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Author(s)	O'Connell, Sarah; Reynders, Glenn; Seri, Federico; Sterling, Raymond; Keane, Marcus M.
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A Standardized Flexibility Assessment Methodology for Demand Response

Sarah O'Connell*[1], Glenn Reynders[2], Federico Seri[1], Raymond Sterling[3], Marcus M. Keane[1]

1. Informatics Research Unit for Sustainable Engineering, College of Engineering and Informatics, National University of Ireland Galway, Galway, Ireland.
2. EnergyVille, Genk, Belgium and VITO, Mol, Belgium.
3. R2M Solution, Madrid, Spain.

*Corresponding author: s.oconnell19@nuigalway.ie

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Abstract

Purpose – The purpose of this paper is to present a standardised four-step flexibility assessment methodology for evaluating the available electrical load reduction or increase a building can provide in response to a signal from an aggregator or grid operator.
Design/methodology/approach – The four steps in the methodology consist of Step 1: systems, loads, storage and generation identification; Step 2: flexibility characterisation; Step 3: scenario modelling; and Step 4: key performance indicator (KPI) label.
Findings – A detailed case study for one building, validated through on-site experiments, verified the feasibility and accuracy of the approach.
Research limitations/implications – The results were benchmarked against available demonstration studies but could benefit from the future development of standardised benchmarks.
Practical implications – The ease of implementation enables building operators to quickly and cost effectively evaluate the flexibility of their building. By clearly defining the flexibility range, the KPI label enables contract negotiation between stakeholders for demand side services. It may also be applicable as a smart readiness indicator.
Social implications – The novel KPI label has the capability to operationalise the concept of building flexibility to a wider spectrum of society, enabling smart grid demand response roll-out to residential and small commercial customers.
Originality/value – This paper fulfils an identified need for an early-stage flexibility assessment which explicitly includes source selection that can be implemented in an offline manner without the need for extensive real-time data acquisition, ICT platforms or additional meter and sensor installations.

1. Introduction

Buildings are becoming an integral part of the energy system as electrical grids evolve from an hierarchical, generation following load structure to a distributed smart grid. Energy flexibility, the ability of a building to reduce or increase its electrical load profile (Østergaard Jensen et al., 2017), is a key measure targeting the three core challenges of grid balancing, hosting capacity (of renewable generation) and stability (of frequency and voltage) (European Commission, 2016). To date, flexibility has been mainly provided by a small number of large industrial users (Ofgem, 2016). However, to enable hosting capacities for distributed renewable energy sources above 25% (DG Energy, 2013), it would be beneficial for a much greater variety of building types e.g. commercial office, multi-family buildings and residential to also participate and offer flexibility. Low participation rates of buildings in demand response services are a result of three main factors: a) regulation (e.g. restrictive energy tariffs and lack

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of appropriate programs) (Baak, 2017); b) lack of clarity around energy flexibility potential, i.e. quantification of flexibility and the financial cost or technical effort required to access it is not well understood (Ofgem, 2016) and c) difficulty in identifying, implementing and actuating many small sources of energy flexibility rather than a few large ones (Annala et al., 2018). This paper aims to address b) and c).

Different criteria apply, depending on the country or region, to enter flexibility markets or demand response programs. Commonly, Distribution System Operators (DSOs) or Transmission System Operators (TSOs) set minimum participation thresholds for demand side programmes based on MW power flexibility capability. For example, in Ireland, it is 4 MW (Eirgrid, 2018). In France direct participation at 0.1 MW (RTE, 2014) is permitted, and with recent regulatory changes (European Commission, 2018) lower levels may become more common. Buildings typically have power flexibility in the kW range, therefore, in most jurisdictions, they need an intermediary, known as an aggregator, to participate in demand side programmes.

Hence to enter flexibility markets, building operators must first assess the flexibility of the building and define its available range so they can negotiate with aggregators for contracts to deliver demand side services. At present, there is no standardised approach for this early stage flexibility assessment. Approaches vary from cursory to very detailed (Grønborg Junker et al., 2018). Cursory approaches are limited to easily accessible sources such as backup generators (Yi et al., 2018) or a focus on a few pre-selected systems, for example, thermal storage (Stinner et al., 2016), lighting (Ma et al., 2015) or HVAC (Kim, 2018). Detailed assessments, such as those incorporating an energy audit (Alczar-Ortega et al., 2015), have the advantage of applying a systematic and structured approach that relies on standardised assessment procedures such as IEA Annex 11, ASHRAE (Coakley et al., 2014) and ISO 50002:2014 (ISO, 2014). However, the systematic and detailed nature of a full energy audit results in many energy systems being analysed which do not provide flexibility. In addition, the implementation of these audits, which generally focus on energy conservation, for energy flexibility, requires an expert with a number of years' experience in a field such as energy auditing, energy management or electrical engineering to adapt the energy audit in a bespoke way so that it can be applied to flexibility. In parallel to detailed audits, significant research efforts are targeting dynamic, online or real-time flexibility characterisation and assessment (Grønborg Junker et al., 2018) (Hu et al., 2018) (Ottesen and Tomasgard, 2015). However, investments on-site are required to implement this, such as installing an ICT platform, additional sensors, meters and actuators and Building Management System (BMS) software upgrades. The disadvantages of these detailed approaches result in either a lack of clarity around energy flexibility potential or a detailed assessment is cost prohibitive resulting in a lack of participation or under participation in demand response services. The approach proposed in this paper is different in that it occurs at a much earlier stage, when the building operator or facility manager is considering participating in demand response programmes but has not yet determined the range in kW which their building can offer to aggregators or the grid.

The objective of this work is to introduce a methodology that defines the maximum bounds of the available power flexibility for the shortest and longest duration events that a building has the technical capability to deliver. The methodology is an off-line, early stage assessment which explicitly includes source selection. In standardising the approach and underpinning it with elements of the ISO 50002 energy auditing standard, which have been adapted by the author for flexibility, the methodology may be implemented by a technical person, who is not an energy or flexibility expert, in a cost effective and time efficient manner. It is to be conducted before any investment decisions in system upgrades, metering or ICT platforms to provide grid services are made.

The output of the proposed methodology is a novel Key Performance Indicator (KPI) label. It is a clear visual indicator which provides defined graphical and numerical metrics on the available power flexibility ranges and associated timescales, at a glance, for stakeholder decision making. The KPI label may also have applicability in the development of the new EU Smart Readiness Indicator (SRI) for buildings, included in the 2018 re-cast of the Energy Performance of Buildings Directive (EPBD) (Verbeke et al., 2018).

