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Quantifying flexibility from a system perspective using limited information: An index to rank electricity users' potential value

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ABSTRACT

As an increasing number of public actors both in the EU and in Sweden – from the highest political level to local operational levels – request greater flexibility and understanding of electrical power systems, additional methods and tools are necessary to identify potentially valuable sources of flexibility. In this study, we developed the Flexibility Value Index (FVI) to quantify and rank the system perspective-value of different electricity users' potential flexibility. Previous studies have mainly concentrated on either broad system levels, assessing total flexibility across an entire sector, country, or technology, or on a very detailed level, analyzing individual buildings based on specific appliance data on a case-by-case basis. However, there is a lack of studies between these two sides that, with limited information, aim to identify users whose consumption behavior or patterns would be valuable to change. This paper presents a quantification method based on five indicators demonstrated by evaluating electricity users from seven categories in Uppsala Municipality, Sweden. The results showed that the largest average FVIs were typically found in the later afternoon and early evenings during weekdays, coinciding with higher grid loads, but also in the mornings and weekends for individual users. Grid owners, public entities, or private businesses can use the developed index in strategic decision-making to identify users who might provide the most valuable flexibility for the power system for further investigations.

1. Introduction

Electric power grids are essential for the ongoing energy transition from fossil fuels. The European Union (EU) is especially committed to this effort, which has become a central focus in many of its decision-making areas over the past decades [1–3]. Two significant system-wide outcomes have been the increase in the amount of renewable energy sources (RES) connected to the grids [4], and the electrification of processes traditionally powered by fossil energy, where the land-based vehicle fleets, in particular, have led to higher locally bound load spikes in the grid due to electrical vehicle (EV) charging [5]. Both of these developments have increased the variability of production and consumption patterns, leading to more interventions from grid operators to maintain grid stability, in addition to leading to an expected increase in demand for ancillary services [6]. However, generating more electricity from RES has solid global support and is a critical objective of the United Nations Sustainable Development Program [7]; thus, this development will most likely continue.

Within the EU, the objective of the package "Clean Energy for All Europeans" is at least 40% cuts in green house gas emissions, a 32% share of renewables in energy production, and at least 32.5% increased energy efficiency by 2030 [8]. Worldwide, electricity demand was approximately 26,000 TWh in 2023, and the goal is to produce this amount – and more – with net-zero emissions in the coming decades [9]. Thus, the energy transition processes are far from complete, and additional analyses, methods, and tools are necessary to tackle the changes and how they affect the grids. One approach that has gained attention over time is flexibility [10]. Flexibility is the ability of a power system to manage changes [11], where demand-side resources comprise this capability among end-consumers through the adjustment of their extraction or injection of energy into the grids — usually evaluated using power (kW) or energy (kWh) [12]. If an electricity user is consciously adjusting its electricity consumption during a so-called demand response (DR) event, in which production and consumption are not balanced, or if the grid capacity is at its limits, it can be viewed as a resource. From an energy security standpoint, and considering the potential system disruptions caused by climate change, extreme weather events, and subsequent forecast errors, the need for flexibility resources is amplified [13]. Energy transition aspects are therefore increasingly

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Acronyms

DER	Distributed energy resources.
DR	Demand response.
DSO	Distribution system operator.
EI	The Swedish Energy Markets Inspectorate.
ENTSO-E	European Network of Transmission System Operators of Electricity.
ESS	Energy storage system.
EU	European Union.
EV	Electrical vehicles.
FVI	Flexibility value index.
HVAC	Heating, ventilation, and air-conditioning systems.
IEA	International Energy Agency.
PV	Photovoltaic.
RES	Renewable energy sources.
TSO	Transmission system operator.

integrated into the development plans of all member nations [14]. From a Swedish viewpoint, flexibility has been emphasized in the Swedish transmission system operator (TSO) Svenska kraftnät's long-term development plan, where demand-side resources are highlighted [15]. The The Swedish Energy Markets Inspectorate (EI) has similarly remarked that it is essential to make information available to increase electricity users' awareness and understanding, and to encourage their capability and willingness to offer flexibility since a deficiency could lead to higher prices and capacity shortages [14].

Widening the scope, the International Energy Agency (IEA) has also highlighted the significance of quantifying flexibility by designating it as a research topic through the Buildings and Communities Programme Annex 67 [16]. Additionally, one of the first documents from the EU Clean Energy package in 2016 (Directive 2018/844) requested a "smart readiness indicator" to evaluate building adaptability to, among other factors, the grid needs [17]. Grids are governed by specific codes that dictate connection and operation rules, and flexibility is gradually becoming a part of these. The latest document from the European Network of Transmission System Operators of Electricity (ENTSO-E) aims to create a legal framework for local markets to address congestion and voltage issues to promote flexibility from end-consumer DRs and distributed energy resources (DER) [18]. The advantage of a general code is that it can foster developments that make energy accessible at the right time and place. Increased awareness and insights into flexibility and its potential are essential to reduce barriers to creating such a code and its subsequent developments.

In modern societies, buildings account for 30%–40% of total primary energy [16,19]. In addition, buildings' load magnitudes and volatility have been rising, making them a significant end-consumer in the energy system [20–22]. Thus, consumption data from different buildings, including the user types that they house, are valuable to analyze. Advancements in appliances over the past decade have enhanced the potential for buildings to provide flexibility through remote management and scheduling of loads [23]. Based on these developments, researchers have suggested energy flexibility to become a standardized key performance indicator in future building standards [21]. If done correctly, it could enable more efficient operations of existing grids and support its expansion while keeping costs down [14]. Moreover, well-considered energy management strategies can often yield economic advantages [24]. Other solutions include reinforcement of the distribution and transmission grids, but they are costly and time-consuming, especially for rural areas, although the exact costs are very case-dependent [25,26].

1.1. Problem statement

Flexibility measures remain underutilized despite gaining attention, which risks leading to missed opportunities and a slower energy transition. For instance, the benefits of system-valuable flexibility are often overlooked in current building energy performance criteria. Prior research has likewise called for indicators to quantify flexibility from buildings [27]. Thus, additional methods of discussing and quantifying flexibility that can be useful for the grid operations are interesting to pursue. Several authorities, both national as the Swedish TSO and EI, international such as the EU, and global such as the IEA, has specified that improved information to different user groups can help bridge the knowledge gap, potentially leading to greater resource flexibility across user categories [28]. A critical aspect in this is the knowledge about the user's qualification [29], but also the value of its potential flexibility from a system perspective. Accessing consumption data is possible for many electricity users. In the EU, e.g., it is supported by the law, while other sources such as eSett provides data per electricity area for the Nordic countries apart from Iceland [30], or ENTSO-E who provides data for the pan-European area on a national level [31]. Consequently, this study aims to create an index exclusively based on electricity load data. The advantage is that these are actual numerical sources that are easily attainable and do not require estimations, installation of additional sensors, or extensive manual data gathering. Two comparable studies are [32–34]; however, in contrast to these and most other previous studies quantifying flexibility, this study does not require a data granularity based on detailed appliance data from several sources, extensive forecasting, optimizations, or general sector-based assumptions to assess flexibility. Instead, this study is designed around using a limited amount of information, i.e., few data sources, and without a need to calculate any baselines to assess the system-perspective value of different electricity users. In the reviewed research and from studies as [20], we identified a research gap for analyses using "limited external" data.

This study proposes a new approach to assess a flexibility value that is solely based on using data from electricity users' energy meters, which is readily available without the need to install additional equipment, through a system perspective that is included by using load data from the grid as a reference, which can be gathered from open data sources or manually estimated. The quality and accessibility to energy meters and open energy data sources have improved over the past decade. This available information should increasingly be used in studies as it is an important enabler for a wider audience of users to perform their own analyses on a local level, from individual residential households to organizations such as municipalities and companies. The amount of data is, however, too large to be analyzed manually; thus, it requires a framework to be assessed.

