Validation of a Flexibility Assessment Methodology for
Demand Response in Buildings

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Abstract. Flexibility in Buildings is an integral part of the solution to address the electrical grid’s challenges of grid balancing and renewable generation hosting capacity. One of the main barriers to greater participation of commercial and residential buildings in demand response schemes is the complexity and cost associated with assessing the flexibility of buildings. To overcome these barriers, an early stage flexibility assessment methodology was developed to provide stakeholders with actionable information in a concise and relevant way, so they can effectively evaluate the flexibility of their building and negotiate with aggregators for demand response participation. This paper validates the early stage flexibility assessment methodology in multiple buildings, demonstrating its ease of implementation and scalability. The validation was conducted at five pilot sites, in different geographical regions, activating a range of flexible sources through experiments on site.

1. Introduction

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. To do this, 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, aggregators primarily target large users, e.g. industrial sites [1] offering few sources of flexibility such as backup generators [2]. However, to achieve the EU goals for renewable integration of more than 50% by 2030 and over 90% by 2050 [3], participation from large numbers of smaller buildings providing flexibility from multiple sources is required.

An early stage standardised four step flexibility assessment methodology was created and implemented by the author [4] as an enabler to increase participation of the building sector in demand response programmes. Increased participation is required for balancing the electrical grid and increasing renewable generation hosting capacity [5]. The methodology addresses the barriers of i) lack of clarity around energy flexibility potential, specifically the quantification of flexibility and the financial cost or technical effort required to activate it [1] and ii) difficulty in identifying, implementing and actuating numerous small sources of energy flexibility rather than a few large systems [6]. The methodology provides an easily implementable protocol for 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. The output of the methodology is a KPI label which may for example have applicability in the development of the Smart Readiness Indicator (SRI) for buildings [7] included in the 2018 re-cast of the EU Energy Performance of Buildings Directive (EPBD). The flexibility assessment methodology 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.

To date, the majority of the available research in flexibility focuses on simulation [8] (Reynders 2018) [9] and published demonstration studies documenting implementation of demand response in real buildings are rare. This paper addresses the need for more published demonstration studies to enable the creation of benchmarks. Experimental validation was conducted in a single building previously [4] demonstrating the viability of the methodology. That work is extended in this paper by demonstrating the scalability and ease of implementation of the methodology through implementation and validation in multiple buildings and districts. Use cases from price-based and market-based demand response programs both current (peak shaving) and future (CO2 minimization) are used in the validation experiments to activate the available flexibility in the buildings and districts.

This paper is structured as follows: Section 2 outlines the flexibility assessment method; Section 3 details the experimental setup including the use cases; Section 4 presents and analyses the results of the validation and Section 5 documents the conclusions.

2. Flexibility Assessment Method

A four-step flexibility assessment methodology was developed by the author [4]. This section provides an overview of the methodology and demonstrates i) its scalability and ii) ease of implementation. The four steps in the methodology are Step 1: Systems, Loads, Storage & Generation Identification; Step 2: Flexibility Characterisation; Step 3: Scenario Modelling and Step 4: KPI Label, shown in Figure 1. To create a structure underpinning the methodology, relevant elements of the energy auditing standard ISO 50002 [10] were selected and modified by the author to address power and energy flexibility assessment rather than energy auditing.

**Figure 1. Four-step Flexibility Assessment Method**
Step 1 identifies the power and energy systems in the building or site which have flexibility potential. To evaluate these, a site visit in conjunction with collecting data from as-built engineering drawings, documents and specifications is performed. Systems are assessed at a high level only. A detailed analysis of the flexible systems is then conducted in Step 2 following the flexibility characterization process. A triage process allows to select flexible sources in a systematic way and reduce the volume of building data, drawings and specifications to be analysed is significantly compared with standard energy auditing procedures. The power, in kW and energy, in kWh, characteristics for each flexible system are identified. In step 3, scenario modelling uses this data to visualise flexibility ranges These illustrate what impact flexibility will have on the power profile of the building being assessed which facilitates building operators and aggregators understanding of what a demand response event will look like for their building. Finally, step 4 captures the flexibility ranges of the building on a KPI label, providing a comprehensive summary of the key technical criteria which indicate the demand response potential of the site. This enables contract negotiation between building operators and aggregators and allows aggregators to quickly and easily assess buildings when creating portfolios of sites to meet the participation thresholds of grid operators.

2.1. Scalability

The scalability of the assessment method is demonstrated by its implementation at five pilot sites. The types of sites range from commercial buildings to a cluster of buildings to residential districts and so cover a wide range of current and future participants in demand response markets. To operationalise the concept of building flexibility to residential and small commercial customers, flexibility assessment needs to be quick, cost effective, repeatable and technically accurate. The validation of the methodology at five pilot sites demonstrates this, enabling roll out of demand response services to a wider spectrum of society.

