time in 2019 for the maximal duration of 15 min (middle sub-plot).

Figure 6 shows that the BS system in “EMS-1” could have made much higher contributions to the aggregated flexibility potential, both positive and negative. The HP-HS system in “SFH-19” could have mostly influenced the aggregated negative flexibility in the cold season, when the heating system was operated much more intensively. Therefore, the aggregated negative flexibility potential during the cold season was higher than in the warm season. Almost all missing values of “EMS-1” occurred in the first, second, and fourth weeks of January, as well as the second week of February 2019. Therefore, the aggregated flexibility potential in these weeks was lower than in other cold months, and the HP-HS system has exhibited a higher contribution to the aggregated flexibility potential in these weeks. The mean annual contribution of the BS to the aggregated positive flexibility potential was 96.4% and to the aggregated negative flexibility potential it was 85.1%. The mean annual contribution of the HP-HS to the aggregated positive flexibility potential was 3.6% and to the aggregated negative flexibility potential it was 14.9%. The presented case study shows that the proposed method of flexibility aggregation can be applied to orchestrate different technologies for the joint flexibility provision.

One of the main goals of the flexibility aggregation is to increase flexibility power. The aggregated flexibility power from the combination of n flexibility providers should be higher than the flexibility power of each component participating in the flexibility provision. In addition, the flexibility aggregation method used in this study aims to identify the most optimal combination of available flexibility providers belonging to different technology types. Only the flexibility providers with available flexibility potential are included in the combination, and the participating flexibility providers are not obliged to contribute with equal power values to the aggregated flexibility. Therefore, each flexibility provider offers the flexibility potential that coincides with its schedule, as well as with the needs of the building occupants.

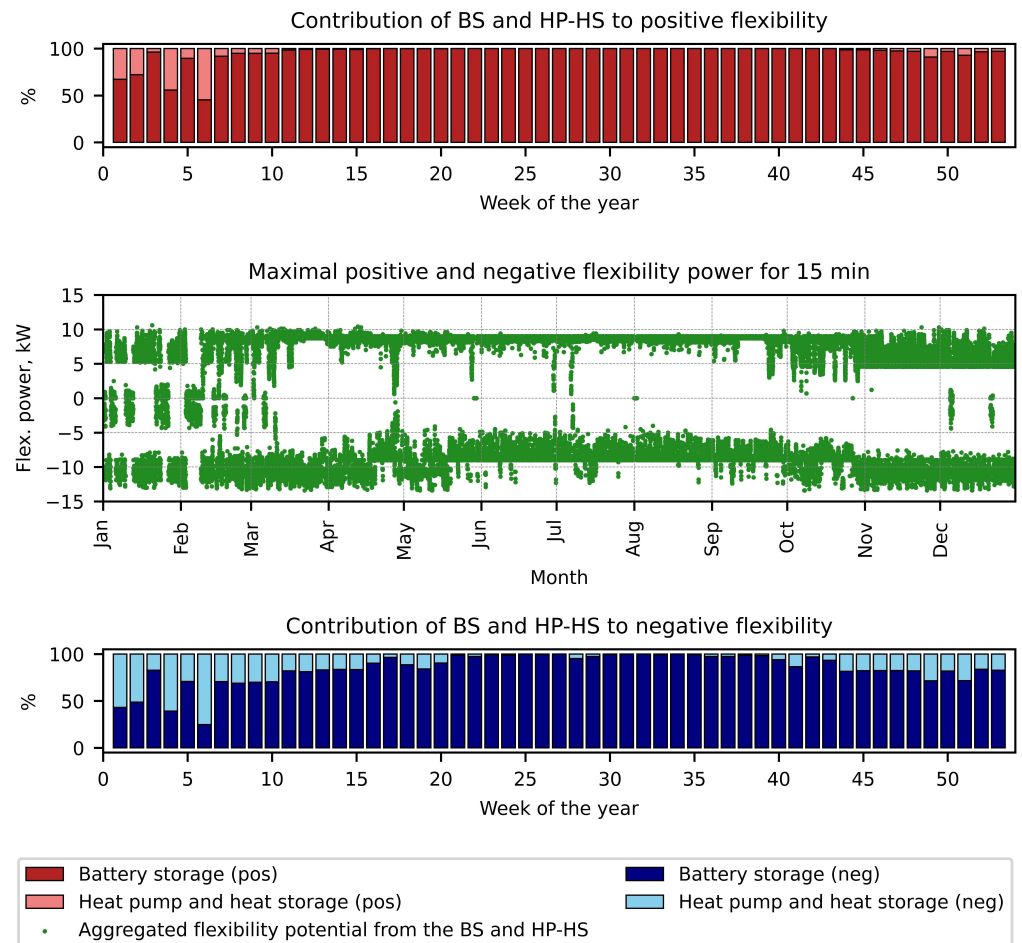


Figure 6. Maximal aggregated flexibility power values that the HP and HS in “SFH-19” and BS systems in “EMS-1” could have provided together for the maximal duration of 15 min at each point in time in 2019.

The flexibility aggregation case study revealed that the contribution of the selected HP-HS system to aggregated flexibility was relatively low. However, investigating and quantifying the flexibility potential of this technology remains highly relevant, as the number of installations is substantial and is expected to grow in the future. For example, in 2019, HPs were installed in 7% of German households, while BS systems were present in 2% [29]. By 2023, the share of households with HPs and BS systems had increased to 10.3% and 3.6%, respectively [34]. Furthermore, HP-HS systems can be incorporated to provide flexibility in cases when only this decentralised energy technology is available in the energy cells.

Nowadays, the majority of decentralised energy systems are operated to optimise the consumption of the buildings where these units are installed, e.g., the charging and discharging of the BS systems is scheduled to maximise the self-consumption of local PV systems. However, this kind of operation does not coincide with the requirements of the power grid and system balance, and it can even have negative impacts on them, such as overloading and increasing power grid and system costs [35,36]. Therefore, operation of decentralised systems in the future should consider both the local requirements as well as those of the power grid and system balance. Combining the high number of flexibility providers belonging to different technologies for joint flexibility provision can make a positive contribution to this goal.

3.4. Integration of PV Variability and Uncertainty into Flexibility Quantification

The next step in this investigation was to incorporate uncertainty into the flexibility quantification process. As we assume that local uncertainties should first be managed by available local flexibility providers, these uncertainties can also be interpreted as local needs for flexibility (see Section 2). In this case study, we demonstrated how to integrate these local flexibility needs into our developed flexibility quantification method using PV systems as an example. The local flexibility needs of PV systems are represented by unexpected power and energy fluctuations due to the variability and uncertainty inherent in their weather-dependent energy generation. In our previous study [24], we developed a framework for quantifying the power and energy fluctuations of any PV system using its historical power values. In this study, we integrated this framework into the method for quantifying the flexibility of energy cells.