1.2. Aim and scope of this study

This paper presents a flexibility value index (FVI) to evaluate and rank electricity users' potential flexibility value from a system perspective by using time series data from electricity users' energy meters combined with a grid load reference from an open data source. The study aims to approach flexibility quantification from a systems perspective in a new way and based on using limited information, i.e., information from few sources that are readily available, easy to obtain, and do not require detailed modeling. Indexes are valuable in various contexts, and as demonstrated in this paper, presenting them in a technologically agnostic format can provide usability and insights that are interpretable for a broader audience. More flexibility is needed, and more utilities have also shown interest in developing DR programs [35], in which improved electricity user knowledge in flexibility will be valuable. However, instead of calculating the energy or power from a single user or aggregated from an entire sector, which has been common in

previous research, this paper focuses on identifying potentially valuable sources for flexibility, which then can be analyzed in-depth. It can benefit organizations such as municipalities, which have a social responsibility and manage numerous users across different categories but usually lack in-depth knowledge about their grid impact. It can also benefit grid operators who aggregate large amounts of load data to evaluate the load behavior of different electricity users. The proposed FVI can help identify users who, if they would reduce their load during specific hours, could provide valuable flexibility for the grid, thus aiding decision-making by directing time and resources for further in-depth analysis toward these users. We believe that the "middle-ground" approach presented in this paper can engage a broader range of readers by expanding the methods on quantifying flexibility, which can focus and support the integration of smart energy management systems to key electricity users that hold value for enhancing grid-responsive capabilities.

1.3. Contribution

This paper's contributions can be summarized as:

1. A generalizable and lightweight quantification index for evaluating the potential flexibility value from the demand side of various electricity users using a system perspective.
2. Providing an evaluation that relies on limited information gathering, which is easy and quick to perform.
3. Evaluating actual data from seven distinct types of activities to assess their potential flexibility value.
4. Using a technology-agnostic presentation format that is simple to share with a broader audience.
5. The overall framework can adjust its reference for further analyses, e.g., matching a user with RES.

The paper continues as follows: Section 2 presents a general overview of flexibility studies; Section 3 discusses flexibility quantification in more detail and connects it to the concept of an index; Section 4 summarizes the method and the indicators used for the created index; Section 5 presents the results; and finally, Sections 6 and 7 discusses and concludes the paper respectively.

2. Overview of flexibility studies

A challenge in analyzing and discussing flexibility is that several different definitions of flexibility exist, ranging from just focusing on power or energy to including other aspects such as, e.g., comfort and cost perspectives [36]. One approach to categorize previous flexibility studies is by their system level and data sources. Is the study primarily bottom-up based, utilizing detailed data from one or a few users? Or does it take a top-down perspective incorporating aggregated data, assumptions, and estimates? Both perspectives are typically quantitative, but the latter is increasingly qualitative.

2.1. Bottom-up vs. top-down

Bottom-up studies generally concentrate on single buildings and model the energy systems in detail based on vital and energy-consuming components [32,34,37,38]. The model implemented can be based solely on data collected from each included device, a pure physical building model, or a mix of both. How much flexibility that studies have concluded is realizable in terms of power or energy is not static but depends on several parameters, such as ambient temperature and the occupants' comfort levels [38,39]. The outcome is also exposed to uncertainties, particularly occupant behaviors [40]. In contrast, a top-down perspective evaluates flexibility on a wider system scale, incorporating multiple perspectives, users, and/or categories while employing estimations, generalizations, and assumptions about their characteristics. Typically, the results include an aggregated flexibility from an entire category [41–46]. These two perspectives do not cover all prior studies but represent two common approaches to flexibility. A similar classification is whether the focus targets a building, district, sector, or system level [23], which creates a gradient from bottom-up to top-down perspectives.

The studied demand-side flexibility resources that ordinarily comprise buildings are heating, ventilation, and air-conditioning (HVAC) systems, lightning, water appliances, and building characteristics such as thermal mass and water storage tanks. As such, previous bottom-up studies have tended to focus on a particular purpose and individual buildings rather than a broader energy system perspective [12], where some examples are [21,37,47–50]. Implemented metrics have usually been integrated into a control and/or optimization schedule, e.g., to use a model predictive control method for heat management to minimize energy costs while ensuring comfort [51], or by comparing it to a rule-based scheme based on metrics that quantified flexibility considering energy, power, efficiency, and cost aspects [52]. Optimization without control schemes also exists studies through different approaches, e.g., how human activities affected appliances and resulting power profiles [53], how a probabilistic method based on a Monte Carlo process could be implemented [54], or how much photovoltaic (PV) that could be self-consumed in buildings [55]. Occasionally, these studies have introduced new terms, e.g., the "flexibility factor", which measured the amount of energy shifted to non-peak hours [56,57]. While numerous other flexibility studies exist, the overarching trend have been to use detailed appliance data through case-specific methods of various complexities.

2.2. Experiment vs. simulation

Another way to categorize flexibility studies is to sort them based on whether they utilized simulations, see, e.g., [58–60], or performed actual experiments, see, e.g., [61,62]. Simulation studies have been the most common by far, accounting for around 85% [23,27], which might give a hint of the efforts and resources required when doing fieldwork to invest in and install sensors. However, regardless of conducting simulations or experiments, data-gathering through sensors, reports, interviews, etc., is time-consuming. In addition, new developments require constant updates to studies. For example, the deployment of EVs and their chargers are increasingly included due to their high power usage [63,64], in addition to other prevalent components such as energy storage system (ESS) and PV arrays [23]. These subsystems – EV chargers, ESS, and PV arrays – are, however, not intrinsic parts of buildings and can be placed elsewhere while still affecting the local grid similarly. Additionally, it is vital to remember that unless each such subsystem has separate metering, it may distort the load analysis since the resulting grid impact of the building at hand is mixed with additional systems.

2.3. Summary of previous research

Bottom-up studies can be challenging, if not impossible, to generalize to other users, thereby supporting this study's scope of providing a more generalized and easy-to-implement assessment of flexibility, which can act as an initial step to identify relevant users before considering the level of detail in typical bottom-up studies. Conversely, top-down studies take a holistic approach and increasingly rely on interviews and/or aggregate numbers based on averages or estimates to present a generalized view of flexibility, and in these scenarios, it can be difficult or even impossible to analyze an individual user within the aggregated context. Consequently, there is an opportunity for studies starting with a data-driven approach that quantitatively analyzes users both individually and collectively. A systematic review from 2021 on flexibility quantification revealed several relevant research gaps in the existing literature, and this paper is directed at its first: "(1) establishing

Table 1
A general overview of bottom-up and top-down studies compared to this study based on Sections 2 and 3.

	Bottom-up studies	Top-down studies	This study
Needed data sources, models, and algorithms	**Several to many** Detailed appliance, building, weather, etc., data from several sources, models for the energy system at hand including algorithms for optimizing the control of appliances and/or forecasting trends used for the analysis are often needed.	**Few to many** Type of users, their numbers and typical electricity consumption values tied to them. Can be gathered or estimated from surveys, interviews, or by aggregating data from additional sources.	**Few** Recorded consumption data from users' energy meters and a grid load reference, e.g., from an open data source, is enough to get started. Many users can be evaluated simultaneously, but it is not mandatory.
Typical assumptions and estimations	**Few to several** Appliances characteristics and how they can be controlled, building characteristics, e.g., material choice, thermal inertia, optimal model parameters	**Several to many** Average or estimated values regarding the number of users, their used appliances including, load patterns. Continuing developments of energy efficiency, technology, industrial expansions, etc.	**Few** Reducing a user's electricity consumption during high load hours on the grid may provide valuable flexibility.
Generalization and implementability	**Low** Often models an electricity user's or building's appliances and specific energy system in detail, which can be complex and difficult to transfer to another user or building.	**Medium to high** The method to arrive at the averages and estimates can be general, e.g., read reports and perform interviews using pre-made questions, but it can be time requiring and needs to be done from the beginning in each new context.	**High** Just need two data sources to get started.
Level of detail	**High**	**Low to medium**	**Medium**
Accuracy	**Medium to high** Depends to a large extent on the modeled energy system and correctness of appliance data and control opportunities. The accuracy has the potential to be very high.	**Low to medium** Can be difficult to assess due to the assumptions and time frame, but might provide a general overall estimate. It typically is low for individual users as they might not behave like the average at all.	**High** Due to using relatively simple and transparent indicators, the accuracy of the result is high. However, the assessed value is an evaluated potential, not a determined amount of power or energy that can be directly verified.

a common definition and performance metrics for energy flexibility of buildings that are technology and application agnostic" [23]. While establishing a strict standard definition might be challenging, expanding the range of performance metrics can be rational. The systematic review summarized 12 other reviews, and while they were described as covering a wide range of approaches, none focused on quantifying flexibility across levels using an external perspective in the same way as this paper. Adopting an external perspective on flexibility requires greater attention, as it allows for examining a broader population of users. This can minimize the risk of committing resources to achieve flexibility from buildings that do not provide any potential value to the system, which could lead to inefficiencies and slower energy transision developments. It can be effective to address the lack of studies that fall between the bottom-up and top-down perspective, while being technologically-agnostic, using limited information from available and open sources. Additionally, it has been noted that collecting all necessary input parameters for model construction can be challenging for both engineers designing the models and the building operators alike [21], in addition to acting as a cost driver. Thus, a method that is easier to implement and can quantify flexibility potential is missing from the existing toolbox when detailed internal information regarding HVAC system, thermal mass, lighting, etc., is unavailable. While internal models can provide detailed answers about a building's function and capability to shift or reduce flexibility, they cannot be employed to identify those buildings within a larger population that have potential value from a system perspective. In Table 1, this study is compared to a simplified overview of the bottom-up and top-down approaches.