2.2. Ease of Implementation

Assessments at each of the five pilot sites were performed by technical evaluators who were not expert in flexibility, using off-line data already available at each site. Training on the implementation of the methodology was provided by the author which consisted of a one-hour presentation, followed by two half-hour online technical support sessions. Evaluators were provided with documentation on guidelines for implementation, templates for capturing flexible system variables and a calculation tool for generating the KPI label. A survey of the evaluators determined that time for assessment was 1-2 weeks and level of difficulty was scored 3 on a scale of 1-5 with 1 being very easy and 5 being very difficult. The evaluators found the level of training and support sufficient and would recommend the methodology to others.

The ease of implementation demonstrated through these multiple implementations by technical evaluators enables building operators to easily and cost effectively evaluate the flexibility of their building. The time frame for implementation is compared with that of a traditional Type 2 energy audit in which all energy systems are analysed in detail. The duration of a Type 2 audit varies depending on the building but based on the author’s experience, conducting energy audits for the pilot sites in this work would take approximately 3 to 4 weeks [11]. By comparison, the flexibility assessment methodology reduces the time for assessment to 1-2 weeks, a reduction of approx. 60%.

Cost may be reduced by up to 80% as the methodology provides a systematic means of capturing the key technical information for flexibility without the individual implementing it requiring a detailed technical knowledge of the domain. This enables implementation by a technical person, e.g. a junior engineer, instead of a flexibility expert, achieving a cost reduction in excess of the time decrease.

While the implementation of the methodology did not require installation of additional equipment, validation of the flexibility ranges predicted by the methodology did. Details of the pilot sites and the experimental setup required for the validation are described in Section 3.

3. Experimental Setup
The flexibility method in Section 2 was implemented at five pilot sites. The types of sites include commercial buildings, a residential district and a cluster of DSO operation’s buildings. A brief description of each site is given below. The development of an ICT Platform was required to enable simulation of demand response events, control of the flexible systems from a remote location and data acquisition from the building. Use cases were selected to demonstrate that based on this simple assessment procedure, the potential of buildings in a wide range of demand response schemes could be quantified.

3.1. Pilot Sites

Commercial Building, Sunderland, UK: The Skills Academy for Sustainable Manufacturing and Innovation (SASMI) building in Sunderland, UK is a 5,500 m² mixed-use commercial building. Its peak power load is of the order of 140 kW and its base load is between 20 to 40 kW. Flexible loads consist of HVAC loads coming from the Variable Refrigerant Flow (VRF) heat pump system and Air Handling Unit (AHU) fans; storage consists of 2nd life EV battery system, with an installed capacity of 48 kWh and on-site renewable generation consisting of a 50 kWp PV array.

Building Cluster, Terni, IT: The ASM Terni pilot site is a cluster of buildings comprised of ASM Terni’s electricity Distribution System Operator (DSO) three operations buildings. Flexibility is provided by 180 kWp and 60 kWp PV arrays and 2nd life battery storage with an operating capacity of 36 kWh. Base load varied between 50 kW and 90 kW and typical peak load was 150 kW.

Commercial Building, Paris, FR: The Ampère building is a 14,000 m² commercial office building located in the La Défense area of Paris. It recently underwent a deep retrofit and is now certified as a sustainable building with HQE and BREEAM certification. Flexibility was provided by a 22 kWh capacity 2nd life battery system. Peak load is of the order of 250 kW.

Commercial Building, Aachen, DE: The E.ON ERC building is located on the RWTH university campus. Load flexibility is provided by HVAC AHU fans. The building has a peak load of 250 kW.

Residential District, Kempten, DE: The test site of Kempten consists of six apartment buildings hosting a 2nd life battery storage system with 66 kWh installed capacity and a 37 kWp PV array. There are no flexible loads. Space heating and hot water are not provided from electrical sources hence the electrical load is low compared with the commercial buildings. Combined peak load is 8.5 kW with an average daily consumption of 45 kWh.

3.2. ICT Platform & Simulation of Grid Signals

An ICT platform was installed at each of the pilot sites and used to validate the flexibility as predicted by the assessment methodology. In an ideal future scenario, the methodology would be implemented and validated on-line in an automated way. However, at present, a technology gap exists which prevents this being implemented in large numbers of buildings in a cost effective and scalable way. ICT platform integration with existing building systems is bespoke, complex, time consuming and expensive. Until ICT platforms for building flexibility reach plug-and-play capability at TRL 9, implementation as described in this paper is required.