First, we drew on the historical measured power values of PV systems from [25] to calculate the PV power ramps and build the cumulative empirical distributions of these. We assumed that 90% of these power fluctuations should first be balanced locally. By σ_5 and σ_{95} , we denoted the 5% quantile and the 95% quantile, respectively. Thus, at each point in time the system should be able to balance the power fluctuation within the interval $[\sigma_5, \sigma_{95}]$.

The results of this calculation are presented in Table 4, and can be interpreted as the power values of the local flexibility needs caused by the variability of the PV systems. Afterwards, $P_{\text{flex.needs}}$ were integrated into the calculation of lower and upper power boundaries of any flexibility provider using Equation (5). For example, 90% of the power ramps of the PV system in the household “EMS-5” lay in the range between -1.2 kW and 1.2 kW. Therefore, we assigned the value of 1.2 kW as the power value of the local flexibility needs caused by the PV system installed in this household.

Table 4. Calculated power values of the local flexibility needs caused by PV variability.

	EMS-1	EMS-2	EMS-3	EMS-4	EMS-5	EMS-9
Max. PV power, kW	7.3	13.7	11.7	9.8	11.6	10.6
P of local flex. needs $ P_{\text{flex.needs}} $, kW	0.8	1.9	1.4	1.3	1.2	1.2
Net power boundary $ P_{\text{max}} $, kW	8.2	7.1	7.6	7.7	7.8	7.8

We utilised global horizontal irradiance (GHI) data from Solcast [37] to predict the energy output of the PV systems using linear regression. This prediction contained a time series with the expected energy generation of these PV systems throughout 2019. Next, we calculated the absolute difference between the predicted and actually measured energy values at each time point during the year. We then averaged these absolute differences over the same points in time for the previous N days. In this study, we suggest that these average values represent the energy of local flexibility needs $E_{\text{flex.needs}}$ due to the uncertainty in PV systems. The relevant equation is presented below:

$$E_{\text{flex.needs}}(t) = \frac{1}{N} \sum_{n=1}^N |E_{\text{pred}}(t - n \cdot 24 \text{ h}) - E_{\text{meas}}(t - n \cdot 24 \text{ h})| \quad (12)$$

where $E_{\text{meas}}(t)$ and $E_{\text{pred}}(t)$ are the measured and predicted energy of the PV system at time t . To calculate $E_{\text{flex.needs}}$ for each point in time during the year, we used the absolute difference values between E_{pred} and E_{meas} at the same time as the previous five days, i.e., $N = 5$. For example, the energy value for local flexibility needs at 10:00 AM on 6 February 2019 was calculated by averaging the absolute difference values from the same time over the previous five days, specifically from 1 February 2019 to 5 February 2019. In this case, we considered the short-term weather trends and local site characteristics, but avoided consideration of long-term weather impacts over different seasons.

For demonstration purposes, Figure 7 displays the energy values of the local flexibility needs caused by the prediction uncertainty of the PV system in “EMS-1” in 2019. Each orange dot displays the corresponding energy of the local flexibility needs at the given point in time, which was calculated by averaging the absolute difference values between prediction and measurement at the same time for the previous five days. These $E_{flex.needs}$ values were integrated into the flexibility quantification method by subtracting them from the upper energy boundary and adding them to the lower one at each point in time, as described in Section 2.3. As is shown in Figure 7, the energy values exhibit a strong seasonal dependency. For example, during winter, when PV power generation is lower, the energy values for flexibility needs were expected to be much lower compared to those in summer.

The inclusion of the power and energy fluctuations of PV systems in calculating the flexibility boundaries can be seen as the local flexibility provider setting aside a specific amount of power and energy to handle unexpected changes in local energy generation and consumption. On the one hand, considering local flexibility needs reduce the interval between the lower and upper boundaries, this in turn decreases the amount of theoretical flexibility potential available to meet external flexibility requests. On the other, it can keep the energy cell (e.g., city district) within its planned residual load, thereby avoiding additional costs and preventing potential overload of the local power grid. This operation of energy cells can be viewed as the system- and grid-oriented operation, which is essential for the future energy infrastructure.

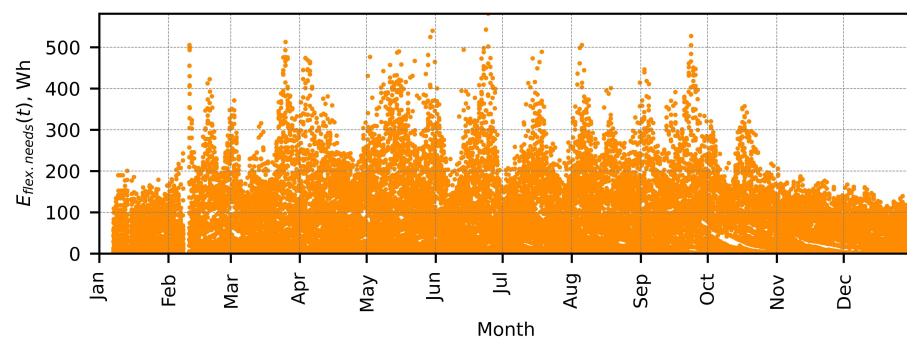


Figure 7. Energy values of the local flexibility needs caused by the prediction uncertainty of the local PV system in “EMS-1”.

3.5. Flexibility Provision

In the next phase of our research, we simulated how the investigated energy systems could respond to flexibility requests from external entities, such as public utility companies or distribution grid operators. We derived these requests from the balancing power per household outlined in Section 3.1.3. Specifically, we treated this balancing power as a flexibility requested from an individual household, where it deviates slightly from regular operation. At each point in time, we simulated whether the investigated BS and HP-HS systems could have met the corresponding flexibility request, i.e., balancing power per household at this point in time, without exceeding their power and energy boundaries during the planning period. For each simulation, the ability to provide balancing power was evaluated independently of other time points. This means that we assumed that the energy systems were operated according to their schedules before the flexibility requests were made.

We evaluated the simulation results using a metric called *theoretical coverage*. This metric quantifies the percentage of time points during which the analysed energy system could reliably provide balancing power as a flexibility for a maximum duration of 15 min, without exceeding its power and energy boundaries. Table 5 presents the annual theoretical coverage values of the BS systems with and without considering PV variability and uncertainty. The columns with household labels contain the theoretical coverage values of the single BS unit belonging to that household. The column “all” contains the theoreti-

cal coverage in the case of combining six BS systems to provide sixfold balancing power per household.