The EU Horizon 2020 project ELSA integrated local storage, in the form of second life Electric Vehicle (EV) batteries, to provide services to the grid (O'Connell and Riverso, 2016, 2017). This paper extends the evaluation of flexibility beyond storage to encompass all systems in buildings which have the capability to provide load or generation modulation.

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The structure of this paper is as follows: Section 2 reviews the current state of the art and identifies the contribution of this paper; Section 3 sets out the four-step flexibility assessment methodology developed; Section 4 is a detailed case study, validated through experiments at the building and Section 5 contains the conclusions of the research.

2. Current State of the Art in Energy Flexibility Characterisation

Section 2.1 reviews approaches for flexibility evaluation, specifically the quantification of flexibility and parameter representation, Section 2.2 reviews existing KPI labels while Section 2.3 evaluates available benchmarks for flexibility. Finally, Section 2.4 addresses the contribution of this paper.

2.1. Flexibility Evaluation

Flexibility has been quantified in a number of different ways. Evaluating the flexibility available at a site or building requires assessing the sources, i.e. loads, storage and generation available, identification of the associated relevant parameters and the quantification of those parameters. Two main elements are considered, i) quantification of flexibility to understand the capability of a source and ii) identification of parameters which are required to characterise the available flexibility of those sources. An analysis of existing approaches was conducted, and gaps identified, summarised in Table 1.

i) Quantification of flexibility

A formula for load flexibility developed by Ma et al. (2013), included three main elements for flexible loads, Sheddable, *S*, meaning it is capable of being turned off or turned down; Controllable, *C*, in that it has some form of automated control system, and Acceptable, *A*, meaning that it is acceptable to the building occupants and operators that the load be reduced or turned off. Flexibility is then calculated as a percentage of the total available load. In multiplying the minimum of C and A (which, as percentages, are <1), the formula may underestimate the available energy flexibility for a building. In addition, this formula focuses only on loads, on-site generation and storage are not included, even though they may provide flexibility. How the sources of flexibility are selected or their criteria are assessed on site is not clear. Identification and quantification of S, C and A for any given time period requires significant effort. There is no mention, for example, of access to historical site data, load profiles or documentation on systems and equipment which may need to be provided to an expert who may perform an energy audit, develop an assessment approach and then use these to deliver a customised evaluation of each criteria. In addition, other relevant parameters such as time in advance notification, are not captured.

A comprehensive review of flexibility quantification methodologies related to thermal storage was conducted by Reynders et al. (2018). From the reviewed approaches, those developed by D' Hulst et al. (2015), De Coninck and Helsen (2016) and Oldewurtel et al. (2013) are applicable to a range of flexibility sources, whereas methods developed by Nuytten et al. (2013), Stinner et al. (2016) and Reynders et al. (2015) were specifically deduced for thermal storage technology and their associated heat producing systems, but may be extended to other sources. However, in each of the methodologies presented, the method of source selection is not considered, in common with Ma et al. (2013) above.

In addition to the Reynders et al. (2018) review, several other methods were assessed. A statistical method (Sajjad et al., 2016) based on studies of time-variable patterns has the advantage of not requiring knowledge of the systems in the site or building but the disadvantages of requiring significant data, in common with D'Hulst et al. (2015), as well as lack of visibility on what systems are providing the flexibility and what their capabilities are. Other studies (Nosair and Bouffard, 2015) (Bucher et al., 2017) look at flexibility from the grid perspective only and do not consider building needs.

ii) Flexible System Description

There are many parameters that may be gathered for each system in the building, however, the important step is to identify the parameters that capture the flexible aspects of the system in a consistent, robust and repeatable way. These parameters may then be used as inputs for scenario modelling and KPI generation. For example, a heat pump system may have technical parameters such as power input, heat output, room temperature set point, Coefficient of Performance, flow temperature and refrigerant type. Of these, the first three are required for

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flexibility evaluation but the others may not be relevant. In addition, there are other parameters, not specified on equipment data sheets but available elsewhere, that are required to define how flexible the system is, these include system availability, percentage of sheddable load, time in advance notification and rebound or pre-heat requirements.

In terms of describing flexible systems using technical parameters, several sources define parameters, but approaches are not consistent and the selection and definition of appropriate parameters differs, as was also found by Reynders et al. (2018). Detailed parameter definition was set out by Alczar-Ortega et al., (2015), however the approach was limited to defining parameters and did not extend to flexibility characterisation. As part of scheduling sources for demand response, Siebert et al. (2015) identified some flexibility activation constraints, but many parameters were insufficiently quantified. There is an implicit assumption that source selection and flexibility have already been assessed and quantified in both this paper and in Ottesen and Tomasgard (2015). An interesting approach of identifying loads as classes is developed by Ottesen and Tomasgard (2015) but the overall approach may be limited to fixed price markets.

The proposed SRI evaluation method uses impact parameters for items such as energy savings, self-generation and comfort (Verbeke et al., 2018). However, in the context of the flexibility characterisation in this paper, these are output metrics rather than input parameters.

Table 1. Review of Previous Approaches and Comparison with Proposed Methodology

Reviewed Approach	Advantages	Gaps	Proposed Methodology
i) Flexibility Evaluation			
DR for Ancillary Services (Ma et al., 2013)	Concepts: Sheddable, S, Controllable, C, and Acceptable, A; Flexibility equation.	Method of determining S,C A not defined; Detailed parameters for loads omitted; Storage & RES not included.	Elements adapted: S, C, A concepts; Gaps addressed: Detailed parameters for loads incorporated; Storage & RES explicitly included.
Statistical Approaches (D'Hulst et al., 2015) (Sajjad et al., 2016)	Rich data set enabled statistical methods such as probability estimation of flexibility and time-variable patterns.	Sources of flexibility pre-selected (residential smart appliances) Required quantity of measured data may not be available.	Gaps addressed: Source selection explicitly included; Does not require large quantities of measured data.
Optimal control approaches (De Coninck and Helsen, 2016) (Oldewurtel et al., 2013)	Dynamic data driven methods which do not require domain knowledge. Automatic parameter identification.	Require significant amounts of data, an ICT platform and if implemented for control, online, real-time data acquisition and actuation capability. Source selection not addressed.	Gap addressed: Early stage flexibility assessment to identify sources prior to installation of ICT platform or other on-site modifications required to enable online real-time control approaches
(Nuytten et al., 2013)	Available flexibility for every hour calculated. Theoretical maximum flexibility	Focused on thermal systems. Electrical power flexibility not considered.	Elements adapted: available flexibility calculated for every hour; Maximum flexibility. Gaps addressed: Focus on electrical systems; Power flexibility explicitly evaluated and range defined.