The ICT platforms control the loads and storage on site to provide flexibility services in response to simulated demand response signals. The pilot site ICT system architecture for two of the buildings, SASMI in the UK and Ampère in France, is shown in Figure 2. The development of this system architecture was led by the author for previous work in optimising energy management in buildings [12] and districts [13]. For demand response applications, the ICT platform was adapted to incorporate simulation of grid or aggregator signals using the OpenADR protocol and the integration of the 2nd life battery management system using a web service API. Meter and equipment data are extracted from the site Building Management System (BMS) using an OPC (OLE for Process Control) server and may be read in real time. In addition, this data is continuously stored in a database in the middleware layer. Set points are sent from the ICT platform to equipment in the building via the BMS. The ICT platform is physically installed at the building and controlled remotely using a remote desktop application. All experiments were conducted remotely.
3.3. 2nd Life EV Batteries

Each of the pilot sites has a stationary battery storage system consisting of 2nd life EV batteries installed. These are early prototype systems at TRL 5/6. For example, for the system installed at the Sunderland pilot site, first life capacity was 72 kWh and 2nd life capacity was 48 kWh. For further information on the 2nd life EV battery system, see www.elsa-h2020.eu.

3.4. Use Cases

Demand response use cases selected for the validation experiments spanned a range of services and included peak shaving, PV power smoothing, CO2 minimisation and a market-based programme that requires the building to respond to a specific grid request.

Peak shaving is a price-based programme. It is the most widely used demand response service globally with Ireland [14], the US [15], France [16] and China [17] including it in their demand side services. It involves reducing grid import of electricity during periods of peak consumption, e.g. between 11am and 3pm. This use case was implemented at the Commercial building in Paris and the cluster of buildings in Terni.

A market-based programme that requires the building to respond to a grid request intra-day within a short timeframe is a more challenging use case than peak shaving. With peak shaving the building operator knows the price and time schedule sometimes more than a year in advance. Market based programmes are more dynamic, as buildings may be called to respond within an hour, for example in Ireland’s Short Term Active Response (STAR) [14] programme. This use case was implemented at the Commercial building in Sunderland.

CO2 based demand response signals have been proposed as an alternative to price based market signals [18] to incentivise electricity use or reduction in times of high or low renewable generation on the grid, respectively. For the CO2 minimisation use case proposed, average CO2 emissions per kWh are estimate at 416.58 g/kWh based on 2017 ENTSO-E generation mix for Germany. In a future grid scenario where hourly or real time generation emissions are available, this may be used by businesses who wish to minimise their carbon footprint or by grid operators to maximise renewable generation consumption. This use case was implemented at the Aachen building.
PV power smoothing is used to mitigate PV generation variability [19]. It requires storage coupled with PV and is activated at the request of the grid operator. The objective of this use case is to smooth PV peak production by storing excess renewable electricity generated to reduce grid export. This use case was implemented at the Kempten Residential District.

In validating the flexibility assessment methodology with the above use cases, the available capacity of the 2nd life EV batteries was used in the calculation of the predicted value. As the 2nd life battery management system is an early prototype at TRL 5/6, still under development, during many of the experimental use case validations the available capacity varied.

4. Results

Validation of the flexibility assessment method was conducted at each of the pilot sites. The output of the flexibility methodology is a range of flexibility the building has the capability of offering. To validate this, predicted flexibility for the particular use cases were calculated based on a selection of the building systems appropriate to that use case, and a calculation of the maximum flexibility achievable for the use case time period. The actual flexibility is the flexibility measured for a specific event and one realisation of that event [20]. The ICT platform was used to trigger demand response events for each use case and measure the corresponding load reduction or increase at the building, cluster or district. The actual results were compared with the predicted flexibility for and both are shown for each pilot site in Table 1. The sources of flexibility are categorised by load, storage and generation as evaluated in Step 1 and Step 2 of the assessment methodology. Load flexibility is denoted as \( F_L \), storage flexibility as \( F_S \) and renewable energy flexibility as \( F_{RES} \). For the pilot sites, \( F_{RES} \) is provided by PV, \( F_S \) by the 2nd life EV battery system and \( F_L \) by HVAC systems. Flexibility is expressed as a percentage of peak load.

| Pilot Site Location | Type                  | Sources | Use Case                        | Use Case Flexibility (%)$^1$ |
|---------------------|-----------------------|---------|--------------------------------|-------------------------------|
|                     |                       |         |                                | Predicted | Actual | Error |
| Sunderland, UK      | Building              | \( F_{RES} \), \( F_S \), \( F_L \) | Intra-day Grid Request         | 36%       | 33%    | 9%    |
| Terni, IT           | Cluster of Buildings  | \( F_{RES} \), \( F_S \) | Peak Shaving                   | 90%       | 81%    | 10%   |
| Paris, FR           | Building              | \( F_S \) | Peak Shaving                   | 9%        | 7%     | 22%   |
| Aachen, DE          | Building              | \( F_L \) | CO2 Minimisation               | 3%        | 3%     | 0%    |
| Kempten, DE         | Residential District  | \( F_{RES} \), \( F_S \), \( F_L \) | PV Power Smoothing             | 103%      | 106%   | 3%    |

$^1$ Use case flexibility is expressed as a percentage of typical peak load for each site. The predicted and actual flexibility for each use case event was calculated based on the load increase or decrease divided by the typical peak load.

