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Development of a Standardised Assessment Methodology relating to Flexibility Analysis for Demand Response

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Abstract

Power and energy flexibility in buildings and sites is an integral part of the solution to address the electrical grid's challenges posed by increasing renewable generation, decarbonisation of the electricity supply and electrification of buildings, transport and industry. Addressing these challenges requires flexibility to deliver demand response services. Commercial buildings, residential buildings and smaller industrial sites have significant underutilised potential due to a lack of consistency associated with assessing their flexibility. To unlock this potential, a scalable, easy to use flexibility assessment methodology is required.

A standardised four-step flexibility assessment methodology was developed during the course of this research, conducted under the scope of the International Energy Agency's Energy in Buildings and Communities Annex 67 'Energy Flexible Buildings'. The four steps in the methodology consist of Step 1: Systems, Loads, Storage & Generation Identification; Step 2: Flexibility Characterisation; Step 3: Scenario Modelling and Step 4: Key Performance Indicators (KPI) Label. Underpinned by adapted elements of the energy auditing standard ISO 50002, the methodology evaluates the available electrical load reduction or increase that a building or site can provide in response to a demand response signal from an aggregator or grid operator. Addressing the need for an early stage flexibility assessment, i.e. before any investment on site and before contracts are negotiated, it explicitly includes flexibility source selection by utilising Shedability, Controllability and Acceptability as a filter or triage step. Detailed parameter definition ensures key performance elements are captured. The output of the methodology is a defined flexibility range which enables contract negotiation between building or site operators and aggregators for demand side services, captured on a KPI label for the building or site. Implementation is in an off-line manner, without the need for real-time data acquisition, ICT platforms or additional installations, as existing assessment approaches would require. Stakeholders consulted during the development of the methodology found it relevant and technically robust, particularly the incorporation of ISO 50002.

A detailed case study for one building, conducted by the author, is described and verified through on-site experiments, establishing the feasibility and accuracy of the methodology. Ease of use and scalability was demonstrated through implementation by others at multiple pilot sites in the context of the Horizon 2020 Energy Local Storage Advanced system (ELSA: 2015 - 2018) project. The pilot sites consisted of different building and site types across Europe, with a number of flexible sources. Benchmarking the results against published demonstration studies showed that three of the pilot sites achieved above average flexibility. Comparing the methodology outputs with experimental results, flexibility prediction was within a 10% error range, an accepted threshold for grid prediction error in the literature, for four out of the five pilot sites.

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Nomenclature

ADR	Automated Demand Response
AHU	Air Handling Unit
API	Application Programming Interface
BER	Building Energy Rating
BMS	Building Management Systems
CapEx	Capital Expenditure
CHP	Combined Heat and Power
CIBSE	Chartered Institute of Building Services Engineers
COP	Coefficient of Performance
CPP	Critical Peak Pricing
DHW	Domestic Hot Water
DR	Demand Response
DRRC	Demand Response Research Centre
DSM	Demand Side Management
DSO	Distribution System Operator
DSR	Demand Side Response
DT	Dèfinition Technique (Technical Definition)
EBC	Energy in Buildings and Communities
ELSA	Energy Local Storage Advanced system (EU Horizon 2020 project)
ENTSO-E	European Network of Transmission System Operators for Europe
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EPN	Energy Positive Neighbourhood
EV	Electric Vehicle
FERC	Federal Energy Regulatory Commission
HVAC	Heating, Ventilation and Air Conditioning

IEA	International Energy Agency
ICT	Information and Communication Technology
KPI	Key Performance Indicator
MILP	Mixed Integer Linear Programming
NoSQL	Not only SQL (Structured Query Language)
OAT	Outside Air Temperature
OpenADR	Open Automated Demand Response
OpEx	Operational Expenditure
PV	Photovoltaic
RES	Renewable Energy Systems
RTE	Réseau de transport d'électricité
SASMI	Skills Academy for Sustainable Manufacturing and Innovation
SCADA	Supervisory Control and Data Acquisition
SEAI	Sustainable Energy Authority of Ireland
SOC	State of Charge
SQL	Structured Query Language
SRI	Smart Readiness Indicator
TIA	Time in Advance (notification)
TOU	Time of Use
TSO	Transmission System Operator
UN	United Nations
UTRC	United Technologies Research Centre
VEN	Virtual End Node
VRF	Variable Refrigerant Flow
VSD	Variable Speed Drive
VTN	Virtual Top Node

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Declaration

This thesis or any part thereof, has not been, or is not currently being submitted for any degree at any other university.

Sarah O’Connell

The work reported herein is as a result of my own investigations, except where acknowledged and referenced.

Sarah O’Connell

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Through the IEA EBC Annex 67, I had the privilege to work with world renowned researchers in the field of flexibility in buildings. Participation in the Annex enabled me to quickly and effectively grow my knowledge in flexibility and in turn share my experiences learned from conducting this research. Writing papers with Dr. Glenn Reynders of VITO was both a privilege and a pleasure and I look forward to future collaborations. I would also like to thank Dr. Soren Østergaard Jensen for bringing me into the Annex 67 family, his extensive efforts in making the Annex a success and for collating the deliverables to which I contributed.

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Chapter 1: Introduction

1.1 Introduction

Electrical power and energy flexibility in buildings and sites is one of the key enablers of the distributed smart grid (Østergaard Jensen et al., 2017). Decarbonisation of the electricity grid coupled with electrification of transport, heating and industry has emerged globally as the preferred path to meeting renewable integration targets and the Paris Agreement (United Nations, 2015). Increasing renewable generation targets create challenges for grid management. Targets are becoming increasingly ambitious, EU renewable generation targets are 50% of power generation from renewables by 2030 and 90% by 2050 (European Commission, 2018b), Denmark has a target of 100% by 2030 and California has set targets of 65% by 2030 and 100% by 2045 (Orths et al., 2019). As electrification intensifies, the quantity of electricity generation required is projected to double between 2015 and 2025 (Brown et al., 2018). This increases the imperative for solutions to manage high levels of renewable penetration leading ultimately to all power generation coming from renewable sources.

Assessment of energy and power flexibility is one of the key solutions for grid management, targeting the core challenges of (European Commission, 2016):

- Grid balancing;
- Renewable generation hosting capacity;
- Frequency and voltage stability.

To date, flexibility has been mainly provided by a small number of large industrial users (Araya Cardoso, 2020). However, to enable hosting capacities for distributed renewable energy sources above 65% (Matevosyan et al., 2019) it would be beneficial for a much greater variety of building and site types e.g. commercial office, multi-family buildings, single residential houses and smaller industrial sites 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 of appropriate programmes) (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 flexibility is not well understood (Ma et al., 2019);

c) Difficulty in identifying, implementing and actuating many small sources of energy flexibility rather than a few large ones (Annala et al., 2018).

This work aims to address the barriers specifically associated with b) and c).

Building and site operators need to know the available range of flexibility in kW or MW which they can offer to the grid to:

i) Make decisions about demand side participation e.g. to decide if participation is a worthwhile option for them;
ii) If participation is worthwhile, understand the level of flexibility they can offer;
iii) Negotiate with aggregators to participate in demand side services.

This requires an assessment of the power and energy flexibility of the building or site to understand what systems can provide flexibility, how much they can increase or decrease their electrical consumption by and, when combined, what total range may be delivered. Such an assessment needs to be performed at an early stage, i.e. before any investment is made in on-site systems e.g. in ICT platforms or the installation of additional sensors or meters, and prior to contract negotiations with aggregators. ***At present, there is no standardised approach for this early stage flexibility assessment.***

1.2 Definitions

Flexibility is the act of modifying the load profile of a building and demand response is the demand side service it provides. A number of definitions exist for both which are outlined below.

The International Energy Agency's Energy in Buildings and Communities Annex 67 on Energy Flexible Buildings (Østergaard Jensen et al., 2017) defined flexibility as: Energy **Flexibility** of a building is the ability of the building or site to manage its demand and generation according to local climate conditions, user needs and grid requirements.

Prior to this definition being finalised, the following definition was developed by the author (O'Connell and Riverso, 2016): **Flexibility** is the ability to modify (decrease or increase) the electrical load profile of a building through load shedding, ramping up, on-site generation and storage, implemented using automatic control of systems, while minimising the impact on occupants and operations. Manual control of systems may also be possible.

Electrical loads are the electrical consumption of a system which, if flexible, can be shifted in time (Knotzer et al., 2019). A load profile is the grid import electrical consumption of a building or site (Østergaard Jensen et al., 2019b).

A **Flexibility Assessment** is defined as a systematic method of determining the range of power and energy flexibility a building or site has the capability to provide (O'Connell et al., 2016).

Demand side measures are referred to as Demand Side Management (DSM), Demand Response (DR) or Demand Side Response (DSR) depending on the jurisdiction.

Demand Side Management is defined as users of electricity having the capability to change their usage from their normal or current consumption patterns (Eirgrid, 2018). This definition is used in Ireland by the Irish Transmission System Operator (TSO), Eirgrid.

Demand Response is defined as changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized (FERC, 2018). This definition was developed in the US by the Federal Energy Regulatory Commission (FERC). Examples of demand-side resources include on-site backup generators, Heating Ventilation and Air Conditioning Systems (HVAC), electrical and thermal storage and other electrical equipment whose load profile may be modified in response to a demand response request.

Demand Side Response is defined as load demand that can be actively changed by a trigger (ENTSO-E, 2014). This definition was created by the European Network of Transmission System Operators for Europe (ENTSO-E). Examples of triggers may be price signals, pre-defined pricing schedules, contract conditions for demand side services or a demand response request.

Of the three terms, Demand Response is the most commonly used term both in in Europe and globally.

A Transmission System Operator (TSO) is responsible for the management of the electrical transmission system (ENTSO-E, 2014). The transmission system transmits electricity at high or medium voltage levels from power generators to sub-stations. In Ireland the TSO is Eirgrid (Eirgid, 2018).

A Distribution System Operator (DSO) is responsible for the management of the electrical distribution system (ENTSO-E, 2014). The distribution system operator distributes electricity from the sub-stations to customers' loads at low or medium voltage. In Ireland the DSO is ESB Networks (ESB, 2020).

An aggregator is a company which acts as an intermediary between the TSO or DSO and buildings or sites. The aggregator buys flexibility from buildings or sites and uses this to sell demand response services to the TSO or DSO (Foggia et al., 2014).

An early stage assessment of flexibility is one which takes place prior to any investment on site in systems to enable flexibility such as additional sensors or meters, Building Management System programming modifications or ICT platforms and prior to contract negotiations between building or site operators and aggregators for demand response services (O'Connell & Riverso, 2016).

Sources of flexibility (Østergaard Jensen et al., 2019b) are systems in a building or site which have the capability to provide power or energy flexibility. Sources may include storage, renewable generation or equipment within the building or site. Examples of flexibility sources are documented in Østergaard Jensen et al. (2019a).

1.3 The Changing Electrical Grid

The electrical grid is changing primarily in response to the need to balance increasing amounts of renewable generation on the grid but also to create a more dynamic, smarter grid which responds to the needs of today's society (Østergaard Jensen et al., 2019b). The traditional hierarchal load following model of power generation is adapting to increased renewable integration by evolving to a distributed smart grid (EPRI, 2019) as shown in Figure 1.1. The pace of this change has been more rapid than expected. As recently as 2017, wind and solar generation were still considered disrupters to the grid whereas now they have become mainstream generation technologies (Smith and Clark, 2019). Hosting renewable generation above 25% was considered extremely challenging in 2013 (DG Energy, 2013) but now 65% of system load (Matevosyan et al., 2019) is the threshold at which grid operators struggle. For example, Ireland now frequently balances a grid with up to 65% (Lew et al., 2019) renewable generation. Electrification of transport, heating and industry means that not only are the renewable generation targets increasing, but the amount of electricity required is also set to increase, with gross electricity generation projected to double between 2015 and 2050 (Orths et al., 2019).

The traditional grid model of unidirectional power flow from fossil fuel fired generation plants to meet the loads of users is no longer viable (ENTSO-E, 2018). Developing in place of the traditional model is a grid where generation and consumption occur simultaneously at distributed nodes, often at distribution level, where users may be prosumers – generators as well as consumers of electricity, and intermittent, non-synchronous generation requires a range of solutions to balance the grid (EPRI, 2019). These solutions include storage (Siebert et al., 2015), ancillary and balancing services (Ma et al., 2013), backup gas fired generation (Yi et al., 2018), grid forming inverters (Matevosyan et al., 2019), curtailment (Ito et al., 2018), energy systems integration (Orths et al., 2019) and flexibility services (Østergaard Jensen et al., 2019b).

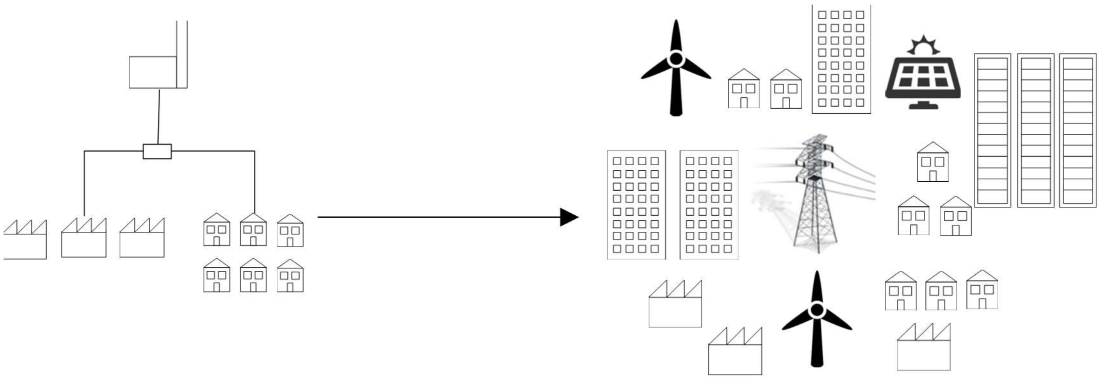


Figure 1.1 The Changing Electrical Grid, showing the traditional grid on the left and the distributed smart grid on right.

However, some of the current strategies come at a price. In Ireland, curtailment of wind generation is currently used as part of the solution (Lew et al., 2019). Curtailment involves intervention to reduce the electrical output of wind turbines when the grid does not have capacity to absorb the generated power (Davies & Madden, 2017). However, curtailment levels in Ireland are almost triple that of other countries with high renewable penetration levels such as Denmark and six times higher than that of Hawa'i, also an island grid (Lew et al., 2019).

Backup fossil fuel generation is also widely used in Ireland (Davies & Madden, 2017). Even though installed renewable capacity is of the order of 75% of peak demand and instantaneous hourly generation levels have reached 65% (Lew et al., 2019), the annual share of renewable generation meeting electricity demand is only 30% (SEAI, 2018). Of this 30% renewable generation, the majority, 25%, is generated from wind and the remainder from hydropower and other sources such as biogas, landfill gas, solar PV and biomass (SEAI, 2018). As only 30% of electricity demand is met from renewable sources (SEAI, 2018), this means that the remaining 70% of electrical demand is currently met by fossil fuels, indicating a high reliance on gas fired generation to balance the grid (Davies & Madden, 2017).

It should be noted that Ireland faces more challenges as an island grid with limited interconnection compared with mainland European grids (Davies & Madden, 2017). Interconnection allows TSOs to sell or spill excess renewable generation in times of high output and import in times of low renewable generation (Eirgrid, 2020). Ireland's TSO, Eirgrid, is anticipating renewable penetration levels of 100%, primarily wind, by 2030 (Lew et al., 2019).

Power and energy flexibility provided by buildings and sites is a more cost effective than strategies such as curtailment or gas fired generation (IRENA, 2018). Flexibility does not require investment in the construction of fossil fuel power plants (Østergaard Jensen et al., 2019b) and reducing the output of wind to meet a technical need while simultaneously paying for fossil fuel generation is not cost optimal (Ma et al., 2019). To achieve Irish and EU targets of over 90% renewables by 2050 (ECF, 2010), more flexibility is needed (Østergaard Jensen et al., 2017). This future state requires participation from a much wider spectrum of buildings (Østergaard Jensen et al., 2019b) such as offices, retail, apartment blocks, and single residential buildings (Rasku and Kiviluoma, 2019) as well as the industrial sites (Araya Cardoso, 2020). These buildings will need to provide greater numbers of flexible systems and deeper ranges of flexibility (Østergaard Jensen et al., 2019b). For buildings and sites, flexibility assessments are currently either brief and cursory (Yi et al., 2018), or complex, expensive and bespoke (Alcázar-Ortega et al., 2015).

1.4 Demand Response & Aggregators

Aggregators act as intermediaries between grid operators and buildings or sites which do not meet grid participation thresholds. Different thresholds for participation apply, depending on the country or region, to enter flexibility markets or demand response programs. Commonly DSOs or 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, 2018b) lower levels may become more common. Buildings typically have power flexibility in the kW range and therefore, in most jurisdictions, they need an intermediary, known as an aggregator, to participate in demand side programmes.

Aggregators combine power and energy flexibility from multiple sites to put together portfolios to meet the minimum participation thresholds. In order to do this, they need to:

- Assess the power and energy flexibility of the buildings or sites;
- Quantify the capacity, range, type and timescale of flexibility that can be provided by each building or site;
- Combine sites with the preferred flexibility characteristics for the particular demand side programme.

Larger portfolios of buildings and sites with higher diversity factors and lower correlation between sites are more beneficial to aggregators (Foggia et al., 2014). Diversity factors in electrical engineering are defined as the ratio of the sum of the maximum power demands of the subdivisions of any electric power system to the maximum demand of the whole system measured at the point of supply (Merriam-Webster, 2020). In practice what this means is that not all flexible systems will be at maximum load at the same time. Instead there is a mix where some sources are on at low load, some may be at medium load, some at maximum and others are off. Lower correlation means that the power profile or power consumption pattern at one site is not related to the powers profile at other sites. Higher diversity factors are more beneficial as flexibility will be less linked to a few operating parameters.

More diverse portfolios with lower correlation and larger volumes of flexibility enables aggregators to improve forecast performance, mitigate uncertainties and reduce risk costs thus resulting in more cost-effective bids for demand response programmes (Foggia et al., 2014).

1.5 Increasing Demand Side Participation

To meet the future grid needs, increased participation from greater variety of building and site types and a greater range of systems with deeper flexibility will be required. Buildings and sites have the capacity to extend the range and depth of flexibility to the grid beyond what is provided by large industrial sites at present by extending participation of:

- Commercial office buildings;
- Multi-family buildings;
- Single residential houses;
- Smaller industrial sites.

Electrification and system integration between heating and electrical energy networks will bring greater need and opportunities for power and energy flexibility. At the residential level, there are many sources of flexibility (Weiß et al., 2019) such as electrification of heating, primarily through heat pump technology (Du et al., 2019), which will bring opportunities for increased flexibility (Afzalan and Jazizadeh, 2019).

Commercial buildings are often already highly electrified and have a high potential for flexibility (Ma et al., 2017). Sources may include heat pumps (Péan et al., 2018), thermal storage (Reynders et al., 2018), lighting (Ma et al., 2013) and AHU fans (O'Connell et al., 2019c).

Small industrial sites such as water and wastewater treatment plants have a high flexibility potential as many processes can be shifted, controllable loads such as pumps are present, and if installed, cogeneration may provide small scale dispatchable, synchronous generation (Orths et al., 2019). Dispatchable means the power generator may be controlled on demand i.e. dispatched (Niu et al., 2019). Synchronous generation is important for grid stability as it matches the AC frequency of grid electricity, unlike wind or solar which is asynchronous (Matevosyan et al., 2019).

Transport electrification, perhaps the most high-profile electrification initiative, creates opportunities at the building or site level through the use of electric vehicles (EVs) battery storage while the vehicle is charging (Zhou and Cao, 2019) and after they have been removed from the vehicle, known as 2nd life batteries (O'Connell and Riverso, 2016).

Cross-energy vector system integration (MacDougall et al., 2019) for example, between district heating and electricity is being used by Denmark (Larsen and Johra, 2019) to achieve their 100% target for renewable electricity consumption by 2030 (Orths et al., 2019).

1.6 Stakeholders

The primary stakeholders which will benefit from a standardised flexibility assessment methodology are building and site operators and aggregators (Ma et al., 2019). For large sites, with flexibility ranges above the MW participation thresholds who may deal directly with TSOs or DSOs, the grid operators are also key stakeholders (Eirgrid, 2018). Building and site operators may include building owners, facility management companies, facility managers (Araya Cardoso, 2020), site operators and site operations managers of residential, small commercial buildings and smaller industrial sites. Other stakeholders which may be involved include energy regulators, policymakers, professional associations of e.g. of grid operators or manufacturers of equipment, industry interest groups, standard organisations, energy consultants and other energy professionals (Ma et al., 2019).

Figure 1.2 shows the interrelationships between the key stakeholders. Building and site operators offer aggregators power and energy flexibility in return for a financial payment. Aggregators pool these small ranges of flexibility together to reach the required participation threshold and then sell demand response services to grid operators i.e. TSOs and DSOs.

The EU's Clean Energy Package stipulates that flexibility markets are to be been created across all EU countries, similar to the wholesale power generation pool markets (Schittekatte and Meeus, 2020). Ireland already has such a market, known as DS3 (Eirgrid, 2018). Where such a flexibility market exists, aggregators bid into the market pool and the TSO or DSO chooses to accept or reject the bids. Flexibility markets are regulated by an energy regulator (CRU, 2020).

The payment terms between the aggregator and grid operator are fixed by the grid operator or an energy regulator (CRU, 2020). On the other hand, payments between buildings and sites are not pre-determined and may be negotiated. A standardised flexibility assessment would allow building and site owners to assess the range of flexibility they have the capability of providing, thereby putting them in a stronger negotiating position with aggregators. In turn, a standardised flexibility methodology would enable aggregators to quickly and effectively assess multiple sites without the additional cost burden of a detailed assessment which they would then have to recoup through their contract with the building or site.

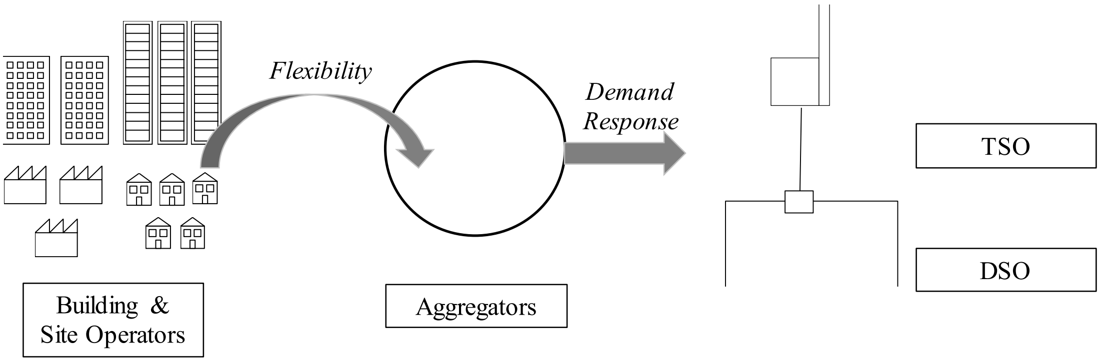


Figure 1.2 Stakeholder Diagram

A one-page output of the flexibility assessment which clearly defines the power and energy flexibility ranges of a building or site would be a **decision support tool** for high level stakeholder decision making such as:

i) Building or site operator decision to participate in demand side services;
ii) Building or site operator demand side services programme participation selection;
iii) DSO or aggregator selection of appropriate sites or buildings for portfolios;
iv) **Enable contract negotiation** between building or site operators and aggregators (or grid operators) for demand side services;
v) Investment decisions in system upgrades, metering or ICT platforms to provide grid services.

Table 1.1 Stakeholder Use of Flexibility Assessment

Stakeholder	Use 1	Use 2	Use 3	Use 4
Building or Site Operator	Site assessment & Decision to participate / not to participate	Demand Response Programme Selection	Contract Negotiation	Investment in system upgrades
Aggregator	Site assessment overview	Portfolio creation	Contract Negotiation	
TSO/DSO	Site assessment overview			

1.7 Drivers

While the primary driver for flexibility is technical, i.e. grid balancing, renewable generation hosting capacity, voltage and frequency stability (EU, 2016), a number of others exist. These include policy, environmental, regulatory, economic, commercial and social drivers.

1.7.1 Technical

The technical challenge created by increased renewable penetration is essentially that non-dispatchable renewable generators such as wind and solar provide intermittent, non-controllable power to the grid (Ma et al., 2013). Traditional fossil fuel generation can ramp up or decrease power output depending on the load, known as load following (Bruninx et al., 2017). However, renewable sources cannot be controlled in the same manner and so the grid needs to balance the peaks and troughs in renewable output while meeting customer load requirements (Ito et al., 2018). A range of technical solutions are employed to achieve this. These include gas fired power plants, grid connected storage, pumped hydro, battery storage, flywheels, smart switchgear and power and energy flexibility (Davies and Madden, 2017). Of these solutions, flexibility is the lowest cost to implement as it does not require investment in capital intensive hardware or infrastructure and can be implemented with the existing grid infrastructure (Østergaard Jensen et al., 2019b).

Distributed generation creates additional complexities (DeConinck and Helsen, 2016). In the hierarchical grid model, power flow was unidirectional (Grønborg Junker et al., 2018). Power generation stations connected to the transmission network fed power to the distribution network which distributed power to customers. This one-way power flow no longer exists, many renewable installations are now connected to the distribution network, and increasingly, building integrated renewables are creating prosumers, buildings which both generate and consume power and energy (EPRI, 2019). Thus, balancing requirements have been created at nodes on the distribution grid or between nodes before the power is exported to the transmission network. Flexibility may be used for this type of localised balancing (Spiliotis et al., 2016) and in addition has the potential to facilitate net zero energy or energy positive communities (Ala-Juusela et al., 2015).

Prediction of renewable output has improved and is approaching 90% in some jurisdictions (Ito et al., 2018). Instead of having large fossil fuel generators on standby to meet the shortfall (Davies and Madden, 2017), flexibility has a faster speed of response (Gonzales et al., 2020) and is therefore a more cost-effective means of bridging the gap (Østergaard Jensen et al., 2019b).

Deferring grid capital expenditure is possible through leveraging flexibility (Spiliotis et al., 2016). For example, instead of upgrading a transformer to a higher capacity, flexibility may be used to balance the grid at that location. This is advantageous for grid operators as OpEx (Operational Expenditure) may be easier to fund than CapEx (Capital Expenditure) (SEDC, 2017).

Sudden drops in real or reactive power may cause voltage or frequency fluctuations disrupting grid stability (European Commission, 2016). Flexibility may be used to balance these and maintain a more stable grid (Ma et al., 2013).

1.7.2 Policy

EU Policy is to create a climate-neutral Europe by 2050 (European Commission, 2018b). A strategy is in the process of being developed to comply with the Paris Agreement (UN, 2015). Globally, the Paris Agreement (UN, 2015) greenhouse gas emissions reduction targets will require significantly increased generation from renewables to achieve, in conjunction with other carbon reduction efforts.

While the EU is already on target to achieve 20% renewables integration by 2020, future European objectives for non-dispatchable (primarily wind and solar) renewable generation are ambitious - to integrate more than 90% by 2050 (ECF, 2010).

EU policy is also to encourage greater participation by smaller buildings such as residential in demand response (European Commission, 2017). This is evidenced through increased investment in high TRL research in the area of residential flexibility through the Horizon 2020 programme (Seri et al., 2018) (REACT, 2018).

1.7.3 Regulatory

Regulatory drivers at EU level for the creation of a low carbon future have impacts at grid scale and for building flexibility. Drivers include:

- Grid: Renewable Energy Directives 2009/28/EC & 2018/2001/EU (European Parliament, 2009) (European Parliament, 2018b)
- Buildings: Energy Performance of Buildings Directive (EPBD) (recast) 2018 2018/844/EU (European Parliament, 2018a)
- Market: State aid exception for capacity mechanisms for demand response MEMO/18/681 (European Commission, 2018a)

While the policy strategy aims for higher renewable integration targets of 50%, the regulatory target negotiated between member states is to increase renewable energy to at least 32% of the EU's final energy consumption by 2030 (European Parliament, 2018b).

In electricity markets, capacity payments are a means to secure access to a resource such as generation or flexibility (Eirgrid, 2018). Participants are typically paid a flat annual fee to be available and activation only results in a minor additional payment to cover costs (Eirgrid, 2018). Increasing the use of capacity mechanisms for flexibility specifically promoting demand response has been permitted by the European Commission as an exemption to state aid rules in France, Greece, Italy and Poland (European Commission, 2018a).

The recent EPBD recast in 2018 (European Parliament, 2018a) specifically included the creation of a Smart Readiness Indicator (SRI) for buildings. The purpose of the SRI is to indicate the energy flexibility potential of the building. The SRI is currently under development by the VITO & Waide Consulting consortium (Verbeke et al., 2020), which is investigating potential implementation options. To date the consortium has identified 9 domains with 32 associated services. Domains include heating, lighting, electricity and EV charging. Services are assessed on five functionality levels from 0 – None to 4 – performance evaluation or similar. The evaluation takes place across a number of different impact factors such as energy savings, comfort and convenience, of which ‘flexibility for the grid and storage’, is one. The use of an impact factor makes the assessment a qualitative rather than a quantitative assessment of flexibility.

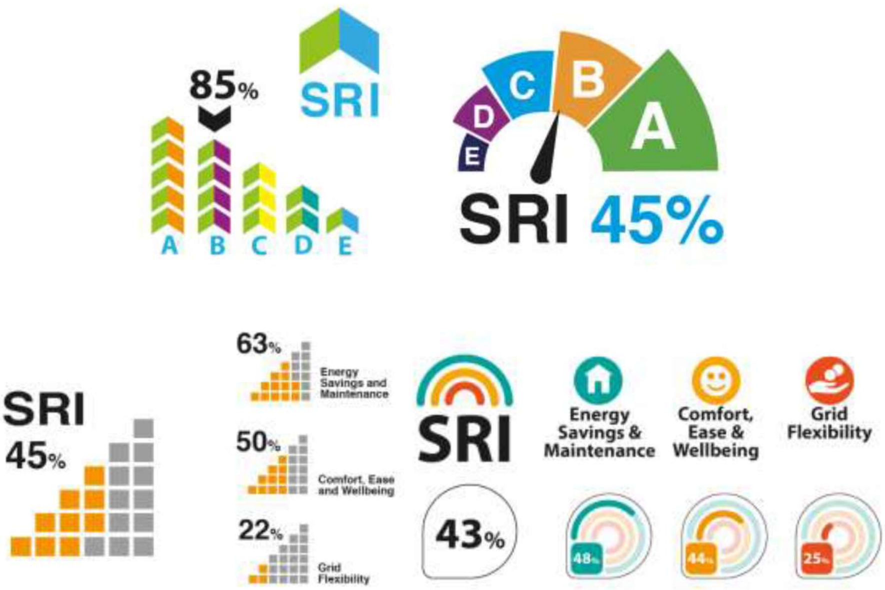


Figure 1.3 Draft SRI Label Options (Verbeke et al., 2020)

The output will be a graphical indicator and examples of potential versions are shown in Figure 1.3. While the SRI will provide useful information for building operators owners and occupants to indicate the overall smart capability of a building, it does not quantify the magnitude of flexibility available in % of peak load or kW / MW. Therefore, the SRI cannot be used by stakeholders for decisions around demand response capability, participation or contract negotiation for demand response services.

1.7.4 Environmental

To achieve the Paris agreement's objective of keeping global temperature increases to well below 2°C and pursue efforts to keep it to 1.5°C (UN, 2015), the world needs to reduce its reliance on fossil fuels and increase renewable generation. A climate emergency has been declared by the Irish government (Dáil Eireann, 2019). As outlined in Section 1.7.1, flexibility is a key enabler in integration of renewable energy systems and reducing fossil fuel dependence.

1.7.5 Economic

The use of flexibility to balance the grid is more economically advantageous than strategies such as curtailing wind generation or the use of backup gas fired power generation (Østergaard Jensen et al., 2019b). Curtailment of wind generation results in reduced electrical power and energy output from the windfarm, decreasing revenues for the operator of the renewable generation asset (Ma et al., 2019). Fuel costs are the largest proportion of the cost of gas fired generation but additional run time hours also result in higher maintenance costs (SEAI, 2018). The cost of standby, maintaining the power station in a state of readiness should ramp-up be required, is also a significant factor (IRENA, 2018).

1.7.6 Commercial

Building and site operators earn financial rewards from participating in demand response programmes (Aghaei and Alizadeh, 2013). Buildings and sites below the minimum participation thresholds set by grid operators can participate through aggregators (Foggia et al., 2014). While the price set at grid level is well defined (SEMO, 2018), the price buildings and sites receive depends on negotiation with aggregators (Ma et al., 2019). To effectively negotiate with aggregators, building and site operators require a means of assessing the flexibility of their building or site (MacDougall et al., 2017).

1.7.7 Societal

Climate action has become an imperative for society with worldwide protests and an increasing frustration among citizens at what is seen as lack of progress in tackling climate change goals (Irish Times, 2019). In addition to aiding the transition to a low carbon society, flexibility enhances the security & reliability of the electricity supply for society (Ma et al., 2019). However, the level of awareness of energy flexibility in society is low and the benefits it can provide are not well known (Østergaard Jensen et al., 2019b).

1.8 Barriers

The barriers to realising a future state with wider building participation include:

1. There is no standardised means of assessing power and energy flexibility in buildings or sites (Reynders et al., 2018);
2. Flexibility assessment is currently either cursory/brief (Yi et al., 2018) or a detailed assessment is bespoke, requires expert evaluators, is expensive and time consuming (Alczar-Ortega et al., 2015), which leads to non-participation or under-participation (Østergaard Jensen et al., 2019b);
3. Aggregators prefer to deal with single large clients (Ofgem, 2016). Dealing with many small building operators is problematic, time consuming and does not provide them with the same impact (Liddy, 2016). However, the flexibility of large industrial users are not sufficient to meet the needs of the future grid and cost effective means of evaluating buildings and smaller sites is required for efficient use of aggregator resources (Østergaard Jensen et al., 2019b);
4. Building operators or managers may not be aware of the potential flexibility of their buildings (Ma et al., 2019);
5. Source selection is frequently not considered, or systems are pre-selected. From the review of existing approaches (D' Hulst et al., 2015), (De Coninck and Helsen, 2016) and (Oldewurtel et al., 2013) (Ma et al., 2013) the method of source selection is not considered. Pre-selection of specific sources was used in methods developed by Nuytten et al. (2013), Stinner et al. (2016) and Reynders et al. (2015). In these approaches, flexible systems have already been selected for the building or site and the available range defined at demand side service contract stage;
6. Significant research efforts are targeting dynamic, online or real-time flexibility characterisation and assessment (Grønborg et al., 2018) (Hu et al., 2018) (Ottesen and Tomasgard, 2015). However, investments on-site are required to do this, such as installing an ICT platform, additional sensors, meters and actuators and Building Management System (BMS) programming upgrades (Ma et al., 2019). After all this, it may transpire that the building may not be suitable for participation in demand response programmes or that the financial return from participation may not justify the investment (Piette et al., 2006);
7. Without a structured approach, the individual conducting the assessment is dealing with a data avalanche of 1,000s documents, specifications, equipment data sheets, 100's drawings, 1,000's data points and 100,000's data values (Li, 2019).

8. Energy auditing approaches, such as those adhering to the ISO 50002 energy auditing standard (ISO, 2014), may be used but these are focused on energy conservation rather than flexibility. For example, a controller that is energy-efficient is typically not price-optimal given the energy markets and the energy-related taxes that exist today (Gronborg Junker et al., 2018);
9. Lack of standardised benchmarks and benchmarking methods similar to those for Energy consumption (Field, 2008) to define what is 'best practice' 'good' 'typical' and 'poor' flexibility performance for buildings and sites;
10. Awareness of flexibility is not widespread among operators of buildings and smaller industrial sites (Ma et al., 2019);
11. Key information quantifying flexibility is not comparable across buildings or sites (Reynders et al., 2018).