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Reviewed Approach	Advantages	Gaps	Proposed Methodology
	calculated. Time periods associated with pre-load and re-bound well quantified		
Quantifying Operational flexibility with thermal energy storage (Stinner et al., 2016)	Quantified in terms of time, power and energy. Power curves bounded by maximum and minimum ranges. Average power flexibility defined.	Some aspects of approach specific to building energy thermal storage	Elements adapted: time, power and energy quantification; Maximum and minimum ranges; average power flexibility. Gap addressed: Methodology applicable to a wider range of building systems.
Reduced order physics based models (Reynders et al. 2015)	Storage capacity, storage efficiency and power shifting potential well quantified.	Limited to building energy thermal storage. Requires a model of a building to implement.	Gaps addressed: Applicable to all electrical building systems; Source selection explicitly included; Model of a building is not required.
Grid perspective (Nosair and Bouffard, 2015) (Bucher et al., 2017)	Focuses on parameters important for grid operators	Building needs not considered. Evaluation of systems and equipment in buildings not considered.	Gaps addressed: Addresses evaluation of flexibility from building perspective; Includes detailed evaluation of building systems.
ii) Parameter Identification			
Certification Prerequisites for DR trading (Alczar-Ortega et al., 2015)	Detailed parameter definition.	Approach limited to defining parameters.	Gaps addressed: Comprehensive assessment methodology; Detailed parameters incorporated.
Scheduling DR and Smart Battery flexibility (Siebert, et al., 2015)	Some flexibility activation constraints identified; Optimisation inputs defined.	Insufficient quantification of parameters; Booleans may not account for load reduction; Flexibility not explicit in approach; Assumption that flexibility (kW/MW) has already been assessed & quantified; Simplified use cases i.e. only one load from each site considered.	Element adapted: Some parameters utilized. Gaps addressed: Comprehensive assessment methodology; Partial loads permitted; Flexibility explicit in approach; Multiple loads from each site included in assessment;
Stochastic scheduling of energy flexibility (Ottesen, and Tomasgard, 2015)	Loads identified as classes; Optimisation inputs defined; Less tied to specific use cases.	Insufficient quantification of parameters; Assumption that flexibility (kW/MW) has already been assessed & quantified; Pricing structure may be limited to fixed price markets.	Gaps addressed: Comprehensive assessment methodology; Classes added to parameter definition; Not linked to any specific price structure.

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2.2. KPI Representation

To facilitate wider participation in flexibility, the key metrics which identify the flexibility of a building need to be communicated in an easily understood, technically relevant and concise manner. A standardised KPI label has the ability to provide a visual, efficient and consistent means of providing actionable data. It can facilitate decision makers in efficiently assessing a site, while providing data that is actionable in terms of deciding what demand side programmes the building can participate in. Building operators require it to choose the demand side programme which is the best fit, or to determine if it is advantageous to participate in the first place. For aggregators it will reduce time, cost and effort in assessing a building's range when creating portfolios of buildings to meet the minimum MW thresholds set by grid operators. Similarly, for DSOs and TSOs instead of reading a lengthy report, the key information is summarised in a concise and relevant way.

Standardised KPIs to measure flexibility in buildings have not yet been developed. KPIs to measure different metrics relating to energy in buildings and communities have previously been proposed by a number of European projects. In addition, the Building Energy Rating (BER) implemented as a result of the EPBD is example of a KPI label with a strong visual impact.

Four KPIs and an energy positivity label for Energy Positive Neighbourhoods (EPN) were developed by Ala-Juusela et al. (2015). The objectives of the KPIs were to enable an assessment of the energy positivity of a neighbourhood and to operationalise the concept of an EPN. KPIs such as Maximum Hourly Surplus, monthly Ratio of Peak hourly demand to Lowest hourly demand may have applicability if adapted for demand response.

The European FP7 project S3C, included 5 possible KPIs for demand response as part of the 13 KPIs in their toolkit for smart grid consumer engagement (S3C, 2012). While the KPIs are aimed at domestic householders, similar parameters may be applicable for commercial and industrial sites. KPIs included peak to average ratio which is useful as it gives an indication of whether there are fluctuations in the power consumption profile. Other KPIs such as energy shift ratio and peak reduction capacity may be interpreted as measuring the same quantities. However, for TSOs and DSOs absolute values may be more relevant.

The EPBD (European Parliament, 2002, 2010, 2018) mandated all member states to introduce Building Energy Rating systems, for commercial, domestic and public buildings. The compulsory nature of the label has helped its adoption even if compliance levels among member states varies (Jenkins et al., 2017) (Pan and Garmston, 2012). The 2018 EPBD recast added the SRI for buildings as optional.

Therefore, in the development of a KPI label a) targeting relevant user requirements which are measurable is key; b) minimising the number of KPIs and ensuring there is no overlap in metrics avoids over-complicating the indicators being communicated; c) a visual indicator in addition to numerical data points increases the likelihood of adoption and d) energy flexibility is a recognised concept in the scientific and technical community, however, it may not be as familiar to facility managers and building operators and a KPI label may help to operationalise the concept more widely

2.3. Benchmarking

Benchmarks for typical and best practice energy consumption for a range of different types of buildings have been standardised through documents such as CIBSE TM46 (Field, 2008). However, similar benchmarks for flexibility have not yet been established but will be required for the SRI implementation (Verbeke et al., 2018). Published results of demonstration studies are rare, as much of the available research in flexibility focuses on simulation (Grønborg Junker et al., 2018) (Reynders et al., 2018) (Stinner et al., 2016). A number of demonstration studies in real buildings were reviewed to understand how much flexibility is typical in buildings.

Studies involving large numbers of real buildings, in some cases up to 28, participating in utility DR programmes were conducted in California. Employing pre-cooling prior to Critical Peak Pricing (CPP) periods resulted in flexibilities of $10 - 25\%$ of peak load during a three-hour event (Xu and Zagreus, 2009). In another study, 18 - 56% of peak load flexibility was achieved for short timeframes, with average flexibilities of $7 - 9\%$ demonstrated during longer events (Piette et al., 2006).