While qualitative perspectives mainly focus on descriptions and interpretations, such as what "flexibility" means and includes, quantitative perspectives are based on measurements and numbers. For flexibility, this typically means estimating available power and energy reductions, and many approaches to do this require detailed inputs from several appliances combined with energy system models and/or more or less advanced optimization algorithms. Another approach is to estimate the amount of flexibility of an entire sector. While this can be valuable for a general overview, the results may rely heavily on assumptions and estimations of different developments. Thus, additional flexibility measures should be tested and studied, which can complement these two approaches while being usable for a broader audience to increase their awareness and knowledge around flexibility. This should preferably be conducted through a transparent and quantitative approach that can benefit from data that is easily accessible.

A final note is that there is a lack of interoperability in previous flexibility studies. This is partly due to a lack of a standardized view on appliances and their resources but also because studies often have been case-to-case specific [23]. The strength of the index proposed in this paper is that it can include any number of electricity users simultaneously since it only needs their recorded energy meter data without any further analysis or transformations other than standard pre-processing to handle excessive missing data, zero-values, or outliers.

3. Quantifying flexibility

This section focuses on the quantification aspect of flexibility and how to relate it to an index. As mentioned, there is no standard definition of flexibility, and the same applies to methods for quantifying it [11,23,65,66]. While definitions are essential to keep a discussion focused, a too strict definition might be irrational for flexibility as it depends on the system in focus [67]. The quantitative analyses of flexibility can be quite different as there are *many* possible ways to include and calculate the qualitative aspects [34,36,68]; consequently, the chosen metrics and indicators and their justification are a vital part of such studies [20]. Flexibility quantification can generally be categorized by whether it is based on physics, is purely data-driven, or is a hybrid of these. Far from all studies on flexibility have a clearly stated view of flexibility, and even fewer have a mathematical formulation to quantify it. However, several do, and a recent review screened 302 articles and focused on those that explicitly adressed energy flexibility characterization and quantification methods. It found that 58% of the 85 selected for scrutinization used a mathematical formulation to quantify flexibility [23]. The review identified 61

Table 2
Example of quantification flexibility aspects.
Source: From [23].

Performance aspect	Definition	Baseline	Example of formulation
Energy (production)	To what degree on-site production can satisfy demand, and/or how energy storage can support it.	Yes	Self-Sufficiency = $\frac{\text{daily generation directly consumed}}{\text{net daily load baseline}}$
Energy (consumption)	Reduced energy consumption during demand response event.	Yes	Energy (E) reduction capacity = $\int_{\text{event duration}}(E_{\text{before}} - E_{\text{baseline}})\ \text{dt}$
Power	How much (nominal or in %) of the power that can be reduced during a DR event.	Yes	Peak power (P) reduction capacity = $\Delta P(\%) = 1 - \frac{P_{\text{peak, flex}}}{P_{\text{peak, baseline}}}$
Cost	How much (in fiat or as a % of typical costs) can be saved by using penalty-aware strategies compared to business as usual (baseline).	Yes	Flexibility Index = $1 - \frac{\text{Cost of flexible operation}}{\text{Cost of baseline operation}}$
Miscellaneous	Can include any numeric measure, including comfort, emissions, temperature, and compare them between low and high load hours.	No	Flexibility Factor = $\frac{Quantity_{\text{low load}} - Quantity_{\text{high load}}}{Quantity_{\text{low load}} + Quantity_{\text{high load}}}$

Table 3
Example of qualitative flexibility aspects.

Aspect	Example of components
Time	Response time, ramp rate, endurance [62].
Spatiality	Location implication on, e.g., temperature, irradiance, wind, which, in turn, affect electricity consumption.
Resource type	What specific systems are installed , i.e., HVAC, lightning, battery, PV, and more [65,70].
Availability	What resource that can be controlled and turned off and when.
Buildingcharacteristics	Thermal insulation and air-tightness [57,65].
Comfort	Indoor temperature, air quality, occupants opinions [71].

metrics among 49 articles covering six performance aspects: energy, power, duration, cost, comfort, and emission, in order of prevalence. An overview of its metrics is shown in Table 2, and they are typically tied to simulations with hourly data without optimizations. Worth noting is that most quantitative studies have not included all quantitative aspects [20]; different studies focus on different aspects. More thorough discussions of metrics and quantitative evaluations can be found in the reviews [23] and [69]. To complement Table 2, some qualitative aspects in previous quantification studies are gathered in Table 3.

Due to this ambiguity, every study on flexibility should at least convey its general understanding of it to avoid misconceptions. In addition, flexibility should be related to DR events including a discussion of the studied users' reasons for providing flexibility, e.g., if it is based on prices or other incentives such as grid considerations as done in [27]. A DER often mentioned in relation to flexibility is ESSs, but in this study, these are not seen as relevant since it is the current behavior that is interesting to analyze and not the potential benefits of an ESS. With an ESS, any behavior can be achieved or changed in theory, although real cases are limited by costs that determine the capability of the ESS. In addition, an ESS could be placed anywhere in the system to provide benefits and does not necessarily have to be placed behind the energy meter of a specific user.

Concerning flexibility quantification and indexes, a survey on evaluation metrics found that diverse metrics have been employed depending on the study's focus. The survey categorized the metrics into two groups based on whether they measured flexibility directly, often tied power and energy, or indirectly, through economic, environmental, or other variables [36]. As this paper is based on load data it is closer to the first group, but since the aim in this paper was to evaluate a system value of a users' potential flexibility rather than estimating the amount of flexible power or energy value, it extends the view of the previous studies summarized by the survey in [36]. Furthermore, a few studies were referenced in the survey that were related to an index within the context of flexibility. One extended the normalized flexibility index that is used in evaluating the grid's flexibility in planning time horizons, i.e., more than a year, to a shorter time frame up to an hour while, in contrast to this paper, focusing on the capability of a production unit to overcome generation and load uncertainties [72]. Another study described the ability of a building to respond to the grid's need for flexibility through a flexibility index; however, in contrast to this study, it was based around a case study to control theoretical building systems to reflect cost savings [62]. In another review on flexibility, the data-driven studies were in the minority, but one of these combined survey data with residential load data to assess a flexibility index, weighted around the consumed energy per month over the year compared to a static limit [73]. It did, however, not use any particular indicators and was based around survey data and assumptions rather than just on actual data. Additional studies were also found that had created different kinds of "flexibility factors". One study proposed two flexibility factors, a forced one and a delayed one, to indicate the ability of a building to transfer parts of its load to a period of more production from RES; these, however, required many inputs, including a load profile from flexible operations and appliance data [74]. Another study took the perspective of using hourly and daily time frames in a microgrid consisting of several users together with cumulative energy curves of different appliances to analyze the ability to decrease or increase the load based around a maximum and minimum case, including ESS and PV system [75]. This method, however, required extensive amounts of data, in addition to being more focused on aggregated users within the specific time frames rather than having a dynamic approach for individual users.

Only a few of the previous studies examined were purely data-driven [23], which is the basis of this study. In addition, no prior study was found that similarly created an index that was not tied directly to power, energy, costs, etc, but instead evaluated time series load data through a number of indicators.

3.1. Index as a concept

An index is generally tied to a reference system and helps measure, organize, sort, and rank data to facilitate discussions and decisions. It can have several strengths and potential drawbacks as listed in Table 4. It is important to remember that each index serves a unique purpose, and usability depends on the thought put into its structure and the context in which it is applied. Indexes can be handy and are common in many sectors, and perhaps the most well-known application

Table 4
Overview of index strengths and drawbacks.