1.9 Early Stage Assessment

If an early stage assessment, i.e. prior to investment on site or negotiation of contracts for demand response, is conducted it will overcome a number of the key barriers identified in Section 1.8 namely:

- Cursory, brief ad-hoc assessment which may miss key flexible sources (Yi et al., 2018);
- Pre-selection of sources before a flexibility assessment has been conducted (Stinner et al., 2016) which may result in not all flexible sources being identified;
- Avoid up-front investment in ICT, automation, sensors or meters being made before the viability of the site for flexibility and demand response has been assessed as would be required for dynamic, online or real-time flexibility characterisation and assessment approaches (Grønborg et al., 2018) (Hu et al., 2018) (Ottesen and Tomasgard, 2015).

A schematic showing the stages of decision making in demand response participation is shown in Figure 1.4.

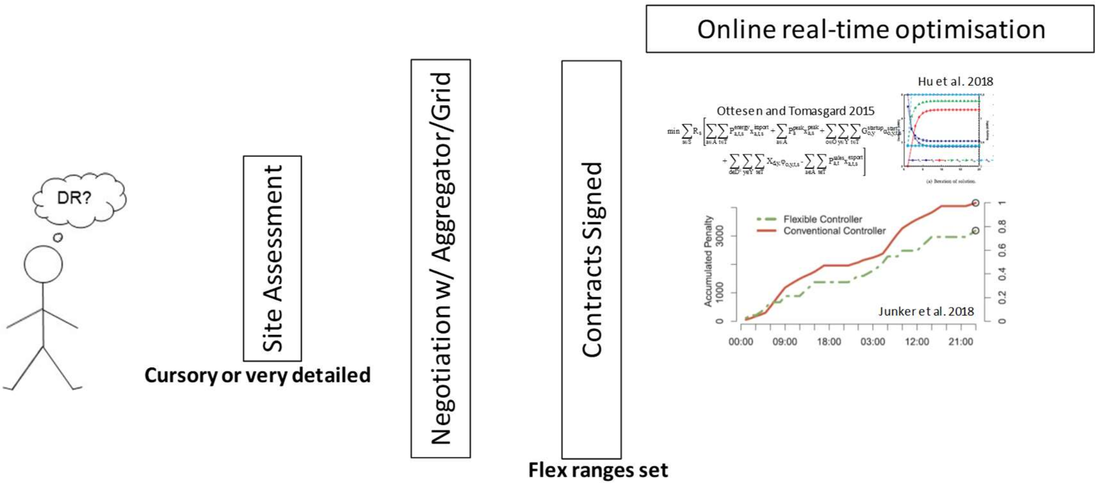


Figure 1.4 Decision Making Steps to Participation in Demand Response Programmes

1.10 KPI Label

KPI labels are clear visual indicators (Xin et al., 2018), which provide defined graphical and numerical metrics (SC3, 2012) for stakeholder decision making (Ma et al., 2019). For example, the Building Energy Rating (BER) or Energy Performance Certificate (ECP) as developed under the EU Energy Performance of Buildings Directive (European Parliament, 2002, 2010, 2018a), has now become ubiquitous in European society, making energy consumption a key decision factor for home buyers and renters (Aydin et al., 2019).

Informing and educating people beyond those in the scientific and technical community, known as operationalising (Ala-Juusela et al., 2015), has been successfully deployed for the concept of Energy Positive Neighbourhoods (EPNs) using KPI labels (Ala-Juusela et al., 2015). A similar operationalising approach using a different KPI label may be effective in bringing flexibility awareness to a wider spectrum of society.

1.11 Problem Statement

At present, flexibility assessments in buildings and sites are either cursory or are complex and bespoke. At present, there is no standardised approach for an early stage flexibility assessment.

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 for energy flexibility, which generally focus on energy conservation, 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 may 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.

In addition to the lack of a standardised assessment, there is also a lack of consistency in how flexibility ranges are communicated. Approaches vary from power curves (Stinner et al., 2016), indices (Grønborg Junker et al., 2018) or a combination of technical and financial parameters (Hu et al., 2018). If a building or site operator hires an energy consultant to perform a flexibility assessment, a bespoke report would be produced, based on their experience and expertise, which will differ from consultant to consultant.

Energy flexibility is a recognised concept in the scientific and technical community but it may not be as familiar to facility managers, building operators and citizens. The lack of a standardised means to operationalise the concept of flexibility may be limiting societal impact.

The disadvantages of current flexibility assessment 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 (Araya Cardoso, 2020).

1.12 Research Question

The research question posed from the above problem statement is:

Can an early stage standardised flexibility assessment methodology be developed that enables greater participation of large numbers of buildings and sites, with a diverse range of systems, in smart grid demand response, without requiring significant up-front investment, to meet renewable integration goals for decarbonisation and electrification?

1.13 Overview of Proposed Approach

The approach proposed in this work is to develop a standardised, user focused, early stage flexibility assessment methodology which 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. It is a key stakeholder enabler, allowing building and site operators to evaluate the power and energy flexibility capability their building or site has; enabling aggregators to create larger, more diversified and non-correlated portfolio of buildings and sites and enabling grid operators to maximise the flexibility potential of buildings and sites to balance the grid. 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, building or site level Key Performance Indicator (KPI) containing label. A clear visual indicator (Xin et al., 2018), the KPI label provides defined graphical and numerical metrics (SC3, 2012) on the available power flexibility ranges and associated timescales for stakeholder decision making. Aggregators may assess buildings or sites at a glance for portfolio creation (Foggia et al., 2014). Grid operators, when dealing with larger sites, may utilise the KPI label for setting contractual ranges (Eirgrid, 2018). For building and site operators, it is one-page summary of their building or site's flexibility capability to support decision making and enable contractual negotiation. The KPI label also has the potential to operationalise (Ala-Juusela et al., 2015) the concept of flexibility to a wider spectrum of society.

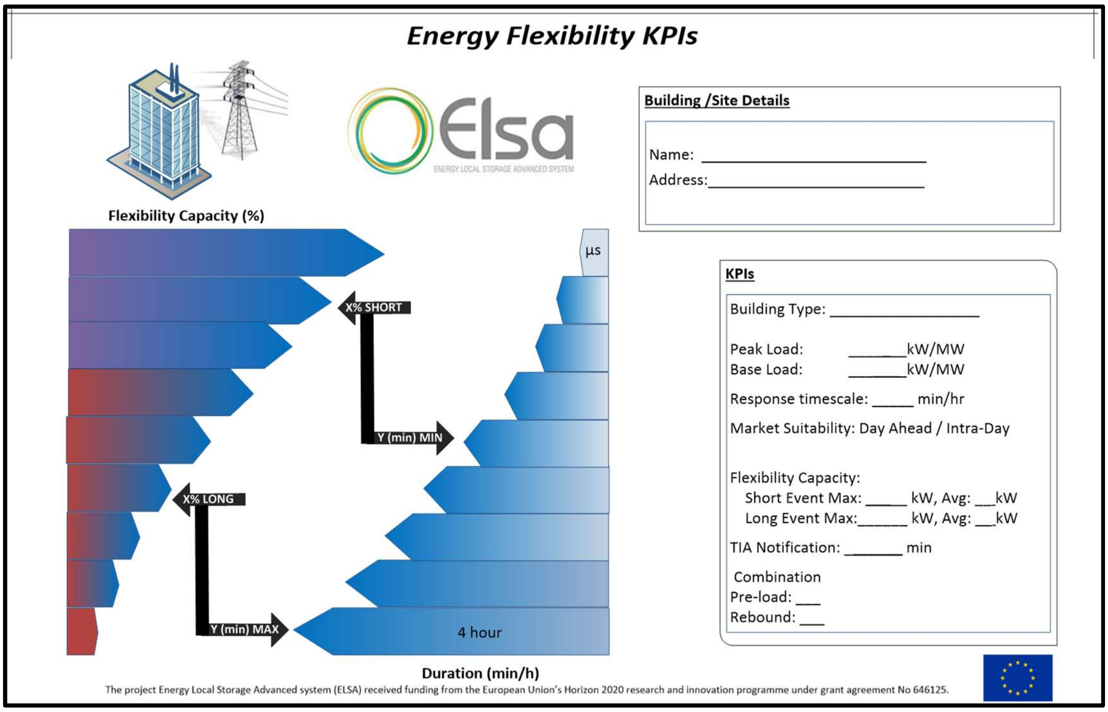


Figure 1.5 KPI Label

The four steps in the flexibility assessment methodology are:

- Step 1: Systems, load, storage and generation identification;
- Step 2: Flexibility Characterisation;
- Step 3: Scenario Modelling;
- Step 4: Key Performance Indicator Label.

1.14 Thesis Outline

The chapters of this thesis are as follows:

- Chapter 2 reviews existing approaches to assessing power and energy flexibility in buildings and sites, identifies the gaps in the existing approaches and proposes a means of addressing those gaps.
- Chapter 3 details the development of the four-step flexibility assessment methodology, incorporating the lessons learned from Chapter 2.
- Chapter 4 implements the four-step flexibility assessment methodology in detail for one pilot site. The detailed case study was conducted by the author, to verify the feasibility and accuracy of the approach. The methodology was then implemented by others at four additional pilot sites to demonstrate ease of use and scalability.

- Chapter 5 proposes potential future states based on a dynamic implementation of the methodology and automation of steps 3 and 4.
- Chapter 6 draws conclusions from the results in Chapter 4 and outlines possible future work.

1.15 Related Publications

This work has resulted in 10 publications to date. These consist of a journal paper (O'Connell et al., 2019a), four conference papers (O'Connell et al., 2019b) (O'Connell and Riverso, 2017) (O'Connell and Riverso, 2016) (Valdivia et al., 2014), a Horizon 2020 project deliverable (O'Connell et al., 2016), two patent applications, in which the author is a co-inventor, (Riverso et al., 2018) (Riverso et al., 2019) and two International Energy Agency reports (O'Connell et al., 2019c) (O'Connell et al., 2019d) which have been finalised and are due for publication in 2020 as book chapters.

Literature review, methodology, and results for a single building case study are documented in the journal publication O'Connell et al. (2019a) which is a synthesis of the core parts of this thesis.

Conference papers (O'Connell and Riverso, 2017) (O'Connell and Riverso, 2016) and a Horizon 2020 project deliverable (O'Connell et al., 2016), detail the development of the methodology from its initial stages. The origins and system architecture of the ICT platform deployed for experimental verification are outlined in Valdivia et al. (2014). Experimental verification at multiple pilot sites is documented in the conference paper O'Connell et al. (2019b).

The two patent applications, of which the author is a co-inventor, have been filed with the US Patent Office (Riverso et al., 2018) (Riverso et al., 2019) and map potential future states for flexibility and demand response in buildings.

International Energy Agency (IEA) reports and deliverables for the Energy in Buildings and Communities Annex 67 – Energy Flexible Buildings, contain the scenario modelling in Step 4 of the methodology (O'Connell et al., 2019c) and elements of the experimental work at the multiple pilot sites (O'Connell et al., 2019d). These reports have been finalised and are published on the Annex 67 website http://www.annex67.org/publications/.

Journal Paper:

O'Connell, S., Reynders, G., Seri, F., Sterling, R. and Keane, M. (2019a) 'A standardised flexibility assessment methodology for demand response', *International Journal of Building*

Pathology and Adaptation, Vol. 38 No. 1, pp. 20-37. https://doi.org/10.1108/IJBPA-01-2019-0011

International Energy Agency Reports & Deliverables:

O'Connell, S. and Keane, M. (2019c) ‘Flexibility Assessment for Demand Response’ in Li, R. (ed.) *'Modelling of Possible Energy Flexibility in Single Buildings and Building Clusters'*, Technical Report, International Energy Agency Energy in Buildings & Communities, Annex 67 Energy Flexible Buildings, available at: http://www.annex67.org/publications/reports/ (Accessed 13th Aug 2020)

O'Connell, S. and Keane, M. (2019d) ‘2nd Life EV Battery Storage’, in Østergaard Jensen, S., Parker, J., Engelmann, P. and Marszal, A. (eds.) *Examples of Energy Flexibility in Buildings*, Deliverable, International Energy Agency Energy in Buildings & Communities, Annex 67 Energy Flexible Buildings, available at: http://www.annex67.org/publications/deliverables/ (Accessed 13th Aug 2020)

Patent Applications:

Riverso, S., Torchio, M., O’Connell, S. (2019) ‘Method for Controlling Building Power Consumption’, Patent Application No. 62/835,130, Filed with US Patent office April 17th 2019.

Riverso, S., Torchio, M., O’Connell, S. and Sobonski. P. (2018) ‘Managing Flexible Grid Resources’, Patent Application No. 62/718,048. Filed with US Patent office 13th Aug 2018.

Horizon 2020 Project Deliverable:

O’Connell, et al., (2016) ‘D1.4 –Flexibility Capabilities per Test Site’, Energy Local Storage Advanced system (ELSA) project, European Union Horizon 2020 Research and Innovation Action, Grant agreement No. 646125, 2016. Confidential deliverable.

Conference Papers:

O'Connell, S., Reynders, G., Seri, F and Keane, M., (2019b) ‘Validation of Flexibility Assessment Methodology for Demand Response in Buildings’, 1st Nordic Conference on Zero Emissions and Plus Energy Buildings, 6-9 Nov 2019, Trondheim, Norway, *IOP Science Conference Series: Earth and Environmental Science*, Vol. 352 No. 1, pp. 1755 - 1315, http://dx.doi.org/10.1088/1755-1315/352/1/012014

O’Connell, S. and Riverso, S. (2016) ‘Flexibility analysis for smart grid demand side services incorporating 2nd life EV batteries’, in: *IEEE PES Innovative Smart Grid*

Technologies, Europe, Ljubljana, Slovenia, October 2016, pp. 1-6, doi: 10.1109/ISGTEurope.2016.7856178

O'Connell, S. and Riverso, S. (2017), 'Flexibility Analysis for Smart Grid Demand Response', Tech. rep., United Technologies Research Centre, Cork, Ireland. *arXiv:1704.01308*, available at: https://arxiv.org/abs/1704.01308

Valdivia, V., O'Connell, S., Gonzalez-Espin, F., El-din Mady, A., Kouramas, K., De Tommasi, L.,Wiese, H., Carballido Villaverde, B., Foley, R., Cychowski, M., Hertig, L., Hamilton, D. and Pesch, D. (2014) 'Sustainable Building Integrated Energy Test-Bed', in: *IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Galway,* Ireland, June, 2014, doi: 10.1109/PEDG.2014.6878709

Chapter 2: Literature Review

2.1 Introduction

This chapter will examine the assessment of energy flexibility in buildings and sites in existing literature with a specific focus on the following:

- Flexibility Evaluation (See Section 2.2);
    - Ad-hoc, cursory or Detailed Approaches;
    - Characterisation of Flexibility;
    - Variable and Parameter Definition;
- Key Performance Indicators (See Section 2.3);
- Benchmarking (See Section 2.4);
- Conclusions & Proposed Approach (See Section 2.5).

A detailed review of existing flexibility evaluation methodologies is presented in Section 2.2, starting with an assessment of existing cursory and detailed approaches and moving on to detailed flexibility quantification assessments. Existing KPI labels for a range of applications are reviewed in Section 2.3 and their applicability to energy flexibility is evaluated. Previous demonstration studies for the creation of benchmarks are reviewed in Section 2.4 to enable comparability of the flexibility assessment outputs. Section 2.5 concludes the literature review by summarising the lessons learned.

2.2 Flexibility Evaluation

2.2.1 Ad-hoc or Detailed Approaches

Current approaches for early stage flexibility assessment are either ad-hoc or cursory, and fail to capture all available flexible power and energy systems, or detailed approaches, such as energy auditing, are expensive, time consuming and not targeted for flexibility.

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. 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., 2013) or HVAC (Kim, 2018).

Detailed assessments, such as those incorporating an energy audit (Alcázar-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). The author has previous experience of developing

(O’Connell, 2010a), implementing (O’Connell, 2009) and managing (O’Connell, 2010b) energy audits in buildings and sites. Processes for energy audits are mature and standards are well established (Coakley et al., 2014) (ISO, 2014). In contrast, flexibility assessments are relatively new (Østergaard Jensen et al., 2017), and a standardised approach has not yet been developed (Alcázar-Ortega et al., 2015). In the context of power and energy flexibility, energy audits may not fully address flexibility for three main reasons:

a) Evaluation of non-relevant systems.

   The systematic and detailed nature of a full energy audit (SEAI, 2017) results in many energy systems being analysed which do not provide flexibility. For example, if only 20% of the systems in a building can provide flexibility, then 80% of the assessment time has been wasted evaluating non-flexible systems.

b) Bespoke Implementation.

   To implement an energy audit for energy flexibility requires that it be adapted in a bespoke way so that it can be applied to flexibility (O’Connell et al., 2016). This requires an expert with a number of years’ experience in a field such as energy auditing, energy management or electrical engineering to use their own experience and expertise to evaluate what is flexible on a case-by-case basis (Ma et al., 2019). The output produced from such an assessment is non-standard (Reynders et al., 2018) and hiring an engineer with the required level of experience and expertise is expensive (O’Connell et al., 2010b) and may not pass a cost/benefit analysis (Aghaei and Alizadeh, 2013).

c) Different objective.

   Energy audits are focused on cumulative energy consumption (kWh) (ISO, 2014) whereas what is important for flexibility is instantaneous power (kW or kVA) (Reynders et al., 2018). Therefore, methods and tools developed to support energy audits may not necessarily support the evaluation of flexibility (Verbeke et al., 2020).

The development of a standardised flexibility assessment methodology would benefit from utilising the strengths of energy auditing, namely its structured approach and systematic assessment, and applying these to flexibility. There are elements of energy auditing standards such as ISO 50002 (ISO, 2014) which may be adapted to provide a robust structure for a flexibility assessment. ISO 50002 was reviewed in detail and specific parts relevant to the assessment of flexibility were identified as follows:

- Part 5.4 Data Collection
- Part 5.6 Conducting the site visit
- Part 5.7 Analysis

- Concept of using an indicator to communicate the key outputs i.e. an 'energy performance indicator'
- Part 5.8 Reporting

2.2.2 Characterisation of Flexibility

Flexibility has been quantified in a number of different ways. Evaluating the flexibility available at a site or building requires assessing the available sources, i.e. loads, storage and generation and identification of the associated relevant variables and parameters which define the elements that give the source its flexibility. Two main elements are considered:

i) Characterisation of flexibility;

ii) Definition of flexible elements which involves the identification of variables and parameters which are required to describe the available flexibility of those sources.

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 these approaches, such as installing an ICT platform, additional sensors, meters and actuators and Building Management System (BMS) software upgrades (Ma et al., 2019). Initial investment costs such as those relating to ICT platforms for flexibility have been identified as a barrier to demand response participation in stakeholder consultations by the IEA Annex 67 on Energy Flexible Buildings (Ma et al., 2019).

The disadvantages of these detailed approaches result in a detailed assessment may be cost prohibitive (Ma et al., 2019) or the uncertainty of the overall financial benefits (Aghaei and Alizadeh, 2013) may result in a lack of participation or under participation in demand response services (Østergaard Jensen et al., 2019b). An approach is required that may be implemented at a much earlier stage, when the building operator or facility manager is considering participating in demand response programmes (Araya Cardoso, 2020) but has not yet determined the range in kW which their building can offer to aggregators (Foggia et al., 2014) or the grid (Eirgrid, 2018) and has not yet signed contracts for demand response services (Schittekatte and Meeus, 2020).

A formula for load flexibility developed by Ma et al. (2013) is shown in Equation 2.1. It includes 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;

- Acceptable, A, meaning that it is acceptable to the building occupants and operators that the load be reduced or turned off.

Flexibility, F, is then calculated as a percentage of the total available load.

$$F_{l,p}(t) = S_{l,p}(t) \cdot \min\{C_{l,p}(t), A_{l,p}(t)\} \qquad (2.1)$$

The subscript l indicates the type of load and p the type of product. Calculation of the resource potential, R, is performed by multiplying the flexibility, F (%), by the load in kW or MW:

$$R_{l,p}(t) = F_{l,p}(t) \cdot L_l(t) \qquad (2.2)$$

In multiplying Shedability, S by the minimum of C, Controllability and A, Acceptability (which, as percentages, are <1), the formula may underestimate the available energy flexibility for a building. This is demonstrated in Figure 2.1 below where the upper line showing Shedability between 25% and 30% of peak load, is multiplied, first by Controllability, and then by Acceptability, to give a percentage peak load reduction of less than 5%. In addition, this formula focuses only on loads, on-site generation and storage are not included, even though they may provide flexibility. How the 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. Other relevant parameters such as time in advance notification, are not captured.

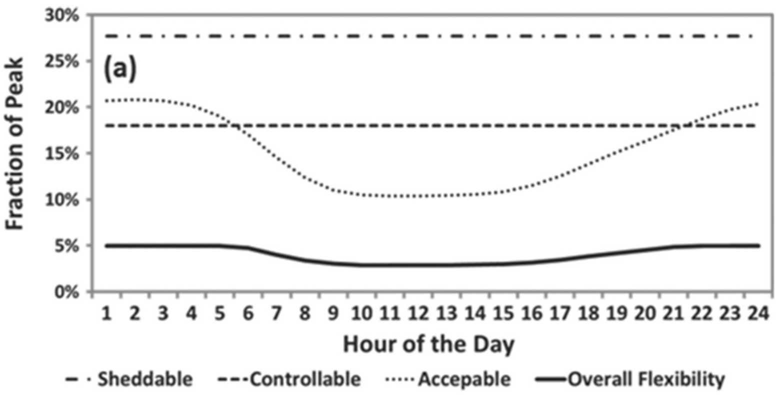


Figure 2.1 Flexibility Graph (Ma et al., 2013)

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 developed for thermal storage technology and their associated heat producing systems, but may be extended to other sources. The concept of flexibility being represented as a matrix is illustrated in Reynders et al. (2018), see equation 2.3.

$$\begin{bmatrix} -\frac{H_{i,we}+H_{vent}+H_{i,wi}+H_{i,f}}{C_i} & \frac{H_{i,we}}{C_i} & \frac{H_{i,wi}}{C_i} & \frac{H_{i,f}}{C_i} \\ \frac{H_{i,we}}{C_{we}} & -\frac{(H_{i,we}+H_{we,e})}{C_{we}} & 0 & 0 \\ \frac{H_{i,we}}{C_{wi}} & 0 & -\frac{H_{i,wi}}{C_{wi}} & 0 \\ \frac{H_{i,f}}{C_f} & 0 & 0 & -\frac{(H_{i,f}+H_{f,g})}{C_{we}} \end{bmatrix} \quad (2.3)$$

Where C_i, C_{we}, C_{wi}, C_f represent the thermal capacities of the indoor air, i, external wall, we, inner walls, wi, and the ground floor slab, f, respectively. H are the heat transfer coefficients, for example between the indoor air and the external wall $H_{i,we}$. The subscripts e, g and vent denote external air, ground and ventilation respectively. This matrix is specific to thermal storage as it quantifies the thermal characteristics of elements of the building which have the capacity to store heat. The concept of a flexibility matrix is useful and was adapted in this work and utilised for a more generalised concept of flexibility.

An activation vector, a, was proposed by Neupane (2017) which combined for days 1 to d, to create a device activation profile, X, see equation 2.4. The activation vector was considered for hourly resolution, group resolution (hours of m groups) and daily resolution.

$$X = \{a_1, a_2, \ldots\ldots a_{d-1},\} \quad (2.4)$$

In each of the methodologies presented in Reynders et al. (2018), the method of source selection is not considered, in common with Ma et al. (2013). Assessment of the approaches from Reynders et al. (2018) were incorporated into this evaluation.

Statistical approaches such as the probability estimation of flexibility (D' Hulst et al., 2015) and assessment of time-variable patterns (Sajjad et al., 2016) have the advantage of not requiring domain knowledge of the systems in the site or building. However, these types of approaches are heavily reliant on a rich dataset i.e. significant volumes of reliable, high quality data. The disadvantages of this is that the required quality and quantity data may not be available. Unless systems are pre-selected, as was done by D' Hulst et al. (2015), there is a lack of visibility on what systems are providing the flexibility and, for both studies, what their capabilities as sources for flexibility are. Data driven approaches rely on data from past performance of the system. If the data recorded only relates to use of the system for its primary purpose e.g. maintaining a room temperature set point, it may not have reached the operating limits of the system and so using that data for flexibility assessment may underestimate its capability.

Optimal control approaches (De Coninck and Helsen, 2016) (Oldewurtel et al., 2013) used dynamic data driven methods which require little or no domain knowledge i.e. knowledge of how and why the systems work. The cost function developed by De Coninck and Helsen (2016) is given in equation 2.5.

$$\text{minimise } J(t, \dot{x}, x, w, y, u) \quad (2.5)$$

$$\text{subject to constraints } F(t, \dot{x}, x, w, y, u) = 0 \quad (2.6)$$

$$g(t, \dot{x}, x, y, u) = 0$$

$$h(t, \dot{x}, x, y, u) \geq 0$$

$$x(0) = x_0$$

Where J is the objective function, t denotes time, u is the control signal and F the system model with states x, algebraic variables y and w disturbances. The constraints g and h are additional generalised inequality constraints. In this and other optimal control approaches, parameters and algebraic variables are automatically identified but may not map to real parameters associated with the systems, building or site e.g. thermal conductivity. As these are numerical approaches, similar difficulties to the statistical methods arise relating to access to data. To implement optimal control approaches, an on-line real time ICT platform is required with data acquisition and actuation capability. As source selection is not addressed in these methods, the installation of an ICT platform and associated site modifications required for it to function, is a significant investment to make before any quantification of flexibility is conducted. Having no early stage assessment to determine if flexibility is a) viable and b) cost effective is a gap in these approaches.

Nuytten et al. (2013) developed a generic model for thermal capacity sizing of a district heating Combined Heat and Power (CHP) plant and associated buffer storage. Minimum and maximum curves for the thermal buffer storage levels linked to the CHP were defined. For example, the minimum curve at time t+1, MIN_{t+1} for the buffer is given as:

$$MIN_{t+1} = MIN_t + 1_{MIN}(t)P_{CHP}\Delta t + E_{AUX,t} \quad (2.7)$$

Where MIN_t is the minimum curve at time t, $1_{MIN}(t)$ is an indicator function describing the operation of the CHP system, $E_{AUX,t}$ is the heat production from the auxiliary heating, if present.

Elements of this approach are useful, such as calculating available flexibility for every hour, identifying maximum and minimum ranges for flexibility and quantifying pre-load and rebound effects. However, the approach focused on thermal energy rather than electrical power and so is not directly applicable.

The approach developed by Stinner et al. (2016) to quantify operational flexibility with thermal energy storage approached the problem in terms of temporal power and energy quantification to create power curves bounded by maximum and minimum ranges. Some elements of the approach are application specific in that they may only be applied to thermal storage in buildings and it would be more beneficial to have an approach that is applicable to a wider range of building systems. The concepts of temporal power increments and maximum and minimum ranges, as shown in Figure 2.2, are useful and were adapted for the method in this work but used in a different way.

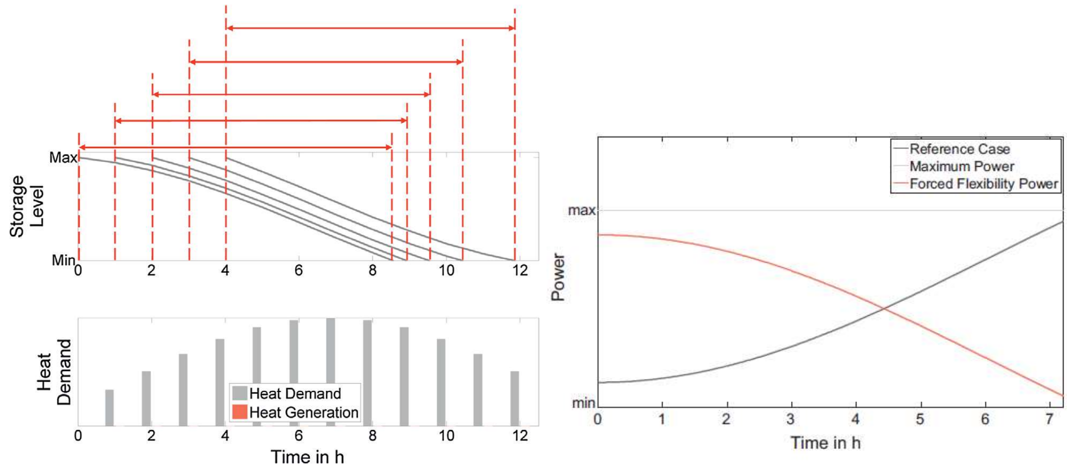


Figure 2.2 Storage Temporal Power (on left) with Max and Min Ranges (on right) (Stinner et al., 2016)

Nosair and Bouffard (2015) and Bucher et al. (2017) look at flexibility from the grid perspective only and do not consider building needs. Focusing on parameters important for grid operators, the evaluation of systems and equipment in buildings or sites is not considered.

The gaps identified in the above review are summarised in Table 2.2

Table 2.1 Gaps in Existing Approaches

Reviewed Approach	Early Stage Assessment	Explicit Source Selection	RES & Storage Incl	No ICT Req	Minimal Data Req	No Detailed Model Req	Price Independent	Building Focused	Detailed Input Variables & Parameters
DR for Ancillary Services (Ma et al., 2013)	√	X	X	P	X	P	√	√	X
Statistical Approaches (D'Hulst et al., 2015) (Sajjad et al., 2016)	X	X	X	X	X	√	√	√	X
Optimal control approaches (De Coninck and Helsen, 2016) (Oldewurtel et al., 2013) (Grønborg Junker et al., 2018)	X	X	X	X	X	√	√	√	X
Generic model for CHP sizing (Nuytten et al., 2013)	X	X	P	n/a	X	X	√	√	X
Quantifying Operational flexibility with thermal energy storage (Stinner et al., 2016)	X	X	P	X	P	X	√	√	P

√ = Meets Requirement, P = Partially meets requirement, X = Does not meet requirement;

Reviewed Approach	Early Stage Assessment	Explicit Source Selection	RES & Storage Incl	No ICT Req	Minimal Data Req	No Detailed Model Req	Price Independent	Building Focused	Detailed Input Variables & Parameters
Reduced order physics-based models (Reynders et al. 2015)	X	X	P	n/a	P	X	√	√	P
Grid perspective (Nosair and Bouffard, 2015) (Bucher et al., 2017)	X	X	√	X	X	X	√	X	X
Certification Prerequisites for DR trading (Alcázar-Ortega et al., 2015)	X	X	X	X	X	X	X	X?	√
Scheduling DR and Smart Battery flexibility (Siebert, et al., 2015)	X	X	√	X	X	P	P	X	P
Stochastic scheduling of energy flexibility (Ottesen, and Tomasgard, 2015)	X	X	P	X	X	X	X	√	√
SRI (Verbeke et al., 2018)	X	X	√	P	P	√	√	√	X

√ = Meets Requirement, P = Partially meets requirement, X = Does not meet requirement;

2.2.3 Variable and Parameter Definition

In terms of describing flexible systems using technical variables and parameters, several sources define these, but approaches are not consistent. The selection and definition of appropriate variables and parameters differs, as was also found by Reynders et al. (2018). In common with the approaches reviewed in Section 2.2.2, there is also an implicit assumption that source selection and flexibility have already been assessed and quantified, for example in Siebert et al. (2015) and Ottesen and Tomasgard (2015).

There are many variables and parameters that may be gathered for each system in a building or site (Østergaard Jensen et al., 2019b). However, the challenge is to identify the variables and parameters that capture the flexible aspects of the system in a consistent, robust and repeatable way (Reynders et al., 2018). These parameters may then be used as inputs for the assessment of flexibility (Li, 2019). 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 (Fischer and Madani, 2017). Of these, the first three are required for flexibility evaluation but the others may not be relevant (DeConinck and Helsen, 2016). 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 parameters include system availability (Stinner et al., 2016), percentage of sheddable load (Ma et al., 2013), time in advance notification and rebound (Østergaard Jensen et al., 2017) or pre-heat requirements (Piette et al., 2016).

Detailed parameter definition was set out by Alcázar-Ortega et al., (2015) as shown in Figure 2.3. While the approach to defining parameters was wide-ranging, it did not extend to a method of flexibility characterisation.

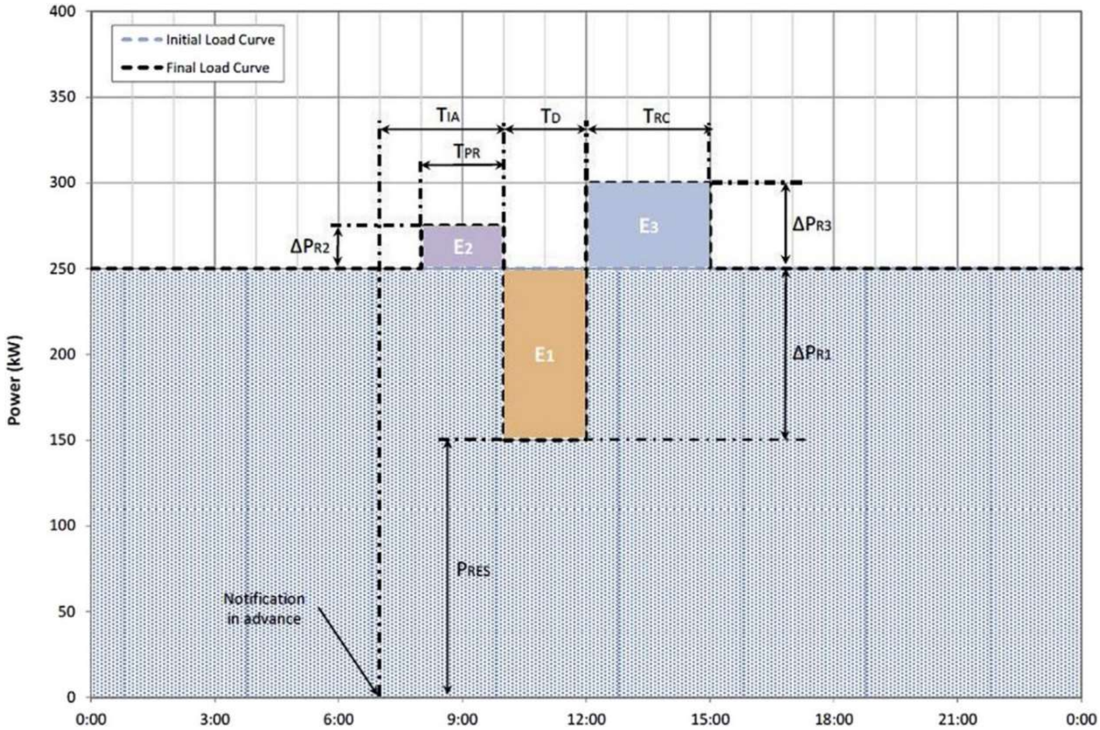


Figure 2.3 Flexible System Parameters as defined by Alcázar -Ortega et al. (2015)

The parameters defined included:

- ΔP_{R1} is Flexible power, the amount of power to be increased or decreased (kW);
- T_D is the duration of the action (h);
- T_{IA} is the notification in advance of the action (h);
- ΔP_{R2} is the extra power required before the flexibility action (kW);
- ΔP_{R3} is the extra power required after the flexibility action (also known as rebound or spring back) (kW);
- T_{PR} is the duration of the preparation, i.e. when ΔPr2 is consumed (h);
- T_{RC} is the duration of the recovery period i.e. when ΔPr3 is consumed (h);
- T_{av} is the available times for the DR service;
- T_{MIN} is the minimum time between flexibility events (h).