As can be seen in Table 5, the individual BS systems (without consideration of local flexibility needs) could theoretically have covered approximately 60% of the balancing power values. The portions of positive and negative flexibility needs that can be covered by the BS systems are also approximately equal to each other.

As anticipated, considering the uncertainties in flexibility quantification reduced the overall external flexibility potential. Table 5 shows that setting aside a portion of power and energy to address potential local fluctuations in PV output led to a decrease in the average theoretical coverage values. The BS systems with consideration of the PV variability and uncertainty could have met about 15 percentage points less potential external flexibility requests in comparison to the BS systems without that consideration.

Table 5. Theoretical coverage of the balancing energy by private households with PV-BS systems with and without consideration of the variability of PV systems.

	EMS-1	EMS-2	EMS-3	EMS-4	EMS-5	EMS-6	all
Theoretical coverage without considering PV variability and uncertainty							
Total, %	63.9	57.4	53.7	66.6	59.2	44.7	72.3
Pos. balancing power, %	69.8	54.4	59.5	81.0	57.8	25.5	75.9
Neg. balancing power, %	57.1	60.8	47.1	50.0	60.8	66.8	68.2
Theoretical coverage with considering PV variability and uncertainty							
Total, %	39.4	26.4	27.1	39.7	31.6	12.1	41.2
Pos. balancing power, %	36.0	21.7	24.4	38.0	25.8	3.5	37.3
Neg. balancing power, %	43.4	31.9	30.3	41.6	38.4	22.0	45.8

Aggregating six BS systems to provide the sixfold flexibility indeed enhanced their theoretical coverage. Specifically, this combination could have met almost 62% of the balancing power values when local flexibility needs were considered, and 83% when they were not. However, this aggregation could still not have covered the full range of requested balancing power values, despite the combined power of the six BS systems being significantly greater than the total balancing power required. The primary reason for this was the timing mismatch between the available flexibility potential of the BS systems and the requested balancing power. The timing mismatch means that the energy systems cannot provide flexibility at the times of the flexibility requests without undermining their primary applications. We assumed that the investigated BS systems were optimised to maximise the self-consumption of PV power, which did not always align with the external flexibility needs based on historical balancing energy.

The same simulation and evaluation were repeated for the HP-HS systems. The theoretical coverage of these was investigated for three levels of temperature deviations in the HS systems, and the results are presented in Table 6. The theoretical coverage values of the individual HP-HS units are presented in the columns with household labels, and the theoretical coverage of six HP-HS systems in the column “all”. The common operation of the HP-HS systems (without flexibility provision) was simulated under the condition that the flow temperatures could not exceed 40 °C and the return temperatures could not fall under 30 °C. For the simulation of the flexibility provision (especially in the calculations of thermal energy stored in HS as well as in that of the energy boundaries), we assumed that the flow and return temperatures were allowed to deviate from their nominal values by up to 5 K. For example, in the case of 2 K deviation, the HS systems were allowed to increase their flow temperatures to 42 °C—while increasing the losses of the HS—and decrease their return temperatures until 28 °C—while reducing the efficiency of the HP—for the purpose of flexibility provision.

Allowing the HS systems to deviate from the nominal flow and return temperatures by up to 2 K led to a notable increase in the average theoretical coverage, improving it by approximately 16 percentage points compared to operations that did not allow deviation. Nevertheless, additional increases in the allowed deviation did not result in further improvements in the theoretical coverage values. The results from all three HP-HS simulations (with deviations by 0 K, 2 K, and 5 K) show that the investigated HP-HS systems were more effective at covering negative balancing power compared to positive balancing power. However, increasing the allowed temperature deviation had a stronger effect on improving the theoretical coverage for positive balancing power.

A central finding of the flexibility provision simulations was a significant increase in the flexibility that could have been provided by the combination of six BS systems or six HP-HS ones in comparison to single units. In other words, six investigated BS and HP-HS systems could have theoretically met more external flexibility requests derived from the balancing energy in comparison to the single units. Moreover, the results of the flexibility simulations confirmed that the operation of decentralised energy systems has a relevant influence on flexibility potential.

Table 6. Theoretical coverage of balancing energy by the private households with heat pumps together with thermal storage systems.

	SFH-3	SFH-8	SFH-9	SFH-12	SFH-18	SFH-19	all
Theoretical coverage at no deviation from nominal temperature difference							
Total, %	33.7	42.0	39.4	30.5	35.6	28.2	42.5
Pos. balancing power, %	6.5	8.5	7.4	4.3	7.5	5.3	9.8
Neg. balancing power, %	65.2	80.7	76.3	60.7	68.0	54.6	80.2
Theoretical coverage at deviation of 2 K from nominal temperature difference							
Total, %	43.0	69.0	70.4	42.6	44.9	39.1	65.8
Pos. balancing power, %	23.1	48.6	55.6	25.9	24.7	25.4	47.0
Neg. balancing power, %	66.0	92.6	87.6	61.9	68.3	54.8	87.5
Theoretical coverage at deviation of 5 K from nominal temperature difference							
Total, %	43.2	72.2	72.1	42.6	45.0	39.1	67.5
Pos. balancing power, %	23.2	50.5	56.9	25.9	24.7	25.4	48.1
Neg. balancing power, %	66.2	97.2	89.7	61.9	68.4	54.8	90.0

The aim of using the historical balancing energy values was to integrate the external requirements into the flexibility provision simulations. The results of the simulations confirmed once again that decentralised energy systems should be operated with consideration of both the local requirements and those of the power grid and system balance. Aggregating the flexibility of a large number of different energy systems can support this intention.

3.6. Flexibility Return

We investigated the influence of flexibility provision on the following operation of energy cells and the power grid with the help of the term *flexibility return* (see Section 2.4). For this purpose, we defined the external flexibility requests with longer durations and simulated the flexibility provision for these. For the definition of a flexibility request, we first selected the highest absolute value of balancing power per day and time t_0 of its occurrence. Then, we determined the time frame for flexibility provision $[t_0 - \Delta_-, t_0 + \Delta_+]$ such that all balancing power values in this interval had the same sign as the balancing power value at t_0 . This time frame was limited to two hours and Δ_- and Δ_+ was at most one hour. We repeated this procedure for all days of the observed year of 2019.