Strengths		Drawbacks	
Organization	Help tracking trends and sorting larger data sets.	Maintenance	Creating and maintaining an index can be resource-intensive.
Efficiency	Makes data retrieval and comparison systematic and fast.	Limited scope	Indexes reflect a part of the whole system and has to be selected carefully.
Benchmarking	Enables comparison and analyzing changes and performance over time.	Over reliance	Users may rely too heavily on an index and overlook qualitative aspects.
Communication	Simplifies discussions and supports a technologically -agnostic representation.	Design challenge	Implementation requires thoughtful design and care of subjective influences.

is inflation in economics. An indicator-based index for flexibility can provide insights for electricity users in general and support identifying and realizing more of it among larger organizations. A challenge is the inherent versatility of flexibility, which can create a lack of consensus on indicators used to construct an index. However, studies need to push the exploration forward with ideas and suggestions, including how they are to be used by relevant stakeholders. As additional studies on flexibility quantification have been requested [23], using an index based on indicators designed around limited information can transparently handle a portfolio of potentially thousands of buildings – in addition to being modular. Previous research have focused mainly on the actual realization of flexibility, including detailed modeling, costs, scheduling, optimization, and more. Nevertheless, there is a lack of a system perspective on flexibility aimed at identifying users whose potential to provide flexiblity would be valuable, before delving into such details. The next section will detail this study's method of quantifying flexibility throughout five indicators, which combined compose the proposed FVI.

4. Method

This section describes the methodology to construct the FVI, which evaluates electricity users across five indicators using grid load data as a reference. The FVI aims to identify electricity users who express a consumption behavior during a selected time interval that could provide value for the grid if it were to be reduced. The system level of most interest can be selected as a reference, e.g., district, city, regional, or national.

4.1. Required data

The data needed for the FVI are time series data of the evaluated users' electricity consumption, which typically is easy to attain through their distribution system operator (DSO), and (local) grid load data, which generally can be found in different open databases at some system level. For the Nordic countries as an example, eSett provides open consumption data for the electricity bidding zones [30]. There are various other sources, but if relevant grid data are difficult to attain, an estimated daily grid profile can be created based on reported high-load hours. The data should at least have an hourly resolution to capture daily load dynamics. As mentioned in the introduction, it is also essential to note if batteries, PV arrays, or EV chargers are placed behind the users' electricity meter as this will distort their real consumption behaviors. However, if these components exist and record their power flows, the recorded data could be used to restore the users' original consumption behaviors; otherwise, these users could be considered to be removed from the evaluation.

4.2. Data subsets and filtering

When evaluating users over an extended time frame, such as a year, the analysis can be improved by dividing the data into distinct subsets to analyze time-related segments independently. For example, suppose noticeable seasonal variations or differences between regular workdays and weekends are present. In that case, it is logical to examine these instances separately from others that do not occur simultaneously or under the same conditions.

Incomplete electricity consumption data is common, often featuring zeros or missing values. Thus, taking appropriate measures to ensure sufficient data quality is vital. Handling outliers can be more complicated, as some users may infrequently consume significantly more electricity than usual. This data should not be discarded or altered since it reflects their actual usage. If the consumer's fuse size or subscription details are known, it can serve as an upper limit. Otherwise, comparing the peak consumption values with averages, their frequency, and time of occurrence can help assess their plausibility.

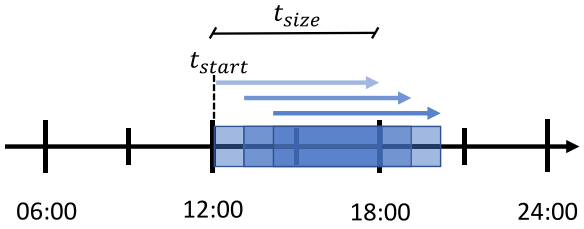

Fig. 1. An FVI zone starting at 12:00 with a duration of 6 h, which then shifts forward in time.

4.3. Flexibility time window

The starting time of a DR event and its duration are crucial parameters [62], and an event typically lasts a few hours [27]. A simple example is comparing lightning to heating — turning the lightning on or off has an immediate effect as the light (without specific materials) cannot be stored. In contrast, heating has inertia in a building, and its system has a dimensioned capacity to handle the coldest considered day [62]. Suppose the endurance of a system is unknown. In that case, one approach is to analyze different starting times and endurance lengths to assess what times and lengths seem to provide the most value for the system and then use this insight to assess the available systems. Hence, the FVI uses a sliding time window called a "FVI zone", exemplified in Fig. 1. It is within this zone that the users' load behaviors are evaluated.

4.4. Flexibility value index indicators

The indicators should focus on different aspects important for flexibility. Each indicator was selected through a *ceteris paribus* principle, i.e., if two users, based on the current evaluation were similar, what additional and reasonable indicator could be added to separate their

perceived flexibility value? The five chosen indicators are calculated for each evaluated user in FVI zone separately before being combined into the FVI.

4.4.1. Indicator 1 – Correlation with the grid load

The first indicator, i_1, is based on correlation, which quantifies the resemblance between two variables and is commonly normalized between −1 to +1, where the magnitude indicates an increasingly dissimilar/similar behavior and a value close to 0 means no resemblance. A higher positive correlation would suggest that the user increases its consumption when the grid load increases, e.g., during peak hours. To avoid negative numbers, the correlation is scaled to be within [0,1] and is weighted evenly between the three most common correlations — Pearson, Spearman, and Kendall. While Pearson is linear, Spearman and Kendall are monotonic measures, enabling them to adequately handle constantly increasing (or decreasing) non-linear trends compared to Pearson. The following expressions use population data. Pearson correlation, ρ_p, is calculated as:

$$\rho_p = \frac{1}{n}\sum \frac{\mathbf{X}-\mu_x}{s_x} \times \frac{\mathbf{Y}-\mu_y}{s_y} \tag{1}$$

where $\mathbf{X}, \mathbf{Y}$ are the time series data vectors, n the number of data points in one of the vectors (they must be of equal length), μ their respective average value and s their standard deviation. Spearman correlation, ρ_s, is calculated similarly as in Eq. (1), but uses ranked variables instead based on their magnitude. Kendall correlation, ρ_k is calculated as:

$$\rho_k = \frac{N_c + N_d}{\sqrt{(N_c + N_d + N_x)(N_c + N_d + N_y)}} \tag{2}$$

where N is the number of all possible pairs P, e.g., (x_i, y_i), between $\mathbf{X}, \mathbf{Y}$ in terms of being concordant, discordant, or tied in x or y. A pair is defined as:

$$P = \frac{x_i - x_j}{y_i - y_j} \tag{3}$$

where the subscript i accounts for every possible pair, one at a time, and where j includes all the other pairs. A concordant pair means $P > 0$, a discordant $P < 0$, and a tie $P = 0$.

Following this, i_1 is calculated using data within the FVI zone as:

$$i_1 = \frac{1}{3}\left(\frac{\rho_p + 1}{2} + \frac{\rho_s + 1}{2} + \frac{\rho_k + 1}{2}\right) \tag{4}$$

4.4.2. Indicator 2 – Average magnitude

The second indicator, i_2, is based on the relation between the average grid load and the user's consumption and indicates how much electricity the user consumes. As the relevant grid load aggregates all connected loads, this will always be [0,1]. As such, i_2, is calculated within the FVI zone as:

$$i_2 = \frac{P_{\text{user, average}}}{P_{\text{grid, average}}} \tag{5}$$

4.4.3. Indicator 3 – High load hours coincidence

The third indicator, i_3, captures the tendency of a user to recurrently consume a larger share of its total demand during high-load hours on the grid. A user with this behavior is viewed as having a greater flexibility value than one who consumes more during low-load hours. The probability that the user has a value above its median, given that the grid load is above its median, is calculated within the FVI zone. All data in the relevant subset is used for the median. As a probability never can be above 100%, the result will always be within [0,1]. Thus, i_3, is calculated as:

$$i_3 = p(P_{\text{user}} > q_{0.5,\text{user}} \mid P_{\text{grid}} > q_{0.5,\text{grid}}) \tag{6}$$

where q means quantile, and $q_{0.5}$ is the median.

4.4.4. Indicator 4 – User variations

A more constant load suggests that a user's consumption is relatively independent of external factors such as time of the day or price changes, meaning continuous operations likely drive it. This can lower the potential of a user to modulate, shift, or turn off a device. As flexibility comes from the ability to alter consumption patterns, a more varying load indicates more opportunities to modify, reduce, or shift the consumption without disrupting constant processes. Thus, the fourth indicator, i_4, is calculated from data within the FVI zone using the standard deviation as:

$$i_4 = \text{Min–max normalization} \Rightarrow \sqrt{\frac{\sum_{i=1}^{n}(x_i - \mu)^2}{n}} \tag{7}$$

Min–max normalization adjusts data points to [0,1], giving a standard deviation within the same range.