As part of scheduling sources for demand response, Siebert et al. (2015) identified some flexibility activation constraints, but many variables and parameters were insufficiently quantified. In particular, the use of Booleans (1/0) does not account for part load reduction in systems as it is not an on/off scenario. Assessment of available flexible systems is cursory as only one source is considered from each site. The variables and parameters identified were:

- Power (t, r) is the power flexibility provided by the resource r for the timestep t where:

$$\text{Power}(t, r) = \text{Res}(t, r) \, . \, \text{EventImpact}(t, r) \tag{2.3}$$

- Res (t, r) is a binary variable (1/0) indicating if resource r is active during timestep t;
- EventImpact (t, r) is the amount of power variation that can be provided by resource r at timestep t (kW);
- EnergyWeight (t) is a unitless weighting factor for time step t, related to electricity price. on a scale from 0 to 2.5;
- ut is the length of the optimisation step (s);
- BidActive (t) is a binary variable (1/0) indicating if the bid is active at time t;
- MinPower is the minimum power that must be provided (kW);
- T is the set of time steps between the bid start and end times.

A method of identifying loads as classes was developed by Ottesen and Tomasgard (2015) which is less tied to specific use cases. Five classes of loads were identified:

- shiftable volume;
- shiftable profile;
- curtailable loads which consist of reducible and disconnectable loads;
- inflexible loads;
- forecast load.

However, there is insufficient quantification of parameters and variables and the overall approach may be limited to fixed price markets (Ottesen and Tomasgard 2015). An example of a source with a shiftable volume would be a HVAC load (DeConinck and Helsen, 2016). In general, heating or cooling may be curtailed during a demand response event but the energy would need to be put in to the building either before (pre-load) or after (rebound). Another example of a shiftable volume source may be an electric vehicle (EV) (Zhou and Cao, 2019). The charging times may vary but the EV still requires a specific volume of energy to be fully charged. A source with a shiftable profile may be white goods equipment such as a washing machine (D'Hulst et al., 2015) or dishwasher (Hu et al., 2018). The cycle of the washing machine cannot be altered but the on/off time may be moved earlier or later. Curtailable loads may be systems such as lighting (Ma et al., 2013). If the lighting levels are turned down (reducible) or turned off (disconnectable) this energy does not need to be put back into the building at another time. Inflexible loads are those which do not have power or energy flexibility (Ottesen and Tomasgard 2015).

Visualisation of simplified shiftable profile and shiftable volume power profiles are shown in Figure 2.4. The shiftable profile may move to different time slots between 1 and 8 but the shape of the profile is fixed. Shiftable volume shows that the total energy may be moved or split into different parts in any time slot between 1 and 8.

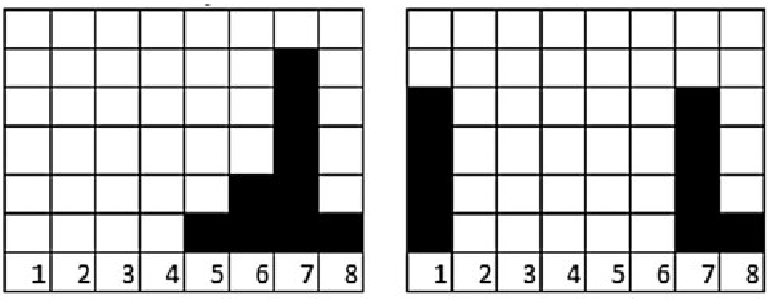


Figure 2.4 Load Classes: Shiftable Profile on left & Shiftable Volume on right (Ottesen and Tomasgard, 2015)

The proposed Smart Readiness Indicator (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.

A summary of the advantages and gaps in the reviewed approaches is given in Table 2.2.

2.2.3.1 Lessons Learned – Flexibility Evaluation

Lessons learned from the literature review in Section 2.2.3 and Section 2.2.2 are summarised as follows:

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, a flexibility assessment must be approached from a building system perspective and not a grid perspective;
c) sources are not limited to loads. 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;
f) detailed variables and parameters for flexible sources are required to be comprehensive and consistently applied across all sources during flexibility characterisation.

The flexibility assessment methodology in Chapter 3 adapts elements of the flexibility characterisation from Section 2.2.3 as well as variable and parameter definitions reviewed in Section 2.2.2. The next Section, 2.3, reviews approaches to representing Key Performance Indicators (KPIs) on labels to provide a visual representation of the output of the flexibility characterisation using variables and parameters identified as being relevant for power and energy flexibility in buildings and sites.

Table 2.2 Summary of Gaps & Advantages of Existing Approaches

Reviewed Approach	Advantages	Gaps
i) Flexibility Characterisation		
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.
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.
Optimal control approaches (De Coninck and Helsen, 2016) (Oldewurtel et al., 2013) (Grønborg Junker et al., 2018)	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.
Generic model for CHP sizing (Nuytten et al., 2013)	Available flexibility for every hour calculated. Theoretical maximum flexibility calculated. Time periods associated with pre-load and re-bound well quantified	Focused on thermal systems. Electrical power flexibility not considered.
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
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.
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.
ii) Variables & Parameters Definition		
Certification Prerequisites for DR trading (Alcázar-Ortega et al., 2015)	Detailed parameter definition.	Approach limited to defining parameters.
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; Assumption flexibility already assessed; Simplified use cases.
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 flexibility already assessed; Pricing structure limited.

2.3 Key Performance Indicators

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 (Østergaard Jensen et al., 2019b).

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 (Ala-Juusela et al., 2015) (S3C, 2012). The Building Energy Rating (BER) approach, implemented as a result of the Energy Performance of Buildings Directives (EPBD) (European Parliament, 2002, 2010, 2018) is also reviewed as it is example of a KPI label with a strong visual impact.

Four KPIs and a draft energy positivity label for Energy Positive Neighbourhoods (EPN) were developed by Ala-Juusela et al. (2015) as part of the European FP7 IDEAS project. The draft energy positivity label is shown in Figure 2.5. 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, Maximum Hourly Deficit and Monthly Ratio of Peak Hourly Demand to Lowest Hourly Demand may have applicability if adapted for demand response. The proposed KPI label has clear visual indicators combined with measurable metrics on the right.

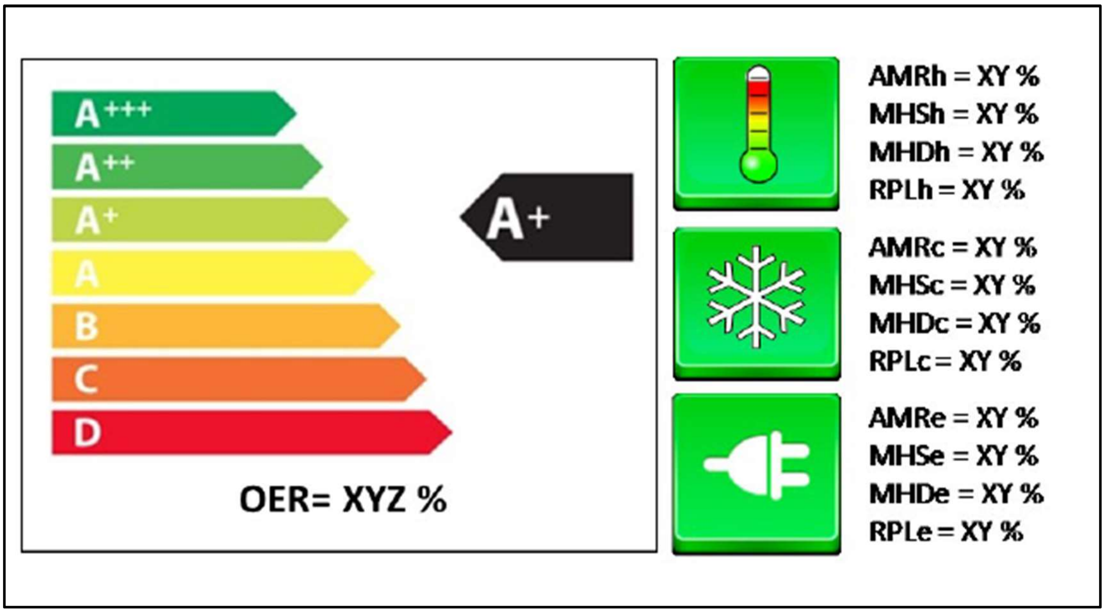


Figure 2.5 IDEAS Draft Energy Positivity Label (Ala-Juusela et al., 2015)

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). The KPIs are shown in Figure 2.6. 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, shifted energy divided by total daily consumption, and Peak Reduction Capacity, peak load capacity divided by total daily consumption, may be interpreted as measuring the same quantities. Consumption per Tariff may be best suited to Time of Use (TOU) pricing structures. As payment structures for participation in demand side services vary depending on the market programmes and jurisdiction (FERC, 2018) (Eirgrid, 2018), it would not be advisable to tie a KPI to one use case. For example, in capacity markets (Schittekatte and Meeus, 2020), the tariff for electricity usage is not relevant as the contracts are based on a fixed annual fee for availability with only additional operating costs paid for by the utility if relevant for an activation. For two of the KPIs, Demand Response Reliability and Consumption per Tariff, it would only be possible to measure these after all the enabling equipment has been installed and the building or site has participated in a number of demand side events. Therefore, these are not applicable for an early stage assessment.

KPI	User	Definition
Peak to average ratio	SME, Utility	Peak power consumption divided by average power.
Energy shift ratio	households, SME, Utility	Shifted energy divided by total daily consumption.
Consumption per tariff	Household, Utility	Amount during the tariff divided by total.
Peak reduction capacity	Utility	Peak load capacity divided by total daily consumption.
Demand response reliability	Utility (automated demand response)	Requested energy shift divided by realized energy shift.

Figure 2.6 SC3 Examples of KPIs for Demand Response (SC3, 2012)

The EPBD (European Parliament, 2002, 2010, 2018) mandated all member states to introduce Energy Performance Certificates (EPCs) or Building Energy Ratings, for commercial, domestic and public buildings. The KPIs implemented in Ireland on the Building Energy Rating (BER) label were annual energy consumption (kWh/m^2/yr) and CO_2 emissions (kgCO_2/m^2/yr) (SEAI, 2019). A sample BER label is shown in Figure 2.7. It targets user requirements, i.e. how much energy the building is expected to use and CO_2 emissions, which are measurable (SEAI, 2020). 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 (European Parliament, 2018). Recent analysis of EPCs in the Netherlands has demonstrated that their use provides standardisation in energy information between buyers and sellers and reduces uncertainty in decision making for buyers (Aydin et al., 2019), demonstrating the relevance of the user requirements the EPC displays.

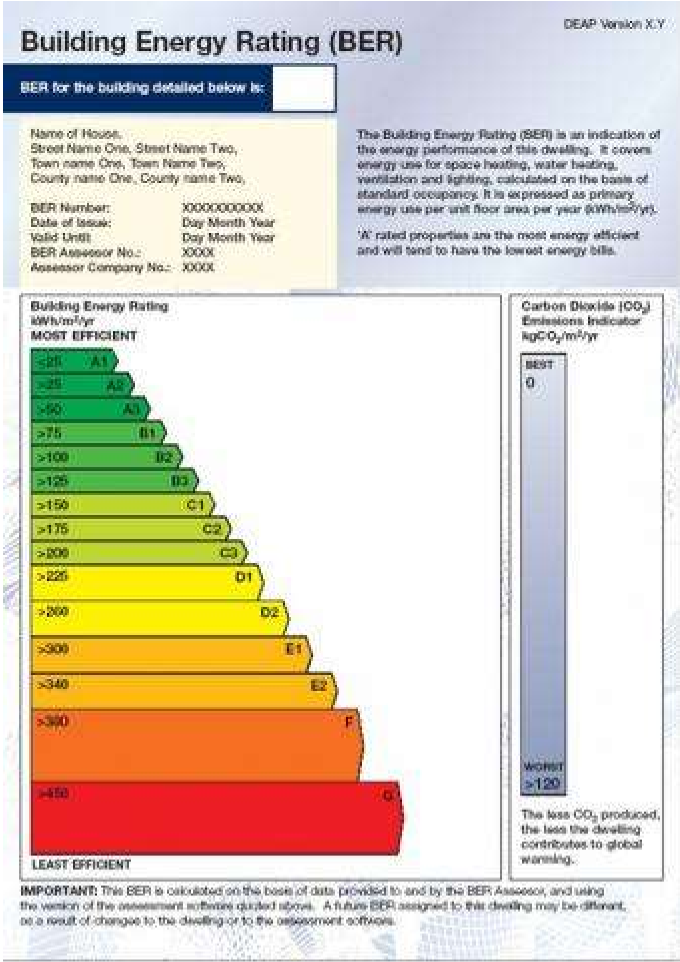


Figure 2.7 Sample Building Energy Rating (BER) Label (SEAI, 2019)

KPIs for flexibility are most frequently represented as the amount of energy or power that can be shifted in time (Østergaard Jensen et al., 2019b). Grid operators specify the power in MW that is required and the time duration of availability for events (Eirgrid, 2018). Aggregators pool power flexibility in kW or MW from a number of buildings and sites (Foggia et al., 2014) to create the portfolios necessary to participate in demand response programmes.

2.3.1.1 Lessons Learned – KPI Label

From the analysis above, the following key elements were identified for the development of a KPI label:

a) targeting relevant user requirements which are measurable;
b) minimising the number of KPIs and ensuring there is no overlap in metrics avoids over-complicating the indicators being communicated;
c) KPIs for flexibility require measurable metrics relating to the amount of energy or power that can be shifted in time;

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.

2.4 Benchmarking

Benchmarks for typical and best practice energy consumption for a range of different types of buildings (e.g. offices, educational, residential, leisure centres) 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 conducted across a range of real commercial and industrial buildings and sites were reviewed to understand how much flexibility is typical and to generate benchmarks for this work.

Studies involving large numbers of real buildings, in some cases up to 28, participating in utility DR programmes were conducted by Lawrence Berkley National Laboratory's (LBNL) Demand Response Research Centre (DRRC) in California (Xu and Zagreus, 2009) (Piette et al., 2006a). These were the first commercial implementation of demand response programmes (Smith and Clark, 2019) and were operated by Pacific Gas and Electric Company 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 two buildings. Piette et al. (2006) achieved up to 56% of peak load flexibility for short timeframes, with average flexibilities of $7 - 9\%$ demonstrated during longer events across 28 buildings.

Results for one of the buildings the Xu and Zagreus (2009) study is given in Figure 2.8. The graph shows the whole building power reduction with pre cooling on hot days. The black line represents the baseline daily power profile i.e. the typical profile if no demand response event took place. The blue, red and grey lines show the effects of different control strategies on the power profile. The blue line shows the effect of pre-cooling with linear reset of temperature, i.e. the temperatures were raised linearly in the afternoon to a maximum indoor air temperature of 25.6 °C. The red line demonstrates a similar reset strategy but with a more aggressive linear increase in temperature while the grey line shows the results using an exponential temperature increase. Moderate to high prices during the Critical Peak Pricing (CPP) periods were in the time window from 12 noon to 6pm. Of the three strategies, it can be seen that the pre-cooling with exponential temperature increase (grey line) achieved the greatest reduction during the event. However, the temperature increases were more rapid and higher which may have impacted on occupant comfort. For the liner strategies, pre-cooling resulted in a larger load reduction than standard operation but it would have been interesting to see results from a pre-cooling and exponential temperature increase combined with comfort monitoring.

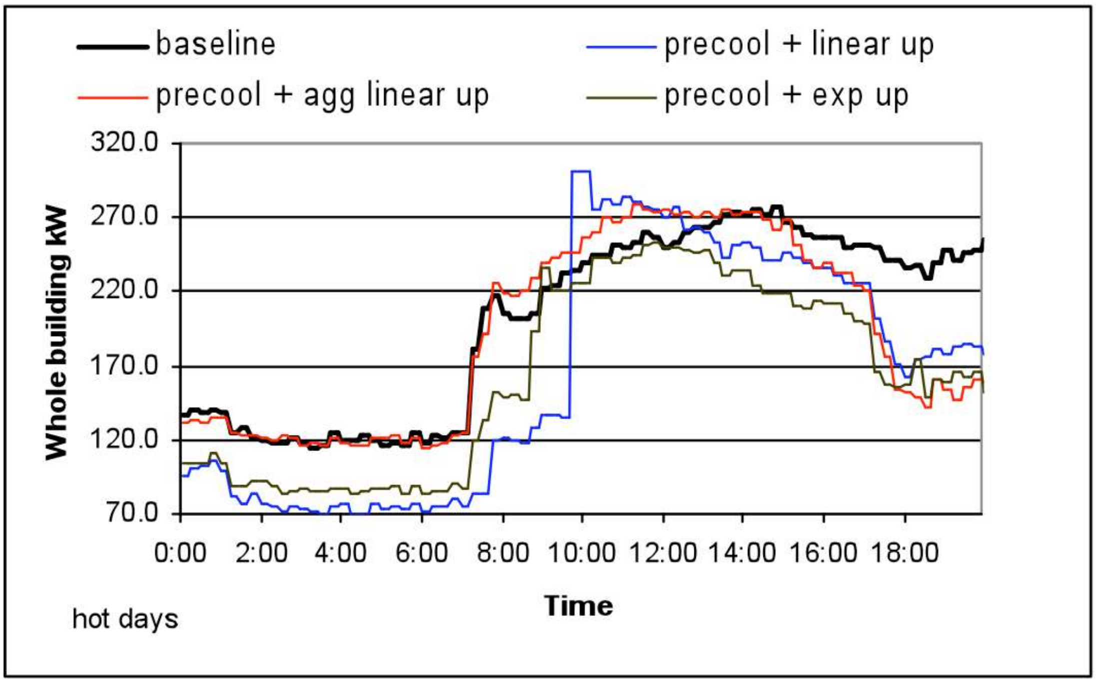


Figure 2.8 Results from Demand Response Activation (Xu and Zagreus, 2009)

Combined demand response reduction results for the 28 buildings and sites in the LBNL CPP study are given in Table 2.3. Different buildings participated in different years; hence the number of participants varies. The number of hours duration for which loads were shed was either three or six. Average savings were between 7% and 9% while max savings achieved were 28%, 38% and 56% of peak load.

Figure 2.9 shows detailed results for five of the 28 sites. Load reduction (savings) are shown in yellow (Piette et al., 2006b). The baseline power profile for the combined five sites is shown by the red line. Each building or site is represented by a different colour,

- Arnold office building – white;
- Chabot space and science centre – purple;
- Echelon office building - pink, Gilead office and laboratories – blue;
- Target retail store - turquoise.

The two key advantages of this demonstration study were:

a) the wide range of building and site types;
b) the large number of buildings and sites participating.

Load reductions were primarily HVAC e.g. AHU, Chiller, temperature set point reduction or increase but some sites also implemented lighting reductions. For the particular day shown in

Figure 2.9, the five sites achieved a combined load reduction of 23%.

Table 2.3 Results for 28 buildings from LBNL CPP Study (Piette et al., 2006a)

Results by Year	Number of Participants	Duration of Shed (Hours)	Average Savings (%)	Max Savings (%)
2003	5	3	8	28
2004	18	3	7	56
2005	12	6	9	38

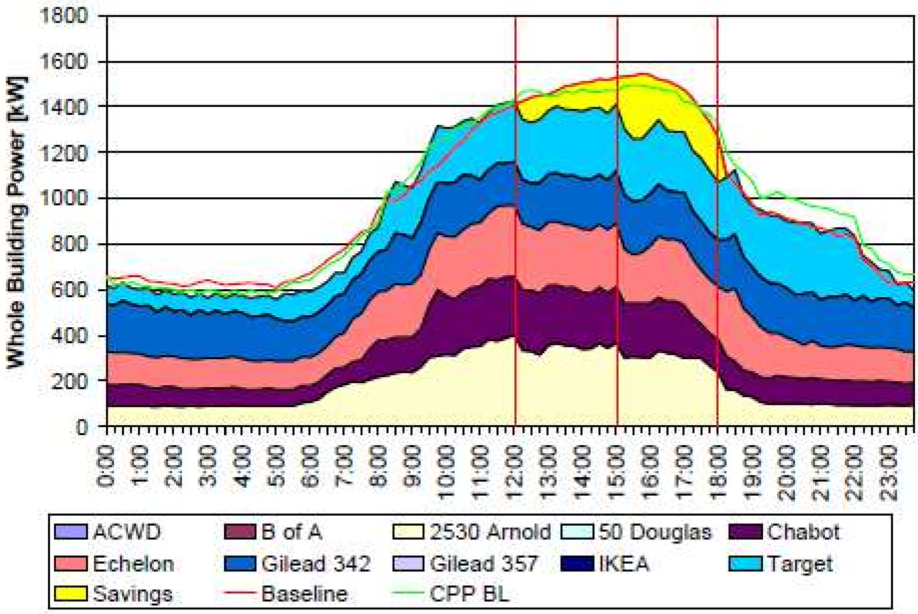


Figure 2.9 Results for five of the 28 sites in the CPP Study (Piette et al., 2006b)

In a recent European study 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 as shown in Figure 2.10. Eight sites, both buildings and industrial, provided loads, in combination with a grid connected Li-ion battery storage and a grid connected PV installation. For the buildings, heating was used as the flexible load while in the industrial sites, pumps were controlled. Figure 2.10 shows the aggregated load in blue bars, the baseline in the grey-green line and the reduction is indicated by the red arrow. The battery system and PV were grid coupled and controlled by an aggregator in coordination with the flexible loads. This reduces the level of autonomy that building operators have over their own systems if the battery system and PV are building based.

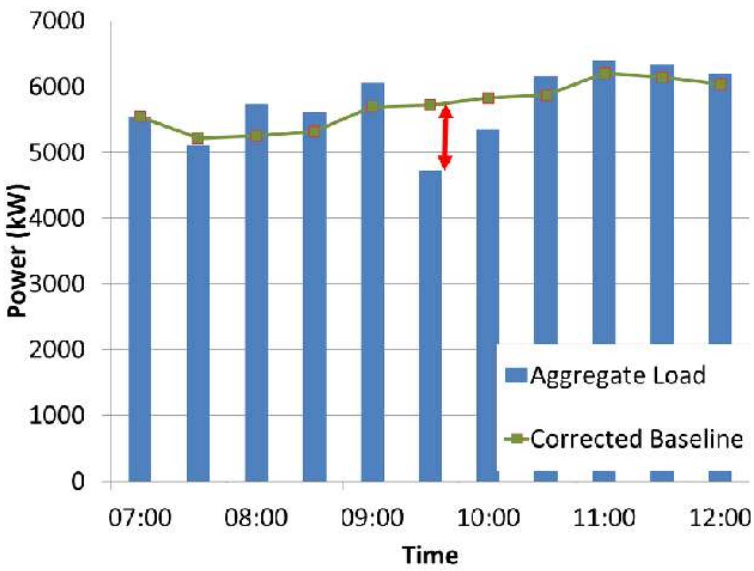


Figure 2.10 Load reduction demonstrated by Siebert et al. (2015)

Picault et al. (2015) demonstrated a load reduction of almost 50% against peak load as part of the French GreenLys project. The demonstrator was a commercial office and laboratory building using Time of Use (TOU) pricing signals for a two-hour duration.

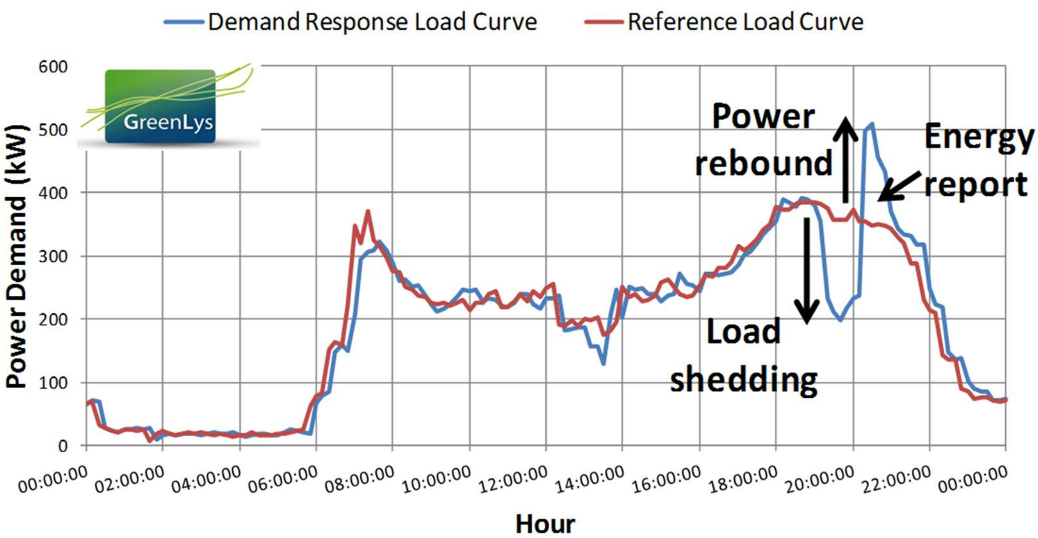


Figure 2.11 Load reduction demonstrated in the GreenLys Project (Enedis, 2019)

As part of the EU FP7 project Grid4EU (2016) (Foggia et al., 2015) 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 two-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.

The results for the four demonstration studies reviewed are summarised in Table 2.4. For each study, the number of buildings or sites in the study, the average power flexibility and maximum power flexibility, where available, are identified. Average and maximum flexibility are expressed as a percentage of peak load.

Table 2.4 Benchmarking Studies Results

Reviewed Study	**No. of Buildings/Sites**	**Average[1]**	**Max[1]**
Piette et al. (2006a)	28	7 – 9%	28 -56%
Siebert et al. (2015)	8	-	15%
Picault et al. (2015)	1	-	50%
Grid4EU (2016)	12	3 - 9%	-

1. Flexibility is expressed as a percentage of peak load for each site.

2.4.1.1 Lessons Learned - Benchmarking

In summary, the lessons learned from the benchmarking review were:

a) more published demonstration studies would be beneficial in developing standardised benchmarks
b) from the published results available, the maximum range for flexibility for buildings is between 18 - 56% of peak load with average flexibilities between 7 – 9% of peak load.

2.5 Quality of Flexibility

The quality of flexibility provided by sources impacts the effectiveness of the service they provide to the grid, as uncertainty in demand response increases costs for grid operators (Hussain et al., 2017). Sources of flexibility in buildings may include heat pumps (Péan et al., 2018), thermal storage (Reynders et al., 2018), lighting (Ma et al., 2013) and AHU fans (O'Connell et al., 2019c). If a source has a high average load reduction or increase capability (Péan et al., 2018) but with significant levels of variability (Neupane, 2017), as indicated by a noisy or unpredictable profile, this may intermittently negate the load reduction and be counterproductive to the grid impact measure it was contracted for (Ofgem, 2016). Uncertainty of the provided demand response thereby increases the operational costs of energy networks (Hussain et al., 2017) as grid operators require more backup systems such as gas fired generation or storage (Orths et al., 2019).

2.6 Error Analysis

To assess the accuracy of the proposed methodology, an error analysis is required. Prediction accuracy from published literature shows that for smart grid applications, prediction accuracy of +/- 10% is considered optimal (Borelli et al., 2018) (MacDougall et al., 2017). However, errors of up to 36% in flexibility prediction for heat pumps (Neupane, 2017) were considered acceptable. For wind generation prediction at grid level, forecast errors of 20% were considered very good but actual errors of up to 60% occur (Lew et al., 2019), which is extremely challenging for grid operators. Wang et al. (2018) found that prediction accuracy improved when the number of sources, in their case dwellings, was increased.

2.7 Conclusions

2.7.1 Gaps in Current Approaches / Lessons Learned

The lessons learned from the reviewed approaches are given in Table 2.5 and summarised as follows:

a) The requirements of flexibility are different to energy conservation and an energy audit may not be the correct tool for a flexibility assessment;
b) Explicit and systematic source selection is required to ensure all available flexible systems are identified;
c) Early stage assessment, prior to any investment on site is necessary to determine if the building or site is suited to participation in demand side programmes before the installation of ICT platforms or additional meters or sensors;
d) 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;
e) To effectively assess building flexibility, it must be approached from a building or site perspective and not a grid perspective;
f) Sources of flexibility are not limited to loads; all types of energy storage and on-site generation are required to be explicitly included in flexibility analysis;
g) A comprehensive assessment methodology that is sufficiently adaptable to capture all types of sources of energy and power flexibility, not only focusing on pre-selected sources, as illustrated in Sections 2.2.1 and 2.2.2, is required;
h) Approaches to be independent of price structure;
i) Detailed variables and parameters for flexible sources are required to be comprehensive and consistently applied across all sources during flexibility characterisation.

For the KPI label, the following lessons were learned:

i. Targeting relevant user requirements which are measurable is key;
ii. Minimising the number of KPIs and ensuring there is no overlap in metrics avoids over-complicating the indicators being communicated;
iii. KPIs for flexibility require measurable metrics relating to the amount of energy or power that can be shifted in time;
iv. Energy flexibility is a recognised concept in the scientific and technical community, however, it may not be as familiar to facility managers, building operators and the general public.

From the benchmarking review, the lessons learned were:

1) There is a lack of demonstration studies and more published demonstration studies would be beneficial in developing standardised benchmarks;
2) From the published results available, the maximum range for flexibility for buildings is between 18 - 56% of peak load with average flexibilities between 7 – 9% of peak load.

Table 2.5 Review of Existing Approaches, Gaps Addressed by Proposed Methodology & Elements Adapted

Reviewed Approach	Advantages	Gaps	Proposed Methodology	
			Gaps Addressed	***Elements Adapted***
i) Flexibility Characterisation				
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.	Detailed parameters for loads incorporated; Storage & RES explicitly included.	S, C, A concepts;
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.	Source selection explicitly included; Does not require large quantities of measured data.	-
Optimal control approaches (De Coninck and Helsen, 2016) (Oldewurtel et al., 2013) (Grønborg Junker et al., 2018)	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.	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	-
Generic model for CHP sizing (Nuytten et al., 2013)	Available flexibility for every hour calculated. Theoretical maximum flexibility calculated. Time periods associated with pre-load and re-bound well quantified.	Focused on thermal systems. Electrical power flexibility not considered.	Focus on electrical systems; Power flexibility explicitly evaluated and range defined.	Available flexibility calculated for every hour; Maximum flexibility.
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.	Applicable to all electrical building systems; Source selection explicitly included; Building model not required.	-

Reviewed Approach	Advantages	Gaps	Proposed Methodology	
			Gaps Addressed	***Elements Adapted***
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.	Methodology applicable to a wider range of building systems.	Time, power and energy quantification; Maximum and minimum ranges; average power flexibility.
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.	Addresses evaluation of flexibility from building perspective; Includes detailed evaluation of building systems.	-
ii) Variables & Parameters Definition				
Certification Prerequisites for DR trading (Alcázar-Ortega et al., 2015)	Detailed parameter definition.	Approach limited to defining parameters.	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.	Comprehensive assessment methodology; Partial loads permitted; Flexibility explicit in approach; Multiple loads from each site included in assessment;	Some parameters utilised.
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.	Comprehensive assessment methodology; Classes added to parameter definition; Not linked to any specific price structure.	Classes adapted.

2.7.2 Addressing Gaps / Lessons Learned

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. Widespread adoption will be facilitated through ease of implementation in a time efficient and cost-effective manner without requiring extensive data acquisition, complex modelling or investment on-site. Table 2.5 maps how each of the lessons from the literature review is addressed in the proposed methodology.

Power flexibility and the associated time duration over which it can be delivered are what matters most to aggregators and grid utilities and these will be clearly identified on the KPI label. The development of a 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.

The flexibility assessment methodology is introduced in Section 2.8.

2.8 Proposed Approach

The objective of this work is to describe 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 flexibility assessment methodology developed from this literature review is detailed in Chapter 3. It adapts elements of the flexibility characterisation from Section 2.2.3 as well as variable and parameter definitions reviewed in Section 2.2.2. Lessons learned from the review of KPI labels in Section 2.3 and benchmarking in Section 2.4 are utilised in the development of the standardised flexibility assessment process.

Chapter 3: Methodology

3.1 Introduction

The proposed methodology addresses each of the lessons learned from the literature review in Chapter 2 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 and sites in demand response programmes.

The four steps in the methodology consist of:

- Step 1: Systems, load, storage and generation identification (See Section 3.4);
- Step 2: Flexibility Characterisation (See Section 3.5);
- Step 3: Scenario Modelling (See Section 3.5.2);
- Step 4: Key Performance Indicator Label (See Section 3.7).

An overview of the methodology is provided in Section 3.3. Detailed descriptions of each step are given in Sections 3.4, 3.5, 3.6 and 3.7.

3.2 Research Method Used

The research method used for this work was a case study approach using quantitative research data. Other research methods available to complete this thesis included qualitative research and mixed-mode (Yin, 2002, Merriam, 1998 and Stake, 1995, cited in Yazan, 2015).

The assessment of flexibility requires measurable technical inputs (Alcázar-Ortega et al., 2015) to create quantified performance indicators (Stinner et al., 2016) (Hu et al., 2018) that provide actionable information for stakeholder participation (Ma et al., 2019) in demand response. Therefore, a quantitative approach was considered the most appropriate. Qualitative and mixed-mode methods have demonstrated benefits in behaviour related aspects of energy in buildings research (Zou et al., 2018) where there may not be a direct correlation between kW power and occupant behaviour. However, for sources of flexibility, the available flexible range can be measured using kW or MW data (Ma et al., 2013) and therefore a quantitative approach is the preferred choice.

Case studies provide a means of a) testing a methodology (Zhou and Cao, 2019) and b) demonstrating its applicability (Stroe et al., 2018). Multiple case studies in a range of different building and site types across different geographical regions (Østergaard Jensen et al., 2019) illustrate scalability and provide insights into the modalities of power and energy flexibility. Case study selection was based on the availability of sites in the ELSA Horizon 2020 research project (ELSA, 2018). A flexibility assessment was required to be conducted for each of the five pilot sites in the ELSA project. Through researching existing flexibility assessment methods, as documented in Chapter 2 Literature Review, it was discovered by the author that no commonly agreed or standardised approach existed for flexibility assessment. From this the author had the idea to develop the standardised four-step flexibility assessment methodology documented in this thesis.

3.3 Methodology Overview

A flexibility assessment methodology was developed to create a standardised approach and reduce complexity when assessing buildings and sites. It is an off-line assessment to give an indication of the range of flexibilities available. Flexibility is not just a single number, but a range bounded by parameters or constraints. The methodology builds on the analysis of formulations and algorithms in the literature review to map a flexibility characterisation process, underpinned by elements of the ISO 50002:2014 energy auditing standard. The flexibility characterisation identifies which systems of storage, loads or on-site generation have flexibility potential and quantifies the parameters and variables associated with each. The parameters are then captured in flexibility technical specification tables which combine to create a flexibility matrix.

In terms of the overall structure of the methodology, elements of the ISO 50002:2014 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 specialised expertise needed to implement the audit, while maintaining technical rigour and addressing the key objectives of the flexibility analysis. Relevant parts of the audit procedure which were selected, applied and modified are identified in Sections 3.4, 3.5, 3.6 and 3.7 below.

A summary of each of the four steps in the methodology is provided below.