First, we applied the flexibility quantification method to confirm that the investigated decentralised energy systems could have provided the required flexibility without undermining their power and energy boundaries over the next 6 h. If this condition was met,

we then simulated the flexibility provision and corresponding deviation of these energy systems from the initial operation. Finally, we calculated the flexibility energy return curves as described in Section 2.4.

The operation of the energy systems in the following 24 h after flexibility provision was taken into account in the calculation of flexibility energy return curve. In this way, we intended to quantify the potential impacts on energy systems and households caused by deviation from their scheduled operation for the purpose of flexibility provision. For instance, because of the positive flexibility provision and resulting energy deficit in the BS system, the household load could not have been covered by the BS as initially planned. In addition, we also integrated the requirements of the surrounding energy system or power grid into the flexibility return quantification. In the worst case, the flexibility provision at a current point in time could lead to an additional system requirement in the future, such that the flexibility provider would not actually cover the need for flexibility but rather postpone it until later. For example, providing positive flexibility at a given point in time could cause higher energy consumption from the power grid later. In order to quantify the potential influence of flexibility provision on the power grid, we extended quantification of the flexibility return by inserting the balancing power per household into the calculations. For the flexibility return, we considered the balancing power values with a sign opposite that of the flexibility power provided. In this way, we attempted to quantify the possible negative effects on the power grid, as well as to make the entire process of flexibility provision more grid- and system-oriented. To summarise, the resulting flexibility return time series was created using both the time series with the operation of the decentralised energy systems and that with the balancing power per household in the following 24 h after the flexibility provision.

For the purpose of better understanding, we demonstrate the simulation results of the flexibility provision and return on the example of the BS system in “EMS-1” on 31 January 2019–1 February 2019. The historical operation of this BS system in the observed period of time can be derived from the scheduled SOC curve represented by the solid grey curve in Figure 8. The green dashed line indicates the minimum SOC value below which the BS cannot be discharged. According to the simulation, the BS received a request to provide 306.7 Wh of positive flexibility from 15:15 until 17:15. As the BS could have provided this required flexibility and kept its scheduled operation in the subsequent 6 h (according to the flexibility quantification method), we simulated the flexibility provision. However, the latter could have caused the energy deficit in the BS system in the following 24 h after the flexibility request, i.e., the SOC fell below its minimal value at 06:00 on 1 February 2019 (see the red dashed curve in Figure 8). Therefore, the energy deficit should theoretically be balanced until this point in time. Otherwise, the BS would not have sufficient energy to cover the household load, which would in turn consume more energy from the power grid.

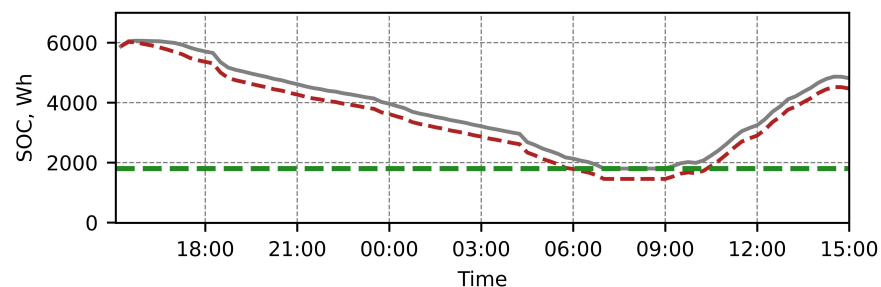


Figure 8. SOC values of BS in “EMS-1” in the case of scheduled operation (grey curve) and flexibility provision (dashed red curve) on 31 January 2019–1 February 2019.

We calculated two energy curves, one being a cumulative energy deficit in the BS system in the 24 h following positive flexibility provision, and another being a cumulative available negative balancing energy per household in the following 24 h. Both curves are displayed in Figure 9.

Figure 9 shows that within the observed time period, the available negative balancing energy per household occurred before the critical time point at 06:00. Therefore, the energy deficit could theoretically have been balanced by providing this negative balancing power. Based on these two energy curves, we calculated the power values of the possible flexibility return considering both the operation of BS and the need for balancing power in the following 24 h. The power curve of the flexibility provision by the BS system in “EMS-1”, as well as the power curve of the flexibility return, are presented in the top subplot in Figure 10. The power curve of the flexibility provision (red solid curve) corresponds to the positive flexibility request that was defined as described at the beginning of this Section. The power curve of the flexibility return (blue dashed curve) was calculated considering the operating power of the BS and the available negative balancing power per household. As can be seen, the flexibility return curve includes power values with a sign opposite the power values of the flexibility provision.

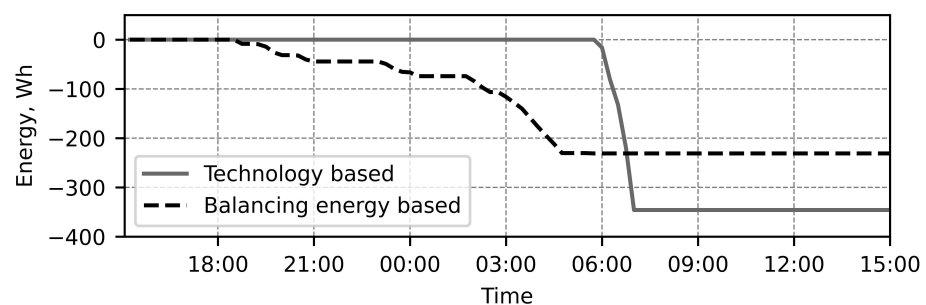


Figure 9. Cumulative energy deficit of the BS in “EMS-1” caused by the positive flexibility provision (solid grey curve) and cumulative available negative balancing energy per household (dashed black curve) on 31 January 2019–1 February 2019.

In order to assess the simulation results, we calculated the *flexibility balance*, which is the percentage of energy provided as flexibility that can be returned within the next 24 h by providing the balancing power with a sign opposite the provided flexibility power values. The flexibility balance is a metric for evaluating the extent to which the flexibility provision can be managed in as a much system- and grid-oriented manner as possible. Within the demonstrated time period, 81.3% of the energy provided as positive flexibility by the BS in “EMS-1” could have been balanced by providing the negative balancing power, as is shown in the bottom subplot in Figure 10.