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Combining Li-ion battery storage, grid connected PV and loads across eight buildings and industrial sites, Siebert et al. (2015) demonstrated 15% combined flexibility during a 30-minute event. For the buildings, heating was used as the load. A study conducted by Picault et al. (2015) demonstrated a 50% reduction against peak load in buildings for a two-hour event. As part of the European FP7 project Grid4EU (Grid4EU, 2016), commercial businesses and residential customers participated in a peak demand reduction demonstration. The total reduction across the 12 businesses was between 3% and 9% of combined demand over a 2-hour duration. Individual demand reduction for each site was not given. In the same study, 180 residential customers reduced their power consumption by 21% on average. However, this only contributed to an overall load reduction of 5% compared with a 52% overall load reduction from the businesses.

2.4. Contribution of this Paper- Advancing the State of the Art

Lessons learned from the reviewed approaches include a) The concepts of Shedability, Controllability and Acceptability (S, C, A) have the potential to be utilised for source selection, if they are adapted and applied in a different way; b) to effectively assess building flexibility, it must be approached from a building system perspective and not a grid perspective; c) all types of energy storage and on-site generation need to be explicitly included in flexibility analysis; d) a comprehensive assessment methodology that is sufficiently adaptable to capture all types of sources of energy and power flexibility, not focusing on pre-selected sources, is required; e) the methodology needs to be independent of price structure; and f) detailed parameters for flexible sources are required to be comprehensive and consistently applied across all sources during flexibility characterisation.

The proposed methodology addresses each of these lessons learned to develop an early stage, standardized, easily applicable flexibility assessment methodology, explicitly including source selection thereby advancing the state of the art and enabling greater participation by buildings in demand response programmes. Power flexibility and the associated time duration over which it can be delivered are what matters most to aggregators and grid utilities and these are clearly identified on the KPI label. Widespread adoption is facilitated through ease of implementation in a time efficient and cost-effective manner without requiring extensive data acquisition, complex modelling or investment on-site. The flexibility assessment methodology is presented in Section 3.

3. Flexibility Assessment Methodology

Based on the analysis in Section 2, a four-step flexibility assessment methodology was developed. The four steps in the methodology, shown in Figure 1, are Step 1: Systems, Loads, Storage & Generation Identification; Step 2: Flexibility Characterisation; Step 3: Scenario Modelling and Step 4: KPI Label.

In terms of the overall structure of the methodology, elements of the ISO 50002 energy auditing standard were adapted by the author as a means of providing a robust framework for this early stage flexibility assessment. The adapted elements were modified to focus on determining the quantity and duration of power and energy which may be increased or decreased instead of addressing energy conservation measures. This reduces the specialized expertise needed to implement the audit, while addressing the key objectives of the flexibility analysis. Relevant parts of the audit procedure which were selected, applied and modified are identified in Sections 3.1 to 3.4 below. The detailed case study in Section 4 illustrates the application of the method.

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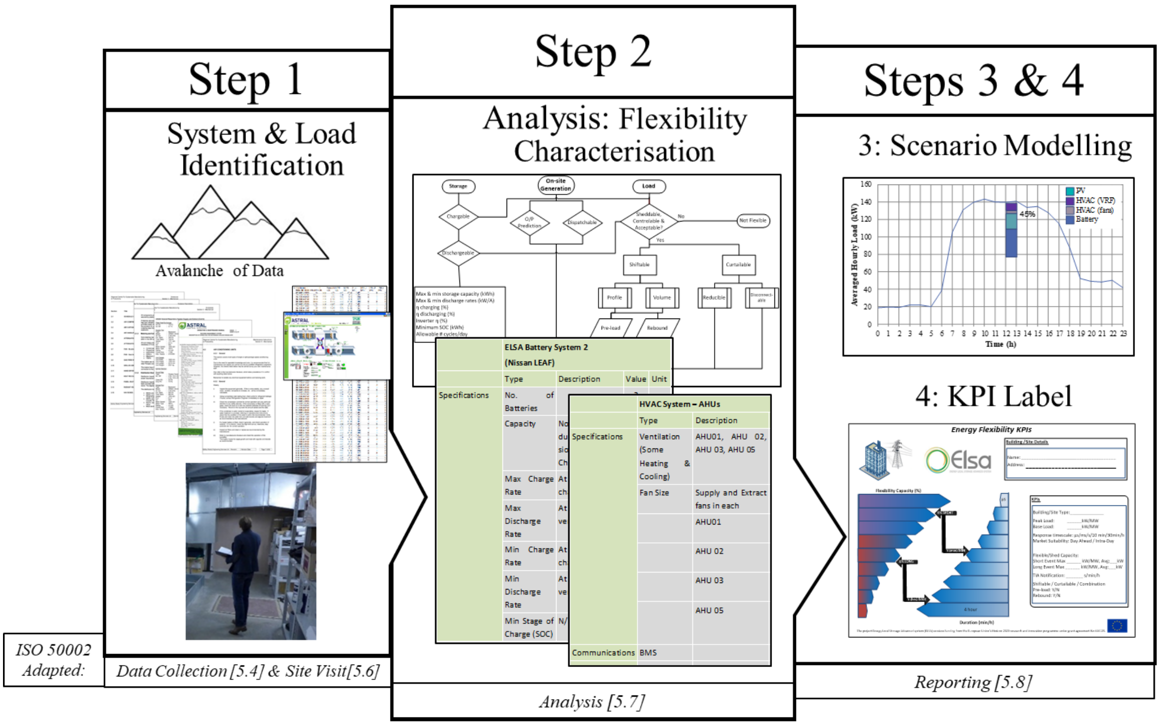

Figure 1. Four-step Flexibility Assessment Methodology Infographic

3.1. Step 1: Systems, Loads, Storage & Generation Identification

As a first step, it is necessary to identify the power and energy systems in the building being assessed and establish how much power, in kW, and energy, in kWh, is available to flex. To do this, the building and its energy systems are evaluated.

The evaluation procedure has been adapted from Part 5.4 (Data Collection) and 5.6 (Conducting the site visit) of the ISO 50002. The adaptation modified the following criteria:

- Audit objective was re-defined as determining the power and energy flexibility of a site by identifying and quantifying loads, local renewable and non-renewable generation and on-site storage which have the capability (or potential) to reduce electrical power consumption on demand;
- Scope was modified to flexible systems as opposed to all energy systems;
- Energy conservation measures were modified to become energy flexibility improvement opportunities.