- Step 1: Systems, load, storage and generation identification consists of identifying the power and energy systems in the building or site and establishing how much power in in kW, and energy, in kWh, is available to flex. This adapts the 'Data Collection' & 'Site Visit' parts of the ISO 50002:2014 standard. (See Section 3.4)
- Step 2: Flexibility Characterisation performs source selection using a filter or triage step and guides the detailed analysis of flexible systems to identify key parameters and variables. This replaces the 'Analysis' part of ISO 50002:2014. (See Section 3.5)
- Step 3: Scenario Modelling is used to visualise the flexibility ranges and assess what impact the proposed flexibility will have on the power profile of the building. 'Reporting' was adapted from ISO 50002:2014 to include scenario modelling. (See Section 3.6)

- Step 4: Key Performance Indicator Label supports stakeholder decision making by presenting key technical information on the flexibility potential of a building or site in a structured, easy to understand, 'at-a-glance' format. This adapts the energy performance indicator concept from ISO 50002:2014 in addition to performing a reporting function. (See Section 3.7)

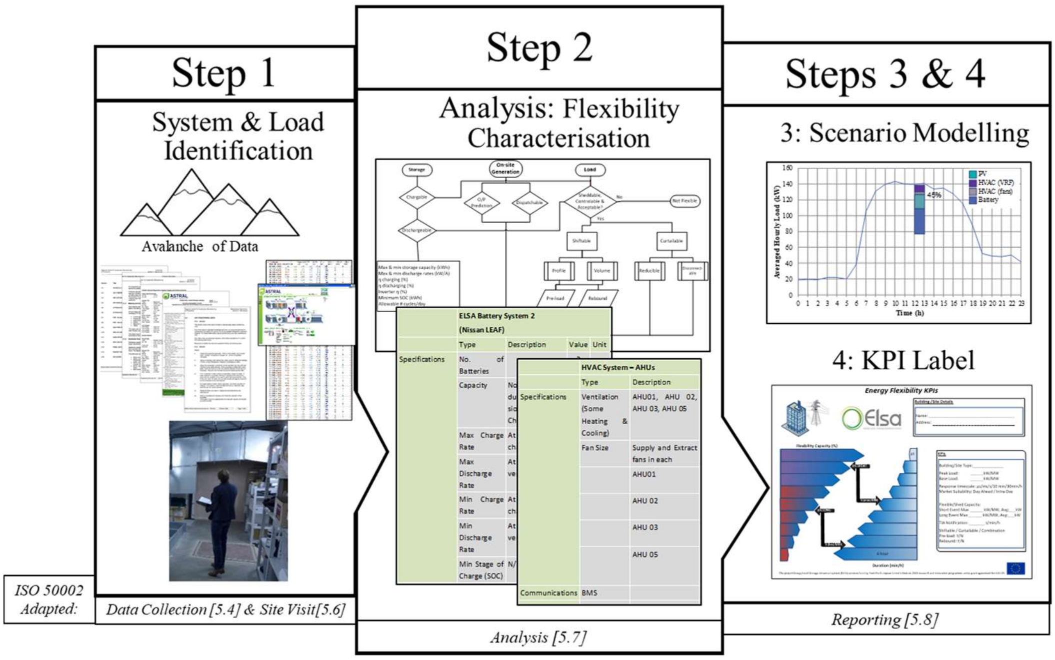


Figure 3.1 Four-step Flexibility Assessment Methodology

3.4 Step 1: System, Loads, Storage and 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 or MW, and energy, in kWh or MWh, 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 50002:2014. The adaptation modified the following criteria:

- Audit objective from Part '3.1 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 from Part '3.4 Energy Audit Scope' to flexible systems as opposed to all energy systems;

- Relevant variables have been adapted from examples for relevant data in Parts '5.2 Energy Audit Planning' and '5.5 g) relevant variables' in the standard;
- Energy conservation measures from Part '5.7.3 Identification of Improvement Opportunities' and '5.7.4 Evaluation of Improvement Opportunities' 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, Building Information Modelling (BIM) models and building automation systems such as BMS, metering systems or Supervisory Control and Data Acquisition (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.

Step 1 is represented graphically in Figure 3.2. During the system, load, storage and generation identification, the individual performing the assessment gathers a large amount of data on the building or site and its systems. This may include engineering and architectural drawings and specifications, the safety file, manuals for items of equipment which may provide flexibility and data from the BMS, metering systems, SCADA systems or other automated monitoring system. Even for a small commercial building, these sources present 1,000's pages of information, 100's of drawings and tens of thousands of data points. This avalanche of data is gathered during Step 1 but it is vital that only a high-level analysis is performed at this stage. The function of this data collection is to provide the information that may be required in Step 2: Flexibility Characterisation, not to conduct a detailed analysis. If a detailed analysis is performed at this stage, time and resources may be wasted evaluating systems which may not provide any flexibility.

The site visit is key to the flexibility assessment as it provides a comprehensive overview of the building, site and systems. This enables the individual undertaking the assessment to achieve an understanding of how the systems work, interact and are sensored or metered. As-built or design drawings and documents often contain inaccuracies and it is through the site visit that their actual locations, quantities and electrical consumption are determined.

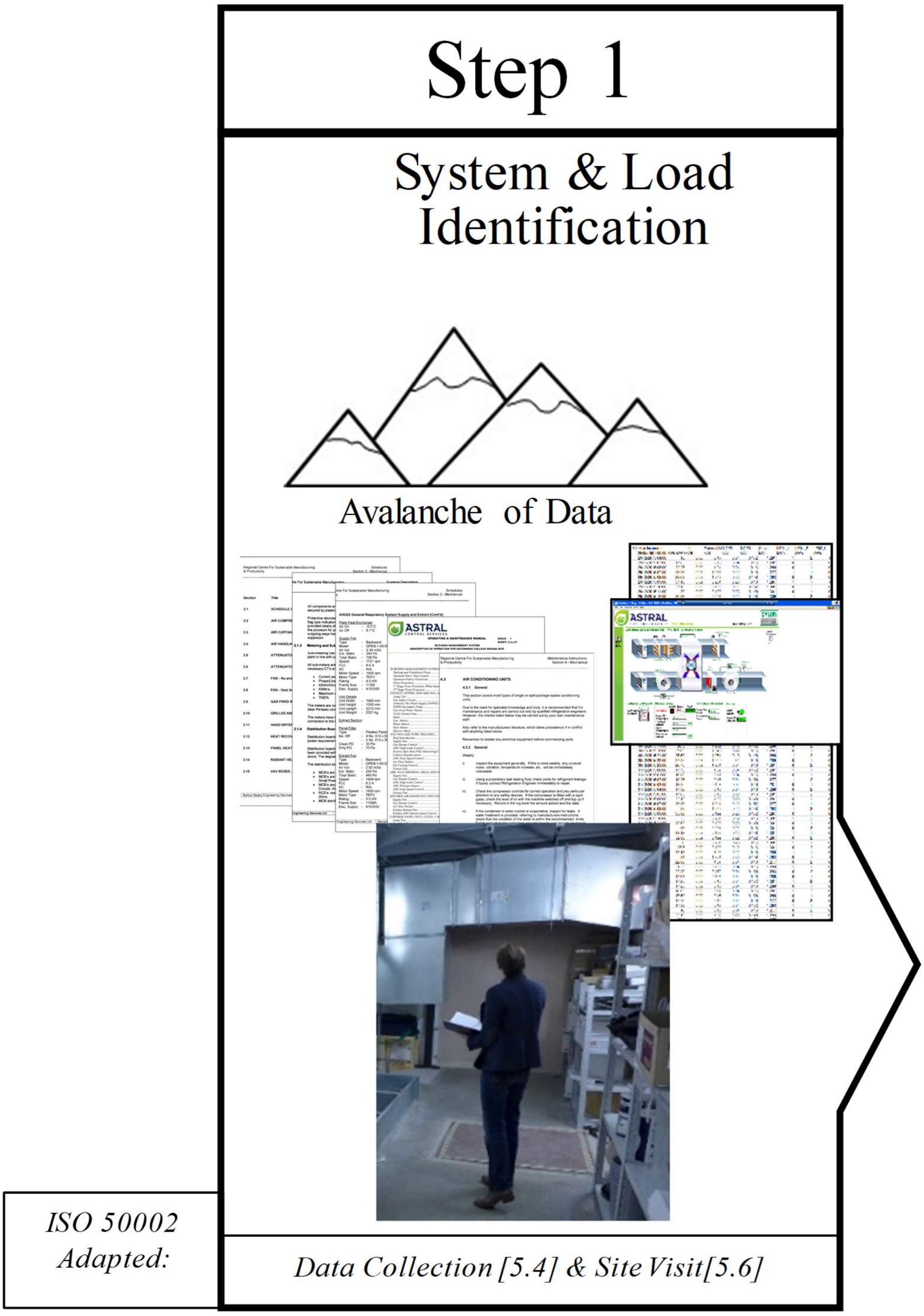


Figure 3.2 Step 1: System, Load, Storage and Generation Identification

During Step 1, systems are assessed at a high level only and detailed analysis such as energy consumption profiles of individual systems is not conducted. This level of detail is addressed in Step 2: Flexibility Characterisation, see Section 3.5.

3.4.1 Step 1 Outputs

The outputs of Step 1 are:

- Identification of Energy Systems. This involves the identification of power and energy consuming loads, storage and generating equipment in the building and their associated systems, quantifying the electrical load they draw from the grid. A graph or pie chart of energy consumption is produced to illustrate which systems have the highest energy consumption (kWh/MWh).
- Generation of a typical power (kW/MW) load profile for the building, with peak and base loads clearly identified.

These outputs provide an overall understanding of the how the building operates and what power and energy systems are present. The systems, loads, storage & generation which have now been identified are the inputs for Step 2: Flexibility Characterisation.

The structure proposed for Step 1 is set out in Section 3.4.2 below. A detailed example of the implementation of this structure is contained in Chapter 4.

3.4.2 Proposed Structure - Step 1

A template for implementing Step 1 is shown in Figure 3.4 and Figure 3.4.

Step 1: System Loads, Storage and Generation Identification

1. Introduction

[Insert paragraph describing building/site]

2. Flexibility Assessment Objective

Determine energy /power flexibility of [name building/site] building or site by identifying and quantifying loads, storage and on-site generation which have the capability or potential to reduce electrical power consumption on demand.

Scope: Existing electrical & thermal systems in the [name building], storage systems [If present] & generation [if present e.g. PV, wind, CHP, generator] installations.

3. Systems & load identification

3.1. Energy & Power Usage

Energy and power usage consists of energy and power consumption data, load profiles, peak & base load, load identification e.g. HVAC, Lighting and small power (plug load).

The graphs below show electrical load profiles for the building. From these, the following values were identified:

Peak Load: ____ kW

Base Load: ____ kW

Figure 3.3 Template for Step 1: System, Load, Storage and Generation Identification (Part 1)

[Insert Graph of Electrical load showing peak and base load.]

[Insert Graph of Typical Weekly Electrical Load Profile.]

[Insert Graph of Typical Daily Electrical Load Profile.]

[Insert Pie Chart of Electrical Power Loads by Type.]

The pie chart above shows the proportion of electrical power consumption by service type.
[discuss loads in pie chart]

4. Relevant Variables

Relevant variables include non-energy parameters such as occupancy schedules, temperature set points, equipment set points, energy pricing & cost structure, weather data (if applicable) and other variables associated with the site which impact the flexibility capability.

4.1 Occupancy Schedule:

Monday – Friday:
Saturday:
Sunday:
Summer
Christmas & Other Holidays:

- Temperature set points:
- e.g. Default room temperature set point: ___ °C

Figure 3.4 Template for Step 1: System, Load, Storage and Generation Identification (Part 2)

3.5 Step 2: Flexibility Characterisation

Flexibility Characterisation is the analysis step in the flexibility assessment. It 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 50002:2014. The primary aim of the flexibility characterization process, shown in Figure 3.5, 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 and variables. These parameters and variables then form the flexibility technical specification for each system.

Even for a small to medium sized commercial building there are 1,000s of specification documents and equipment data sheets, 100s of drawings and 1,000s sensors, equipment parameters and meters continuously generating 100,000s of values every day. The objective of the flexibility characterisation process is the elimination of non-flexible systems and identification of key parameters and variables for flexible storage, on-site generation and loads.

The method is designed to be implemented by technical individuals who are not experts in energy or flexibility analysis, thereby overcoming the barrier to participation in demand response whereby flexibility is either underestimated by a cursory examination or a comprehensive evaluation by a domain expert is expensive, time consuming and may not pass a cost benefit analysis.

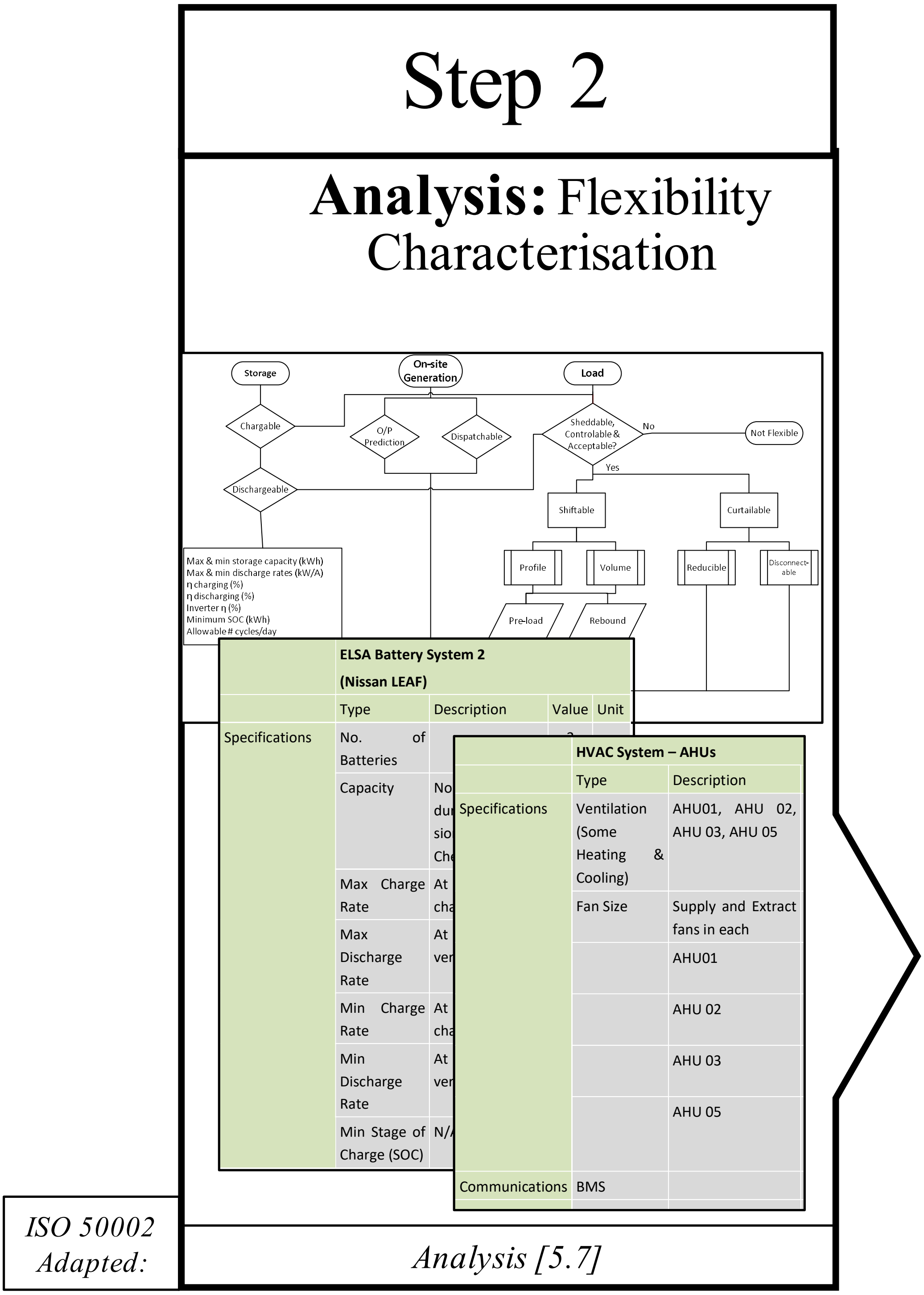


Figure 3.5 Step 2: Flexibility Characterisation

3.5.1 Flexibility Characterisation Process

The core element of flexibility characterisation is the process shown in Figure 3.6. Three categories of flexible sources - Load, On-site generation and Storage are the starting points for the flexibility characterisation. Once the appropriate starting point is selected, the source is then evaluated through a number of decisions, guiding to the relevant data that defines flexibility criteria for that source. The data that is gathered forms a Flexibility Technical Specification for the source. The combined Flexibility Technical Specifications are then stored in a repository known as the Flexibility Matrix.

For Load sources, filtering of flexible systems from non-flexible systems is performed using the concepts of Shedability, 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 or triage 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 criteria, 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 ensuring all available sources are identified. This avoids the risk of missing flexible sources which may occur during a cursory assessment.

ii) the volume of building data, drawings and specifications to be analysed is significantly reduced compared with a detailed approach such as an energy audit. 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 applied to storage or generation.

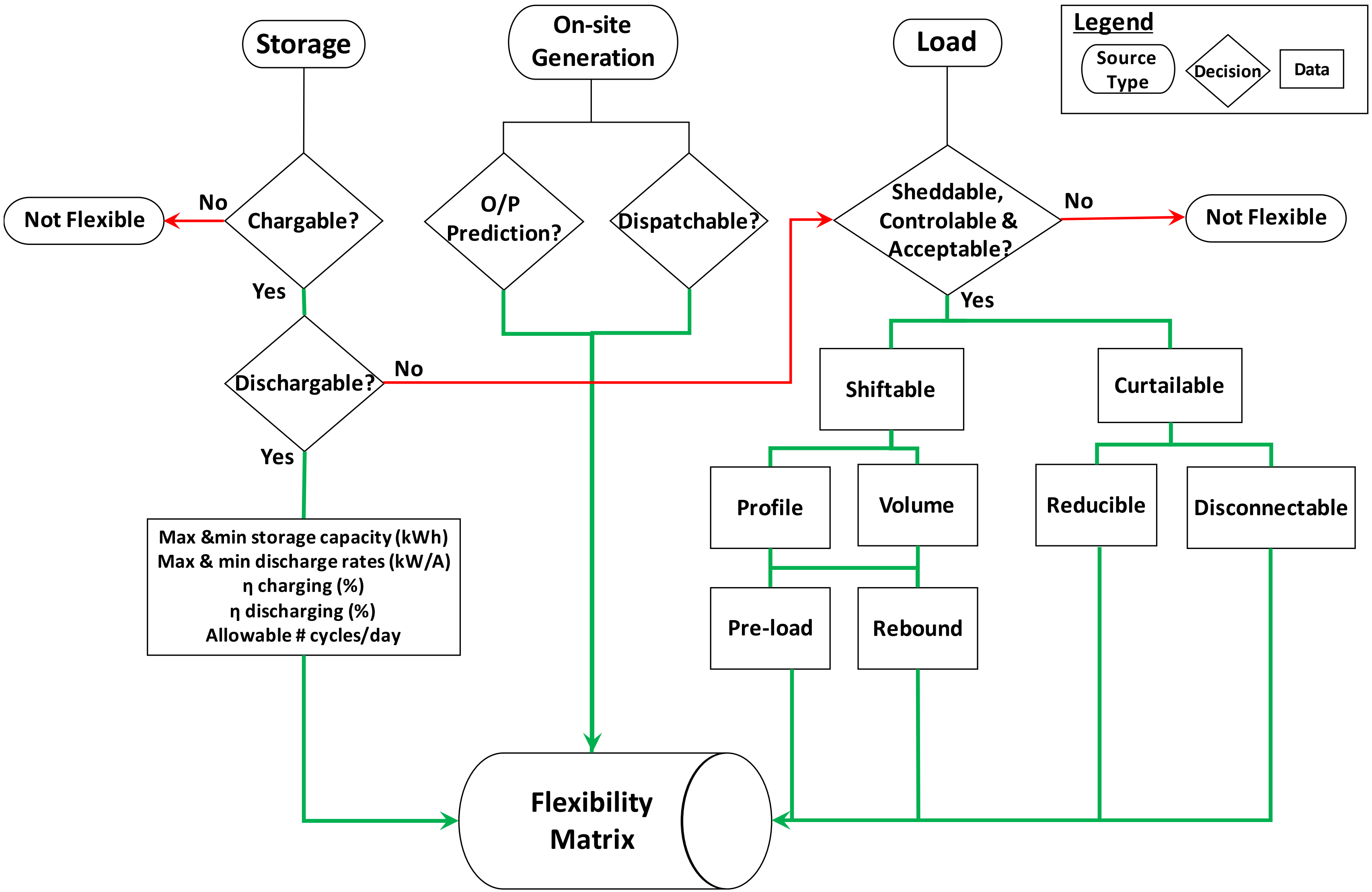


Figure 3.6 Flexibility Characterisation Process

3.5.2 Flexibility Technical Specification

Through applying the flexibility characterisation process in Figure 3.6, parameters and variables associated with each source of flexibility are collected and stored in the Flexibility Technical Specification tables which combine to create 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 Chapter 2. The review determined that detailed parameters and variables for loads are required to be comprehensive and consistently applied across all sources during flexibility characterisation.

Relevant variables and parameters may include the

- 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);
- Minimum and maximum discharge rates (the instantaneous power output the storage system can deliver in kW);
- 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.

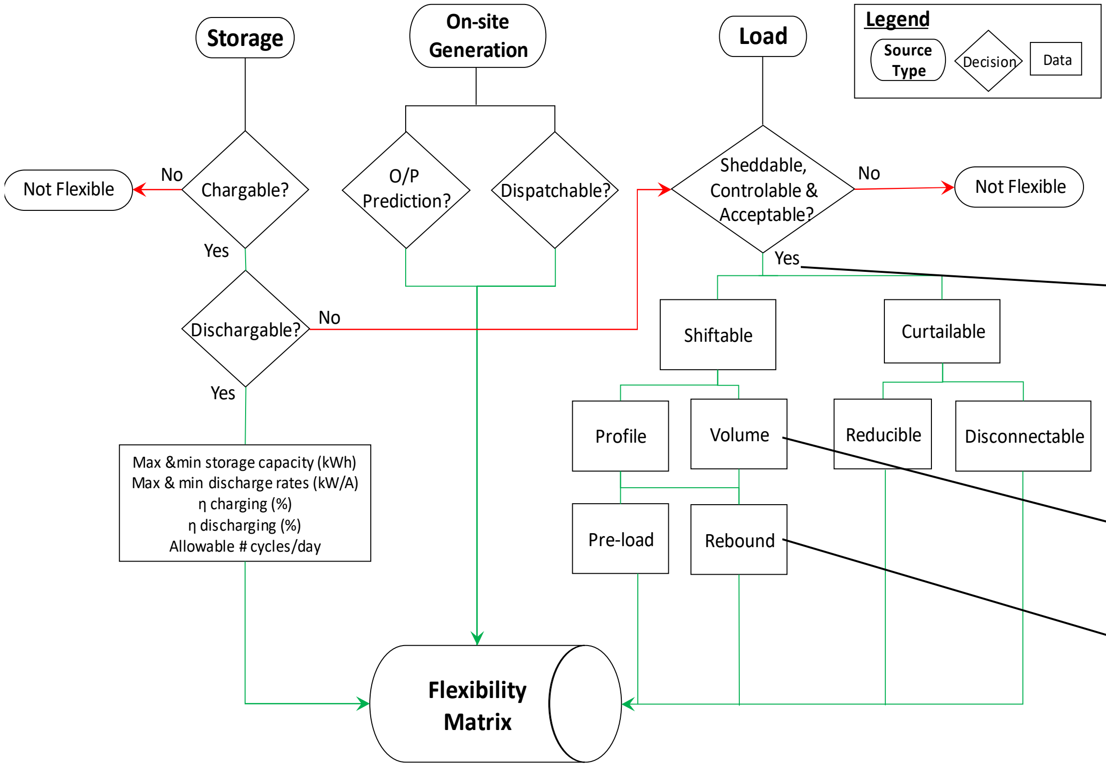
These parameters are then utilised in Step 3: Scenario Modelling and Step 4: KPI Label.

The variables and parameters associated with each flexible system are gathered using flexibility technical specification tables, the structure of which is shown in Table 3.1. These tables may be customised for individual systems. The flexibility characterisation process in Figure 3.6 guides the assessor through the steps that need to be considered in order to gather the variables and parameters that describe in a technical way the flexibility of the system. In essence, it creates a flexibility technical specification for each flexible system. The tables may be combined to create the flexibility matrix. The structure and content of these tables is novel and has been developed by the author.

Table 3.1 Flexibility Technical Specification Template

	[System / equipment name]			
	Type	***Description***	***Value***	***Unit***
Specifications				
Communications				
Control Parameters				
Flexibility	Max			kW
	Min			kW
	4 Hour Average			kW
	Pre-load/ Rebound			kW
	TIA			min
	Load Availability			
	Min time between events			h
	Rebound delay			
	Disutility cost			
	Shed time			min
	Interactions			-
	Day ahead /Intra day			-

Mapping of the parameters and variables from the flexibility characterisation process to the flexibility technical specification is shown in Figure 3.7. The type of system being mapped is a load. After the ‘Sheddable, Controllable, Acceptable’ filter or triage step, the ‘Specifications’, ‘Communications’ and ‘Control Parameters’ variables and parameters are collected and stored in the table. The load is shiftable, therefore ‘Flexibility’ variables such as those related to flexible volume and rebound are then gathered. These include maximum and minimum flexible volume in kW and the duration and quantity of rebound effect, if applicable.



	HVAC System – AHUs			
	Type	Description	Value	Unit
Specifications	Ventilation (Some Heating & Cooling)	AHU01, AHU 02, AHU 03, AHU 05		
	Fan Size	Supply and Extract fans in each		
		AHU01	1.5 x 2 = 3	kW
		AHU 02	4.0 x 2 = 8	kW
		AHU 03	3 x 2 = 6	kW
		AHU 05	0.75 x 2 = 1.5	kW
Communications	BMS			
Control Parameters	Fan Speed	Set on commissioning but requested change to set point	0- 100	%
	CO_2	On AHU01 at present but requested for all	750 - 1,125	ppm
	Temperature	Return duct sensor set point	20 - 22	°C
	Duct Pressure	Fan speed control on AHU02 only	150	Pa
	Recirculation Damper	AHU01 only	-	%
	Recouperator Damper	AHU02, 03, 05	-	%
Flexibility	Max	Estimated 20%	1.4	kW
	Min	Estimated 10%	2.8	kW
	4 Hour Average	10-20%		kW
	Pre-load/ Rebound	Not for ventilation, may occur on AHU01 on cooling	n/a	kW
	TIA		10 - 15	min
	Load Availability	As per occupancy schedule		
	Min time between events	Provided max ppm of CO2 is met, no restriction on ventilation control, may be restriction due to interactions	TBD	h

Figure 3.7 Mapping to the Flexibility Technical Specification

3.5.3 Flexibility Matrix

A flexibility matrix for sources, i, in a specific time period, j, has been developed by the author (O'Connell and Riverso, 2016). In the literature review, Neupane (2017) proposed an activation vector for hourly or daily profiles and Reynders et al. (2018) created a thermal response matrix for building thermal storage. The flexibility matrix implemented here is different from those in the literature review, in that it is for a more generalised flexibility application, i.e. it captures all flexibility source types, not just storage. In addition, it is not limited to just a vector for activation but encompasses both the quantity of flexibility and the time duration.

The proposed matrix is a k x n matrix, with k being the number of time intervals, j, in a 24-hour period and n being the number of flexible systems, i. For example, a time interval j =1 hour, with 4 flexible systems will produce a 24 x 4 flexibility matrix.

Flexible systems i

$$F_{total} = \begin{bmatrix} F_{1,1} & \cdots & F_{n,1} \\ \vdots & \ddots & \vdots \\ F_{1,k} & \cdots & F_{n,k} \end{bmatrix} \quad (3.1)$$

Time period j

Looking at individual sources, the flexibility of each individual source, i, may be expressed as a k x 1 matrix, whereby k is the number of time periods.

$$F_i = \begin{bmatrix} F_{i,1} \\ F_{i,2} \\ \\ F_{i,k} \end{bmatrix} \quad (3.2)$$

These individual sources may then be combined to produce an overall flexibility matrix for the building or site.

The matrix is implemented in a static way in the proposed methodology. This addresses the stakeholder need to have an upfront quantification of flexibility range prior to any investment on site, to provide decision support for participation in demand response programmes and negotiations with aggregators. If the matrix were to be applied to a real-time dynamic implementation, a multi-dimensional matrix would be required to capture all the possible combinations of flexibility for different time steps, available combinations of systems and to take account of previous or future activations and interactions between systems. The online real-time implementation would address a different stakeholder need, as it would take place after the decision has been made to participate, contracts have been signed and demand response events are taking place.

An example of how flexibility is represented in the flexibility matrix is given below. For four-hour flexibility events and three flexible sources, the k x n matrix has dimensions 6 x 3.

$$F_{total} = \begin{bmatrix} F_{1,1} & F_{2,1} & F_{3,1} \\ F_{1,2} & F_{2,2} & F_{3,2} \\ F_{1,3} & F_{2,3} & F_{3,3} \\ F_{1,4} & F_{2,4} & F_{3,4} \\ F_{1,5} & F_{2,5} & F_{3,5} \\ F_{1,6} & F_{2,6} & F_{3,6} \end{bmatrix} \qquad (3.3)$$

For example, if the flexible sources have available flexibility of 20 kW for time period 2 & 4 for source 1, 30 kW for time period 3 & 5 for source 2 and 40 kW for time period 4 for source 3 respectively, he flexibility matrix would look like:

$$F_{total} = \begin{bmatrix} 0 & 0 & 0 \\ 20 & 0 & 0 \\ 0 & 30 & 0 \\ 20 & 0 & 40 \\ 0 & 30 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad (3.4)$$

3.5.4 Energy Flexibility Improvements

During the flexibility characterisation process, there may be systems which are not currently flexible but with minor sensor or control improvements could become flexible. These energy flexibility improvement opportunities are to be identified and their associated sensor or control improvements documented. The system may then be assessed as a potentially flexible system. There may also be additional metering requirements, if there is insufficient electrical sub-metering within the building or if specific systems, e.g. renewable generation, do not have a dedicated bi-directional meter.

3.5.5 Examples of Flexibility Characterisation Implementation

Three examples of the implementation of the flexibility characterisation process and one example of the Flexibility Technical Specification are given below. The first characterisation process example is for a fan in an Air Handling Unit while the second applies the process to an Electrical Vehicle (EV). The third is for a Variable Refrigerant Flow (VRF) heat pump system. The Flexibility Technical Specification example is for a heat pump.

3.5.5.1 Characterisation Process Example 1: AHU Fan

A fan is considered a load, therefore the starting point is the load section of the flexibility characterisation process. Figure 3.8, tracks the application of the process for this example. The path of the characterisation is shown in blue. 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 a Building Management System (BMS), making it **controllable**. The occupants require a minimum ventilation level to keep CO_2 levels below a specified threshold but the ventilation the fan provides exceeds this, therefore it is **acceptable** to reduce its load, provided it complies with the CO_2 requirements. Provided the fan does not impact on the heating or cooling requirements of the building, it may be categorised as a curtailable load. Minimum ventilation levels need to be maintained in the building therefore fans are a reducible rather than a disconnectable load.

If reducing the ventilation rate does impact heating or cooling there may be a rebound effect after the flexibility event and so it should be categorised as shiftable. Rebound may also depend on the duration of the event. For a short event, e.g. 30 minutes, there may be no rebound effect but for a longer event, e.g. 4 hours, any thermal system is likely to require replacement of at least a portion of the energy curtailed during the demand response event.

Fans are a shiftable volume load. They do not follow a set electricity consumption profile like a shiftable profile load such as a washing machine would.

Through following the flowchart process, the assessment is guided towards the technical aspects which enable the system to be flexible. This facilitates the collection of parameters and variables to create the flexibility technical specification of the system.