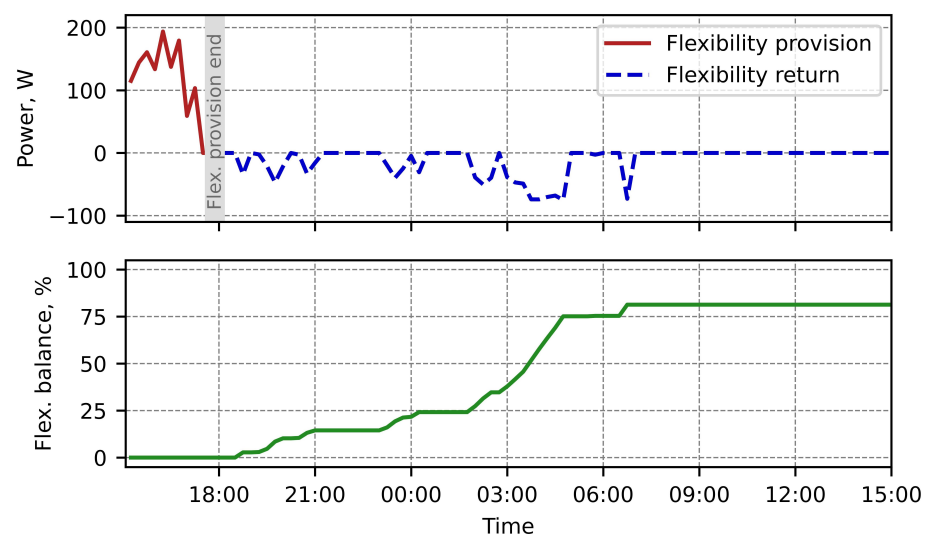


Figure 10. Top subplot: power values of the positive flexibility (red curve) provided by the BS in “EMS-1” and those of the flexibility return (blue curve). Bottom subplot: flexibility balance (green curve) of the BS in “EMS-1” on 31 January 2019–1 February 2019.

As is shown in Figure 10, the energy deficit caused by the positive flexibility provision on 31 January 2019 could not have been fully balanced by providing the negative balancing energy. However, as the flexibility return was managed by providing the negative balancing energy per household, this flexibility return means that this BS system provided flexibility to the power grid again.

We repeated these simulations for the entire year of 2019 and all the investigated energy systems. Then, we calculated the annual flexibility balance values of all investigated energy systems (see Table 7).

Table 7. Calculated mean annual flexibility balance values for all households in 2019.

	EMS-1	EMS-2	EMS-3	EMS-4	EMS-5	EMS-9	SFH-3	SFH-8	SFH-9	SFH-12	SFH-18	SFH-19
Flex. balance, %	55.0	35.8	46.8	51.9	47.7	28.7	19.9	51.1	53.0	23.2	23.9	23.0

During the observed year, 55% of the flexibility provided by the BS in “EMS-1” could have been returned by supplying the balancing power with a sign opposite the power values of the flexibility provision. The HP-HS systems in “SFH-8” and “SFH-9”, which are supposed to be operated year-round, have higher flexibility balance values compared to other HP-HS systems that are only supposed to be operated during the cold season (October to April). The flexibility balance values indicate that in 44% of the BS cases and 32% of the HP-HS ones (mean values averaged over all investigated energy systems) the operation of the decentralised energy systems and power grid was not adversely affected by the flexibility provision. This was achieved by balancing the resulting energy surplus or deficit via the flexibility return approach.

The flexibility balance of 100% signifies situations in which the energy deficits or surpluses caused by flexibility provision were fully balanced in a system- and grid-oriented manner, meaning that the flexibility provision at that point in time did not create new flexibility requests in the power grid. However, operation of the decentralised energy systems and power grid in 2019 did not always feature optimal conditions for balancing the energy deficits or surpluses within the 24 h following flexibility provision. Despite this, any remaining portion of the energy surpluses or deficits could theoretically be balanced at a later time through coordinated efforts between the power grid and decentralised energy systems if necessary or required.

4. Conclusions and Outlook

4.1. Conclusions

In this study, we investigated the fundamentals of the flexibility provision process: the quantification of potential, aggregation, consideration of uncertainty, the simulation of provision and evaluation of impacts using the example of the multiple PV-BS and HP-HS systems in residential buildings in 2019. The results of the study demonstrate that the developed flexibility quantification method can be applied for calculating the time-varying flexibility potential of diverse decentralised energy systems that belong to different technologies, and have various primary applications, and therefore different operational schedules. The output of our flexibility quantification method consists of universal values, such as flexibility power and the duration of providing the given power. Thus, numerous evaluation metrics can be applied to assess and compare the flexibility of decentralised energy systems without technological restrictions.

The time-varying flexibility potential of energy systems is significantly influenced by their modes of operation, the amount of energy stored in the BS and HS systems at a given time and their planned operation following flexibility provision. For instance, the impact of the operational mode on the flexibility potential was clearly evident in the investigated HP-HS systems. If the operational temperature of the HS systems was allowed to deviate by

up to 2 K from the set levels to provide flexibility, the HP-HS systems under investigation could have met approximately 16 percentage points more flexibility requests.

The flexibility aggregation method was demonstrated on the basis of the example of one BS and one HP-HS system. The selected HP-HS system could have contributed much less to the aggregated flexibility by comparison to the BS system. Nevertheless, the combination of the high number of energy systems belonging to different technologies for the purpose of joint flexibility provision can offer the following benefits: first, aggregation increases the flexibility power values, and second, it contributes to the system- and grid-oriented operation of decentralised energy systems.

The operating power of the investigated BS systems often remained below their nominal capacity, indicating a potential for greater flexibility, both in increasing and decreasing power output. In contrast, the investigated HPs typically operated either near their nominal power or were switched off entirely. This inflexible operating mode reduced the flexibility potential of the HP-HS systems. Incorporating the building envelope into flexibility quantification could theoretically enhance the flexibility potential of HP-HS systems by increasing overall storage capacity. However, this approach requires additional input data and more complex calculations, making it more challenging to quantify the flexibility of HP-HS systems compared to BS ones. Despite these challenges, HP-HS systems can still offer valuable flexibility in energy cells where other flexibility providers are unavailable, making their inclusion in future flexibility portfolios essential. Each unit in such a portfolio can contribute to maintaining system balance and ensuring stable operation of the power grid.

The next step was the integration of variability and uncertainty into the flexibility quantification. For this purpose, the power and energy fluctuations caused by variability and uncertainty were proposed to be considered in the second calculation step when quantifying the power and energy boundary values of the flexibility providers. A definite amount of power and energy could therefore be reserved for cases where local flexibility providers would have to mitigate these unexpected fluctuations. The integration of variability and uncertainty was demonstrated with the example of PV-BS systems. On the one hand, the BS systems could have power and energy reserved to mitigate the internal power and energy fluctuations of own PV systems at each point in time. On the other, BS systems taking into account the variability and uncertainty could have covered 15 percentage-points less potential external flexibility requests than those without this consideration.