Data Collection is used to gather information on the systems from the available sources such as engineering drawings and specification documents, operation and maintenance files, BIM models and building automation systems such as BMS, metering systems or SCADA. Information to be gathered includes power and energy consumption of flexible systems, identification of sensors and actuators required to measure and implement flexibility and characteristics such as rated power input. Conducting the site visit is recommended to enable the individual conducting the assessment to confirm if the drawings and specifications match what is installed in the building, assists in physically understanding what systems are present and how they interact with the building and each other. For example, it is often easier and quicker to trace which electrical meter is associated with a specific item of equipment on-site in the building than from documentation. During Step 1, it is important to assess systems at a high level only and avoid detailed analysis such as energy consumption profiles of individual systems. This level of detail is addressed in Step 2: Flexibility Characterisation.

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3.2. Step 2: Flexibility Characterisation

Flexibility Characterisation is the analysis step in the flexibility assessment and is a novel approach, developed by the author and does not share common factors with the analysis process from energy audits, hence replacing part 5.7 (Analysis) from ISO 50002. The primary aim of the flexibility characterization process, shown in Figure 2, is to perform source selection by filtering out flexible systems from non-flexible systems and guide the detailed analysis of those flexible systems to identify key parameters.

Filtering is performed using the concepts of Sheddability, Controllability and Acceptability (S, C, A) from Ma et al. (2013), but adapting them and applying them in a different way. In practice the filter stage is implemented as follows: if the answer to the question 'is a load Sheddable (capable of being turned down or off), Controllable (capable of being controlled by an automated system such as a BMS or SCADA) AND Acceptable (is it acceptable to the building operator and occupants to reduce or turn off this load)?' is not 'yes' for all three, then the load is not flexible, and the assessment process moves on to the next load, storage or renewable generation system. The two advantages of this approach are i) flexible sources are selected in a systematic way and ii) the volume of building data, drawings and specifications to be analysed is significantly reduced. For example, if only 20% of the systems are capable of providing flexibility, this reduces the analysis effort by up to 80% compared with a full energy auditing approach.

On-site generation and storage are explicitly included in the flexibility characterisation process, unlike previous approaches reviewed. Storage may be electrical or thermal and it may be considered flexible if it shifts or reduces electrical consumption in the building in a controllable way. As these systems are less numerous than loads and have different initial selection criteria, the S, C, A filter is not required.

Through applying the flexibility characterisation process in Figure 2, parameters associated with each source of flexibility are collected and stored in the flexibility matrix. An example of its application is given in the case study in Section 4. Selection of relevant parameters is based on the flexible system description review performed in Section 2, which determined that detailed parameters for loads are required to be comprehensive and consistently applied across all sources during flexibility characterisation. For example, incremental power flexibility increase or decrease in kW associated with each flexible system, minimum and maximum storage capacity (the energy a storage system can store in kWh) and minimum and maximum discharge rates, (the instantaneous power output the storage system can deliver in kW). Other parameters stored include time duration of availability for demand response events in seconds, minutes or hours; pre-load or rebound power with associated time constraints; Time in Advance (TIA) notification in minutes or hours and the time period during which requests are permitted. These parameters are then utilised in Step 3: Scenario Modelling and Step 4: KPI Label.

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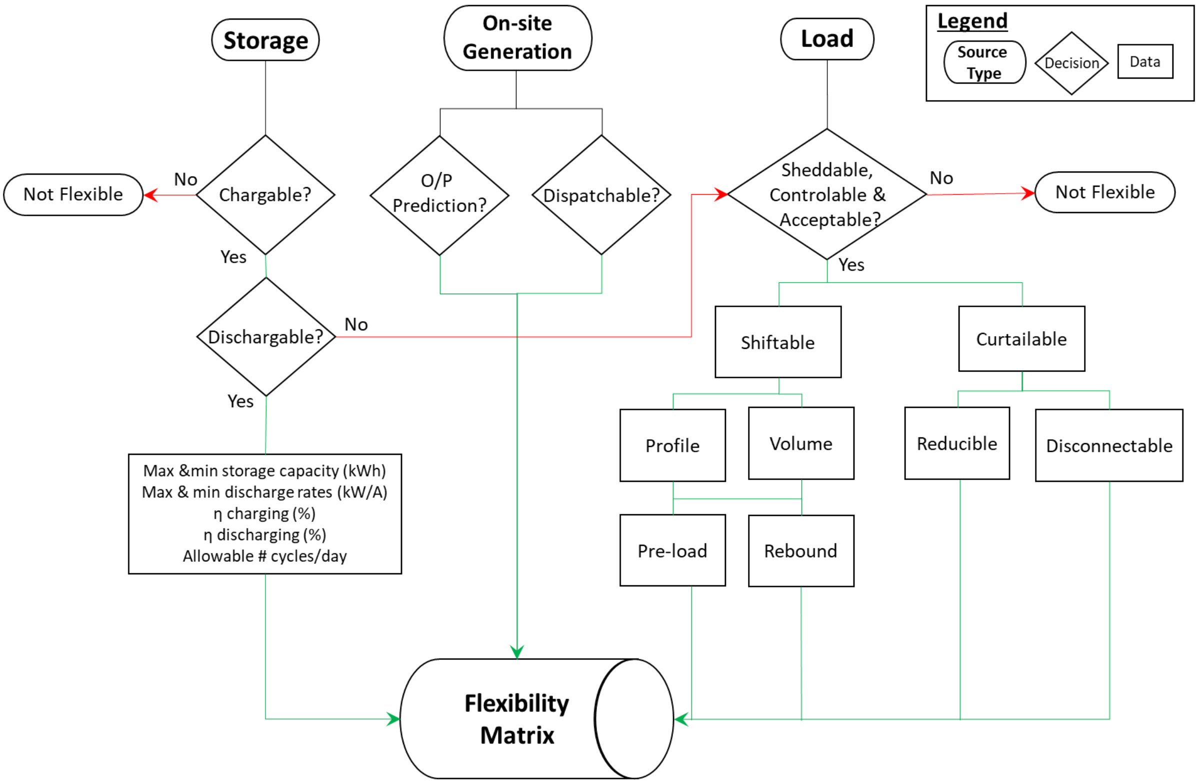