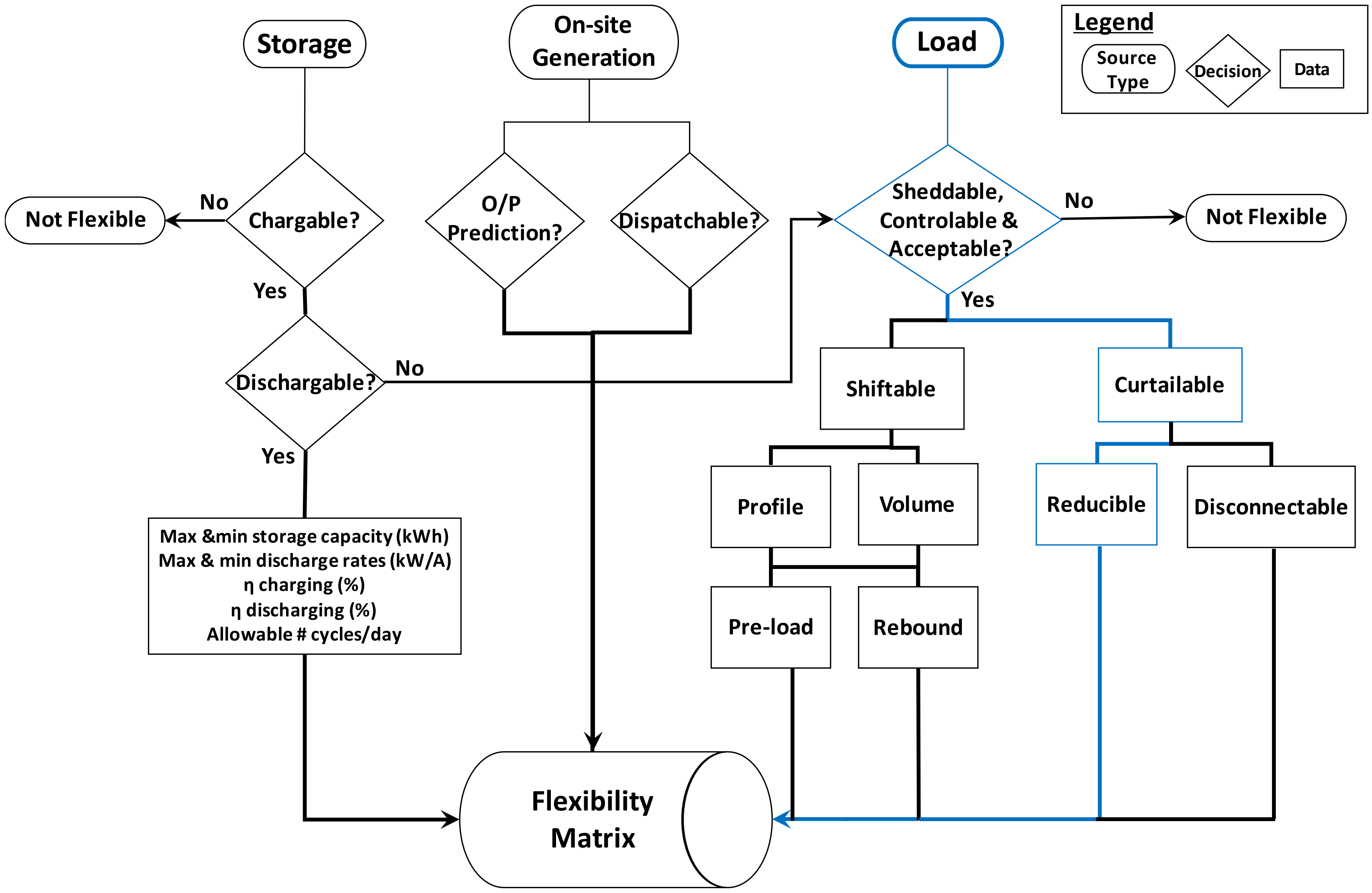


Figure 3.8 Characterisation Process Example 1: AHU Fan

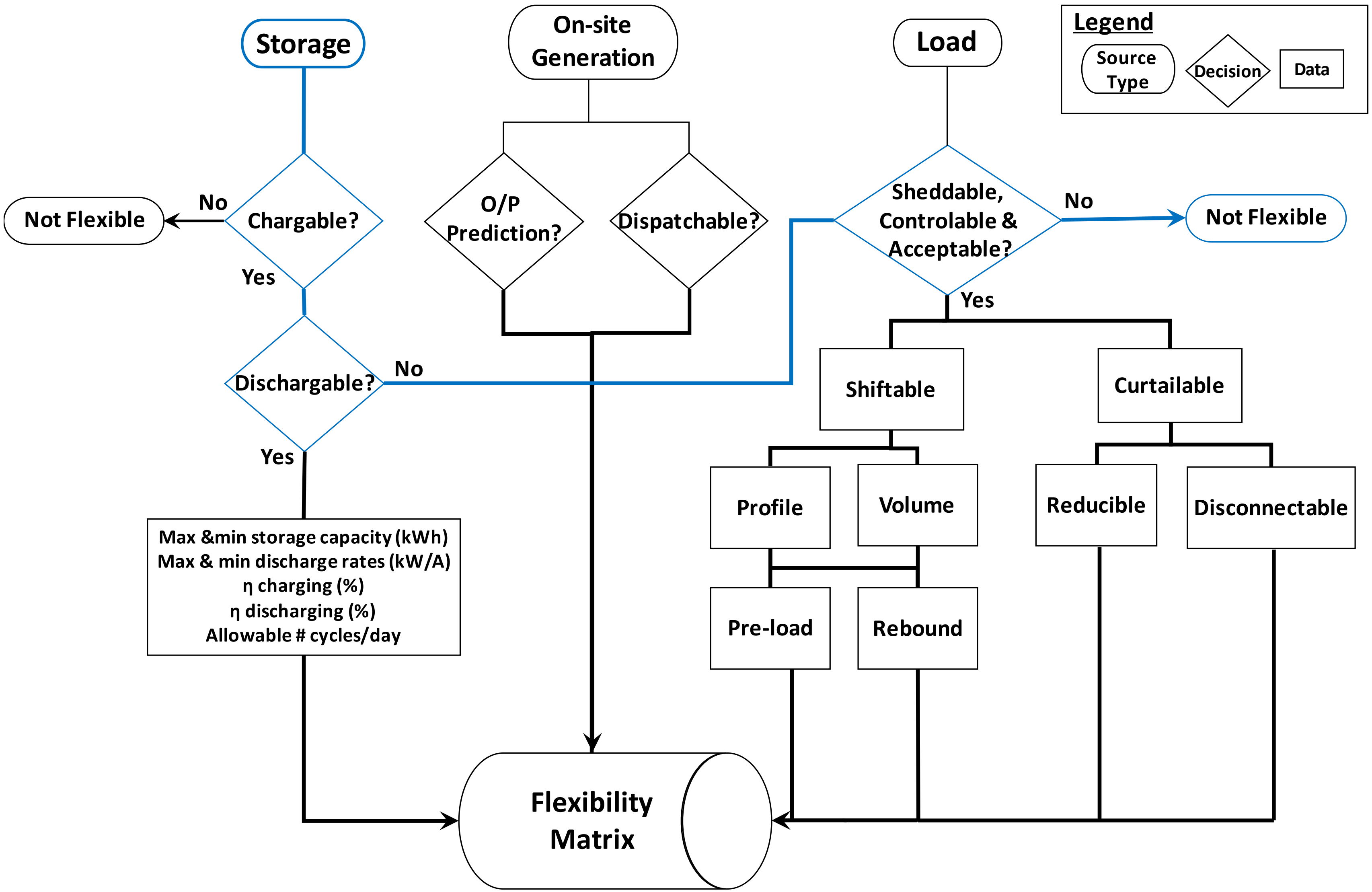


Figure 3.9 Characterisation Process Example 2: Electric Vehicle

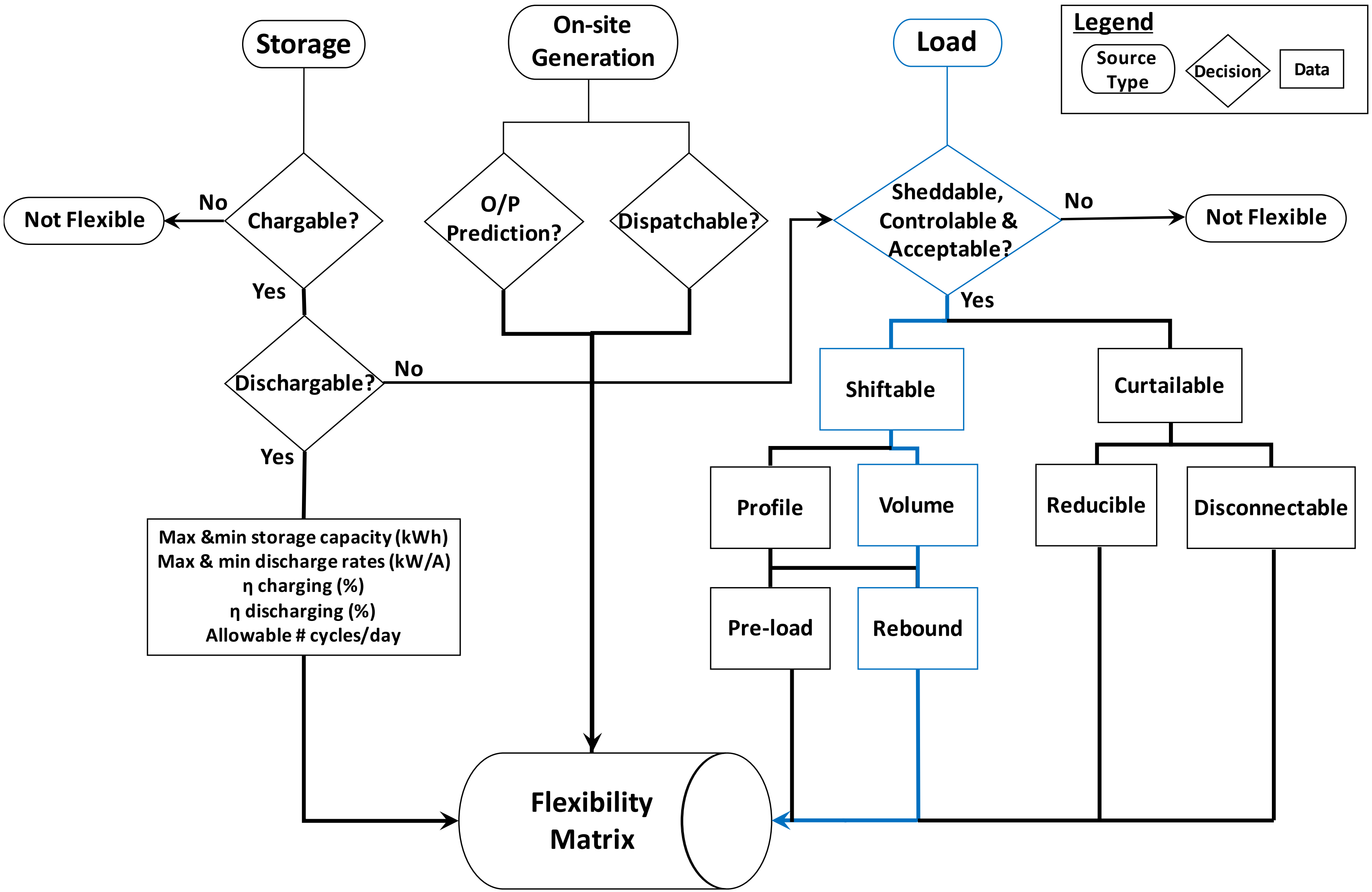


Figure 3.10 Characterisation Process Example 3: VRF Heat Pump

3.5.5.2 Characterisation Process Example 2: Electric Vehicle

An EV may be considered storage. Starting at the storage branch of the process in Figure 3.6, the EV is **chargeable**, therefore the next question is - is it **dischargeable**? This depends on the jurisdiction, type of EV and facilities available. If it is not dischargeable, then the assessor transfers it to the load branch of the process. If it is dischargeable, then it stays within storage and the relevant parameters and variables are gathered. These include maximum and minimum storage capacity in kWh, maximum and minimum discharge rates in kW or kVA. Charging and discharging efficiency in percentage and the allowable number of cycles per day.

3.5.5.3 Characterisation Process Example 3: Variable Refrigerant Flow Heat Pump System

A Variable Refrigerant Flow (VRF) heat pump system is a type of HVAC load that provides heating and cooling in buildings. It is possible to reduce the load over a short period, therefore, it is **Sheddable**. These are typically controlled by a dedicated manufacturer's controller or a Building Management System (BMS) so it is **Controllable**. It must be determined if it is **Acceptable**, to the building operator to reduce the VRF power consumption by reducing or increasing temperature set points or by displacing electrical heating by gas fired systems. HVAC loads, including VRF, are generally shiftable, but it may be partly curtailable. E.g. if thermal energy is reduced during a flexibility event, there is often a rebound effect afterwards where more energy is needed to restore the building to the temperature set point. However, if the duration of the event is short, it may be possible to curtail the load with minimal impact on indoor air temperature, depending on building thermal mass and air changes per hour, and thereby avoid rebound. The parameters gathered through this process are then input into the flexibility technical specification which contributes to the flexibility matrix, and the process is repeated for other loads, storage and on-site generation sources on site.

3.5.5.4 Flexibility Technical Specification Example: Heat Pump

An example is provided in

for a technical specification implementation of a heat pump system. In the heat pump example, specifications may include items such as whether it performs heating, cooling or both; the number of external condensers; and the installed capacity for both electrical and thermal sides of the system. Control parameters may include temperature set points.

Table 3.2 Example of Heat Pump Flexibility Technical Specification

	Heat Pump System			
	Type	***Description***	***Value***	***Unit***
Specifications	Heating & Cooling			
	No. of Condensers	External Condensers		-
	Installed capacity	Electrical Load		kWe
		Heating		kWth
		Cooling		kWth
Communications	[name controller here if present]			
Control Parameters	Temperature Set point		T	ºC
	[insert other control variables here, if present]			
	[insert other control variables here, if present]		-	-
Flexibility	Max			kW
	Min			kW
	4 Hour Average			kW
	Pre-load/ Rebound			kW
	TIA	Varies depending on the load reduction. For large load reductions (e.g. ≥ 20%) over a long period (e.g. 4 h), day ahead notification required;	15 min – 24 h	min
	Load Availability	As per occupancy schedule		
	Min time between events	For short events ≤ 1 hr, 2 -3 may be permitted per day; Events > 1 hr, 1 per day;	2 - 24	h
	Rebound delay	May be possible with day ahead notification		
	Disutility cost		n/a	
	Shed time		10 - 15	min
	Interactions	[name systems if there are interactions]	Yes/No	-
	Day ahead /Intra day	Possible for both but may be more suited to day ahead	-	-

Maximum and minimum flexibility may be estimated from functional tests, historical data or, if available, a model of the system. Criteria such as load availability are typically determined by the occupancy schedule of the building. Rebound is likely to occur with a thermal system but it may be possible to shift the time period of the rebound using techniques such as pre-cooling or pre-heating. Shed time for any system controlled by a BMS is typically 10 - 15 minutes.

It may be possible to utilise a heat pump for both day-ahead and intra-day demand response events but if minimising the impact on thermal comfort is a priority, day ahead events are preferable for longer duration events e.g. 4 hrs. For short events e.g. 30 min, there may be minimal impact on thermal comfort and therefore these may be acceptable for intra-day events.

3.5.6 Step 2 Outputs

The outputs of Step 2: Flexibility Characterisation are:

- Flexible systems identified;
- Detailed parameter and variables quantified for each flexible system to create a Flexibility Technical Specification;
- Energy flexibility improvement opportunities identified, if applicable. The aim is to capture loads which may not be controllable at present but with minor control alterations could provide flexibility, for example heating or Air Handling Unit (AHU) loads;
- Recommended sensor and control improvements identified, if applicable. Examples may include meters to enable power measurement of specific loads or Building Management System (BMS) programming modifications.

Through applying the flexibility characterisation process, parameters and variables associated with each source of flexibility are collected and stored as flexibility technical specifications which combine to create a flexibility matrix. The flexibility matrix hosts the parameters and variables which are necessary for the generation of scenario models in Step 3: Scenario Modelling, see Section 3.6, and key performance indicators in Step 4: KPI Label in Section 3.7.

The structure proposed for Step 2: Flexibility Characterisation assessment is set out in Section 3.5.7 below. A detailed example of the implementation of this structure is presented in Chapter 4.

3.5.7 Proposed Structure - Step 2

A template for implementing Step 2 is shown in Figure 3.11.

Step 2: Flexibility Characterisation

1. Introduction

This section consists of outputs of flexibility characterisation process, elimination of non-flexible loads and identification of the flexibility matrix for storage, on-site generation and loads.

2. Flexibility Characterisation Process

To identify load flexibility, the flexibility characterisation process is applied to the loads identified in Part 1. The pie chart in that section shows the power loads by system type and the proportion of power they use in the building. Starting with the largest load type, the loads, storage and on-site generation at the building are assessed for flexibility.

Assess whether a load is flexible using the filter or triage step: Is the load

- **Shedable,**
- **Controllable**
- **and** is it **Acceptable** to shed or reduce that load?

If the answer is not **Yes** to all 3 of these criteria, the load is not flexible. It is to be set aside and the next load is to be assessed. Only if the load passes this initial triage step should any further technical details be analysed.

In summary, the loads in the building which have the capability to provide flexibility are:

- [list loads]

3. Energy flexibility improvement opportunities

[If the building/site may provide more flexibility using additional sensors / meters, include descriptions here]

The site has the potential to provide additional flexibility in a number of ways.

a) [first item] e.g. if the variable speed drives for the Air Handling Unit (AHU) fans were added to the BMS. This would enable direct fan speed control, allowing the electrical load profile of the fans to be modified on demand. In turn this would facilitate the increase or decrease of the electrical load of the building during a demand response event.

b) [second item] etc.

4. Recommended sensor & control improvements

Electrical Metering

[Any proposed new meters and what they are measuring e.g. kW, kWh and zone, area or equipment they relate to]

Additional Sensors

[Insert other sensors which are proposed here e.g. temperature sensors, smart plugs ….]

e.g. Pyranometer - To be installed at same angle of inclination as PV array.

5. Load Flexibility Technical Specification

The flexibility characterisation identified loads which have the capability to provide additional flexibility, in some cases, provided recommended sensor and control improvements are implemented. These variables and parameters associated with each flexible system are gathered using the tables

Figure 3.11 Template for Implementation of Step 2

The rationale behind the timescales in the Flexibility Technical Specification is given in Section 3.6.1.

3.6 Step 3: Scenario Modelling

Scenario modelling, represented in Figure 3.12, is used to visualise flexibility ranges. This illustrates what impact flexibility will have on the power profile of the building being assessed. The visualisation of sample scenarios informs building operators' and aggregators' understanding of the resulting energy demand profiles which would occur in practice for their building or site during a demand response event.

The method developed transforms data into actionable information using the outputs of the flexibility characterisation and a mathematical model. The flexibility characterisation process in Section 3.5, navigates the high volume of data available for buildings to select flexible systems early on, identify the key parameters and variables of each system and avoid unproductive analysis of systems which are not relevant. Scenario modelling then uses the key parameters and variables to calculate flexibility as a percentage of total load. The output of the modelling process is scenario generation, a means of visualizing the available flexibility against a standard daily load profile.

Scenario modelling fits within the 'Reporting' concept of ISO 50002:2014 part 5.8. It is an element developed by the author and is not specifically mandated in the energy auditing standard.

3.6.1 Mathematical Model

The scenario 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).

$$f_{Total}(t_j) = \sum_{i=1}^{n} f_i(t_j) \qquad (3.5)$$

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

$$F = \left(\frac{f_{Total}(t_j)}{P_{Peak}}\right).100 \qquad (3.6)$$

Where P_{peak} is the peak power load for the building in kW or MW and f_{Total} is as defined in (3.5). Human reasoning is required to evaluate the flexibility of each source for a specific timeframe from the flexible system technical specification parameters and variables, 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 or site. This is performed both for individual energy systems and a combination of systems.

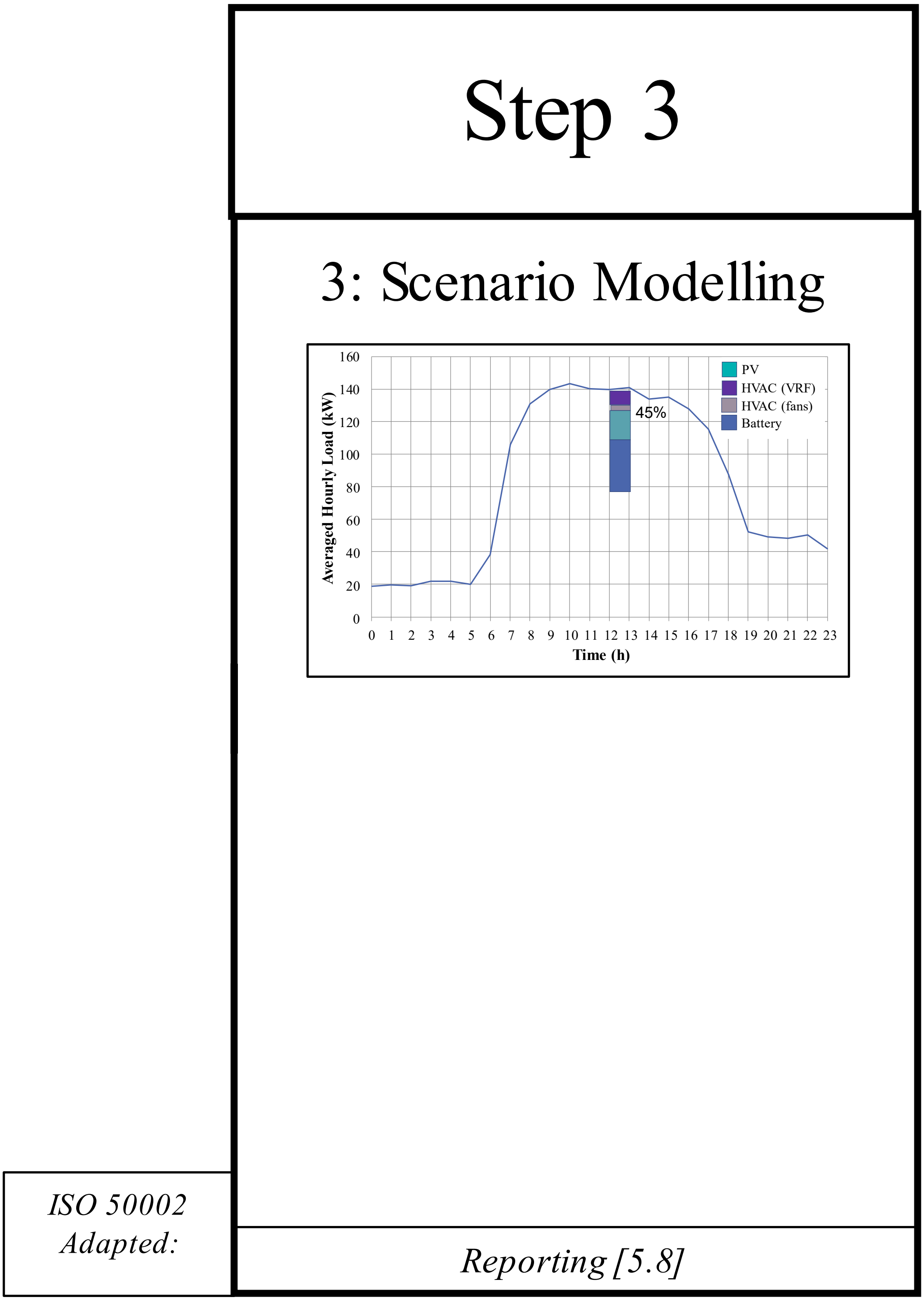


Figure 3.12 Step 3: Scenario Modelling

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;
iii) 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.

An example calculation of f_{total} using the values in the example flexibility matrix in Section 3.5.3 is provided below.

$$F_{total} = \begin{bmatrix} 0 & 0 & 0 \\ 20 & 0 & 0 \\ 0 & 30 & 0 \\ 20 & 0 & 40 \\ 0 & 30 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad (3.4)$$

For the four-hour scenario which the matrix in 3.4 is developed for, the maximum amount of flexibility is in time period 4. Summing the flexibility of source 1 which is 20 kW, source 2 which is 0 kW and source 3 which is 40 kW, the maximum range for a four-hour flexibility event is 60 kW, as illustrated in equation 3.5 below.

$$20 + 0 + 40 = 60 \text{ kW} \qquad (3.5)$$

The quantity, in power (kW) and duration (time) of flexibility available are visualised through scenario generation. Examples of scenario modelling are included in the detailed case study in Chapter 4.

3.6.2 Step 3 Outputs

The outputs of Step 3: Scenario Modelling are:

- Typical daily power profiles for a building or site showing a visualisation of the projected drop or increase in power that would occur during a demand response event. The scenario models are produced for:
  - Specific time periods;
  - Selected or all flexible systems.

The scenario models may be used as inputs into Step 4: KPI label if the maximum and minimum ranges of flexibility for the shortest and longest time period have been modelled in Step 3.

3.6.3 Proposed Structure - Step 3

A template for implementing Step 3 is shown in Figure 3.13.

> Step 3: Scenario Modelling
>
> [Using a typical daily power profile for the building or site generate scenario models for time periods appropriate for the assessment. E.g. 1 hour and 4 hours for all or a selected range of flexible systems]
>
> [Insert Graph of X- hour Flexibility Scenario Model]
>
> [Insert Graph of Y- hour Flexibility Scenario Model]

Figure 3.13 Template for Step 3: Scenario Modelling

3.7 Step 4: Key Performance Indicators Label

The aim of the KPI label, in Figure 3.14 Step 4: KPI Label, is to indicate at a glance the flexibility potential of a site for demand side services. Based on the literature review in Chapter 2, the KPI label, shown in Figure 3.15, has been formulated to

i) enable contract negotiations for demand side services
ii) operationalise the concept of flexibility by creating a strong visual indicator with key metrics communicated in an easily understood way.

The KPI label is the culmination of the preceding three steps in the methodology.

The primary purpose of the KPI label is a decision support tool to enable negotiations between building or site operators and aggregators for demand side services. Building or site operators may use it to decide which programme to participate in or if participation is worthwhile. Aggregators may use it to assess a large number of sites (Foggia et al., 2014) quickly and effectively when creating portfolios of buildings to meet grid operators' minimum participation requirements (Eirgrid, 2018).

At present, there is no standardised approach for flexibility assessment (Østergaard Jensen et al., 2019b) therefore the outputs may vary from a lengthy bespoke report (Alcázar-Ortega et al., 2015) to a one-line 'use the backup generator' (Yi et al., 2018) type response. A standardised one-page label (Jenkins et al., 2017) which contains the relevant technical information presented in a concise and relevant way with clear graphical indicators (Aydin et al., 2019) is an enabler for multiple stakeholders (Ma et al., 2019) to make decisions around demand response participation.

Flexibility may be well understood in the technical and scientific community but not in society as a whole (Østergaard Jensen et al., 2019b). To meet renewable integration targets (European Commission, 2018b), power and energy flexibility will be required from smaller buildings and sites (Araya Cardoso, 2020) including residential buildings (Rasku and Kiviluoma, 2019). The novel KPI label proposed in this work has the capability to operationalise (Ala-Juusela et al., 2015) the concept of flexibility to a wider spectrum of society, enabling smart grid demand side services roll out to residential and small commercial customers.

The 'energy performance indicator' part of ISO 50002:2014 was modified 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. Step 3 and Step 4 both fit within the 'Reporting' concept of ISO 50002:2014, Part 5.8.

From the literature review and analysis of parameter and variables definition in Chapter 2, the key factors for flexibility identified on the KPI label, shown in Figure 3.15, are:

a) quantity of power reduction or increase in kW or MW and the timescale in which that load reduction or increase in grid import is achieved;

b) notification time-in-advance and shed time;

c) market type;

d) peak load and base load;

e) rebound and pre-load.

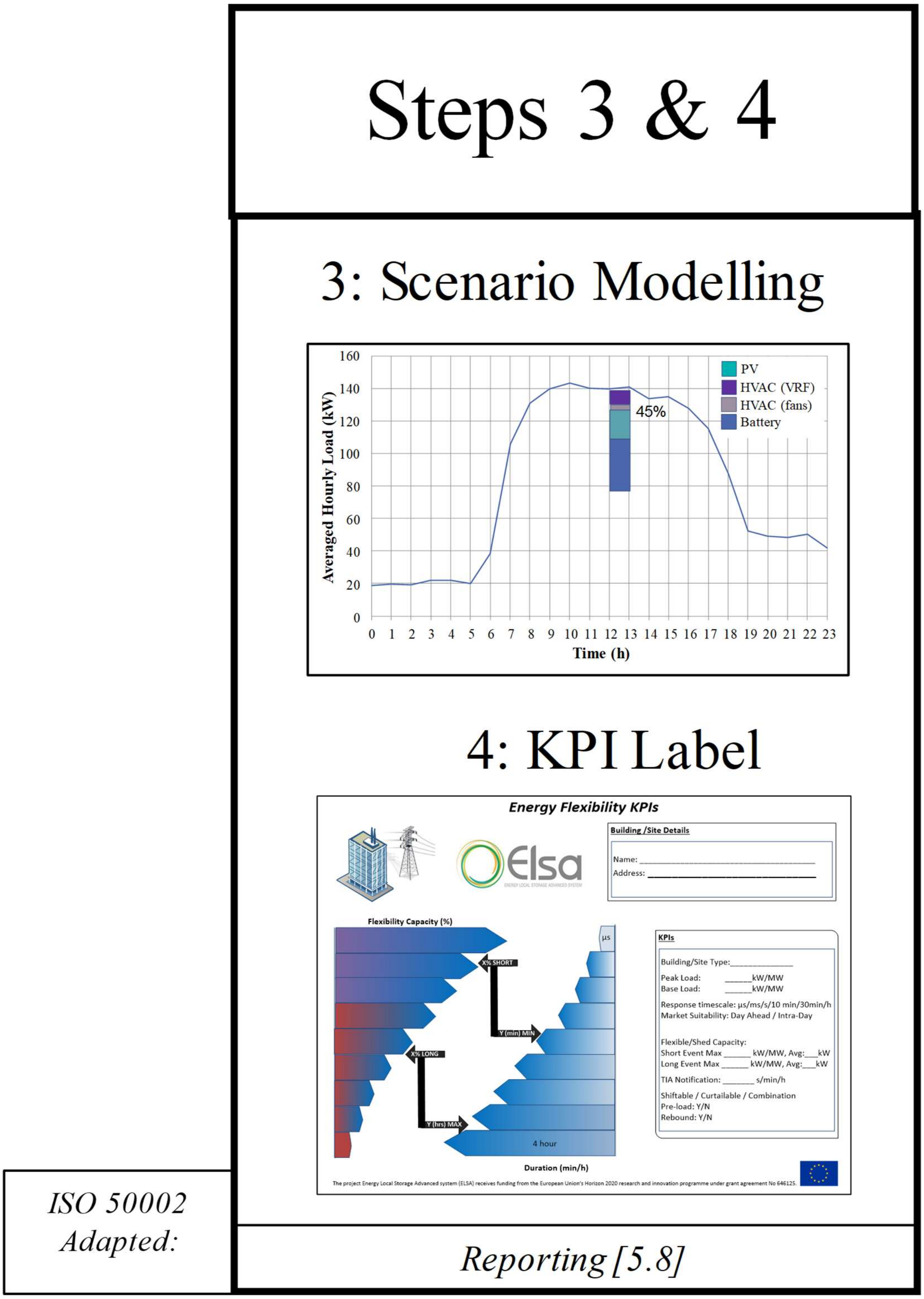


Figure 3.14 Step 4: KPI Label

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.

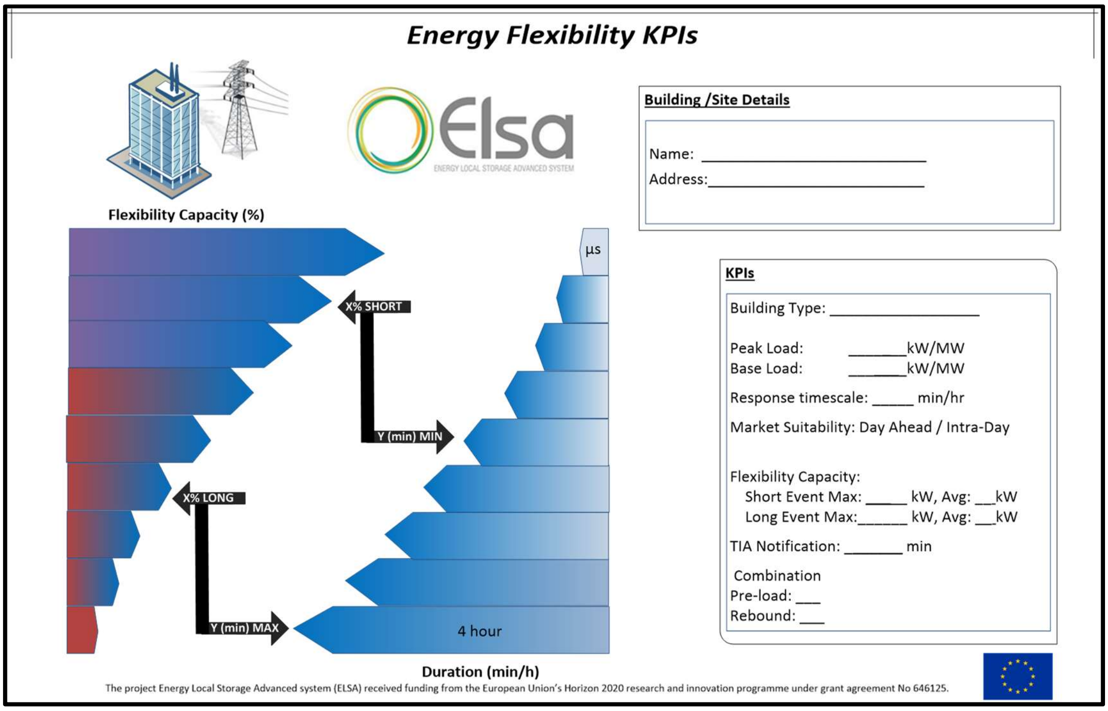


Figure 3.15 KPI Label

3.7.1 KPI Label Generation

The KPI label is generated from the parameters and variables in the flexibility technical specification in Section 3.5 and the scenario generation models in Section 3.6.

Quantity of power reduction or increase in kW or MW and the timescale in which that load reduction or increase in grid import is achieved may be taken from the scenario models if the required quantities were generated. The KPI label requires maximum and minimum flexibility for the shortest and longest time scales the building or site has the capability to provide. If these were not generated in the scenario models, the load reduction, storage shifting capacity and renewable generation capability are calculated for each system using the flexibility technical specifications parameters and variables. These are then combined to determine the overall capability for the building or site.

Time-in-advance notification and shed time come from the flexibility technical specifications, as do market type, rebound and pre-load.

Peak load and base load are determined from Section 3.4 Step 1: System, Loads, Storage and Generation Identification. The assessment in Step 1, as outlined in Section 3.4, includes an evaluation of power and energy usage, part of which involves the generation of typical power profiles for the building or site. Energy and power usage comprise energy and power consumption data, load profiles, peak & base load and load identification e.g. HVAC, Lighting and small power (plug load). Graphs show electrical load profiles for the building. From these graphs, Peak Load and Base Load in kW or MW values were identified.

3.7.2 Step 4 Output

The KPI label is the culmination of the technical analysis in the preceding steps and is the overall output of the methodology. It provides a technical and graphical representation of the range of flexibility that a site has the capability of providing, based on an up-front, off-line assessment. The KPI label incorporates the key factors in an easily understood format which can be interpreted at a glance.

The KPI label is a **decision support tool** for investment grade decision making such as:

i) Building or site operator decision to participate in demand side services;
ii) Building or site operator demand side services programme participation selection;
iii) DSO or aggregator selection of appropriate sites or buildings for portfolios;
iv) **Enable contract negotiation** between building or site operators and aggregators (or grid operators) for demand side services;
v) Investment decisions in system upgrades, metering or ICT platforms to provide grid services.

It is a clear visual indicator which provides defined graphical and numerical information on the available power flexibility ranges and associated timescales, at a glance, for stakeholder decision making.

3.7.3 Proposed Structure - Step 4

An electronic file template is provided for the generation of the KPI label for the building or site. The relevant technical parameters and variables are input and used to calculate the information required for the label.

3.8 Scalability and Ease of Implementation

For the methodology to become more widely adopted, it needs to be both:

a) Scalable, i.e. capable of being implemented in different building and site types in different geographical regions;
b) Easy to implement, i.e. implementable by a technical person who is not expert in flexibility in a shorter timescale than an energy audit.

Scalability and ease of implementation are key to operationalising the methodology to smaller sites, commercial buildings and residential buildings. The methodology needs to meet cost benefit criteria such as being quick to implement, cost effective, repeatable and technically accurate.

Scalability was evaluated through implementation at multiple pilot sites of different building and site types in different geographical regions. Results from the multiple implementations are documented in Chapter 4, Section 4.7.

Ease of Implementation was evaluated using a questionnaire developed by the author as shown in Appendix C. A number of questions were based on the Likert scale, providing a quantitative assessment of the ease of implementation (Cervera et al., 2015) of the methodology. The questionnaire was designed to provide quantitative survey outputs to measure the experience of those who implemented it at their own pilot sites. Results of the questionnaire were evaluated during the implementation of the methodology, documented in Chapter 4, Section 4.8.4.

3.9 Stakeholder Consultation

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 in a PowerPoint presentation (Croce and Riverso, 2016) and was very favourably received (ELSA, 2016). It was considered relevant, specific to their needs and communicated the key metrics required based on technical parameters and variables, assessed using a robust technical process.

The 4-step methodology was presented to the members of the International Energy Agency's Energy in Buildings and Communities Annex 67 – 'Energy Flexible Buildings' (Østergaard Jensen et al., 2017) 4th working meeting in Freiburg, Germany. The members of the annex are domain experts in flexibility drawn from commercial and public research institutes, academia and industry across the world. Feedback from the members was very positive, as documented in the meeting minutes (Østergaard Jensen, 2017) and several partners requested the detailed structure and templates to apply the methodology at their own sites (Nørregaard Jørgensen et al., 2017). From discussions with Annex members at this and other Annex 67 working meetings, underpinning the methodology with ISO 50002 was viewed as a particular strength (Englemann, 2019), as it gave the approach a technical rigour missing from other assessments.

3.10 Conclusions

An early stage, standardised four-step flexibility assessment methodology was created. It consists of Step 1: System, Loads, Storage and Generation Identification, Step 2: Flexibility

Characterisation, Step 3: Scenario Modelling and Step 4: KPI Label. The methodology 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. The lessons learned from the literature review in Chapter 2 as set out in Table 2.2 Summary of Gaps & Advantages of Existing Approaches, were applied to create the four-step process. Step 1 involves the identification of loads, storage and on-site generation systems at the site or building. Step 2 analyses these systems to determine if they are flexible and if so, create a flexibility technical specification. This is then an input to Step 3: Scenario Modelling where power profiles of potential demand response events are created. The output of the flexibility assessment methodology is the novel KPI label, created in Step 4.

The KPI label is a decision support tool for high-level decision-making such as demand side programme selection by site operators and portfolio creation by aggregators. By clearly defining the available flexibility ranges in a standardised way, it enables a framework structure for negotiation between building or site operators and aggregators of grid operators for demand side services contracts.

Stakeholders were consulted on an early draft of the KPI Label and they found it relevant, specific to their needs and that it communicated the key metrics required based on a robust technical assessment process (Croce and Riverso, 2016).