For the simulation of flexibility provision, the external flexibility requests per household were derived from historical balancing energy data in Germany for 2019. Each investigated BS (excluding PV fluctuations) could theoretically have met approximately 60% of the external flexibility requests, whereas each HP-HS (with a 2 K temperature deviation) could have met approximately 50% of these requests. Although the nominal power and capacity of the investigated BS and HP-HS systems exceeded the balancing power per household, a single unit was still insufficient to fully satisfy these requests on its own. The primary reason for this was that the locally optimised operation of these energy systems did not temporally align with the flexibility requests derived from balancing energy. However, the aggregation of energy systems led to an increase in the theoretical coverage of flexibility requests. A combination of six BS systems could theoretically cover up to 20 percentage points more flexibility requests, and a combination of six HP-HS units could cover up to 14 percentage points more flexibility requests, compared to individual ones.

Decentralised energy systems can undergo energy deficits or surpluses after providing positive or negative flexibility, respectively. To address this, we quantified the amount of energy that is either exceeding or missing in these energy systems at each point in time over the subsequent 24 h period following the flexibility provision. In addition, we analysed historical balancing energy data to identify appropriate time periods within the next 24 h when the energy provided as flexibility could be theoretically fed into or consumed from the power grid without causing additional overload. By combining this information, we developed a *flexibility return energy curve*. The simulation results indicated that nearly half

of the flexibility provided by the BS systems and one-third of that provided by the HP-HS systems could theoretically be returned without adversely affecting the power grid. In these cases, the external flexibility needs were sustainably met, rather than merely postponed.

Decentralised power generators, storage systems, and controllable loads have the potential to provide flexibility in addition to their primary applications, both within the energy cells in which they are installed as well as outside to support system balance and power grid requirements. We assume that providing flexibility within the energy cells reduces their external flexibility needs, and may therefore contribute to the more system- and grid-oriented operation of the energy cells. However, even with a large number of these decentralised energy systems in operation, they will not be sufficient to meet all future flexibility needs. We strongly assume that they will constitute just one potential source of flexibility in the future energy infrastructure. The future portfolio of flexibility sources will also include energy systems in industrial and commercial properties, hydrogen storage systems, fuel cells-based power generators, district heating networks, and other technologies. In principle, flexibility should be developed and provided from all available sources across all voltage levels of the power grid.

4.2. Outlook

Future research can adapt the developed method to quantify and aggregate the flexibility potential of other technologies, including electric vehicles, CHP systems, district heating networks, and various controllable loads. Furthermore, the proposed methodology could be applied to data of decentralised energy systems in other countries with varying climate conditions and energy consumption profiles. In such cases, the flexibility potential would likely exhibit different values and distinct daily and seasonal patterns. Additionally, future studies could explore the influence of other variability and uncertainty sources on the flexibility potential, such as load prediction uncertainty, the risk of energy system failures, and variations in occupant behaviour. Moreover, this study can serve as a fundamental basis for future studies regarding the economic feasibility, business models and flexibility markets for providing flexibility as an additional service of decentralised energy systems.

Developing, integrating, and supporting the flexibility provision of decentralised energy systems require a combination of technical solutions, business models, regulatory frameworks, and social acceptance. Technical recommendations include, among other things, the widespread roll-out of smart meters and smart energy management systems, as well as the standardisation of communication interfaces across all stakeholders. The smart energy management systems have to ensure optimal operation of energy systems and avoid possible negative impacts of flexibility provision on efficiency, service life, and other key performance characteristics. Therefore, these systems are responsible for overall system efficiency while maintaining optimal performance.

It is further recommended that end users, including private households and residential districts, be encouraged to optimise the operation of local energy systems according to their specific needs while also providing flexibility to support system balance and meet power grid requirements. To promote such system- and grid-oriented operation, the integration of dynamic electricity tariffs and/or variable network charges should be considered. Accordingly, energy supply companies are encouraged to offer dynamic electricity tariffs to all categories of end users. Another key recommendation concerns distribution grid operators that have to develop and integrate a low-voltage control centre enabling grid transparency, real-time monitoring, load management, automated control, as well as compliance with regulatory frameworks.

Neighbouring buildings equipped with decentralised energy systems might be recommended to establish an energy-sharing community to aggregate their flexibility potential values. This approach enables internal energy and flexibility management as well as support of system balance and provision of aggregated flexibility to the power grid. The necessary regulatory framework should ensure that the provision of flexibility for system and grid purposes aligns, or at least does not hinder or conflict with, the self-optimisation of

decentralised energy systems for end user needs. To enable the effective flexibility provision of decentralised energy systems, collaboration among all stakeholders is essential, including manufacturers and operators of energy technologies, smart meters, energy management systems, energy supply companies, power grid operators, communities, legislators, and relevant governmental organisations.

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Abbreviations

The following abbreviations are used in this manuscript:

BS	Battery storage
HP	Heat pump
HS	Heat storage
PV	Photovoltaic

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Part III.

Epilogue

Chapter 6.

Conclusion

Distributed energy generators, energy storage and sector-coupling technologies are nowadays widely installed in different types of buildings for concrete primary applications, such as optimisation of self-consumption, space heating, cooling, domestic water heating, and further needs of building occupants. These systems are technically able to provide flexibility inside and outside their installation sites by changing their initial or scheduled operation. Numerous studies have explored the flexibility potential of decentralised energy systems by optimising their operations based on dynamic electricity prices. While this approach is valid and effective, it does not account for local conditions, such as energy generation and consumption in particular buildings, quarters or city districts, nor does it consider the state of local transformers and cable sections. For example, high electricity generation of large-scale wind and PV power plants combined with low electricity consumption at a given point in time leads to lower (and sometimes even negative) electricity prices. This may trigger a simultaneous increase in electric vehicle charging, potentially causing local grid congestion. Therefore, it is essential to establish local signals and quantify local flexibility values to ensure effective grid management and prevent such issues. The flexibility quantification of decentralised energy systems must include consideration of occupant needs, representation of flexibility in a universal and technologically agnostic form, as well as aggregation of flexibility values of multiple energy systems belonging to different technologies and having different operational modes.

To address the recognised research gaps, this thesis developed methods for quantifying and aggregating the flexibility potential of various decentralised energy systems and storage solutions in buildings and city districts. The quantification method considers the primary applications of these systems and therefore the needs of building occupants, as well as local variability and uncertainty, by calculating power and energy boundaries within which flexibility is quantified. To demonstrate the functionality of these methods, the entire flexibility provision process was simulated, including flexibility quantification, flexibility aggregation, as well as calculation and simulation of external flexibility requests and flexibility provision.