4.4.5. Indicator 5 – Spread/Ramp rate

The fifth indicator, i_5, captures the rate of change in a user's load. A larger rate presumably shows that one powerful or several less powerful but jointly controlled appliances are turned on or off within the FVI zone, which can provide opportunities to reschedule the sudden changes in consumption. As such, i_5 is calculated using data from within the FVI zone as:

$$i_5 = 1 - \frac{q_{0.01,\text{user}}}{q_{0.99,\text{user}}} \tag{8}$$

where $q_{0.01}$ and $q_{0.99}$ are the lowest and largest percentiles of the user's consumption. This indicator is between [0,1], being closer to 1 if a large difference exists between the percentiles and vice versa with 0.

4.5. Indicator visualization

In Fig. 2 the five indicators presented are visualized. The grid load reference is represented by a thick blue line, where the thin and solid black line incurs a higher score than the thin and dashed black line in every case. In *(a)*, the solid line has a stronger correlation with the reference; in *(b)*, it has a larger average; in *(c)*, more of its larger values coincide with the reference; in *(d)*, it has a larger variance; and in *(e)*, it has a larger spread between larger and smaller values.

4.6. Forming the flexibility value index

The FVI is generated by multiplying all the indicators. The indicators are multiplied together for three reasons: (1) it keeps the index bounded within [0,1]; (2) the bounded index range makes it comparable between different users, categories, and locations; (3) it provides a clear numerical distinction among studied users, supporting a more definitive ranking. Thus, it is formulated as:

$$\text{FVI} = \prod_{k=1}^{5} i_k \in [0, 1] \tag{9}$$

5. Results

This section illustrates the flexibility evaluation using the FVI on data from seven different types of electricity users in Uppsala, Sweden, during 2021 with an hourly resolution. Six user types were defined as "large" and consisted of a single public or commercial activity with a typically larger load. The seventh type consisted of several residential consumers split into four groups based on their subscriptions (fuse size and number of phases). The residential data were provided by Vattenfall, a major DSO in Sweden, and comprised anonymous and randomly chosen households' consumption data. The larger users' data were provided by their respective owners, and the local grid load reference data came from the UPP network area, in which all studied users

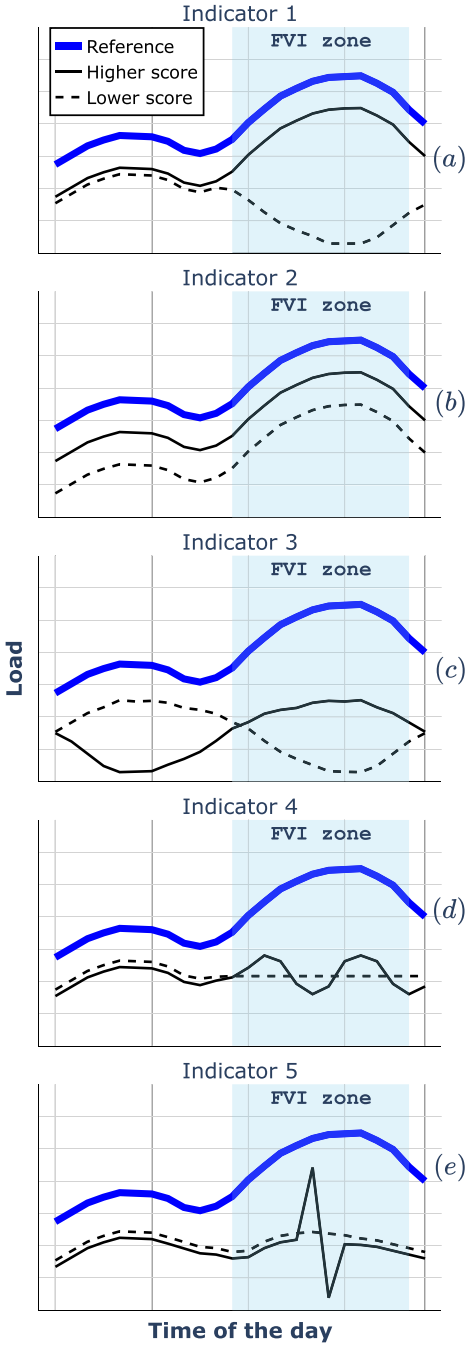

Fig. 2. Visualization of the indicators.

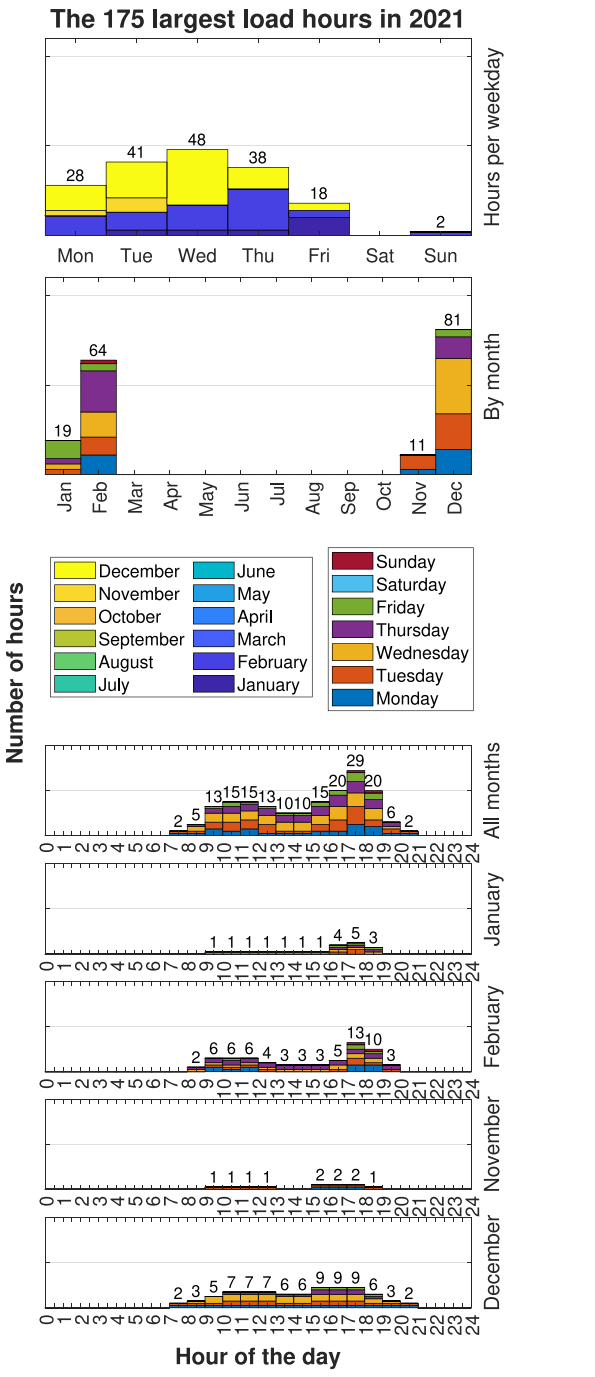

Fig. 3. Occurrences of the 175 largest load hours in studied grid, UPP, during 2021.

were located, and was provided by the Swedish TSO.[1] The following list summarizes the studied users:

- **Larger users**
  - A train station building with a waiting room, a pharmacy, and food places.
  - An office with a few hundred workers.
  - An outdoor sports facility with football fields during the summer and ice rinks during the winter.
  - A high school with a few hundred pupils.
  - A garage with around 50 EV chargers.
  - An old goods depot building transformed into a commercial space for a few stores, a cafe, and a restaurant.
- **Smaller users**
  - 46 apartments (16 A 1-phase).
  - 125 apartments (25 A 3-phase).
  - 130 single or double houses (16 A 3-phase).
  - 62 single or double houses (35 A 3-phase).

[1] The network areas in Sweden and their extension can be examined at https://natomraden.se/.