A key societal implication of the KPI label is that has the capability to operationalise the concept of flexibility to a wider spectrum of society to include facility managers, operators of commercial buildings and smaller industrial sites and residential property owners and occupiers. This will enable smart grid demand side services roll out to residential and small commercial customers, whose participation will be required in demand side programmes to balance the grid in order to achieve higher renewable integration targets.

The detailed case study in Chapter 4 illustrates the application of the four-step methodology. Multiple implementations by others at their pilot sites demonstrated its scalability and ease of use.

Chapter 4: Implementation & Results

4.1 Introduction

This chapter implements the flexibility assessment methodology and demonstrates its viability, scalability and ease of implementation through experimental work at multiple pilot sites. The chapter consists of:

- Methodology Implementation, Detailed Case Study: Sunderland, UK
- Experimental Results, Detailed Case Study: Sunderland, UK
- Pilot Sites
- Use Cases
- Experimental Setup
  - ICT Platform
  - Simulation of Grid or Aggregator Signals
  - 2nd Life EV Batteries
- Implementation & Experimental Results: Multiple Pilot Sites
- Analysis of the Results
- Benchmark Comparison

The four-step flexibility assessment methodology developed in Chapter 3 was implemented in five pilot sites and the predicted flexibility tested through experimental demonstrations using specific use cases. Use cases were selected to demonstrate that based on the proposed assessment procedure, the potential of buildings in a wide range of demand response programmes could be quantified. 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 provide data acquisition from the sites. The ICT platform architecture was developed by the author for a previous project (Valdivia et al., 2014) and adapted for demand response by the inclusion of the OpenADR emulator. The results were then analysed and benchmarked against published demonstration studies.

The viability of the assessment methodology was demonstrated through a detailed case study for one site, implemented by the author. A mixed-use commercial building, the detailed case study building was located in Sunderland, UK and is presented in Section 4.2.

Experimental verification was performed by the author for the detailed case study and the results are presented in Section 4.3. Results were then compared against predicted values from the implementation in Section 4.2.

Pilot sites where the methodology was implemented by others are described in Section 4.4. Use cases developed for the verification at each pilot site are given in Section 4.5. These varied from price-based and market-based demand response programs both current (peak shaving) and future (CO_2 minimisation) and were applied in the experiments to activate the available flexibility in the buildings and districts.

In order to verify the implementation of the methodology, experiments were conducted to demonstrate the flexibility achieved on site for the specific use cases. The experimental setup required for this verification is outlined in Section 4.6.

The implementation of the methodology and results of the experimental demonstration at the other four pilot sites are presented in Section 4.7. Demonstration of the scalability and ease of implementation of the methodology was performed through implementation and experimental verification in multiple buildings and districts by others. Training, technical support and template materials were provided by the author to the partners implementing the methodology at their pilot sites. The five pilot sites were in different geographical regions and consisted of a range of building and district types.

The predicted and measured flexibility for each use case was then analysed in Section 4.8 and compared against benchmark studies in Section 4.9. To date, the majority of the available research in flexibility focuses on simulation and published demonstration studies documenting implementation of demand response in real buildings are rare. This work addresses the need for more published flexibility demonstration studies to enable the creation of standardised benchmarks for flexibility, similar to those available for energy auditing.

This chapter is structured as follows: Sections 4.2 and 4.3 contain the detailed case study. Pilot sites are introduced in Section 4.4 while use cases are established in Section 4.5. Experimental setup for flexibility verification is summarised in Section 4.6. Section 4.7 details implementation and experimental results for other four pilot sites. Section 4.8 analysis the results which are benchmarked in Section 4.9. Finally, Section 4.10 documents the conclusions.

4.2 Methodology Implementation, Detailed Case Study: Sunderland, UK

A detailed case study demonstrating the application of the flexibility assessment methodology and verifying through experiments the effectiveness of the approach was conducted at the Skills Academy for Sustainable Manufacturing and Innovation (SASMI) building, Gateshead College, Sunderland, UK. This building was one of the five pilot sites in the ELSA H2020 project (ELSA, 2018) and access for flexibility assessment methodology implementation and experimental verification was facilitated by Geoff Watson of Zero Carbon Futures (O’Connell et al., 2019a).

An on-site assessment is required for Step 1 and Step 2 of the methodology. This was conducted by the author in January 2016, prior to the installation of PV and battery systems on site. System upgrades, recommended by the flexibility assessment methodology, were determined during the on-site assessment and in the post-site analysis as part of Step 2. These were implemented after the site visit assessment.

4.2.1 Step 1: System, Loads, Storage and Generation Identification

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.

The SASMI building is a mixed-use facility with a floor area of 5,700 m^2 consisting of classrooms, offices, workshops and catering facilities. It is part of Gateshead College, a 3rd level institution in Newcastle, UK but is an off-campus building located adjacent to the Nissan manufacturing plants in Sunderland. The building provides training facilities for technical personnel, many of which go on to work in the nearby Nissan manufacturing plants. It was constructed in 2011 and has an Energy Performance Certificate (EPC) rating of 'C'. While this rating may seem low for a new building, it does contain comfort cooling and mechanical ventilation which add to the energy load and are penalised in the EPC assessment. These systems are a potential source of load flexibility and so are beneficial for participation in demand side services.

Flexibility Assessment Objective: Determine energy flexibility of the Gateshead College SASMI building by identifying and quantifying loads, storage and on-site generation which have the capability or potential to reduce electrical power consumption on demand.

Scope: Existing electrical & thermal systems in the Gateshead College SASMI building, planned storage system of estimated capacity 48 kWh Li-ion battery & planned PV 50 kWp installation.

Energy and power usage: Consisted of energy and power consumption data, load profiles, peak & base load, load identification e.g. HVAC, Lighting and small power (plug load).

Loads in the building consist of:

- Heating: Mainly gas direct burners, Variable Refrigerant Flow (VRF) spilt units (heat pumps) in classrooms & offices.
- Ventilation: 5 AHUs Air Handling Units (AHUs) with Variable Speed Drives (VSDs) on all fans.
- Cooling: VRF split units (heat pumps), DX (Direct Expansion) chiller units in AHU-01.

- Domestic Hot Water (DHW): Gas fired direct hot water cylinders
- Lighting: Indoor lighting is locally switched, External lighting is on the BMS and has Lux, time and on/off control.
- Other loads: door curtain, air compressor.

Installations which took place in the building after the on-site assessment included:

Storage:

- 3 x 16 kWh Nissan Leaf 2nd life batteries

Generation:

- 50 kWp PV array

Other:

- Additional sensors, meters and BMS programming changes to enable additional flexibility
- ICT system.

The graphs below show electrical load profiles for the site. There is little seasonal variation as the main heating load is met from gas fired generation. From these the following values were identified:

- Peak Load: 140 kW
- Base Load: 40 to 20 kW

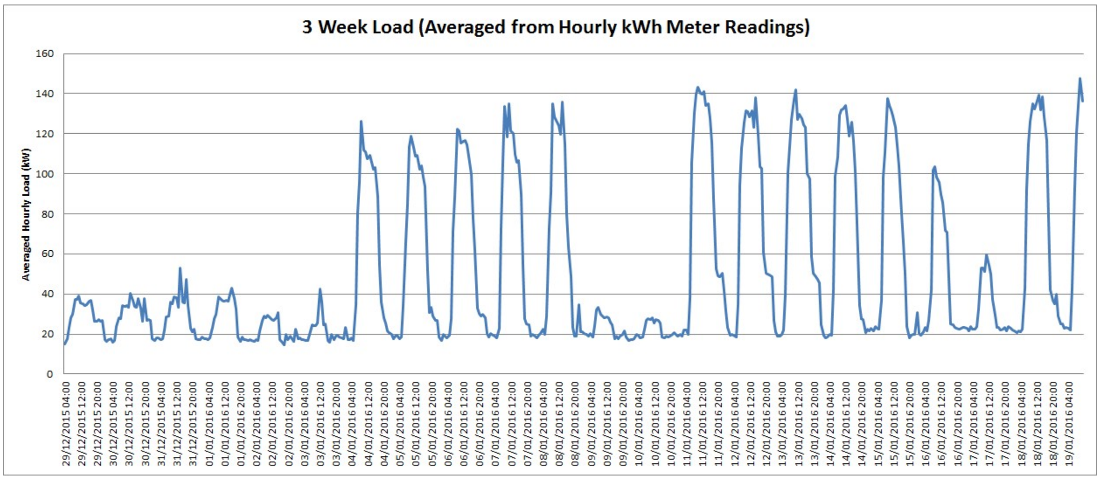


Figure 4.1 Graph of Electrical load showing peak and base load.

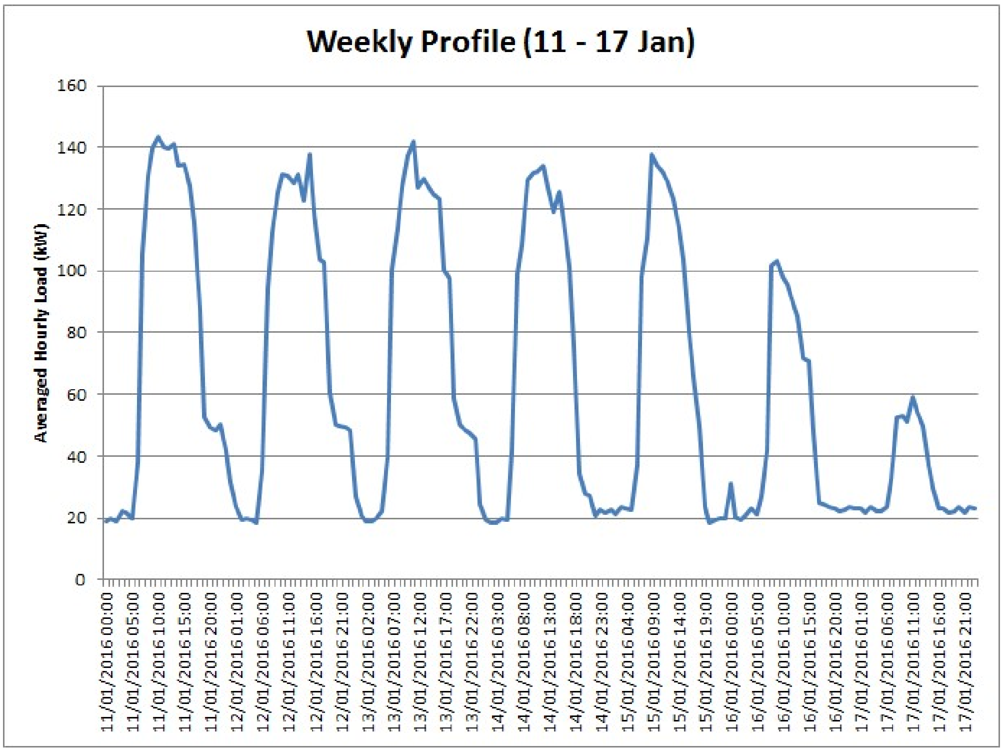


Figure 4.2 Graph of Typical Weekly Electrical Load Profile

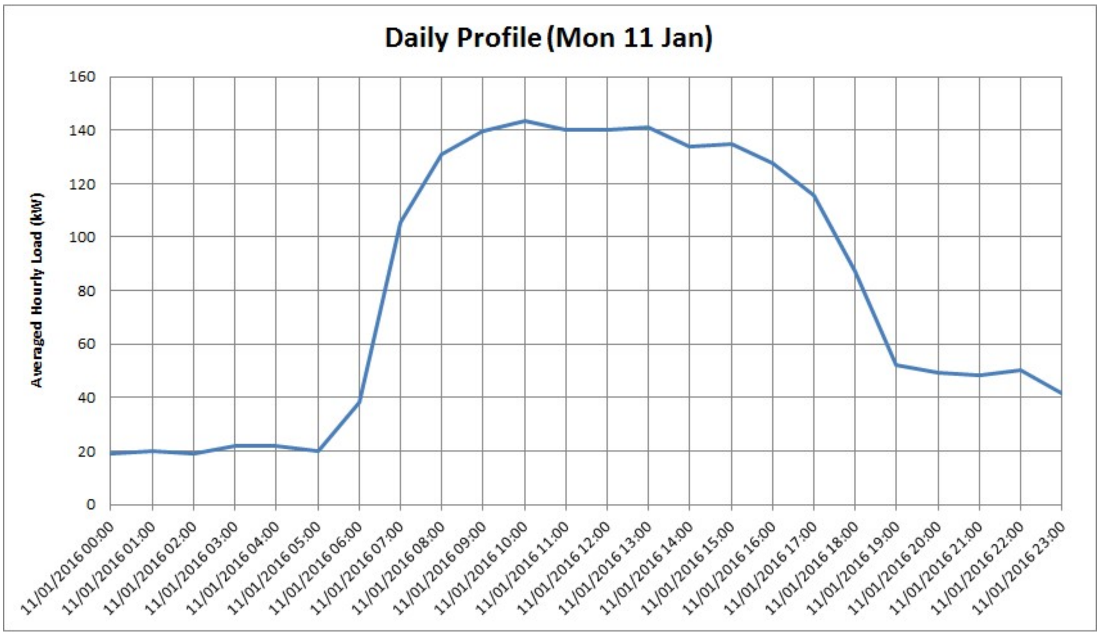


Figure 4.3 Graph of Typical Daily Electrical Load Profile

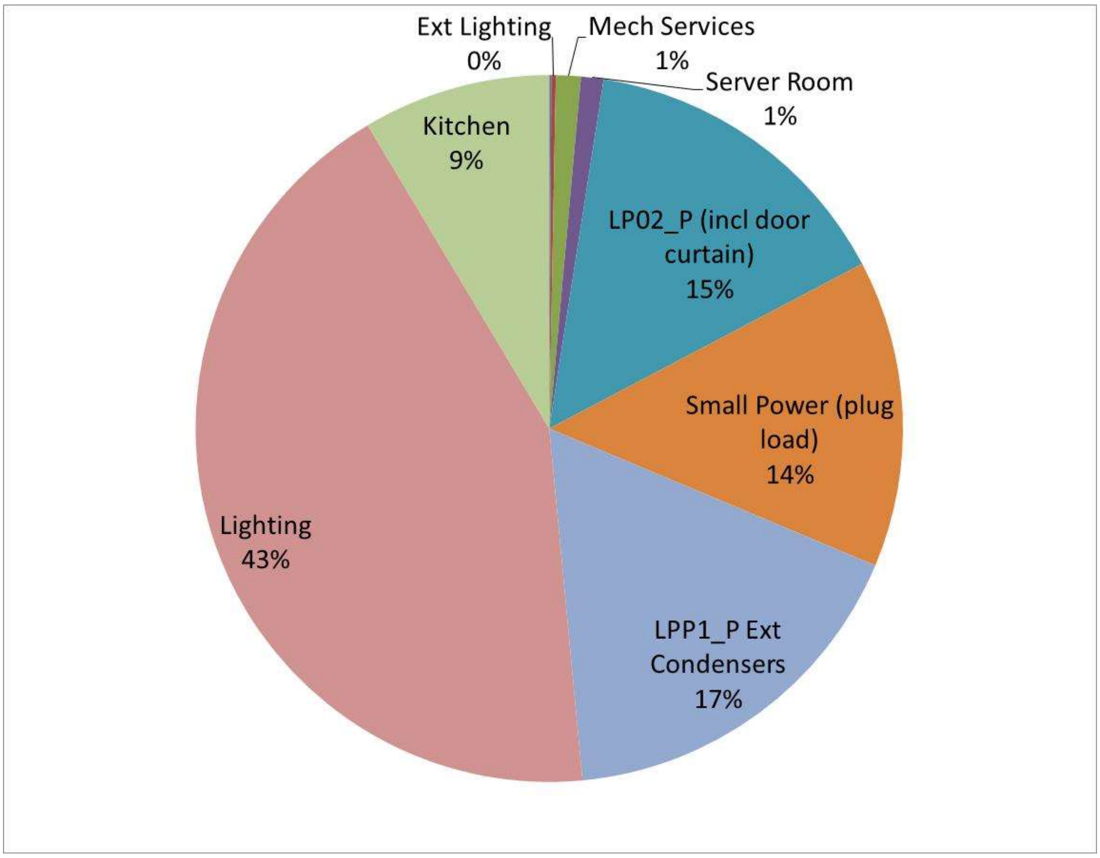


Figure 4.4 Electrical Power Loads by Type

The pie chart above shows the proportion of electrical power consumption by service type. Instantaneous power is used as the metric. Lighting is the largest load type followed by the VRF external condensers at 17%. Small power, sometimes known as plug load, is power used by plug-in devices, mainly computers. The loads on sub-distribution board LP02 are a combination of end uses, the main component of which is the air curtain over the entrance door. This makes up 12 kW of the 19 kW load, the remainder being small power. Other loads such as the server room and lift do not form a significant portion of power consumption, being 1% or less. The mechanical services meters exclude fan loads in AHUs and the VRF system, but do include an air compressor. Even though the air compressor has a 22 kW motor, it does not operate frequently enough to impact the load as the total contribution is approximately 1%.

During the flexibility assessment there were two meters which were not functioning. MCP1, which measures mechanical services load in the second-floor plant room and LP03_P, which measures power consumed by the workshop area. These represent approximately 11% of the total load and are not included in the graph above.

External lighting does not form a significant part of the power load. Even during the hours of darkness, it is approximately 2 kW total, less than 1.5 % of peak load.

Relevant Variables: Relevant variables includes non-energy parameters such as occupancy schedules, temperature set points, equipment set points, energy pricing & cost structure, weather data (if applicable) and other variables associated with the site which impact the flexibility capability.

Occupancy Schedule:

Monday – Friday: building open 6 am – 6 pm, occupants arrive ~ 7 am, depart ~ 5.30 pm

Saturday: open all day but only 1 training course takes place (TPM)

Sunday: Closed

Summer Shutdown: 2 weeks, last week July, 1st week August

Christmas Holidays: approx. 2 weeks

Temperature set points:

- Default room temperature set point: 21 °C
- Local control of room temperature set point for VRF ceiling cassettes in classrooms and offices is user adjustable if not locked by Facility Manager on BMS.

Equipment set points:

AHU 01 Lecture Theatre

VSDs: 75% (Controlled by CO_2 ppm set point)

Space Area Set point: 18 °C

CO_2: 750 ppm

AHU 02 General Areas

VSDs: 100% (controlled by pressure set point)

Space Area Set point: 22 °C (measured in return air duct)

Pressure Set point: 150 Pa

AHU 03 Workshop

VSDs: 100%

Space Area Set point: 22 °C

AHU 04 Kitchen

VSDs: 75%

Space Area Set point: 21 °C

AHU 05 Changing Areas

VSDs: 100%

Space Area Set point: 20 °C

Compressor: Air pressure set point 50 Pa

Door Curtain: enabled via main time schedule

External Lighting: 300 Lux, time schedule

Energy Pricing & cost structure:

Time of Use (TOU) pricing, fixed tariff

£0.076065 per kWh (day rate)

£0.065271 per kWh (night rate)

Weather data:

- UK Met office hourly temperature data for Durham.
- Global radiation data (hourly) for Durham provided by Gateshead College.
- European Commission Photovoltaic Geographical Information System provides location specific solar radiation data at: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php.

4.2.2 Step 2: Flexibility Characterisation

Step 2: Flexibility Characterisation was then implemented using the process in Chapter 3. It was applied to the loads, storage and generation sources identified in Section 4.2.1. The pie chart in that section shows the power loads by system type and the proportion of power they use in the building. Starting with the largest load type, the loads, storage and on-site generation at the building were assessed for flexibility.

An assessment of whether a load is flexible was performed using the filter step: Is the load **Shedable, Controllable AND** is it **Acceptable** to shed or reduce that load? If the answer is not **Yes** to all 3 of these criteria, the load is not flexible. It is to be set aside and the next load is to be assessed. Only if the load passes this initial filter or triage step should any further technical details be analysed.

Air Handling Units are present in the SASMI building. The fan in an Air Handling Unit (AHU) is considered a load, therefore the starting point is the load category of the process in Figure 4.5. The fan provides ventilation and it is possible to reduce its speed, making it **Sheddable**. It has a variable speed drive controller which was not originally linked to the BMS but following sensor and metering upgrade recommendations it was connected, 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 exceeded this. To ensure the CO_2 concentrations limits were not breached, CO_2 sensors were installed in the return air duct of the air handling unit, again as part of a sensor recommendation identified in Energy Flexibility Improvements. High levels of fresh air ventilation increase occupant comfort but during a flexibility event there is scope to minimise the ventilation levels. Therefore, it is **Acceptable** to reduce the fan load within CO_2 limits. If the fan speed 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.

The above process was applied for all loads, storage and on-site generation at the building. A summary of the other load assessments is included below.

- Lighting is the largest load but it is not sheddable or controllable.
- VRF (Variable Refrigerant Flow) external condensers are sheddable, controllable and it is acceptable to either displace the heat using gas or increase the temperature set point during summer cooling.
- Small power (plug load) is not sheddable or controllable.
- Door curtain is not currently controllable but it is possible to add it to the BMS. If this is done, it will be sheddable and controllable. Acceptability may be permitted depending on duration and outside air temperature.
- Kitchen load shed is not acceptable.
- External lighting is sheddable and controllable but is less than 1% of total load.
- An air compressor is present but the load is less than 1%, therefore it was discounted as a flexible source.

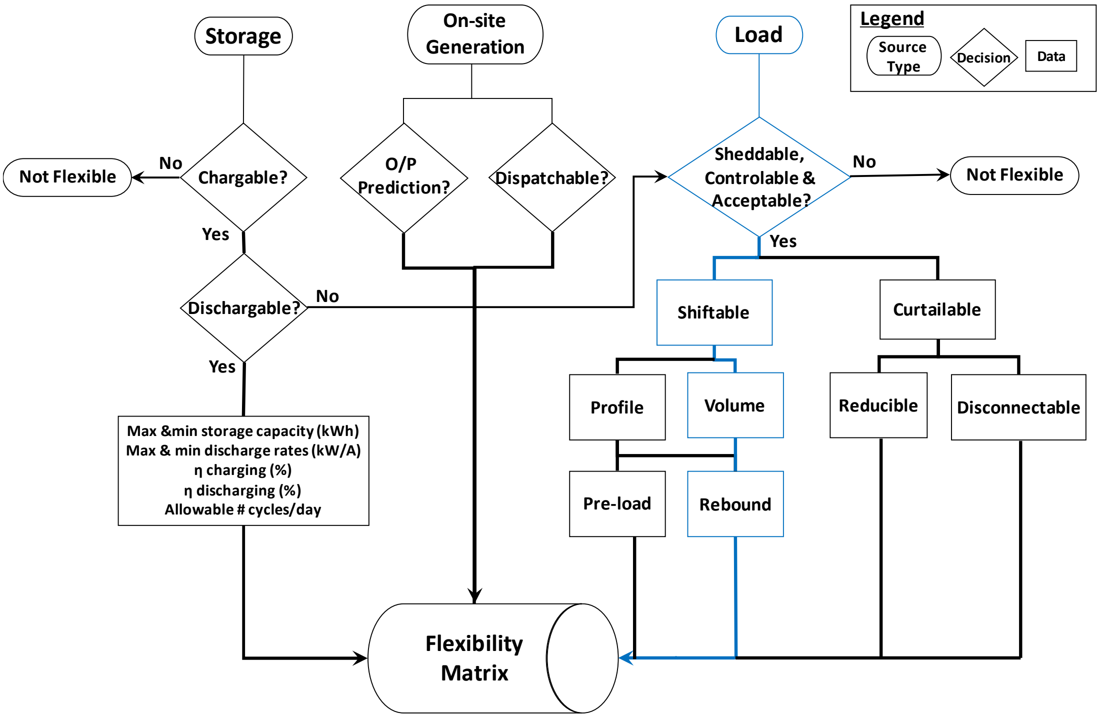


Figure 4.5 Characterisation Process AHU Fan

Thus, the **sources of flexibility identified in the building** were

<u>Loads:</u>

- HVAC loads
    - AHU fans – if energy flexibility improvement opportunities were implemented, see below
    - Variable Refrigerant Flow (VRF) heating and cooling heat pump system

<u>Storage:</u>

- second life EV battery system, consisting of three Nissan Leaf batteries with a combined capacity of 48 kWh (first life capacity was 72 kWh)

<u>Generation:</u>

- 50 kWp PV array.

Implications of the flexible load choices:

The implications of the flexible load choices for each system are detailed below.

- AHU fans: as the fans are used for ventilation, the return air CO_2 levels require monitoring to ensure indoor air quality remains within permitted limits (Daniels, 2016) (ASHRAE, 2018).
- AHU fans: In winter, the AHUs provide base load heating in addition to ventilation. As a result, any reduction in fan speed may reduce thermal energy provided to the building from gas fired heating in the AHU fans with the result that the VRF heat pump electrical consumption may increase. Functional tests may be required to determine if this linkage is significant. If it is significant, acceptability limits for AHU output air temperature may be required.
- VRF heat pump: the VRF heat pump system allows for individual temperature set points to be selected in each room where the system is installed. During a flexibility event, global temperature set point control is utilised which overrides individual room set points. If the temperature set point change is significantly different from an individual preference and the flexibility event is long, this may result in some user discomfort or complaints to the building operators. From the literature (Xu and Zagreus, 2009) (Piette et al., 2006a), a 2°C global temperature set point change did not result in user discomfort. However, if the global temperature set point is typically 20°C and is decreased to 18°C during a winter event, but an individual user prefers a set point of 22°C, then the individual user may experience a temperature reduction of up to 4°C depending on the thermal mass of their environment, the surface temperatures in the room and duration of the flexibility event.
- Battery system: For the battery system to be fully dischargeable, it must first be fully charged. In the battery system flexibility technical specification in Table 4.3, it may be seen that the maximum charging rate of the battery system at 9 kW is lower than the maximum discharge rate of 36 kW, while the capacity is 48 kWh. Thus, even though the battery may fully discharge in just over an hour, it takes 5.3 hours for it to re-charge. Depending on tariffs (e.g. reduced night rate), or requirements such as charging the battery only from PV to maximise renewable energy, the time periods when the battery may be permitted to re-charge are limited. Based on the long re-charge time, the battery discharges may be limited to twice per day, or three times per day with partial discharge.
- Battery system: the battery system provides a means of moving energy from one period of time to another, but this comes at a cost. The charging and discharging efficiency of the battery means that energy is lost each time the battery is charged

or discharged (Berrueta et al., 2018). In addition, Li-Ion battery systems have standing losses and degrade over time (Sakti et al., 2017).

- PV: the non-dispatchable and intermittent nature of PV generation means that it may not always be available at the predicted levels during a flexibility event.

Figure 4.6 AHU with Variable Speed Drives

Figure 4.7 VRF External Condensers

Figure 4.8 2nd Life EV Batteries

Figure 4.9 PV Installation at Case Study Building, Sunderland, UK

Energy flexibility improvement opportunities: The site has the potential to provide additional flexibility in a number of ways.

a) If fan speed control for the variable speed drives was implemented on the BMS, this would enable direct control of the AHU fans during a demand response event, thereby lowering electrical consumption of the fans. This requires CO_2 sensors on all AHUs, to monitor CO_2 levels and ensure limits were not breached during the flexibility event.

b) If a single global temperature control was implemented for the VRF system, it would be possible to simultaneously increase or decrease the temperature set point for the system prior to or during a demand response event, thereby decreasing or increasing the electrical load of the external condensers.

The following flexibility improvements were identified but not implemented during the experimental demonstration.

c) During Winter operation, by reducing the temperature set point of the VRF ceiling cassettes, it would enable heating needs be met by the AHUs during a winter flexibility event. Heating in AHUs is provided by gas direct burners. The gas burner in the AHU is controlled by a temperature sensor in the return duct. Using the AHUs to maintain room temperatures allows for reduction in electrical load as the VRF system does not need to meet the heating load. The gas burners were installed in the AHUs when the building was constructed, therefore the opportunity for additional fuel shifting is limited.

d) During winter operation, if the door curtain on/off control was enabled via the BMS, it would be possible to turn off the door curtain (12kW load) during a flexibility event, provided it was of short duration (e.g. < 1 hour) and within acceptable out-door air temperature limits (e.g. > 10 ◦C). Limits to be agreed with Facility Manager.

e) For a summer flexibility event, increasing the outside air ventilation rate using AHU fan speed control may reduce the cooling load on the VRF system. This flexibility may not be implemented if fan speed control is in operation.

f) If the ASHRAE 55 (ASHRAE 2013) adaptive comfort approach was used, instead of a single set point, then it may be possible to increase the room temperature in summer, thereby decreasing the VRF electrical load. However, this may not be acceptable to the Facility Manager or building occupants.

Recommended sensor & control improvements: The recommendations below were implemented to enable flexibility implementation. A number of other proposed recommendations were recommended but not implemented due to budgetary or technical constraints.

Electrical Metering

- Meter data. kW, kVA, V, Frequency, add to the BMS for all meters
- Meter for PV
- Meter for battery – bi-directional

- Main incomer – check if bi-directional. If no export of PV power allowed outside of SASMI building, meter does not need to be Bi-directional.

Sensors

- CO_2 sensors for AHUs 02, 03 & 05. In duct return air sensors.
- Temperature sensor in entrance lobby. To be located near reception desk.
- Weather station – wind speed, wind direction, relative humidity, rain sensor, wet bulb temperature

BMS Programming

- Single global temperature set point for temperature (for all areas on VRF system)
- Direct Fan VSD speed (%) control set point on AHUs 01, 02, 03 & 05.
- Override for fan control based on duct pressure – enable/disable (may be via OPC only if preferred). Required on AHU 02. It is not clear if AHU 03 has a pressure set point. If it does, override required. Other AHUs do not appear to have duct pressure control but if they do, override required.
- Door Curtain on/off control
- On/off control of room AC units (VRF) on BMS

Remedial Items

- Repair meters MCP1 (2nd floor plant room) & LP03 (workshop).
- Verify external lighting lux control is operating correctly. Current set point reads: 300.0kgCO2.

Additional recommendations not implemented due to technical or budgetary constraints:

- Meter on supply to DX chiller
- Meter on supply to VRF external condensers
- Main gas meter to be connected to BMS.
- CO2 sensors in all rooms supplied by AHUs 02, 03 & 05. Wall mounted sensors, wired for power, signal may be wired or wireless.
- PIR (motion detection) in classrooms and offices rooms with AC units
- ASHRAE 55:2013 Sensors
- Relative Humidity (RH)
- Globe Temperature sensor (for measuring Mean Radiant MRT)
- Room Air Velocity – hand held measurements may be sufficient
- Pyranometers –1 direct & 1 diffuse (with motorised shading ring). To be installed at same angle of inclination as PV array.

- On/off control of DX chillers
- Recouperator damper control set point for AHU 02, 03 & 05.
- Recirculating damper control set point for AHU 01

Table 4.1 AHUs Flexibility Technical Specification

	HVAC System – AHUs			
	Type	***Description***	***Value***	***Unit***
Specifications	Ventilation (Some Heating & Cooling)	AHU01, AHU 02, AHU 03, AHU 05		
	Fan Size	Supply and Extract fans in each		
		AHU01	1.5 x 2 = 3	kW
		AHU 02	4.0 x 2 = 8	kW
		AHU 03	3 x 2 = 6	kW
		AHU 05	0.75 x 2 = 1.5	kW
Communications	BMS			
Control Parameters	Fan Speed	Set on commissioning but recommended change to BMS set point	0- 100	%
	CO_2	On AHU01 at present but requested for all	750 - 1,125	ppm
	Temperature	Return duct sensor set point	20 - 22	ºC
	Duct Pressure	Fan speed control on AHU02 only	150	Pa
	Recirculation Damper	AHU01 only	-	%
	Recouperator Damper	AHU02, 03, 05	-	%
Flexibility	Max	Estimated 20%	2.8	kW
	Min	Estimated 10%	1.4	kW
	4 Hour Average	Estimated 20%	2.8	kW
	Pre-load/ Rebound	Not for ventilation, may occur on AHU01 on cooling	n/a	kW
	TIA		10 - 15	min
	Load Availability	As per occupancy schedule		
	Min time between events	Provided max ppm of CO2 is met, no restriction on ventilation control, may be restriction due to interactions	TBD	h
	Rebound delay		n/a	
	Disutility cost		n/a	
	Shed time		10-15	min
	Interactions	with other HVAC systems (VRF)	Yes	-
	Day ahead /Intra day	Possible for both	-	-

The rationale underlying the timeframes for flexibility in the flexibility technical specifications below are as per the details in Section 3.6.1.

Table 4.2 VRF Heat Pump Flexibility Technical Specification

	HVAC System – VRF Heat Pump Split System			
	Type	***Description***	***Value***	***Unit***
Specifications	Heating & Cooling	Toshiba Carrier		
	No. of Condensers	External Condensers	6	-
	Installed capacity	Electrical Load	16.7 x 6 = 100.2	kWe
		Heating	35.5 x 6 = 213	kWth
		Cooling	33.5 x 6 = 201	kWth
Communications	BMS			
Control Parameters	Temperature Set point	Room cassette units	T	ºC
	Mode, Fan, Louver	Adjustable settings		
	Lock Remote	Control may be locked at BMS	-	-
Flexibility	Max	Estimated 20%	9.2	kW
	Min	Estimated 10%	3.5	kW
	4 Hour Average	Estimated 20%	9.2	kW
	Pre-load/ Rebound	Present for longer events		kW
	TIA	Varies depending on the load reduction. For large load reductions (e.g. ≥ 20%) over a long period (e.g. 4 h), day ahead notification required;	15 min – 24 h	min
	Load Availability	As per occupancy schedule		
	Min time between events	For short events ≤ 1 hr, 2 -3 may be permitted per day; Events > 1 hr, 1 per day	2 - 24	h
	Rebound delay	May be possible with day ahead notification		
	Disutility cost		n/a	
	Shed time		10- 15	min
	Interactions	with other HVAC systems	Yes	-
	Day ahead /Intra day	Possible for both but may be more suited to day ahead for longer events	-	-

Table 4.3 Battery System Flexibility Technical Specification

	ELSA Battery System 2 (Nissan LEAF)			
	Type	***Description***	***Value***	***Unit***
Specifications	No. of Batteries		3	-
	Capacity	Nominal. TBD during Commissioning Capacity Check	16 x 3 = 48	kWh
	Max Charge Rate	At DC side of charger	3 x 3 = 9	kW
	Max Discharge Rate	At AC side of inverter	12 x 3 = 36	kW
	Min Charge Rate	At AC side of charger	0.85	kW
	Min Discharge Rate	At AC side of inverter	1.2	kW
	Min Stage of Charge (SOC)	N/A		
	Min time between charging & discharging	Cold start to discharging	60	s
		Cold start to charging	20	s
		Change to discharging (worst case)	25	s
		Discharge to Charging (worst case)	20	s
		Standby to Charging	20	s
		Standby to Discharging	25	s
	No. of cycles/day	Full charge/discharge cycles	2	-
Efficiency & Losses	Inverter Efficiency	Lower limit for Efficiency TBD	Up to 96	%
	Battery System Energy Efficiency	Approximate value for a system of 3 batteries.	75	%
	Fixed Power Consumption	Industrial PC, ventilation etc. Estimated value	0.3	kW
Communications	Web Services API	Between UTRCI EBEMS and BYES ESMS	-	-
	Delay	BYES ESMS	5 - 6	s
Control Parameters	Charge Power rate	Confirmed	0.85 - 9.0	kW
	Discharge Power rate	Confirmed	1.2 - 36	kW
Flexibility	Max	1.3 hour	36	kW
	Min	40 hours	1.2	kW
	4 Hour Min		9	kW

Table 4.4 PV Flexibility Technical Specification

	PV System			
	Type	***Description***	***Value***	***Unit***
Specifications	Panel Area		320.25	m^2
	Capacity		49.66 (191 x 260W panels)	kWp
Efficiency & Losses	Inverter Efficiency		98	%
	Fixed Power Consumption	(if any)	Not known	kW
Communications	Electrical Meter	To be installed and connected to the BMS	kW, kWh, V, I, F	-
	Delay	Meter delay		s
Flexibility	Summer Max		22	kW
	Winter Max		8	kW
	Summer Average		15	kW
	Winter Average		5	kW

4.2.3 Step 3: Scenario Modelling

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

4.2.3.1 Assumptions

The assumptions made in relation to the scenario modelling include:

- PV output is based on average predicted output for a typical summer day based on historical weather data for the site location. It is assumed the PV is available when required and output will be as per typical day;
- Battery system is fully charged, has full technical capacity across all modules as specified in the flexibility technical specification, maximum discharge rate is as per the flexibility technical specification and is available for the flexibility event;
- AHU fan speed reduction is permitted (Acceptable) while CO_2 levels remain below acceptable limits, in this case, 1,200 ppm;
- A 2°C reduction or increase in global VRF heat pump temperature set point for the building will result in a 20% decrease in electrical consumption as per previous demonstration studies (Xu and Zagreus, 2009) (Piette et al., 2006a).