To better understand and attribute the contributions and key findings of this thesis, it is important to note that the research was conducted within the following boundaries.

Chapter 6. Conclusion

First, the investigation of flexibility provision as well as quantification and aggregation of flexibility potential was based on energy simulations using time-series with historical power measurements of the energy systems. It was assumed that the operation of these systems was driven by the fulfilment of specific local requirements, such as maximising self-consumption of the PV systems and maintaining a comfortable indoor temperature. The thesis did not include a comparison with operation exclusively for flexibility provision or with a multi-objective optimisation, such as simultaneously optimising self-consumption and flexibility provision. Second, the quantified flexibility potential values are not universally transferable to other decentralised energy systems of the same technology. Rather than determining a typical flexibility potential for a specific energy technology or estimating the total flexibility potential of all such systems in Germany, this research focused on developing methodologies for calculating the flexibility potential of a specific decentralised energy system at any point in time. Third, this thesis did not comprise social, economic, and regulatory aspects, such as cost-benefit analysis, business model development, social acceptance of flexibility provision, evaluation of financial and non-financial incentives, impact of regulatory and policy frameworks on flexibility provision. And fourth, this study did not consider the conditions, states, and requirements of the power grid, such as frequency and voltage control, congestion management, and other grid stability aspects.

The following paragraphs highlight the main contributions and findings of this thesis, taking into account the boundaries described above. The thesis provided evidence that the different decentralised energy systems in buildings could have provided flexibility as an additional service, without undermining their primary applications, i.e. without threatening the needs of building occupants. The conducted energy simulations indicated that the flexibility of these decentralised energy systems had a variable and time-varying nature, as flexibility was assumed to be solely an additional service. The time-varying flexibility potential of energy systems was significantly influenced by their actual modes of operation, the actual amount of energy stored in systems, their planned operation following flexibility provision, time of the day, and season. For example, the negative flexibility potential of the investigated battery storage systems 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 season has also shown a strong influence on the flexibility potential of the investigated heat pumps. The flexibility potential was higher in colder months due to the more frequent and intensive operation of these systems to provide sufficient thermal energy for comfortable room temperatures. In contrast, with minimal heat demand in warmer months, the investigated heat pumps were operated much less frequently, resulting in significantly lower flexibility potential during this period. However, increasing the deviation of operating temperature limits in heat storage systems by up to 2 K from the set levels could significantly increase the flexibility potential of heat pumps.

The developed method of flexibility quantification includes calculation of technology and schedule-specific boundary values. These boundary values consider technological

limitations, actual mode and expected operation of the energy systems in the following hours. As long as the flexibility potential is calculated considering boundary values, the flexibility can be provided without undermining the primary applications, and therefore without threatening the needs of building occupants. Furthermore, the use case with PV and battery storage systems demonstrated that local variability and uncertainty can also be incorporated into the flexibility quantification method. The first calculation step of this use case involved computing the distribution of power ramps and the deviation from the predicted daily energy generation using the developed method for quantifying power and energy fluctuations of PV systems. Second, these values were then integrated into the calculation of the power and energy boundaries of the investigated battery storage systems. Therefore, definite amounts of power and energy could be reserved in advance to mitigate possible unexpected local fluctuations, such as those caused by the variability and uncertainty of on-site rooftop PV systems.

Although the flexibility quantification method includes technological and operational specific calculation steps, the resulted flexibility potential is presented in a universal and technologically agnostic form, such as flexibility power and the maximal duration of providing this power. By calculating the maximal duration of flexibility provision for a range of flexibility power values, a flexibility potential curve is built presenting a universal graphical depiction of entire flexibility potential, both positive and negative. The universal form of flexibility potential enables the comparison, evaluation and aggregation of flexibility values from different energy systems without technological restrictions. The main intention of the developed flexibility aggregation method is to estimate the most technically appropriate compositions of flexibility values offered by energy systems for providing the aggregated flexibility. Therefore, the aggregated flexibility potential curve at a given point in time may become balanced, meaning that the positive and negative flexibility potentials are approximately equal, even if the individual decentralised energy systems have significantly different flexibility potentials.

In the next step, the historical values of balancing energy in Germany were downscaled in order to simulate the external flexibility request and following flexibility provision of a single household with at least one flexible energy system or storage. Each investigated battery storage could theoretically have met approximately 60 % of external flexibility requests, whereas each heat pump could have met approximately half of these requests. A combination of six investigated battery storage systems could theoretically cover up to 20 percentage points more flexibility requests, and a combination of six investigated heat pumps could cover up to 14 percentage points more flexibility requests, compared to individual ones. The simulation results indicated that a frequent timing mismatch between the available flexibility potential and the requested balancing power was a key factor limiting the ability to fully cover flexibility requests. In other words, the locally optimised operation of the energy systems did not temporally align with the flexibility requests derived from balancing energy.

The energy simulations showed that decentralised energy systems can undergo energy deficits or surpluses after providing positive or negative flexibility, respectively. The

simulation results indicated that nearly half of the exceeding or missing energy resulted from flexibility provision of the investigated battery storage systems and one-third of that resulted from flexibility provision of the investigated heat pumps could theoretically be balanced without adversely affecting the power grid. In these cases, the external flexibility needs were sustainably met, rather than merely postponed.

The research of this thesis made essential contributions and introduced significant novelties to the investigating, quantifying and assessing the demand-side flexibility of small-scale decentralised energy systems:

- The thesis developed the adaptive flexibility quantification method that explicitly considers the primary applications of energy systems and the needs of building occupants by calculating technology- and schedule-specific boundary values for power and energy.
- A novel procedure was introduced for integrating variability and uncertainty into flexibility quantification by considering internal flexibility needs when calculating these boundary values. To quantify internal flexibility needs arising from PV system variability and uncertainty, this thesis developed a novel method for quantifying PV power and energy fluctuations.
- The quantified flexibility potential was proposed to be presented in a universal, two-dimensional, and technology-agnostic form, enabling the aggregation of flexibility values of different energy systems.
- To evaluate the impact of flexibility provision on energy system operation and the power grid, a novel concept of flexibility return was proposed, which calculates whether providing flexibility at one point in time can cause operational challenges or additional flexibility needs in the future.

A general advantage is that all methods developed in this research represent data-driven methodologies that eliminate the need for complex physical modelling and configuration, enhancing practicality and scalability. To summarise, the developed concept, methods, procedures and forms can be applied to investigate the flexibility of various energy technologies in different regions and countries to enable widespread application of local flexibility sources.