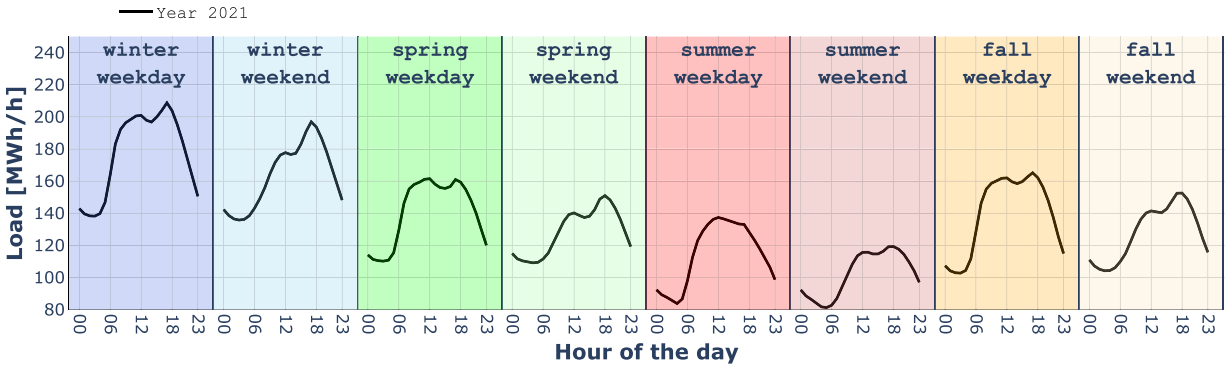

Fig. 4. Average hourly grid load in UPP during 2021 for each subset.

The consumption data from the train station and the old goods depot building did not include the separate business owners' consumption, only the lighting/ventilation/elevators, called a "peripheral" load. In addition, each data source was pre-processed using standard measures where individual users with numerous missing values or registered zeros were removed, and those kept had the faulty values interpolated between the existing ones.

5.1. Data subsets

Each day in the data was sorted into eight subsets based on the ambient temperature that was connected to the four recurring seasons in Sweden and whether the day was a typical working day (Monday to Friday) or a typical day off (Saturday and Sunday), similar to as in [76]. Since temperature and normal working days significantly impact electricity consumption, this split improved the identification of valuable differences. The grid's average load in these subsets is shown in Fig. 4.

5.2. High grid load hours and flexibility time window

When the time window, i.e., the FVI zone, is selected manually, it should be centered around the daily demand patterns in the studied grid to identify the users that could contribute with (more) valuable flexibility. Two transformer stations are located inside the network area used for the grid reference in this study, which connects the grid to the TSO's transmission system. Previously, these two connection points have exceeded their subscription limit around 2% of the time annually (i.e., around 175 h) and consistently during the winter [77]. In Fig. 3, the 175 highest grid load hours in UPP and their occurrence during 2021 are shown. It can be concluded that most of the highest load hours occurred between 14:00 and 20:00 during weekdays. They were also concentrated to typical winter months, aligning with the previously reported limit exceedance at the TSO stations in UPP.

5.3. Evaluated cases

The FVI assessment was conducted over three cases: Case 1 focused on winter weekdays and utilized a FVI zone that included the typical high load hours found, set to start at 14:00 and end at 20:00. The other two cases allowed the FVI zone to start at midnight in all subsets and then shifted it over the day with durations ranging from one to five hours through where Case 2 aimed at finding the start time and duration for the single largest FVI, and Case 3 did the same but for the largest average index value.

5.3.1. Case 1: Winter weekdays

Case 1 is explained and visualized in detail using the larger users during winter weekdays. The average daily consumptions of the larger users in this subset are shown in Fig. 5 together with the selected FVI zone highlighted in blue. Note that the sports facility had a much larger consumption than the other users, and a red dashed line and a separate y-axis represent it. The legend shows each users' FVI in decreasing order using a base of 10^{-6} to avoid displaying decimal numbers with several leading zeros. In Table 5, each resulting indicator from winter weekdays are listed for each of the larger consumers. Since the aggregated grid load is significantly larger than each separate user's load, the second indicator, i_2, is shown with a base of 10^{-3}.

Among the larger consumers, the sports facility had the largest FVI, mainly due to its much larger average load, indicator i_2, but also due to its high load hours coinciding with the grid's high load hours, indicator i_3, and the facility's ramp rate, indicator i_5. The train station and high school ranked second and third in terms of the FVI. While the high school had several larger consumption values within the FVI zone compared to the train station, it still was assessed to a lower FVI as the train station had a stronger correlation, indicator i_1, and more coinciding high load hours. At the bottom, the supermarket coolers ranked last, which is perhaps not surprising as they constantly run to keep a stable temperature and only have a slightly increased load when the cabinet doors are opened more frequently, which is indicated by a low score on both i_2, i_4, and i_5.

The results for evaluating the smaller residential consumers are summarized by Table 6. Due to the larger numbers of users in these groups, the tablet is limited to the largest five FVIs in each subscription group in addition to the group's average index value. A few users in each group had a significantly larger FVI than the group average, but the index value decreased quickly from the top-ranked users. This is especially prominent in the apartment group with 25 A 3-phase, where the top-ranked user had an FVI over ten times larger than the group's average. This user, and the top-ranked users in the single or double house-groups, had an FVI comparable to the two lowest-ranked larger users studied.

5.3.2. Cases 2 and 3: Highest FVI values

The goal of Case 2 and Case 3 was to find the largest single and average FVIs in each subset, respectively, using a shifting time window over the whole day, and the results are presented in Table 7 for the larger consumers. The largest single and average FVIs over all subsets are marked in bold with red as a comparison for other index values, and the results became quite similar for both Cases 2 and 3. The sports facility always had the largest single FVI, generally followed by the train station and the EV garage. The longest FVI zone occurred on winter weekdays from 15:00 to 18:00. Notable is that most often, the largest values in both these cases were found during the afternoon using a shorter zone of one hour, typically when the grid load started to increase or peak, referring to Fig. 4. The resulting FVI zone commonly

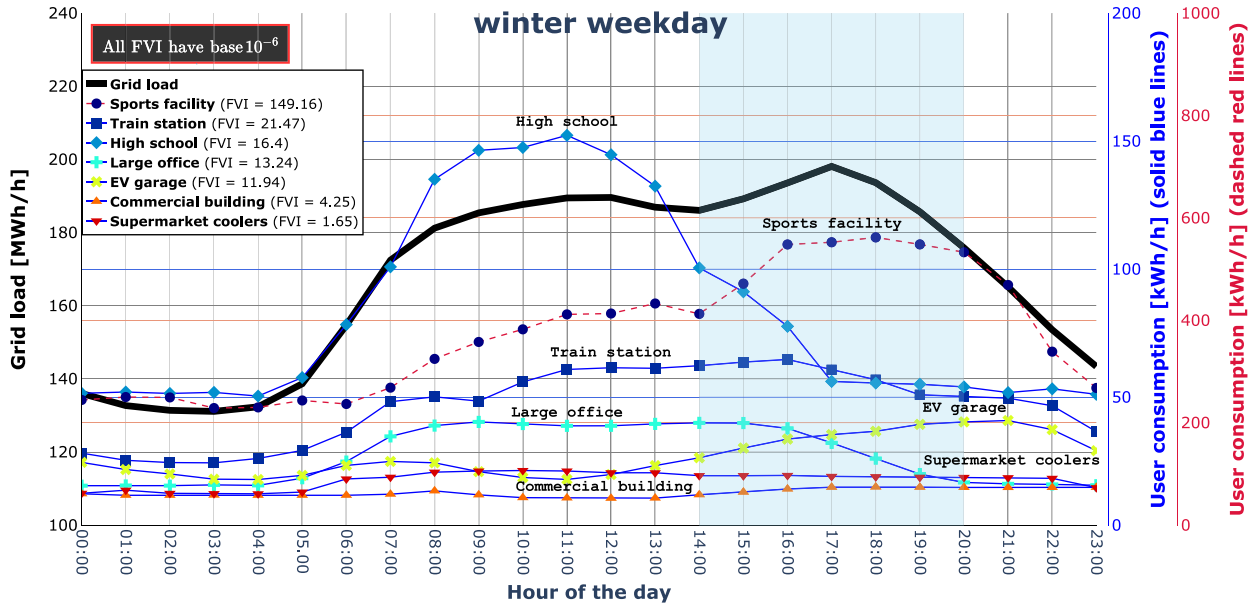

Fig. 5. The average daily time series for the UPP grid and the larger consumers during winter weekdays. The blue rectangle between 14:00 and 20:00, which captures the typical grid high load hours, indicates the FVI zone in which the users were evaluated.

Table 5
Each indicator and resulting index for the larger consumers during winter weekdays with an FVI zone between 14:00 to 20:00, as shown in Fig. 5. Note that indicator i_2 and the FVI are represented with another base compared to the other number to avoid many leading zeros.