Figure 2. Flexibility Characterisation Process

3.3. *Step 3: Scenario Modelling*

Scenario modelling is used to visualise flexibility ranges as it helps to illustrate what impact flexibility will have on the power profile of the building being assessed. The visualisation of sample scenarios assists building operators and aggregators in understanding what resulting energy demand profiles would look like in practice during a demand response event. The models are calculated as follows: the total flexibility at any given time interval, j, is the sum of all the individual sources i, which have flexibility in that time interval. Flexibility, f, is expressed in power (kW or MW).

$$f_{Total}(t_j) = \sum_{i=1}^{n} f_i(t_j) \qquad (1)$$

To express flexibility as a percentage of peak load, F, the following formula is used:

$$F = \left(\frac{f_{Total}(t_j)}{P_{Peak}}\right).100 \qquad (2)$$

Where P_{peak} is the peak power load for the building in kW or MW and f_{Total} is as defined in (1). Human reasoning is required to evaluate the flexibility of each source for a specific timeframe from the flexible system parameters, a step which may be automated in future. The flexibility, F, for storage, generation and loads for specific time frames are then plotted as a percentage of peak power load against typical daily profiles for the building as shown in Section 4.1. This is performed both for individual energy systems and a combination of systems.

The time frames selected are one hour and four-hour scenarios. The reasoning behind the time frame selection are threefold: i) common demand response service timeframes, ii) building response capability and iii) to gain an

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understanding of what systems can provide short-term flexibility and which are better suited to longer events. An analysis of common demand response timeframes shows that peak shaving demand response is typically between 2pm to 5pm (Xu and Zaregus, 2009) but may be up to 6 hours (Piette et al., 2006). In Ireland, Eirgrid's (2018) demand side programme requires a capability to reduce load for at least two hours as a pre-requisite for participation, but actual events may be shorter, particularly in the intra-day market where grid operators require flexibility to deal with unexpected events. In addition, pricing of electricity in wholesale markets is on an hourly basis (SEMO, 2018). Building response capability is based on control and automation capability. Equipment in buildings is typically controlled by BMS systems. These have response times of 10 - 15 minutes, therefore during a one-hour event four data points will be gathered providing a reasonable dataset for evaluation and validation. To understand what systems can provide short-term and longer-term flexibility, generating a one-hour scenario will highlight systems with high short-term power flexibility whereas a four-hour event will demonstrate systems which have greater energy flexibility capability.

Examples of scenario modelling are included in the detailed case study in Section 4.

3.4. Step 4: KPI Label

The aim of the KPI label, shown in Figure 3, is to indicate at a glance the flexibility potential of a site for demand side services. Based on the review in Section 2, the KPI label helps to operationalise the concept of flexibility by creating a strong visual indicator with key metrics communicated in an easily understood way.

The 'energy performance indicator' from ISO 50002 was modified was to create flexibility KPIs. An energy performance indicator is not relevant for flexibility as it quantifies the energy efficiency of a building, not its flexibility. The concept of using an indicator to communicate the key outputs was taken from the ISO standard but the development of the KPI label and the metrics for flexibility are unique to this work. As contracts for demand response services are based on kW or MW increases or decreases (Eirgrid, 2018) (RTE, 2014) and load reduction durations are specified (Eirgrid, 2018) for flexibility, power load reduction and duration are the most important factors to capture on the KPI label.

From the parameter identification analysis in Section 2.1 the key factors for flexibility identified on the KPI label shown in Figure 3, are: a) quantity of load reduction in kW or MW and the timescale in which that load reduction is achieved; b) notification time-in-advance and shed time; c) market type; d) peak load and base load; e) rebound and pre-load. A short event, will typically have a higher maximum power flexibility as the time duration is less, whereas a long event may provide more energy reduction in kWh but the instantaneous power reduction in kW may not be as large. The time scale is shown from micro seconds to a four-hour period to enable comparison across buildings and sites. The flexibility scale on the graphic is shown from 0% to 100% while the absolute values are given in the text portion of the label.

An early draft of the KPI label proposed in this paper was presented to stakeholders including aggregators, building managers and DSOs at the ELSA stakeholder workshop (Croce and Riverso, 2016) and was very favourably received. It was considered relevant, specific to their needs and communicated the key metrics required based on measured parameters.

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https://doi.org/10.1108/IJBPA-01-2019-0011