As renewable energy sources and decentralised energy systems increasingly become essential components of the energy infrastructure, this research enhances the technical understanding of flexibility. It provides a novel comprehensive methodology for quantifying the flexibility of decentralised energy systems, thereby laying a foundational step toward more sustainable, dynamic and adaptive energy infrastructure.

Chapter 7.

Outlook

The limitations identified in this study provide possible themes for further research. The future research may conduct the sensitivity analysis of different operational strategies to assess their impact on the flexibility potential of decentralised energy systems. This can involve, for instance a multi-objective optimisation considering cost-effectiveness, energy efficiency, sustainability, and flexibility. Another direction for future research can be the extension of the procedure for calculating power and energy boundaries to other energy technologies, based on the calculation steps developed in this study. Furthermore, flexibility quantification can be enhanced by integrating additional sources of variability and uncertainty, such as load prediction errors, system failures, and variations in occupant behaviour. For instance, the method developed to quantify PV power and energy fluctuations might be adapted to quantify load fluctuations, which can then be integrated into flexibility quantification.

Beyond the technical scope, future research should complement this study by addressing socio-economic and policy aspects of flexibility provision. This may include conducting cost-benefit analyses, developing business models and local flexibility markets, assessing social acceptance through surveys, evaluating financial and non-financial incentives, and analysing the impact of regulatory frameworks on flexibility provision. Future research can also incorporate real-time conditions and requirements of the local power grid into the flexibility quantification of decentralised energy systems to enhance the practical relevance of the findings. Finally, the developed framework can be scaled for larger areas with multiple diverse energy technologies (e.g. city district or large residential quarters) and adapted for real-world applications through empirical studies, pilot projects, and field testing.

To enable flexibility provision, several key technical requirements must be implemented. These include the widespread deployment of smart meters and smart energy management systems, as well as the standardisation of communication interfaces across all stakeholders. Energy supply companies and system operators should incentivise all types of energy consumers, including households and residential districts, to operate their local energy systems not only to achieve individual objectives but also to provide flexibility for system- and grid-oriented purposes. This can be facilitated through dynamic electricity tariffs, variable local signals, and a combination of financial and non-financial

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incentives. Furthermore, distribution system operators should develop and integrate low-voltage control centres to enhance grid transparency, enable real-time monitoring, manage loads effectively, automate control processes, and ensure compliance with regulatory frameworks.

A potential approach for aggregating the flexibility of multiple energy systems within a given area is the establishment of energy-sharing communities. This concept enables internal energy and flexibility management, supports system balancing, and enables the provision of aggregated flexibility to the power grid. A well-defined regulatory framework is necessary to ensure that flexibility provision for system and grid stability aligns with, or at least does not hinder, the individual objectives and needs of energy consumers. Effective flexibility provision requires collaboration among all relevant stakeholders, including manufacturers and operators of energy technologies, smart meters, and energy management systems, as well as energy supply companies, system operators, municipalities, legislators, and governmental organisations.

The methodologies developed in this thesis, along with the proposed extensions and real-world integration, can contribute to the establishment of a comprehensive system for flexibility assessment and the effective flexibility management of small-scale decentralised energy systems. In turn, this enables these systems to actively participate in future local energy and flexibility markets, including energy and flexibility exchange, supporting system balance, and providing ancillary services. In this way, buildings and city districts with small-scale energy systems can contribute to the effective integration of renewable energy sources, as well as to grid stability, system resilience, and overall energy reliability.

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List of publications

N. Maitanova, S. Schlüters, B. Hanke, K. von Maydell, and C. Agert “Quantifying power and energy fluctuations of photovoltaic systems” in *Energy Science & Engineering*, Volume 10, Issue 12, Pages 4496-4511, December 2022, doi: <https://doi.org/10.1002/ese3.1285>

N. Maitanova, S. Schlüters, B. Hanke, and K. von Maydell “An analytical method for quantifying the flexibility potential of decentralised energy systems” in *Applied Energy*, Volume 364, Pages 123150, 2024, doi: <https://doi.org/10.1016/j.apenergy.2024.123150>

N. Maitanova, S. Schlüters, B. Hanke, K. von Maydell “Investigating the Full Process of Flexibility Provision from Decentralised Energy Systems: From Quantification of Flexibility Potential to the Evaluation of Flexibility Provision Impacts” in *Energies*, Volume 17, Issue 24, 2024, doi: <https://doi.org/10.3390/en17246355>

N. Maitanova, J.-S. Telle, B. Hanke, M. Grottke, T. Schmidt, K. von Maydell, C. Agert “A Machine Learning Approach to Low-Cost Photovoltaic Power Prediction Based on Publicly Available Weather Reports” in *Energies*, Volume 13, Issue 3, 2020, doi: <https://doi.org/10.3390/en13030735>

J.-S. Telle, **N. Maitanova**, T. Steens, B. Hanke, K. von Maydell, M. Grottke “Combined PV Power and Load Prediction for Building-Level Energy Management Applications” in *Fifteenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Monte-Carlo, Monaco, 10.-12.9.2020, doi: <https://doi.org/10.1109/EVER48776.2020.9243026>

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B. Hanke, M. Bottega, D. Peters, **N. Maitanova**, J.-S. Telle, M. Grottke, K. von Maydell, C. Agert “Fully automated photovoltaic system modelling for low cost energy management applications based on power measurement data” in *35th Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC)*, Brussels, 24.-28.09.2018, oral presentation, doi: <https://doi.org/10.4229/35thEUPVSEC20182018-6B0.8.2>

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Erklärung gemäß §12 der Promotionsordnung

Mit dieser Dissertation soll der Grad eines Doktors der Ingenieurwissenschaften erlangt werden. Hiermit versichere ich, dass ich diese Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe. Zudem erkläre ich hiermit, dass die vorliegende Dissertation bereits in Teilen veröffentlicht wurde. Eine Liste der Publikationen ist dieser Dissertation angehängt. Diese Dissertation hat weder in ihrer Gesamtheit, noch in Teilen einer anderen wissenschaftlichen Hochschule zur Begutachtung in einem Promotionsverfahren vorgelegen, bzw. liegt einer anderen wissenschaftlichen Hochschule zur Begutachtung in einem Promotionsverfahren derzeit vor. Außerdem erkläre ich hiermit, dass die Leitlinien guter wissenschaftlicher Praxis an der Carl von Ossietzky Universität Oldenburg befolgt wurden, und im Zusammenhang mit dem Promotionsvorhaben keine kommerziellen Vermittlungs- oder Beratungsdienste (Promotionsberatung) in Anspruch genommen worden sind.