4.1. Analysis of the Results

In Table 1, the predicted and actual flexibility was largest for the Terni site and Kempten residential district. For Kempten, flexibility was over 100% of the site’s peak load at 103% predicted and 106% actual. The PV output in Kempten during the event was greater than predicted, with the result that the actual flexibility was 3% higher than predicted. For all the other pilot sites, actual flexibility was lower than predicted. Both Terni and Kempten had large PV installations and, in Kempten’s case, a large battery system relative to the electrical load of the site. As heating in Kempten was not provided by electrical sources, the electrical load was low, thus, even though the battery capacity was similar to that of Sunderland, it was able to provide a much larger percentage of flexibility. The Sunderland building was the only building to combine all three sources - load, storage and generation, and had predicted and
actual flexibility of approximately one-third of its peak load. The sites with only one source, Paris and Aachen buildings, had the lowest flexibility at 7% and 3% of peak load respectively. It is worth noting that load flexibility, particularly HVAC, is generally linked to building physics and floor area whereas there may be more scope to add additional flexibility through generation and storage at the building scale. From the results in can be seen that i) number of available flexible systems, ii) size of installed renewable generation and iii) installed storage capacity are the three factors which most influence the flexibility of buildings or sites.

4.2. Validation
The error between prediction and accuracy for each pilot site is given on the right-hand side of Table 1. This show flexibility prediction within a 10% error range for four out of the five pilot sites. The site with the highest error, the commercial building in Paris, had a very low predicted flexibility, 9% of peak load, therefore the error was large relative to the quantity of power available to flex. For this building, only one source of flexibility was used, the battery system. It was found by [21] that prediction accuracy improved when the number of sources, in their case dwellings, was increased, which correlates with the validation results.

For smart grid applications, prediction accuracy of +/- 10% is considered optimal [22] [23]. However, errors of up to 36% in flexibility prediction for heat pumps [24] were considered acceptable. All of the sites are within the 36% range while the majority of the pilot sites are within the 10% error range.

4.3. Benchmark Comparison
Benchmarking is required to understand how the pilot site’s flexibility compares to that of a typical site. As previously mentioned, standardised benchmarks are not yet available, therefore demonstration studies with i) a large number of buildings and ii) systems providing flexibility similar to the pilot sites were selected as benchmarks for the pilot sites. Benchmark 1 involved 28 buildings providing HVAC flexibility who participated in a utility led demand response programme in California [17]. Benchmark 2 consisted of a demonstration project with similar sources of flexibility to the pilot sites, namely PV, battery storage and loads [25]. These studies demonstrated a maximum range for flexibility between 18% to 56% with average flexibilities between 7% to 9% for Benchmark 1.

Comparing the flexibility ranges with the benchmarks in Table 2, the sites with multiple sources have flexibility equivalent to, or greater than, the benchmarks. The Sunderland building was within the range of Benchmark 1, which was expected as it is a commercial building similar to those in the comparison study, and exceeded the range for Benchmark 2 which was surprising as the systems installed were similar. The Terni site and the Kempten residential district far exceeded the benchmarks. However, this is not surprising as the installed capacity of the PV and storage systems is large compared with the peak load of the sites. The Paris and Aachen sites with are not within the maximum range for either benchmark but the Paris building is within the average range for Benchmark 1, this is due to only one source of flexibility being activated in each, and additionally in Paris’s case, the battery system being small relative to the peak load of the building.

| Benchmark      | Max flexibility [%] | Average Flexibility [%] | Sunderland UK | Terni, IT | Paris, FR | Aachen, DE | Kempten, DE |
|----------------|---------------------|-------------------------|---------------|-----------|----------|------------|-------------|
| Benchmark 1    | 28 - 56             | 7 - 9                   | Within max    | > max     | Within   | < average  | > max       |
| Benchmark 2    | ~18                 | -                       | > max         | > max     | < max    | < max      | > max       |

5. Conclusions
Validation of the early stage, four step flexibility assessment methodology was conducted at five pilot sites using an ICT platform whereby grid signals were simulated using OpenADR protocols. Specific
demand response use cases were implemented to trigger flexibility events at each of the sites and the resulting reduction in grid import electricity was measured. Sites with multiple sources of flexibility and large storage or renewable generation systems delivered higher levels of flexibility than those with single sources. Comparing actual flexibilities achieved to the predicted values from the methodology, four out of the five pilot sites were within 10% of the predicted flexibility. Benchmarking the results against other demand response demonstration studies indicated that three of the four sites were within or above the maximum range of flexibility, one was within the average range and one below average.

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