4.2.3.2 Flexibility Event - 1 hour

From the flexibility technical specifications, Representing the available flexibility from the flexibility characterisation tables in a flexibility matrix for one hour time periods, the developed matrix is given in 4.1 below. Source 1 is the battery system, source 2 the HVAC AHU fans, source 3 the HVAC VRF Heat Pump system and source 4 the PV array.

$$F_{total} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 2 & 5 & 3 \\ 0 & 3 & 5 & 6 \\ -9 & 3 & 0 & 10 \\ 0 & 0 & 0 & 14 \\ 0 & 0 & 0 & 15 \\ 36 & 3 & 9 & 15 \\ 12 & 3 & 9 & 15 \\ 0 & 3 & 9 & 15 \\ -9 & 3 & 9 & 15 \\ -9 & 0 & 0 & 15 \\ -9 & 0 & 0 & 14 \\ -9 & 3 & 5 & 11 \\ -3 & 2 & 5 & 7 \\ 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad (4.1)$$

For the one-hour scenario which the matrix in 4.1 is developed for, the maximum amount of flexibility is in time period 11. Summing the flexibility of source 1 (battery) which is 36 kW, source 2 (AHU fans) which is 3 kW, source 3 (VRF heat pump) which is 9 kW and source 4 (PV array) with an average of 15 kW, the maximum range for a four-hour flexibility event is 63 kW, as illustrated in equation 4.2 below.

$$30 + 3 + 9 + 15 = 63 \text{ kW} \qquad (4.2)$$

A scenario model for a one-hour flexibility event, illustrates graphically in Figure 4.10, Figure 4.11 and Figure 4.12 the percentage reduction in peak load which renewable generation from PV, electrical HVAC system loads and battery storage may deliver on receiving a demand response request from an aggregator or grid operator. The battery system alone has the capacity to provide a flexibility of up to 26% of building peak load, shown in Figure 4.10.

HVAC loads have a predicted flexibility of 8% while PV has predicted flexibility of 11% in summer. Figure 4.11 combines HVAC and PV to provide a flexibility capability of 19%. Total flexibility for all available systems, shown in Figure 4.12, is 45% of peak load.

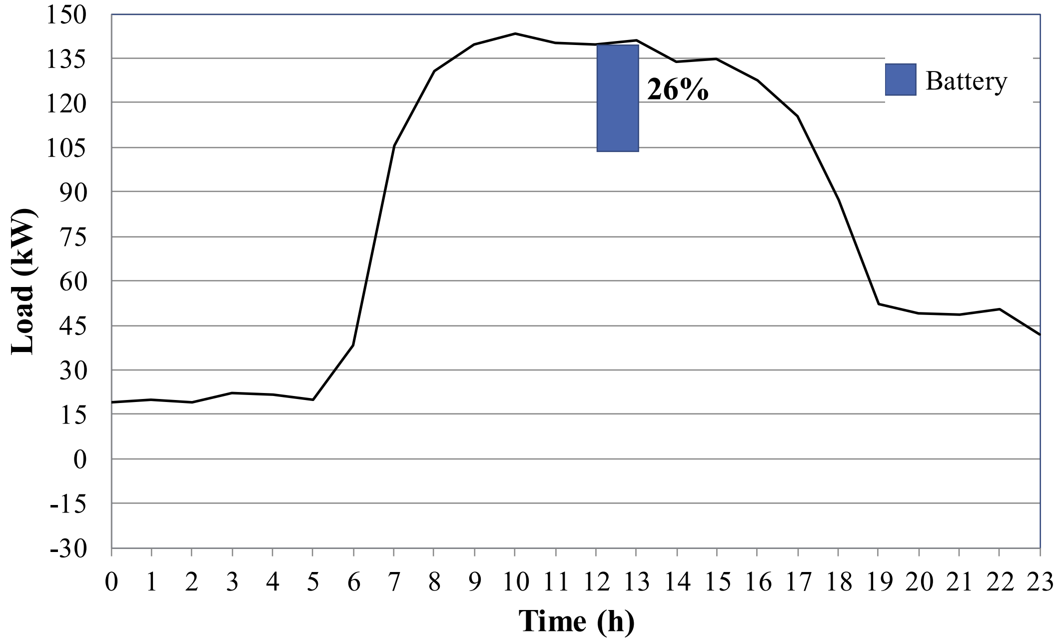


Figure 4.10 One-hour Scenario Model: Battery System Flexibility

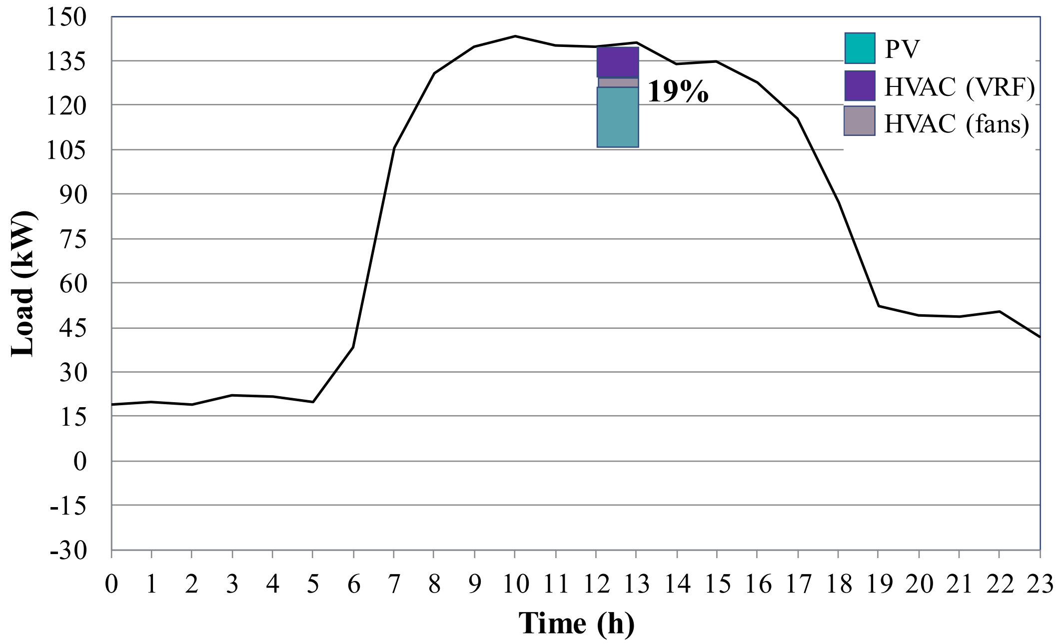


Figure 4.11 One-hour Scenario Model: PV & HVAC Systems Flexibility

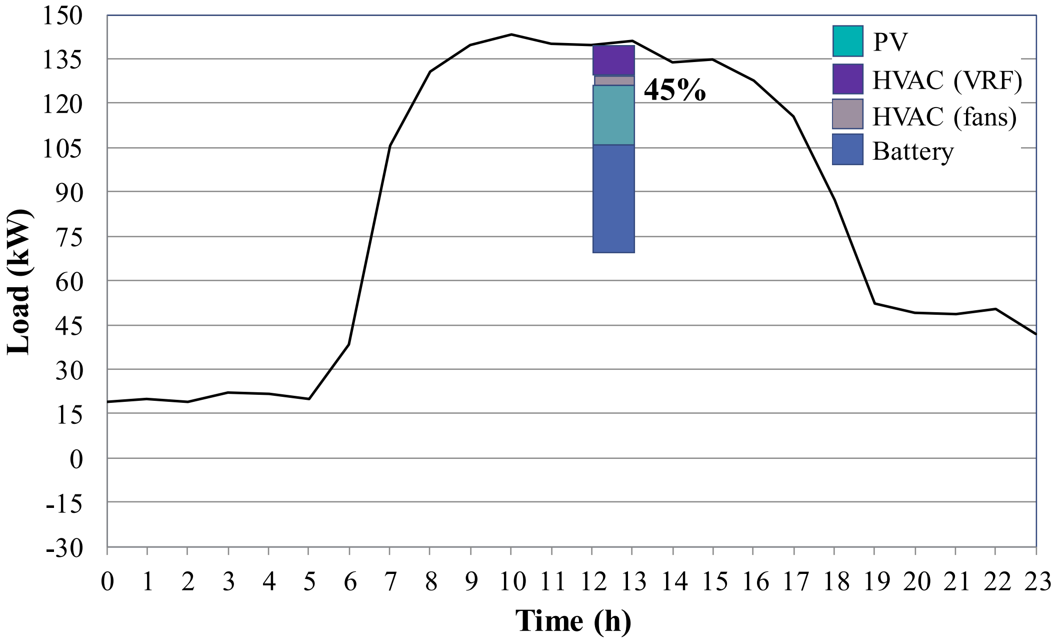


Figure 4.12 One-hour Scenario Model: Total Flexibility for all Available Systems

4.2.3.3 Flexibility Event - 4 hours

A scenario for a four-hour flexibility event, illustrates the flexibility the sources may deliver during a longer event at the Sunderland pilot site. The battery system alone has the capability to provide flexibility of up to 8% of building peak load, as shown in Figure 4.13. Applying the same HVAC loads reduction and PV generation as per the previous scenario provides a modelled flexibility of 19% in Figure 4.14. 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). Figure 4.15 illustrates the total flexibility for all available systems for the four-hour scenario model, giving a predicted flexibility of 27% of peak load.

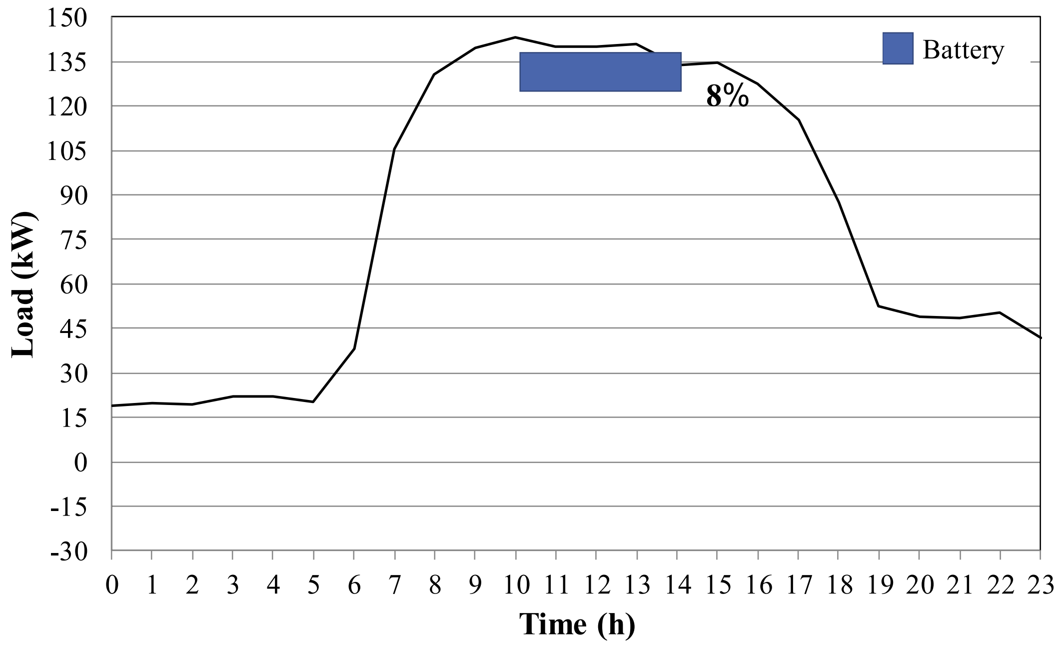


Figure 4.13 Four-hour Scenario Model: Battery System Flexibility

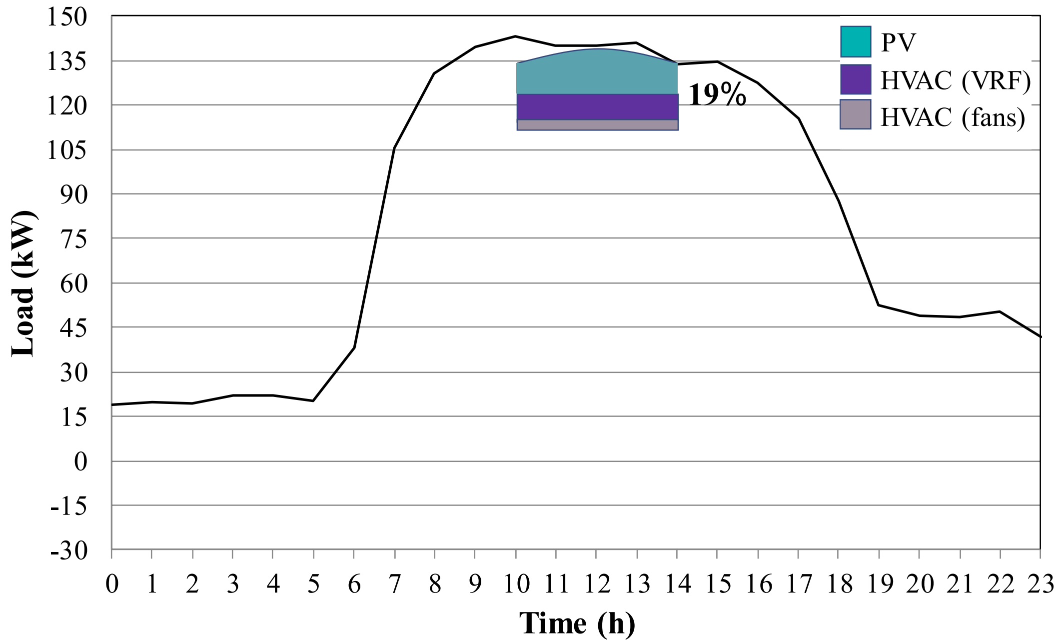


Figure 4.14 Four-hour Scenario Model: PV & HVAC Systems Flexibility

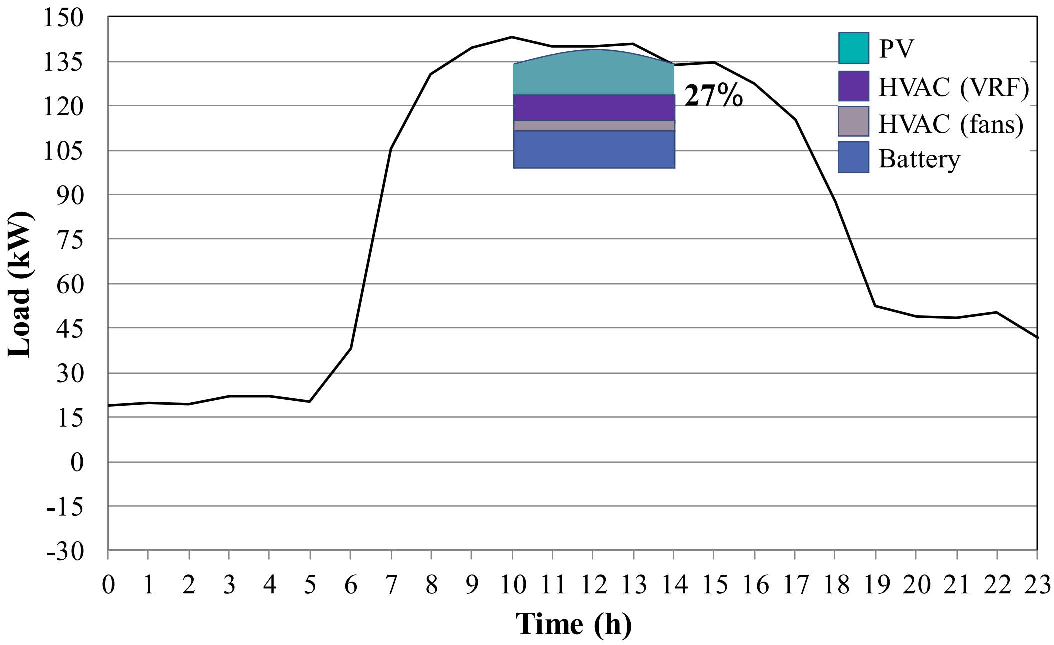


Figure 4.15 Four-hour Scenario Model: Total Flexibility for all Available Systems

4.2.4 Step 4: KPI Label

Based on the predicted power flexibility calculated in the scenario models in Step 3, a KPI label was generated for the case study building, shown in Figure 4.16. The graphic shows the maximum and minimum timeframes for flexibility events that the building has the capability to participate in. The minimum timeframe is 15 minutes, a short event, while the maximum timeframe is 4 hours, a long event. The power flexibility associated with each timeframe is expressed as a percentage of peak building or site load. For a short event, the greatest power flexibility the building is predicted to have is 45% while for a long event it is 27% of peak load.

In the text portions of the label, the building details are given on the top right hand corner, while the numeric data associated with the percentage KPIs from the graphic is shown in the 'KPIs' text section. Peak load and base load from Step 1 are identified as 140 kW and 20 - 40 kW respectively. The shortest response timescale, identified in Step 2, is given as 10 - 15 minutes. This is constrained by the BMS response capability. Market suitability, day ahead or intra-day, was also identified in Step 2. When participating in a day ahead market, a building or site will be given at least 24 hours' notice of a demand response event. Intra-day markets require the building or site to respond within the day. An aggregator or grid operator places a request and the building or site may need to respond within an hour or two hours.

Flexibility capacity, expressed as percentages in the graphic, is given in power values of kW for the short and long events in the KPI text section. The 45% short event has a maximum flexibility of 63 kW while the long event 27% flexibility is equivalent to 38kW. Time in advance notification is given as 10 - 15 minutes, again constrained by the BMS response capability. Finally, other flexibility characteristics such as pre-load and rebound effects are identified at the base of the text box.

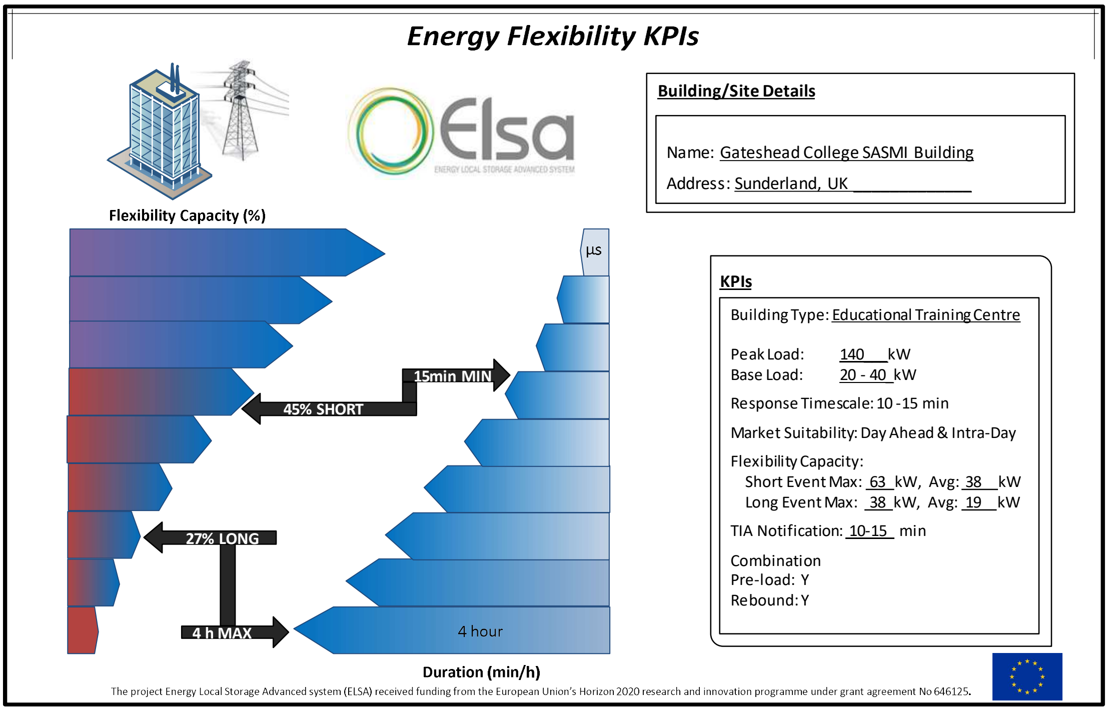


Figure 4.16 KPI Label Predicted Flexibility, Detailed Case Study

4.3 Experimental Results, Detailed Case Study: Sunderland, UK

Experiments were conducted to verify the results of the methodology implementation for the case study building located in Sunderland, UK. To run the experiments, a standard operating procedure was developed with the pilot site. Use cases were selected and an experimental setup was devised. An ICT platform was required conduct the experiments which allowed remote access to the flexible systems in the buildings in real time for control and data acquisition. Flexible systems included the 2nd life Electric Vehicle battery storage system. Aggregator or grid signals were simulated using the OpenADR protocol in the ICT platform.

4.3.1 Building Summary

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

4.3.2 Standard Operating Procedure

A standard operating procedure (SOP) was developed by the author to facilitate interactions with the pilot site for the experiments. The purpose of the SOP was to ensure:

- Clear communication between all parties regarding what was planned for the experiment;
- Safe operation of the systems during the experiment;
- Explicit and documented permission to conduct the experiment was obtained from the pilot site operator;
- Awareness of any comfort implications for occupants were highlighted and approved by the pilot site operator;
- If supervision of equipment e.g. the 2nd life battery system, was necessary during the experiment, that the pilot site operator was aware of the requirement and could co-ordinate with the researchers conducting the experiment when best to facilitate the required supervision.

An example of an SOP is given in Appendix B – Experiment Standard Operating Procedure.

4.3.3 Use Cases

Two demand response use cases were selected, peak shaving and an intra-day request. Peak shaving is a price-based programme. 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.

An intra-day request is made in a market-based programme. It 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).

4.3.4 ICT Platform

An ICT platform installed at the building was used to actuate the sources of flexibility during the experiment and record data. The architecture of the ICT platform is shown in Figure 4.17 ICT Platform System Architecture, Sunderland Pilot Site.

Aggregator or grid signals were emulated using an OpenADR protocol (OpenADR Alliance, 2019). 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 used the OPC (OLE for Process Control) protocol.

The ICT platform was initially developed as part of previous projects led by the author for whole building power and energy management test beds (Valdivia et al., 2014) (Monti et al., 2017) at building and district scale. The ICT platform was then adapted for demand response implementation in the case study building as part of the ELSA project (O'Connell & Riverso, 2016). The architecture of the ICT platform was created by the author and the implementation programmed by software developers in the project teams. The building scale test bed (Valdivia et al., 2014) (Monti et al., 2017) incorporated a microgrid, while the district scale (Blanke et al., 2017) included a district heating system which provided both heating and electricity using a Combined Heat and Power (CHP) plant. Both test beds were located at Cork Institute of Technology.

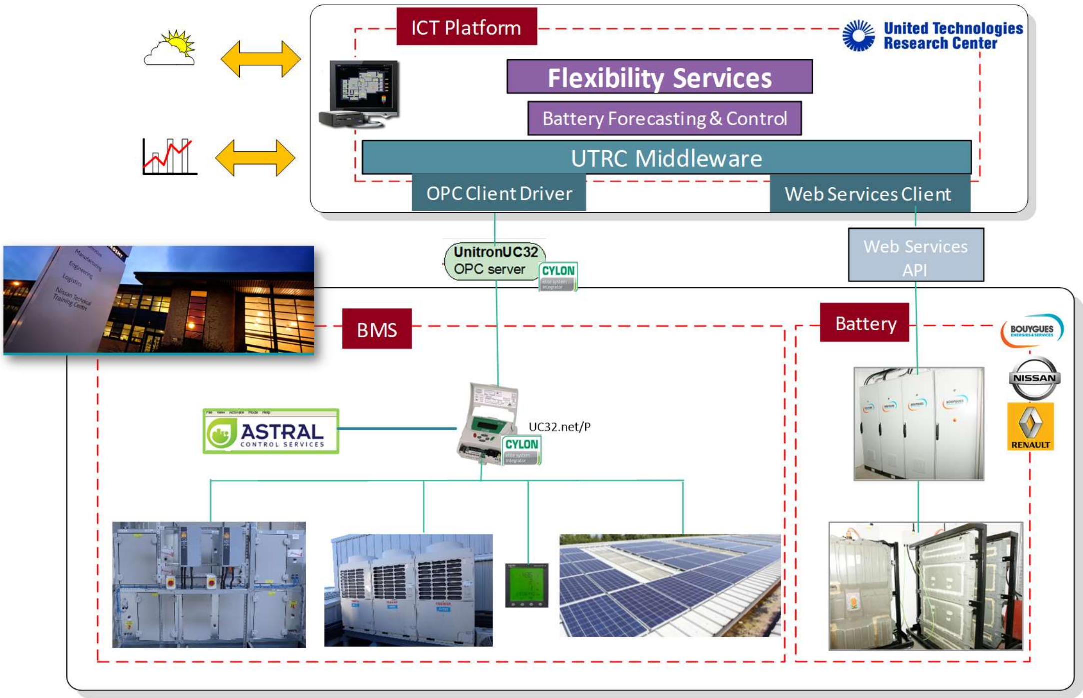


Figure 4.17 ICT Platform System Architecture, Sunderland Pilot Site.

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 were 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 was 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. All experiments were conducted remotely.

The ICT platform was installed at Gateshead College's main campus in Newcastle and connected to the BMS for the SASMI building and the battery management system. While the BMS was located in Newcastle, it controlled the systems in the SASMI building in Sunderland. The ICT platform also connected to the battery management system, located in the SASMI building in Sunderland. In order to access the ICT platform from UTRC's offices in Cork, two remote desktop (RDP) connections were required. The first to a dedicated pilot site PC, also located in the Cork office, the second RDP from the Cork office to the Newcastle ICT platform. Firewall exceptions were required at both the UTRC IT security network and the Newcastle IT security network. Static or fixed IP addresses for both PCs were also required.

The database used in the ICT platform was a Cassandra NOSQL database. This approach was selected during the initial development of the ICT platform as part of the CIT test bed project. Conventional SQL databases are limited by the quantities of data that they can host.

NOSQL, which is taken to mean Not Only SQL, databases are better equipped to handle big data type datasets. Recording large amounts of building data over a number of years at high frequency results in a very large dataset. Extracting data from the Cassandra database was more complex than data acquisition from a SQL database and required some additional processing.

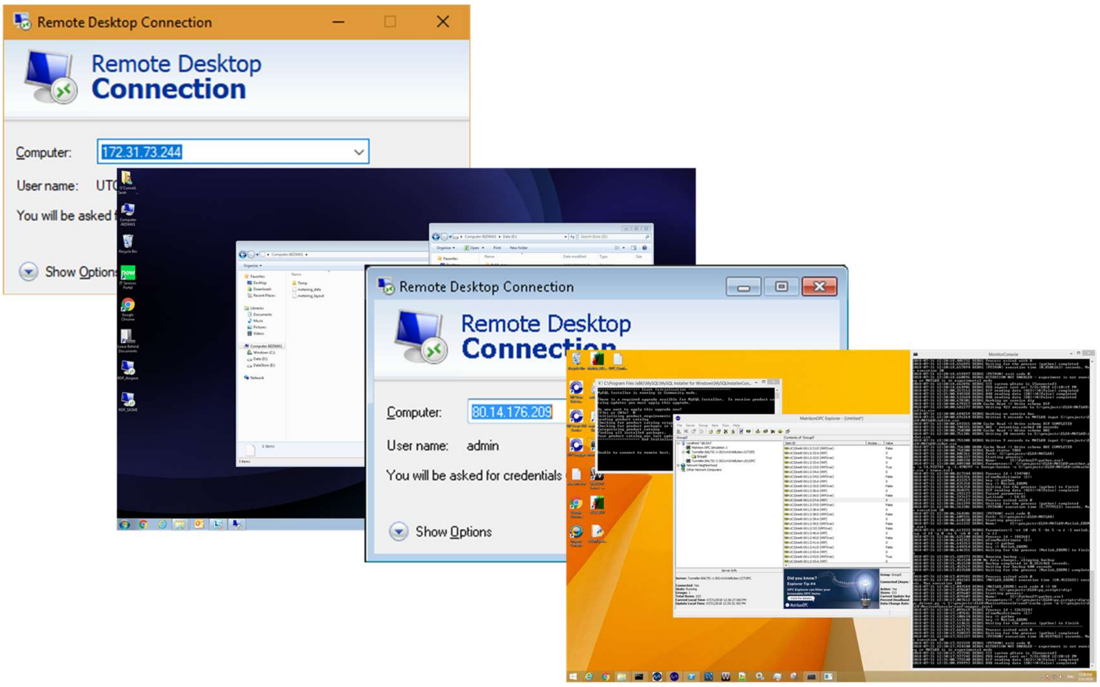


Figure 4.18 Remote Desktop Connections to Demonstration Site, Sunderland, UK

Figure 4.19 UTRC Middleware in Operation

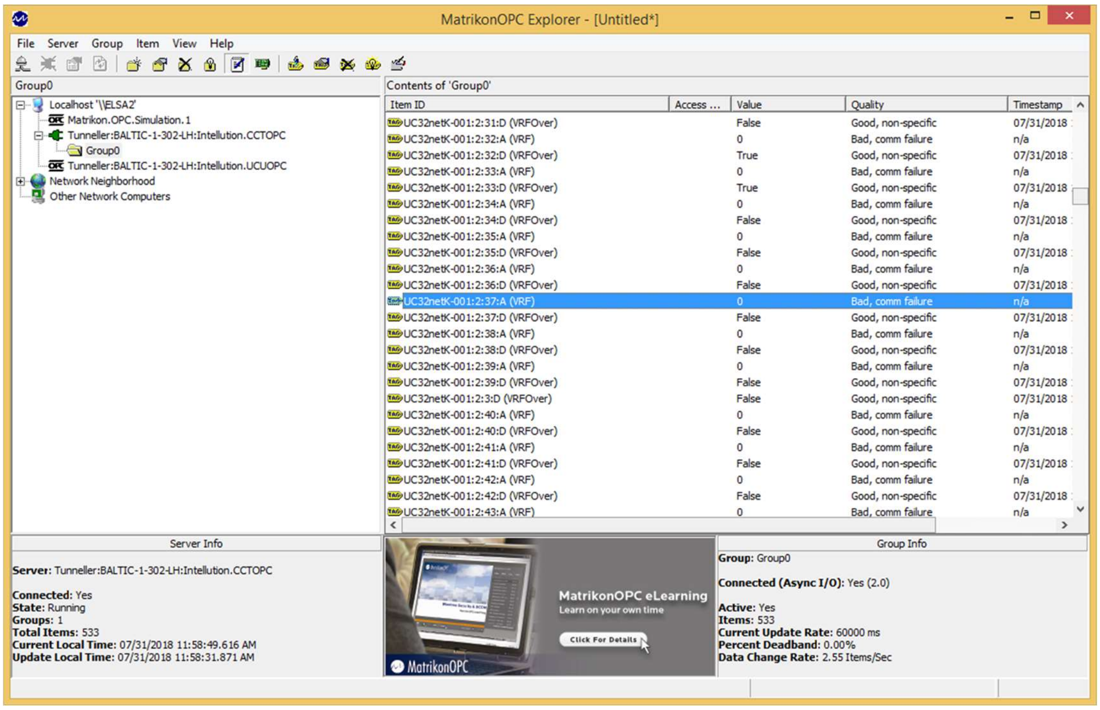


Figure 4.20 Changing Set Points of HVAC Equipment in BMS Remotely

4.3.5 Implementation

To activate the sources of flexibility in the building, set points of the loads and storage were adjusted using the ICT platform. PV output is not controllable and so was monitored during the experiments using its electrical meter. The set points for each source were as follows:

- AHU fans: 20% fan speed reduction;
- VRF system: 2°C global temperature set point increase;
- Battery system: -36 kW for one-hour event, -12 kW for four-hour event.

The load reductions for the HVAC systems were selected based on previous demonstration studies reviewed as part of the literature review in Chapter 2 (Xu and Zagreus, 2009) (Piette et al., 2006). The experiment was conducted during summer hence the temperature set point was an increase and not a decrease.

Before proceeding with the experiments, permission was required from the pilot site. A Standard Operating Procedure (SOP) was put in place, see Appendix B – Experiment Standard Operating Procedure, to obtain explicit written permission to conduct the experiment from the building operator. The SOP outlined what the experiment involved, the systems required, any supervision requirements on-site and highlighted any potential impacts on occupants. The

SOP was signed off by the facility manager for the building and the project contact for the pilot site.

4.3.6 Experimental Results

The results of the demonstration experiments are shown on the right-hand sides of Figure 4.22 and Figure 4.23. The demonstration 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 4.5.

The database used in the pilot site ICT platform was a Cassandra NOSQL database which required a python programme to extract the data recorded during the experiment. A screenshot of the extraction code is shown in Figure 4.21. The data start and stop times were specified and the output is a .csv file. Results were then graphed using the data in the .csv file.

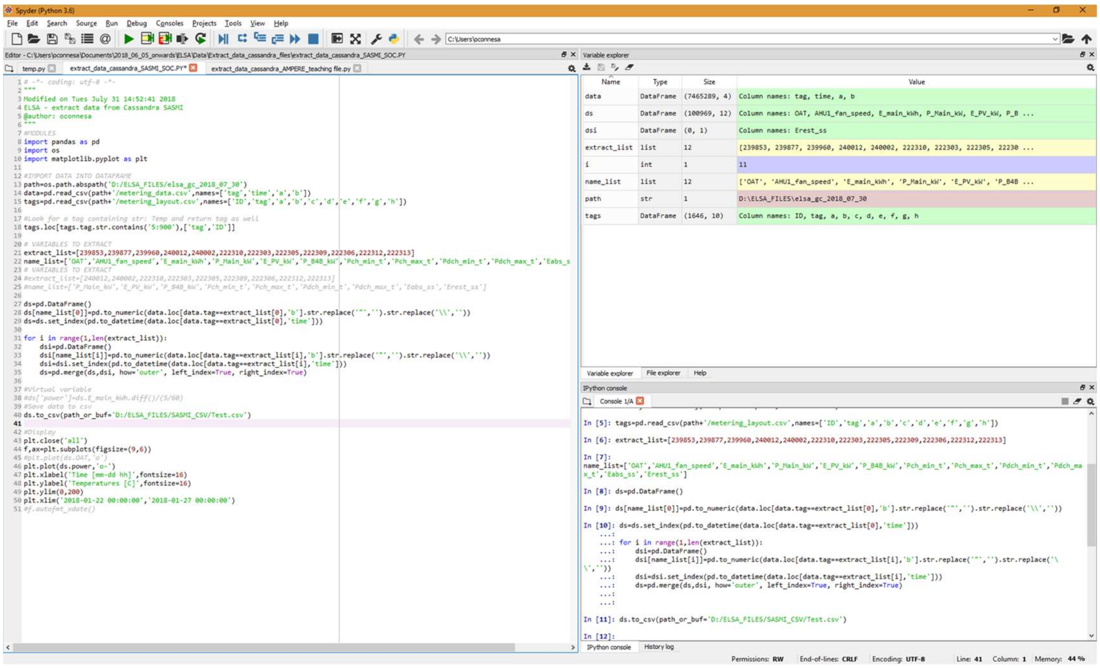


Figure 4.21 Data Extraction from Cassandra NOSQL database

For the one-hour scenario, shown in Figure 4.22, the overall flexibility achieved was 33% of peak load compared with 45% predicted. HVAC load and PV flexibilities were very close to those 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.