What	Explanation	EV garage	SM coolers	High school	Large office	Sports facility	Train station	Comm. building
i_1	Average rescaled correlation	0.57	0.56	0.60	0.68	0.44	0.73	0.50
i_2	Average magnitude user/grid (base 10e−3)	0.18	0.10	0.37	0.16	2.74	0.31	0.07
i_3	High load coincidence probability	0.82	0.66	0.47	0.62	0.84	0.79	0.70
i_4	Standard deviation of min–max norm	0.16	0.18	0.24	0.27	0.17	0.24	0.25
i_5	Ramp rate based on quantiles	0.84	0.24	0.66	0.71	0.87	0.51	0.67
FVI	**Indicator product index (base 10e−6)**	**11.94**	**1.65**	**16.40**	**13.24**	**149.16**	**21.47**	**4.25**

Table 6
Evaluation of the seventh user type consisting of residential consumers using the FVI during winter weekdays between 14:00 to 20:00.

Residential user subscription group	Average FVI	#1 FVI	#2 FVI	#3 FVI	#4 FVI	#5 FVI
Apartments 16 A 1-phase	0.06	0.32	0.3	0.19	0.17	0.15
Apartments 25 A 3-phase	0.12	1.33	0.43	0.39	0.34	0.32
Single or double houses 16 A 3-phase	0.42	1.88	1.76	1.7	1.46	1.35
Single or double houses 35 A 3-phase	1.78	5.5	3.76	3.53	3.53	3.28

started a few hours earlier on weekends, and compared to Case 1, the FVI was larger for both Cases 2 and 3. Also, an important note is the variety of starting times, durations, and resulting FVIs over the subsets — especially in comparison to using all data that is included for both Cases 2 and 3. The detailed results for the smaller residential consumers can be found in Tables A.1 to A.4 in the Appendix. The durations of the FVI zones to find the largest index values were generally short and similar to the larger consumers, while the starting times differed a little bit. For the apartments with the smallest subscriptions, the FVI zones that gave the largest average values tended to start an hour later compared to the houses with the largest subscriptions, but in general, the groups had similar starting times and durations. Interestingly, the largest average FVIs were found during weekends for all the residential groups. For the individually largest FVI, there were two subsets – spring weekdays for the houses with a smaller subscription and fall weekdays for the larger subscriptions – where the largest values, in contrast to all others, were found in the morning between 07:00 to 08:00.

6. Discussion

Overall, the residential users' FVIs were significantly smaller than among the larger consumers. However, within the residential subscription groups, both the largest single and average FVIs increased several times over from apartments with 16 A 1-phase subscriptions to houses with 35 A 3-phase. The advantage of the smaller residential consumers is their numbers, and aggregating them could give a combined FVI of considerable size.

Otherwise, the most interesting result is how the FVI differed over the eight subsets. When grid alleviations were needed the most during winter weekdays, the FVI was not the largest; that occurred during the fall weekends for both Cases 2 and 3. The sports facility heavily

Table 7
The results for the larger consumers over all subsets when searching for the largest single and average FVIs, marked with bold red. The abbreviations refer to winter (win), spring (spr), summer (sum), fall (fall), weekday (wd), and weekend (we).

	Seas.	Days	Start time	Dur. (h)	Avg. FVI	#1 FVI	#2 FVI	#3 FVI	#1 User	#2 User	#3 User
Largest single FVI	ALL	ALL	17	1	53.74	338.10	9.66	9.12	Sports facility	Large office	EV garage
	Win	**wd**	18	2	31.95	188.38	13.91	13.15	Sports facility	EV garage	Train station
		we	14	1	45.62	259.72	27.48	19.1	Sports facility	Train station	EV garage
	Spr	**wd**	18	1	60.63	398.04	12.38	5.44	Sports facility	EV garage	Commercial building
		we	13	1	66.06	450.99	3.57	2.66	Sports facility	Train station	Large office
	Sum	**wd**	18	1	26.94	149.42	14.94	10.06	Sports facility	EV garage	Train station
		we	14	1	70.25	451.46	14.57	11.65	Sports facility	Train station	EV garage
	Fal	**wd**	15	1	118.85	748.81	25.11	19.59	Sports facility	Train station	Large office
		we	14	1	**132.40**	**880.01**	19.74	15.92	Sports facility	Train station	EV garage
Largest average FVI	**ALL**	**ALL**	12	1	53.93	266.50	72.56	19.96	Sports facility	High school	Large office
	Win	**wd**	15	3	33.47	166.91	21.13	14.09	Sports facility	Train station	High school
		we	14	1	45.62	259.72	27.48	19.1	Sports facility	Train station	EV garage
	Spr	**wd**	18	1	60.63	398.04	12.38	5.44	Sports facility	EV garage	Commercial building
		we	13	1	66.06	450.99	3.57	2.66	Sports facility	Train station	Large office
	Sum	**wd**	10	1	30.85	87.66	82.58	18.62	Sports facility	High school	Large office
		we	14	1	70.25	451.46	14.57	11.65	Sports facility	Train station	EV garage
	Fal	**wd**	15	1	118.85	748.81	25.11	19.59	Sports facility	Train station	Large office
		we	14	1	**132.40**	**880.01**	19.74	15.92	Sports facility	Train station	EV garage

influenced the average FVI due to its large value and the sample size of larger users evaluated. If the public entities in Uppsala want to start searching for valuable flexibility in the local grid, the sports facility is a given user to examine further. Of the other larger users evaluated, most of their loads likely came from HVAC systems or other peripheral loads, except for the EV garage, where the majority of the load came from EV charging. The EV garage also opened at the end of 2020, just before the studied period in this paper, and if the number of EVs has been increasing since then, the garage's load may have become an even more valuable flexibility resource — something that hopefully can be realized by using different so-called "smart" charging schedules.

An important reminder is that the FVI cannot tell if the users with a higher result can be flexible, but changing their consumption could provide a valuable ancillary service for the grid. To find out if the identified value is realizable, one must map out what appliances the users have, how much electricity they consume, when they are active, and if their operations can be changed based on, e.g., comfort and process requirements. The idea of the FVI is consequently to help identifying those users where this should be studied in more detail. As the FVI does not model an energy or power that could be measured, but rather quantifies a perceived dimensionless value, it cannot be directly verified. Domain knowledge could be useful in this process to provide insights regarding, e.g., if certain types of users tend to be more or less controllable. This could be a topic for further research, which would include field work to, e.g., study the larger consumers included in this paper to analyze what lies behind their load behavior and if it can be changed, or send out surveys to the studied residential consumers and investigate if the consumers with the larger FVIs could provide more power and energy to the system at a given signal.

The presented method could also be utilized in further studies to identify what RES sources would be a good match for different users. By changing the reference from an aggregated grid load to the production from, e.g., PV or wind, the index would give a score based on how well the production pattern from the RES would fit with different users' consumption behaviors, where a larger index value would indicate a better match. Such an analysis could help to, e.g., reduce the grid stress in rural areas by leading to a higher amount of the local production would be self-consumed.

7. Conclusions

Quantifying the flexibility from different building and user types is an open issue. In this study, we have proposed a method based on five indicators to evaluate the potential flexibility value of any number of electricity users through a model-free and discussion-friendly metric called the flexibility value index (FVI). The index is designed around accessible and limited information, and it requires only the evaluated users' electricity consumption data, which can be acquired from energy meters, and a referenced based on (local) grid load data, which can be accessed through open data sources or estimated if needed. The used indicators are transparent, and the constructed index is a ratio-type variable with a determined zero and bound to be between [0,1], making it both rankable and comparable between users and locations. The presented index can support organizations, such as public entities or grid operators, to focus their time and resources on users within their organizations that have a flexibiliy potential that is valuable from a system perspective, thus providing input for strategic decision-making. Additionally, its technologically-agnostic nature makes it easier to communicate.

Seven types of user activities were studied in this paper. Six of them were represented by a single larger public or commercial user, while the seventh type was represented by four different subscription groups of residential consumers consisting of 62 to 130 individual households in each. Three cases were studied, where Case 1 assessed the FVI in a time interval around typical grid peak load hours in the studied grid, while Cases 2 and 3 used a dynamic starting time and time interval to find the largest single FVI and average FVI respectively among the larger users and in each residential subscription group. The results showed that the larger consumers had a significantly higher potential value than the residential consumers in general, but also that the FVI differed a lot over the eight subsets created to separate different seasons and types of days for an independent analysis; for instance, the largest average FVI was 4.9 times bigger than the lowest average FVI among the larger users, and for the smaller users 2.2 times bigger considering all residential groups in Case 3. All data without any splits was also included as a comparison, and as it was only occasionally similar to a few of the subsets, it emphasized the need to split the studied data into different subsets based on the local context. The indicators typically scored higher in Cases 2 and 3, where the dynamic time interval almost always found the largest FVI using a FVI zone of one hour, compared to Case 1, which used a five-hour FVI zone. As a DR event often lasts a few hours, this is not a problem but rather the opposite.