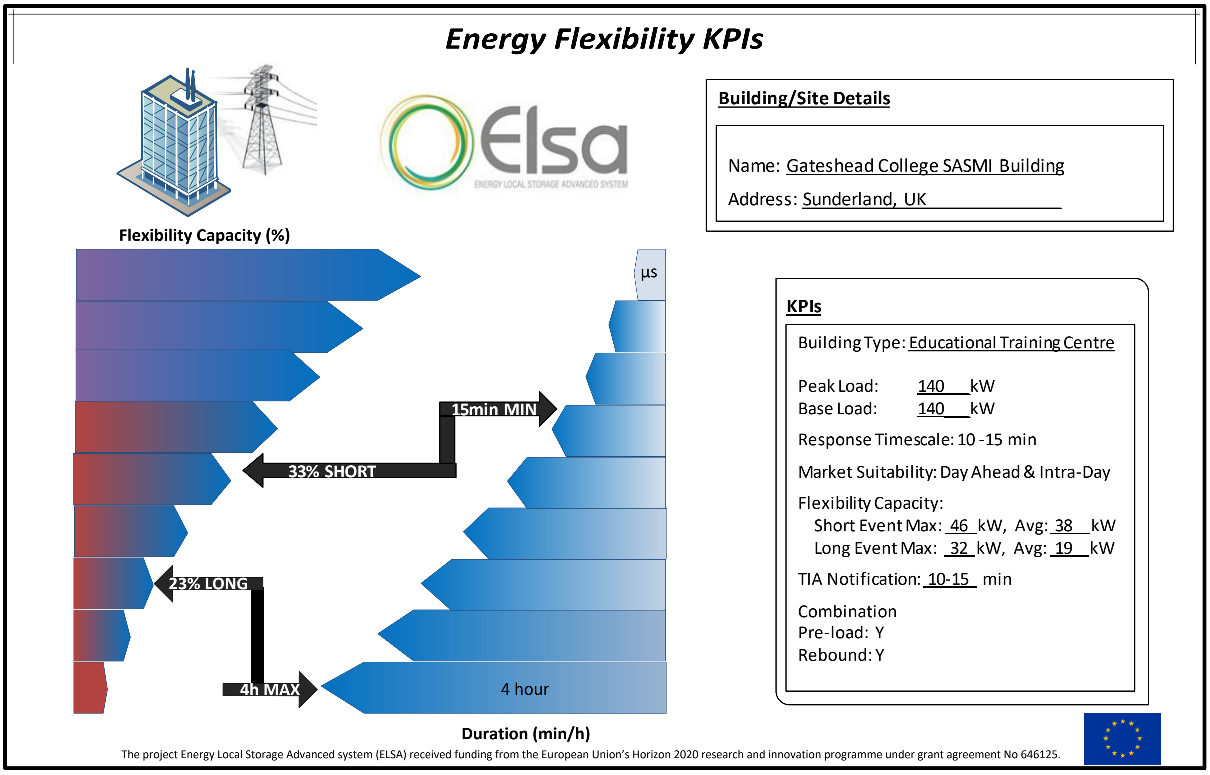

Figure 3. KPI Label

4. Detailed Case Study

A detailed case study demonstrating the application of the flexibility assessment methodology and validating the effectiveness of the approach was conducted at the Skills Academy for Sustainable Manufacturing and Innovation (SASMI) building, Gateshead College, Sunderland, UK.

4.1. Methodology Implementation

An overall understanding of the how the building operates and what power and energy systems are present was attained during the implementation of Step 1: Systems, Loads, Storage and Generation Identification. It is a mixed-use building with a floor area of 5,700 m^2 consisting of classrooms, offices, workshops and catering facilities. Its peak power load and base load are deduced from a selected (typical) daily electricity profile and are respectively of the order of 140 kW and approximately 20 to 40 kW.

Step 2: Flexibility Characterisation was then implemented. An example of the implementation of the process in Figure 2 is as follows. A fan in an Air Handling Unit (AHU) is considered a load, therefore the starting point is the load category of the process. The fan provides ventilation and it is possible to reduce its speed, making it Sheddable. It has a variable speed drive controller which is linked to the BMS, making it Controllable. The occupants require a minimum ventilation level to keep CO_2 concentrations below a specified threshold but the ventilation the fan provided far exceeds this. Therefore, it is Acceptable to reduce its load within CO_2 limits. If the fan does not impact on the heating or cooling requirements of the building, it may be categorised as a curtailable load. If reducing the ventilation rate does impact heating or cooling, there may be a rebound effect after the flexibility event therefore it should be categorised as shiftable. This may also depend on the duration of the event.

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The above process was applied for all loads, storage and on-site generation at the building. Thus, the sources of flexibility identified in the building were Loads: AHU fans and a Variable Refrigerant Flow (VRF) heating and cooling heat pump system, both of which are HVAC loads; Storage: the second life EV battery system, consisting of three Nissan Leaf batteries with a combined capacity of 48 kWh (first life capacity was 72 kWh) and Generation: a 50 kWp PV array.

Step 3: Scenario Modelling was conducted using the outputs of Step 2 to visualise flexibility ranges and show what power and energy flexibility would look in sample demand response scenarios. Scenario A is for a one-hour event and Scenario B is for a four-hour event.

i) Flexibility Event - 1 hour

A scenario for a one-hour flexibility event, presented on the left-hand side of Figure 4 illustrates the percentage reduction in peak load which the PV, electrical loads and battery storage may deliver on receiving a demand response request from an aggregator or grid operator. The results on the right-hand side of Figure 4 will be dealt with in Section 4.2. The battery system alone has the capacity to provide a flexibility of up to 26% of building peak load. Combining this with renewable generation from the PV array increases the flexibility capability to 37% during the summer season. With the addition of the two HVAC loads, the modelled load reduction increases to 45%.

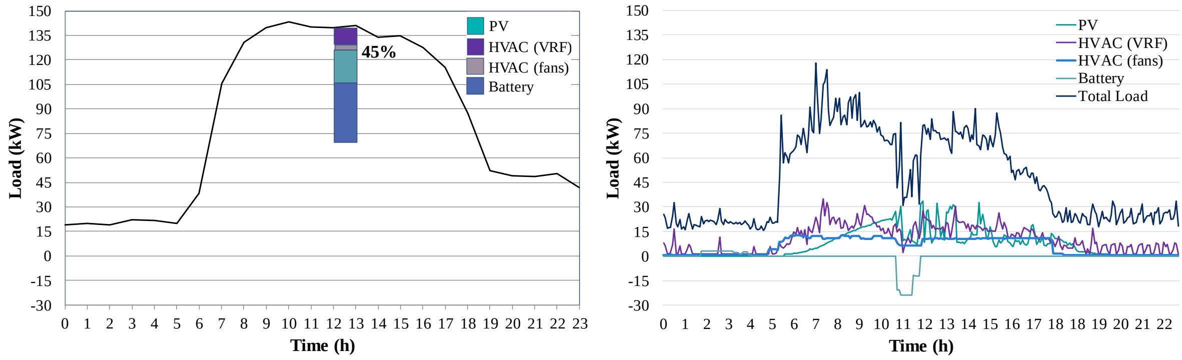

Figure 4. One-hour Flexibility Scenario Model (on left) and Validation Results (on right).

ii) Flexibility Event - 4 hours

A scenario for a four-hour flexibility event, presented on the left-hand side of Figure 5, illustrates the flexibility the sources may deliver during a longer event. The results on the right-hand side of Figure 5 will be dealt with in Section 4.2. The battery system alone has the capability to provide flexibility of up to 8% of building peak load. Including the PV renewable generation improves the maximum range to 19% during summer. Applying the same HVAC loads reduction as the previous scenario increases the overall flexibility to 27%. It is worth noting that the impact of the HVAC loads reductions is much more significant during the four-hour event. Conversely, the contribution of the battery storage system is reduced as its capacity is distributed over a longer time period. The flexible HVAC loads double the flexibility range from 8% (battery) to 16% (battery & HVAC loads).