A final point is which user to focus efforts on to realize flexibility. Reaching a similar FVI as the largest single user studied, the sports facility, during Case 1 would require around 2500 apartments with the smallest subscription or close to a hundred houses of the largest

subscription, using average group values. In contrast, matching the second ranked largest user, the Train station, would require around 350 apartments or 12 houses. When trying to find and realize potential flexibility values, it is important to consider if it would be easier to contact/promote/control a few larger users or many smaller ones. This process may heavily rely on domain knowledge, and further work will likely be needed to gain insights into the study users to answer this question fully. For instance, the largest FVIs among the residential consumers were seemingly connected to typical dinner (and breakfast) time in Sweden, which perhaps makes the load behavior challenging to alter without an ESS. Another trend was that a few users circulated the top positions over several subsets, which also was the case for the larger consumers. Thus, the FVI assessment would suggest approaching these consumers first and then continuing along the ranked list to search for system-valuable flexibility.

CRediT authorship contribution statement

Carl Flygare: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Marcus Nystrand:** Investigation. **Robert Eriksson:** Supervision. **Valeria Castellucci:** Writing – review & editing, Supervision.

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.

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Appendix

See Tables A.1–A.4.

Data availability

Data will be made available on request.

Table A.1
Apartments 16 A 1-phase.

	Seas.	Days	Start time	Dur. (h)	Avg. FVI	#1 FVI	#2 FVI	#3 FVI	#1 User ID	#2 User ID	#3 User ID
Largest single FVI	**ALL**	**ALL**	20	1	0.06	0.64	0.16	0.16	28	81	26
	Win	**wd**	18	1	0.09	0.52	0.33	0.27	26	65	81
		we	20	1	0.13	0.75	0.58	0.43	26	81	28
	Spr	**wd**	20	1	0.07	0.57	0.23	0.19	28	81	26
		we	21	1	0.07	0.64	0.26	0.19	28	3	81
	Sum	**wd**	18	1	0.06	0.27	0.22	0.21	3	57	78
		we	18	1	0.10	0.46	0.33	0.33	3	5	78
	Fal	**wd**	15	1	0.07	0.97	0.48	0.18	28	4	81
		we	14	1	0.10	**1.3**	0.62	0.42	28	4	81
Largest average FVI	ALL	ALL	19	1	0.06	0.57	0.21	0.19	28	65	26
	Win	**wd**	19	1	0.09	0.45	0.44	0.3	28	26	65
		we	19	1	**0.14**	0.71	0.51	0.5	26	65	81
	Spr	**wd**	19	1	0.08	0.45	0.3	0.22	28	65	3
		we	19	1	0.10	0.42	0.37	0.32	28	81	3
	Sum	**wd**	19	1	0.06	0.23	0.23	0.21	5	3	57
		we	18	1	0.10	0.46	0.33	0.33	3	5	78
	Fal	**wd**	18	1	0.10	0.79	0.48	0.29	28	4	81
		we	19	1	**0.14**	0.98	0.61	0.45	28	35	4

Table A.2
Apartments 25 A 3-phase.

	Seas.	Days	Start time	Dur. (h)	Avg. FVI	#1 FVI	#2 FVI	#3 FVI	#1 User ID	#2 User ID	#3 User ID
Largest single FVI	**ALL**	**ALL**	17	1	0.14	0.91	0.58	0.50	101	67	69
	Win	**wd**	15	2	0.14	**1.61**	0.54	0.52	101	69	45
		we	14	1	0.14	1.59	0.54	0.44	101	146	16
	Spr	**wd**	17	2	0.16	0.84	0.61	0.52	101	69	16
		we	16	1	0.16	0.9	0.58	0.57	69	67	101
	Sum	**wd**	18	1	0.14	0.99	0.58	0.57	63	13	101
		we	16	1	0.17	1.01	0.81	0.59	69	101	85
	Fal	**wd**	18	1	0.17	1.28	0.57	0.54	101	67	12
		we	16	1	0.19	1.59	0.69	0.69	101	69	85
Largest average FVI	**ALL**	**ALL**	17	1	0.14	0.91	0.58	0.50	101	67	69
	Win	**wd**	17	1	0.19	1.6	0.69	0.62	101	69	45
		we	17	1	**0.23**	1.34	0.8	0.79	101	16	45
	Spr	**wd**	17	1	0.18	0.79	0.64	0.56	101	69	77
		we	18	1	0.21	0.8	0.57	0.56	101	65	69
	Sum	**wd**	17	1	0.14	0.73	0.65	0.63	69	63	101
		we	18	1	0.21	0.86	0.81	0.79	85	63	101
	Fal	**wd**	17	1	0.18	1.25	0.94	0.64	101	67	77
		we	17	1	0.21	1.58	0.72	0.7	101	85	75

Table A.3
Single or double houses 16 A 3-phase.

	Seas.	Days	Start time	Dur. (h)	Avg. FVI	#1 FVI	#2 FVI	#3 FVI	#1 User ID	#2 User ID	#3 User ID
Largest single FVI	**ALL**	**ALL**	19	1	0.45	1.71	2.04	9.12	96	63	10
	Win	**wd**	17	1	0.59	3.02	2.84	2.58	8	63	43
		we	18	1	0.66	3.5	2.59	2.59	63	8	33
	Spr	**wd**	7	1	0.25	2.41	1.47	1.08	63	33	44
		we	22	5	0.26	3.27	1.83	1.37	107	63	96
	Sum	**wd**	17	1	0.37	2.43	2	1.04	8	96	20
		we	17	1	0.51	**3.88**	2.13	1.61	8	96	117
	Fal	**wd**	17	1	0.57	3.71	2.44	2.02	8	96	46
		we	17	1	**0.68**	3.5	2.83	2.33	8	46	3
Largest average FVI	**ALL**	**ALL**	17	1	0.49	2.82	2.39	2.29	96	8	63
	Win	**wd**	17	1	0.59	3.02	2.84	2.58	8	63	43
		we	17	1	**0.68**	3.21	3.03	2.53	43	63	8
	Spr	**wd**	17	1	0.53	2.29	2	1.73	20	8	33
		we	18	1	0.64	2.73	2.56	2.39	20	63	96
	Sum	**wd**	17	1	0.37	2.43	2	1.04	8	96	20
		we	18	1	0.52	3.27	2.44	2.18	8	96	33
	Fal	**wd**	17	1	0.57	3.71	2.44	2.02	8	96	46
		we	18	1	**0.68**	2.9	2.57	2.56	46	63	8

Table A.4
Single or double houses 35 A 3-phase.

	Seas.	Days	Start time	Dur. (h)	Avg. FVI	#1 FVI	#2 FVI	#3 FVI	#1 User ID	#2 User ID	#3 User ID
Largest FVI	**ALL**	**ALL**	19	1	2.19	7.12	5.4	4.55	45	4	50
	Win	**wd**	16	1	2.08	6.66	5.38	4.38	4	45	50
		we	16	1	2.12	6.01	4.88	4.26	4	45	50
	Spr	**wd**	19	1	1.85	**7.42**	3.69	3.66	45	4	12
		we	19	1	2.28	5.67	5.29	5.01	45	4	50
	Sum	**wd**	18	1	1.11	5.11	3.62	3.33	2	52	73
		we	17	1	1.40	5.36	5.09	3.91	76	2	52
	Fal	**wd**	7	1	1.70	6.78	5.43	5.17	37	50	4
		we	12	1	1.79	7.24	5.41	4.96	45	37	50
Largest average FVI	**ALL**	**ALL**	19	1	2.19	7.12	5.4	4.55	45	4	50
	Win	**wd**	18	1	2.28	5.8	5.53	4.95	4	45	50
		we	17	1	2.30	5.59	4.61	4.61	4	45	50
	Spr	**wd**	19	1	1.85	**7.42**	3.69	3.66	45	4	12
		we	19	1	2.28	5.67	5.29	5.01	45	4	50
	Sum	**wd**	18	1	1.11	5.11	3.62	3.33	2	52	73
		we	18	1	1.44	5.34	5.26	3.91	76	2	52
	Fal	**wd**	17	1	2.20	6.52	6.02	5.05	4	45	64
		we	18	1	**2.46**	6.61	5.74	5.59	4	45	39

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