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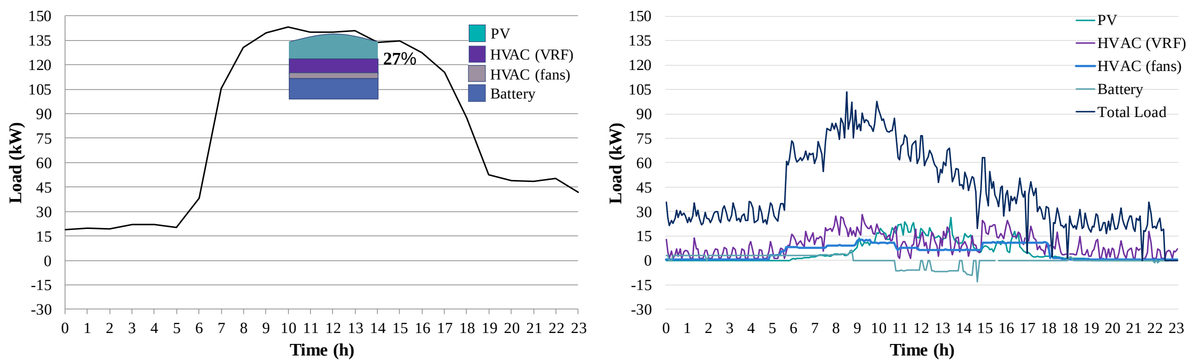

Figure 5. Four-hour Flexibility Scenario Model (on left) and Validation Results (on right)

4.2. *Experimental Validation*

Experimental validation was conducted to validate the results of the methodology for the case study building. Two use cases were selected, peak shaving, which is a price-based programme, and a market based programme that requires the building to respond to a grid request in the intra-day market within a short timeframe. In Ireland this is implemented as Short Term Active Response (STAR) (Eirgrid, 2018). Peak Shaving is the most widely used demand response service globally with Ireland (Eirgrid, 2018), the US (Piette et al., 2006), France (RTE, 2014) and China (Li et al., 2017) including it in their demand side services. The peak shaving use case was applied for the four-hour event validation. The response to a grid request in the intra-day market use case was applied for the one-hour event validation.

An ICT platform installed at the building was used to actuate the sources of flexibility during the experiment and record data. Aggregator or grid signals were emulated using an OpenADR protocol (OpenADR Alliance, 2016). The management system for the 2nd life battery storage was an early prototype system at TRL 5/6. Communication between the battery management system and the ICT platform is via a web services API while the BMS uses the OPC (OLE for Process Control) protocol. Earlier versions of the ICT platform were successfully deployed on previous projects (Valdivia et al., 2014) (Monti et al., 2017) prior to it being utilised for the case study building.

The results of the validation are shown on the right-hand sides of Figures 4 and 5. The validation profiles are strongly influenced by intermittency in the PV output causing significant fluctuation in the total load profile. This created volatility in the recorded data, requiring analysis to extract the actual flexibility achieved. Power flexibilities for each of the sources are given in Table 2. For the one-hour scenario, shown in Figure 4, the overall flexibility achieved was 33% of peak load compared with 45% predicted. HVAC load and PV flexibilities were very close to predicted. However, the battery system delivered 14% flexibility, less than the predicted 26%. This was due to the battery installation at the case study building being an early prototype at TRL 5/6 and not all of the battery modules were operational. Of the HVAC loads, the AHU fan flexibility gave a steady load reduction whereas the VRF system was more volatile.

Validation of the four-hour scenario is shown in Figure 5. As seen in Table 2, the HVAC loads and PV flexibilities were again very close to predicted with the battery system having a reduced discharge, similar to the one-hour validation. Total flexibility achieved was 23%.

Table 2. Experimental Validation of Flexibility Scenarios

	F^L (HVAC)	**F^{RES} (PV)**	**F^S (Battery)**	**Total**
1 Hour Scenario				
Predicted	8%	11%	26%	45%

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	F^{L} (HVAC)	F^{RES} (PV)	F^{S} (Battery)	Total
Validated	8%	11%	14%	33%
4 Hour Scenario				
Predicted	8%	11%	8%	27%
Validated	8%	11%	4%	23%

F^{RES} = Renewable Energy System Flexibility, F^{S} = Storage Flexibility, F^{L} = Load Flexibility

Step 4 generated the KPI label for the case study building based on the validated results, shown in Figure 3. The shortest event the case study building can participate in is 15 minutes, the minimum timeframe, during which it can provide 33% of peak load as flexibility. Four hours, the maximum timeframe, has been selected as the longest event, during which the building can provide 23% flexibility.

4.3. Benchmark Comparison

Benchmarking is required to understand how the case study building flexibility compares to that of a typical building. From the review of demonstration studies in Section 2.3, studies with i) a large number of buildings and ii) systems providing flexibility similar to the case study building were selected. Benchmark 1 (Piette et al., 2006) (Xu and Zagreus, 2009) involved a large number of real buildings, 28, participating in a utility led demand response programme in the US. HVAC loads were reduced in all of the buildings during a critical peak pricing programme. Benchmark 2 (Siebert et al., 2015) was a demonstration project with similar sources of flexibility to the case study building, namely PV, battery storage and loads and was conducted in Europe. The 8 pilot sites each provided a single load, heating in buildings or pumps in industrial sites. The PV and battery storage elements were similar to the case study presented here but were managed centrally by an aggregator, instead of the building controlling its own renewable generation and storage. These studies demonstrated a maximum range for flexibility between 18 - 56% of peak load with average flexibilities between 7 – 9% of peak load. Comparing the flexibility ranges with the benchmarks, the case study building is within the average range of Benchmark 1 for a one-hour event and exceeds the ranges for Benchmark 2.

Possible future work may include: a) validation of the method at multiple buildings to demonstrate scalability and ease of implementation b) automation of scenario models possibly using AI techniques; c) maturing 2nd life battery storage technology to TRL 9 and d) development of standardised benchmarks for flexibility across a wide range of building types.

5. Conclusions

An early stage, standardised four step flexibility assessment methodology was created, implemented and validated. It provides an easily implementable way of assessing the power flexibility of buildings, overcoming the requirement for hiring building energy experts or conducting detailed on-line data acquisition. Explicit and systematic source selection ensures flexible systems are not missed during cursory assessments and avoids time wasted on non-flexible systems in detailed assessments.

A detailed application of the methodology was shown for a case study building and the method validated through experiments at the building. The validation verified the modelled flexibility for PV and HVAC systems but the early prototype nature of the battery system for that particular site meant that the measured values were less than predicted. As this is an equipment specification issue, the method is considered robust and validated.

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The KPI label, developed to operationalise the concept of flexibility more widely, communicates the quantity and timescale of achievable load reduction for a given building and may have applicability in the development of the SRI for buildings.

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