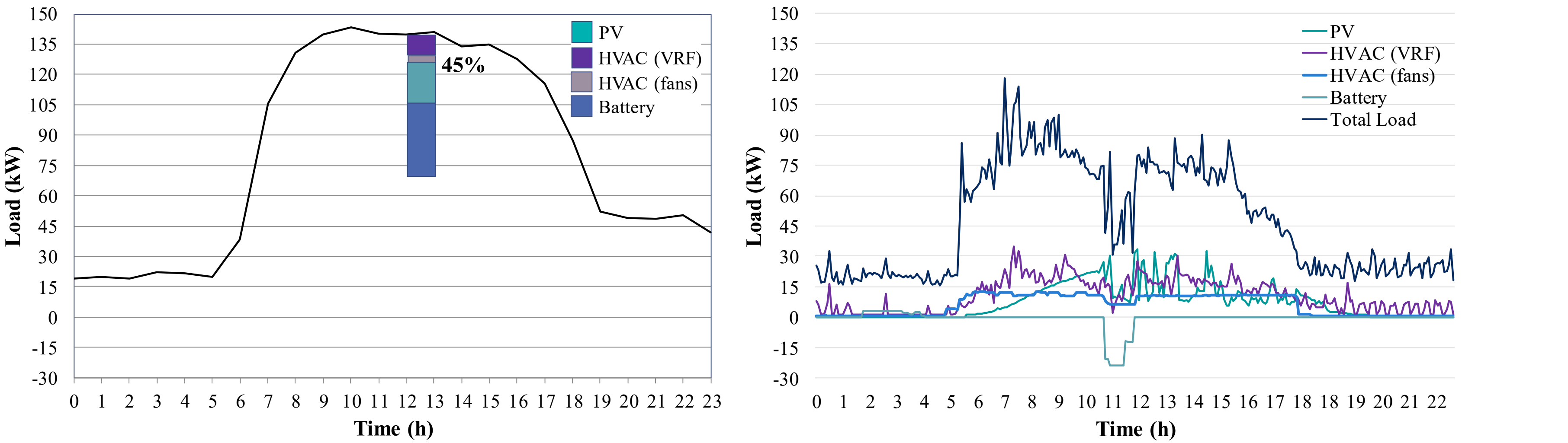


Figure 4.22 One-hour Flexibility Scenario Model (on left) and Experimental Results (on right)

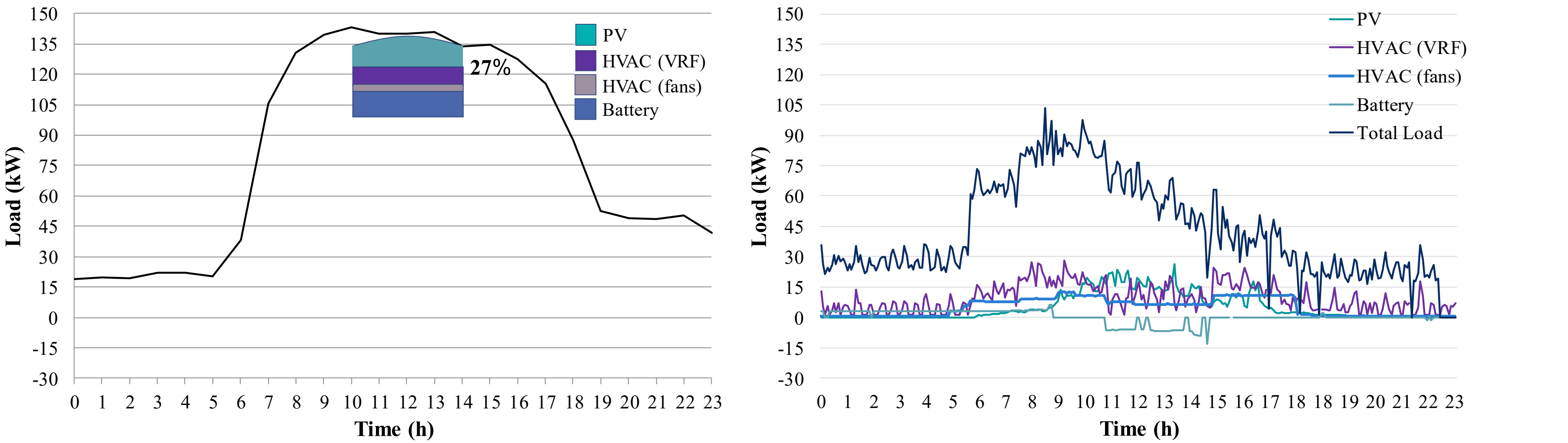


Figure 4.23 Four-hour Flexibility Scenario Model (on left) and Experimental Results (on right)

Experimental results for the four-hour scenario are shown in Figure 4.23. As seen in Table 4.5, 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 verification. Total flexibility achieved was 23%.

Table 4.5 Experimental Verification of Flexibility Scenarios

	F^L (HVAC) (%)	F^{RES} (PV) (%)	F^S (Battery) (%)	Total (%)
1 Hour Scenario				
Predicted	8%	11%	26%	45%
Verified	7%	11%	14%	32%
4 Hour Scenario				
Predicted	8%	11%	8%	27%
Verified	8%	11%	4%	23%

Notes: F^L, load flexibility; F^{RES}, renewable energy system flexibility; F^S, storage flexibility;

4.3.6.1 Discussion

The variation between predicted and actual flexibility was 1%, if the technical issues with the early prototype 2nd life battery system were excluded. This indicated that HVAC systems proved to be a more reliable source of flexibility than the non-mature battery storage technology. The HVAC sources used were AHU fans and a VRF heat pump system. The fans in particular provided an extremely stable load reduction. When the fan speed set point was reduced, the fan load stayed at a consistent level throughout the experiment. The VRF system was more volatile but achieved greater depth of flexibility and as its overall power consumption is higher, it had a greater impact on the load reduction achieved.

The VRF system reduction was achieved by reducing the global temperature set point of the VRF system by 2°C. The volatility in the load reduction is caused by compressors in the external condensers ramping up and down. To achieve a similar stability of load reduction as the AHU fan, it would be necessary to engage with system manufacturers to control the load at the compressor level and not through a temperature set point.

While predicted average PV output was achieved during the experiments, it must be noted that PV output is volatile and large variations occurred which may adversely impact demand response events. Day-to-day PV output also varies depending on weather conditions and on a different day, the average PV output may be lower or higher than predicted. Having a means of anticipating PV output both in a 24-hour timeframe and for localised effects such as cloud cover would be a means of mitigating this. Dynamic predictive models or utilising the battery system for PV power smoothing are two means of managing PV volatility.

4.3.6.2 KPI Label

Step 4 generated the KPI label for the case study building based on the experimental results, shown in Figure 4.24. 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.

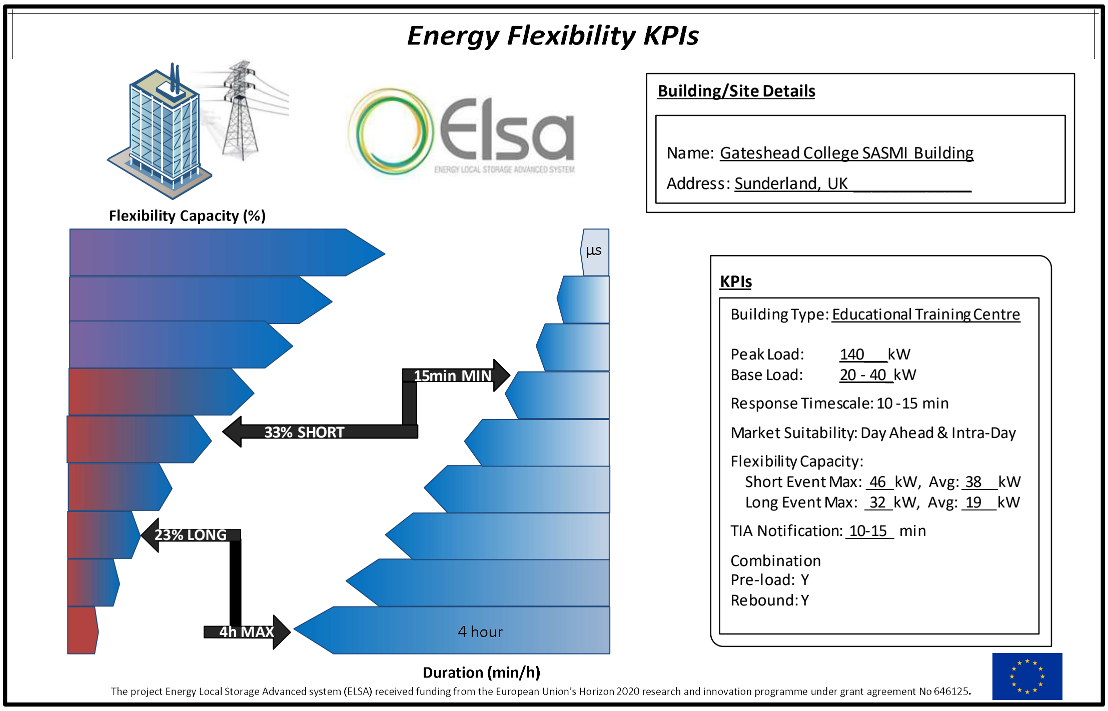


Figure 4.24 KPI Label, Experimental Results, Detailed Case Study

4.3.7 Benchmark Comparison

Demonstration studies selected as benchmarks were Benchmark 1 (Piette et al., 2006) (Xu and Zagreus, 2009) and Benchmark 2 (Siebert et al., 2015). Benchmark 1 was a study with a large number of real buildings, 28, participating in a utility led demand response programme (Piette et al., 2006) (Xu and Zagreus, 2009). Benchmark 2 was a demonstration project with similar sources of flexibility to the pilot sites, namely PV, battery storage and loads (Siebert et al., 2015). These studies demonstrated a maximum range for flexibility between 18 - 56% with average flexibilities between 7 – 9%. 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.

4.4 Pilot Sites

After the viability and accuracy of the methodology was demonstrated in the detailed case study, it was then implemented by others at four additional pilot sites. The four additional implementations demonstrated the scalability and ease of use of the methodology. As part of the implementation, experimental verification of use cases was conducted. Training, technical support and template materials were provided by the author to the partners implementing the methodology at their pilot sites. The four pilot sites were in different geographical regions and consisted of a range of building and district types.

- Building Cluster, Terni, IT;
- Commercial Building, Paris, FR;
- Commercial Building, Aachen, DE;
- Residential District, Kempten, DE.

The types of sites included commercial buildings, a residential district and a cluster of a DSO operation's buildings. 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 provide data acquisition from the sites. The ICT platform for the detailed case study building in Sunderland and the Paris pilot site were developed by the author under a previous project (Valdivia et al., 2014) but modified for demand response application. The ICT platforms for the other pilot sites were developed by other partners in the ELSA Horizon 2020 project (ELSA, 2018). Use cases were selected to demonstrate that based on the proposed assessment procedure, the potential of buildings in a wide range of demand response programmes could be quantified.

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 m^2 commercial office building located in the La Defence 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.

4.5 Use Cases

Demand response use cases selected for the verification experiments at the pilot sites spanned a range of services and included peak shaving, PV power smoothing, CO_2 minimisation and a market-based programme that requires the building to respond to a specific grid request.

Use cases define the specific type of demand response event for the experimental implementation. They may differ from the more generalised scenario models in that certain use cases have specific requirements. For example, CO_2 minimisation may be optimal if only loads are reduced and PV power smoothing requires a PV panel to be installed.

4.5.1 Peak Shaving

Peak shaving is a price-based programme. It is the most widely used demand response service globally with Ireland (Eirgird, 2018), the US (Piette, 2006a), France (RTE, 2014) and China (Li et al., 2017) 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.

4.5.2 Intra-day Grid Request

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) (Eirgrid, 2018) programme. This use case was implemented at the Commercial building in Sunderland.

4.5.3 CO_2 Minimisation

CO_2 based demand response signals have been proposed as an alternative to price based market signals (Stoll et al., 2014) (Péan et al., 2018) to incentivise electricity use or reduction in times of high or low renewable generation on the grid, respectively. For the CO_2 minimisation use case proposed, average CO_2 emissions per kWh are estimated at 416.58

g/kWh based on 2017 ENTSO-E generation mix for Germany (ENTSO-E, 2019). 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.

4.5.4 PV Power Smoothing

PV power smoothing is used to mitigate PV generation variability (Stroe, 2018). 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.

4.6 Experimental Setup

The four-step flexibility assessment methodology in Chapter 3 was implemented and verified through experimental demonstration of the above use cases at four additional pilot sites. The types of sites included commercial buildings, a residential district and a cluster of a DSO operation's buildings. 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 the standardised 4-step assessment method developed, the potential of buildings and sites in a wide range of demand response programmes could be quantified.

The use case experiments are a specific snapshot in time, for the particular set of systems available and the time of year in which they were conducted. They may not always align with the more generalised scenario models.

4.6.1 ICT Platform

An ICT platform was installed at each of the pilot sites and used to verify the flexibility as predicted by the assessment methodology. In an ideal future scenario, the methodology would be implemented and verified 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 as evidenced by the large numbers of research projects which require the development of dedicated ICT platforms (Monti et al., 2016) (O'Connell et al., 2019) (Valdivia et al., 2014) (Sterling, 2015) (Dinkelbach et al., 2018) (Foggia et al., 2014). Until ICT platforms for building flexibility reach plug-and-play capability at TRL 9, implementation as described in this work is required.

The ICT platforms control the loads and storage on site to provide flexibility services in response to simulated demand response signals. A number of different ICT platforms were developed for the pilot sites. The ICT system architecture for the Paris pilot site was very similar to the Sunderland pilot site. Other pilot sites developed their own ICT platforms.

4.6.2 Simulation of Grid or Aggregator Signals

OpenADR, or Open Automated Demand Response, is a communications protocol that allows ICT platforms to receive requests from a grid utility or aggregator. It was integrated into the ICT platform for the Sunderland, Paris, Aachen and Terni pilot sites to enable simulation of demand response signals from a grid operator or aggregator. OpenADR was developed by the OpenADR alliance, a not for profit organisation, based in the US, consisting of industry stakeholders. The alliance supports the development, adoption and compliance with the OpenADR standards (OpenADR, 2019).

The OpenADR protocol enables the exchange of demand response signals and information between grid operators, aggregators, and buildings or sites. In a typical installation, the main installation or server is installed at the aggregator or grid operator's ICT platform. Buildings and sites providing demand response services are then clients to this server installation. In OpenADR, servers are known as Virtual Top Nodes (VTNs) and clients are known as Virtual End Nodes (VENs).

During an OpenADR event, one or more signals may be transmitted. Each signal has a sequence of durations, the sum of which must equal the full duration of the active period. Each signal element also contains the signal type. An associated signal payload contains the value of the signal for each duration. Examples of signals include:

- ELECTRICITY_PRICE
- ENERGY_PRICE
- DEMAND_CHARGE
- BID_PRICE.

The Electrical Power Research Institute (EPRI) has developed open source implementations of both a VTN and a VEN which are freely available (EPRI, 2019). The software is a VTN and VEN reference implementation of OpenADR 2.0 Profile B. This was implemented in the Sunderland and Paris pilot sites.

An example of the implementation for the Sunderland experimental use case verification is given in Appendix A – OpenADR Implementation.

4.6.3 2nd Life EV Batteries

Each of the pilot sites has a stationary battery storage system consisting of 2nd life EV batteries and a battery management system installed. These are early prototype systems at TRL 5/6. The second life EV battery system installed at the Sunderland pilot site consisted of three Nissan Leaf batteries with a combined installed capacity of 48 kWh. The first life capacity of the batteries when they were installed in the vehicles was 24 kWh each. Thus, the total first life capacity was 3 x 24 kWh = 72 kWh. This represents a 33% decrease in Li-Ion battery capacity. For further information on the 2nd life EV battery system, see www.elsa-h2020.eu.

The battery management system was developed by Bouygues Energies et Services and Renault. Integration between the battery management system and the ICT platform was performed using a web services API. The API allows read/write access between the ICT platform and the battery management system. Read access permits data acquisition while write access enables control of set points in the battery system. However, this was not utilised in the Sunderland or Paris experimental work as all signals were transmitted via the ICT platform and API interface.

Figure 4.25 Nissan Leaf with EV Battery (shown in orange) (Chapman, 2018)

Figure 4.26 2nd Life EV Batteries Installed at Sunderland Pilot Site

Figure 4.27 Battery Management System Installed at Sunderland Pilot Site

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 verifications the available capacity varied. The Graphical User Interface (GUI) for the Kempten pilot site is shown in Figure 4.28. The installed system consists of six 2nd life EV batteries. During some experiments at the pilot sites, not all of the batteries in the system were available. The unavailable batteries are marked with a red x. This reduced the available capacity of the battery system to only the available batteries. In Figure 4.28, this was one battery with a capacity of 11 kWh when fully charged but is almost fully discharged in the GUI screenshot below.

Figure 4.28 Battery Management System Controller Showing Unavailable Batteries (x) (Lapedra et al., 2018)

4.7 Implementation & Experimental Results: Multiple Pilot Sites

Implementation of the 4-step flexibility assessment methodology was conducted at each of the other four pilot sites by others. Use case experiments were subsequently run at each pilot site.

The output of the flexibility methodology is a range of flexibility the building has the capability of offering. To verify 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. Predicted flexibility for the use cases at each of the pilot sites is shown in Table 4.6. Predicted flexibility is expressed as a percentage of building or site peak load.

Table 4.6. Use Case Predicted Flexibility for Pilot Sites

Pilot Site Location	**Type**	**Sources**	**Use Case**	**Predicted Use Case Flexibility (%)[1]**
Sunderland, UK	Building	F^{RES}, F^{S}, F^{L}	Intra-day Grid Request	36%
Terni, IT	Cluster of Buildings	F^{RES}, F^{S}	Peak Shaving	91%
Paris, FR	Building	F^{S}	Peak Shaving	9%
Aachen, DE	Building	F^{L}	CO_2 Minimisation	3%
Kempten, DE	Residential District	F^{RES}, F^{S},	PV Power Smoothing	103%

1. Use case flexibility is expressed as a percentage of typical peak load for each site, with the exception of CO_2 minimisation. 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.

The actual flexibility is the flexibility measured for a specific use case event and one realisation of that event (Lapedra et al., 2018). The ICT platforms were 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 graphs in the experimental verification at multiple pilot sites were taken from the ELSA public deliverable Lapedra et al. (2018), and the quality of the images is variable.

4.7.1 Terni Pilot Site

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, shown in Figure 4.29.

Figure 4.29 ASM Terni Pilot Site (Lapedra et al., 2018)

4.7.1.1 Step 1: System, Load, Storage and Generation Identification

A typical power profile for the Terni pilot site is shown in Figure 4.30. The power characteristics of the site are

- Peak Load: 120 kW in spring/autumn and 170 kW in winter/summer. Average peak load used in flexibility calculations was 150 kW.
- Base Load: 50-60 kW in springer/autumn and 80-90 kW in winter/summer.

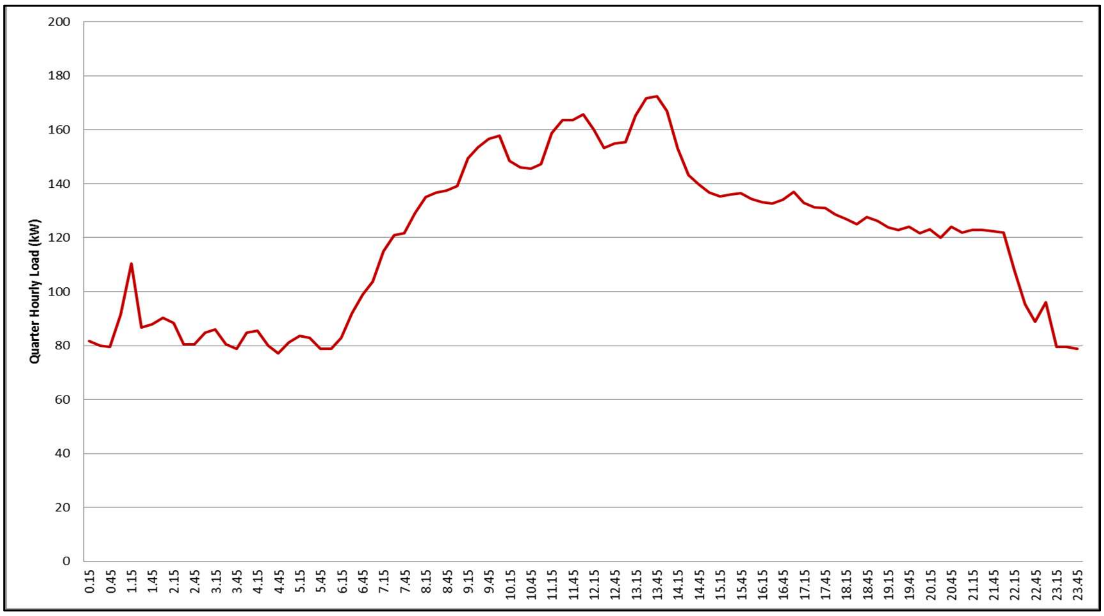


Figure 4.30 Typical Daily Power Profile, Terni Pilot Site (O'Connell et al., 2016)

The site contains two PV installations, a 2nd life battery system installation and other loads such as HVAC systems and EV charging stations.

4.7.1.2 Step 2: Flexibility Characterisation

The flexible systems identified at the Terni pilot site were:

- PV Flexibility provided by 180 kWp and 60 kWp PV arrays
- 2nd life battery storage with an installed capacity of 36 kWh.

The HVAC systems and EV charging stations were found to be not capable of offering flexibility.

The results of detailed flexibility characterisation for the flexible systems at the Terni pilot site are given in the flexibility technical specification tables below.

Table 4.7 Battery System Flexibility Technical Specification, Terni Pilot Site

	ELSA Battery System (Renault Kangoo)			DT3	DT4
	Type	***Description***	***Unit***	***Value***	***Value***
Specifications	No. of Batteries		-		6
	Capacity	Nominal	kWh		66
	Max Charge Rate	AC side of SPC (Smart Power Converter)	kW		72
	Max Discharge Rate	AC side of SPC	kW		72
	Min Charge Rate	AC side of SPC	kW		0
	Min Discharge Rate	AC side of SPC	kW		0
	Min Stage of Charge (SOC)				N/A
	Min time between charging & discharging	Cold start to discharging	s		2.5
		Cold start to charging	s		2.5
		Change to discharging (worst case)	s		0.5
		Discharge to Charging (worst case)	s		0.5
		Standby to Charging	s		0.5
		Standby to Discharging	s		0.5
	No. of cycles/day		-		2
Efficiency & Losses	Inverter Efficiency		%		Up to 96
	6 Battery System Energy Efficiency	Approximately : higher than 80%	%		
	Fixed Power Consumption	Approximately : less than 0.5	kW		
Communications	Web Services API		-		Confirmed
	OPC-UA				
	IEC 61850				
	Delay		s		
Control Parameters	Charge Power rate	If SPC of 96kW selected	kW		0 - 72
	Discharge Power rate	If SPC of 96kW selected	kW		0 - 72
Flexibility	Max		kW		72
	Min		kW		0
	4 Hour Min		kW		24

Table 4.8 180 kW PV Array Flexibility Technical Specification, Terni Pilot Site

	180 kWp PV array			
	Type	***Description***	***Value***	***Unit***
Specifications	Panel Area	Located at the employee parking area	2,009	m^2
	Capacity		180	kWp
Efficiency & Losses	Inverter Efficiency			%
	Fixed Power Consumption		3	kW
Communications	Electrical Meter		kW, kWh, V, I, F	-
	Delay	Meter delay		s
Flexibility	Summer Max	Peak power output	125	kW
	Winter Max	Peak power output	125	kW
	Summer Average	Peak power output	100	kW
	Winter Average	Peak power output	80	kW

Table 4.9 60 kW PV Array Flexibility Technical Specification, Terni Pilot Site

	60 kWp PV array			
	Type	***Description***	***Value***	***Unit***
Specifications	Panel Area	Located at the customer parking area	653	m^2
	Capacity		60	kWp
Efficiency & Losses	Inverter Efficiency			%
	Fixed Power Consumption		1.1	kW
Communications	Electrical Meter		kW, kWh, V, I, F	-
	Delay	Meter delay		s
Flexibility	Summer Max	Peak power output	50	kW
	Winter Max	Peak power output	50	kW
	Summer Average	Peak power output	40	kW
	Winter Average	Peak power output	27	kW

4.7.1.3 Step 3: Scenario Generation

Scenario modelling was conducted for the Terni pilot site. A one-hour scenario with PV and battery storage system is shown in Figure 4.31. Predicted power flexibility was 95% for the one-hour scenario.

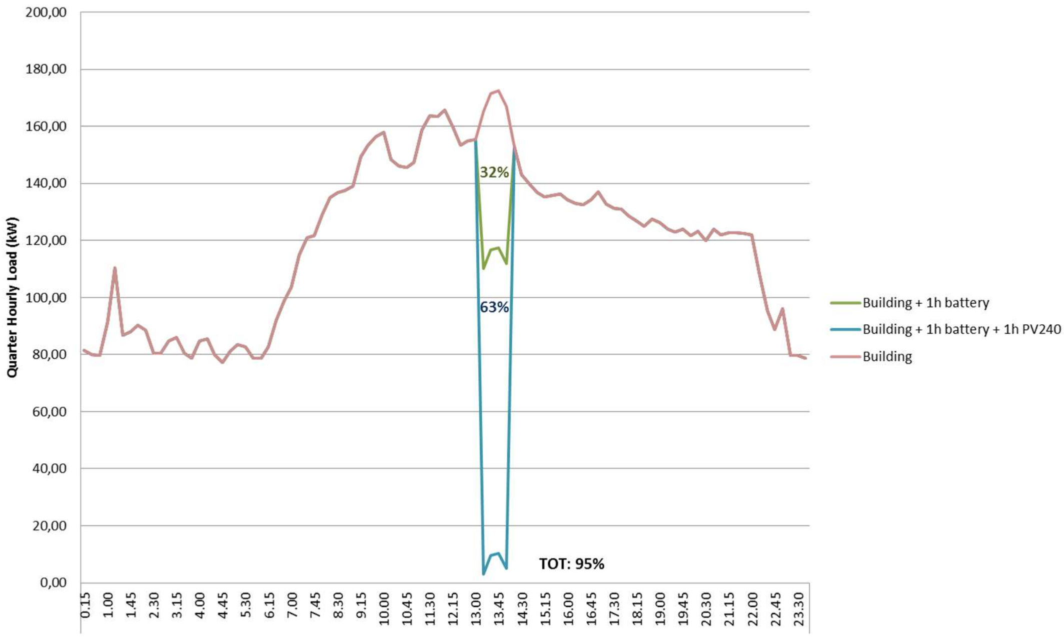


Figure 4.31 One-hour Scenario Generation, Terni Pilot Site (O'Connell et al., 2016)

4.7.1.4 Peak Shaving Use Case Verification

Experimental results from the peak shaving use case, implemented on 4th October 2018 at the Terni site are included in Figure 4.32 below. The actual site power profile is shown in green in the top graph. The battery system discharging is shown in blue on the lower graph. PV output is not metered separately therefore the power profile is showing a negative value of approximately -50 kW during the one-hour flexibility event between 17:40 and 18:40. The PV power output during the flexibility event was estimated at 100 kW.

During the event, only three of the installed six 2nd life batteries in the battery system were operational. This reduced the available capacity to 33 kWh and the maximum discharge capability to 36 kW.

The predicted flexibility for the peak shaving use case was 136 kW comprised of 36 kW battery system and 100 kW PV generation. Expressed as a percentage of the average peak load of 150 kW this is equivalent to 91 %.

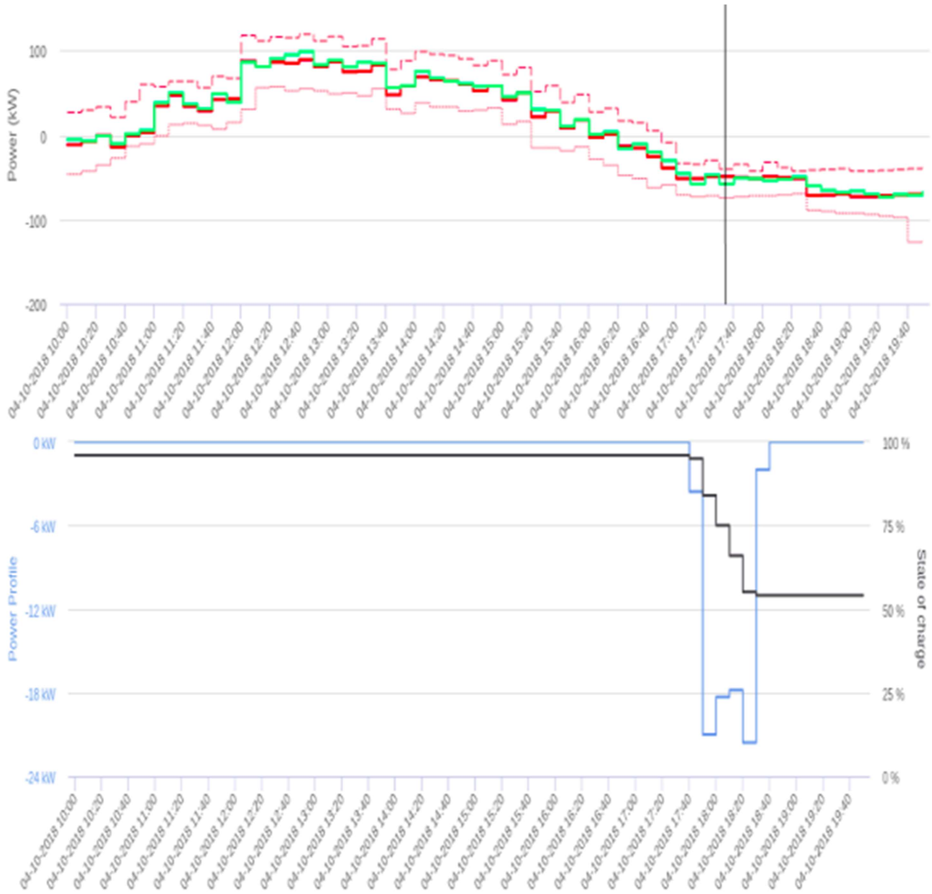


Figure 4.32 Experimental Use Case, Terni Pilot Site (Lapedra et al., 2018)

The actual battery discharge power during the event varied was an average of 21 kW, lower than the predicted 36 kW. This resulted in a total flexibility of 121 kW comprised of 100 kW PV combined with 21 kW battery system. Expressed as a percentage of the average peak load of 150 kW this was 81%.

Comparing this with the predicted value of 91% for the peak shaving using case the prediction error is 10 %. Comparing the experimental result with the scenario generation value of 95% for a one-hour event, the difference is 14%.

Experimental verification of a long event was not conducted. Therefore, the site flexibility capability for a longer event was extrapolated from the one-hour peak shaving use case results. During the one-hour event, the battery system discharged at an average of 21 kW and reached a 50 % state of charge. Over a four-hour event, this would result in the battery system providing 10 kW of power on continuous discharge. Combining this with a PV output of 100 kW gives a total flexibility of 110 kW. Expressing this as a percentage of 150 kW peak load gives 73% flexibility for a four-hour event.

4.7.1.5 Step 4: KPI Label

The flexibility capability of the Terni pilot site is represented on the KPI label in Figure 4.33.

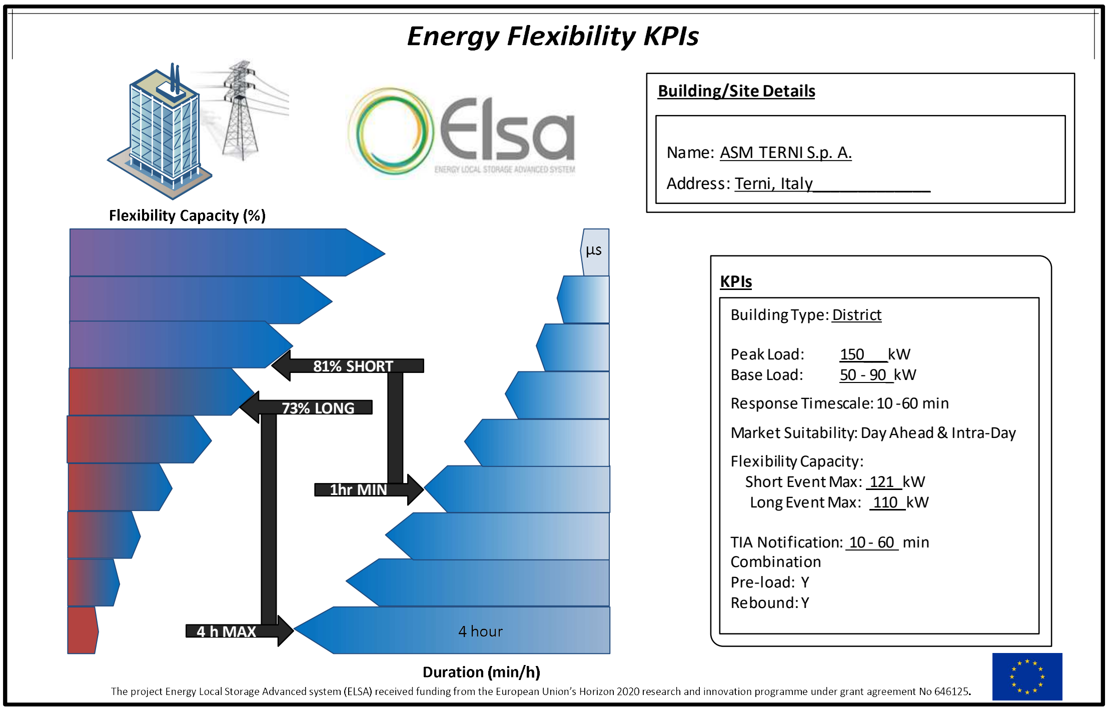


Figure 4.33 KPI Label, Terni Pilot Site

4.7.2 Paris Pilot Site

Commercial Building, Paris, FR: The Ampère building is a 14,000 m^2 commercial office building located in the La Defence business district of Paris. Initially constructed in 1985, it underwent a deep retrofit between 2014 and 2017 and is now certified as a sustainable building with HQE and BREEAM certification. The building is shown in Figure 4.34.

Figure 4.34 Ampere Building, Paris Pilot Site (Lapedra et al., 2018)

4.7.2.1 Step 1: System, Load, Storage and Generation Identification

The Ampere building was undergoing a deep retrofit renovation when the on-site flexibility assessment was performed in 2016. Measured energy and power consumption was not available for the building. As an alternative, electrical load estimates by the design team were used to assess the anticipated energy and power usage of the site.

The electrical load profile in Figure 4.35 is an estimated daily average hourly load profile. The estimate is based on design data, the expected operating schedule for the building and assumptions regarding the operation of the systems in the building. From the load profile, the power characteristics of the site were approximated as:

Estimated Peak Load: 525 kW

Estimated Base Load: 117 kW

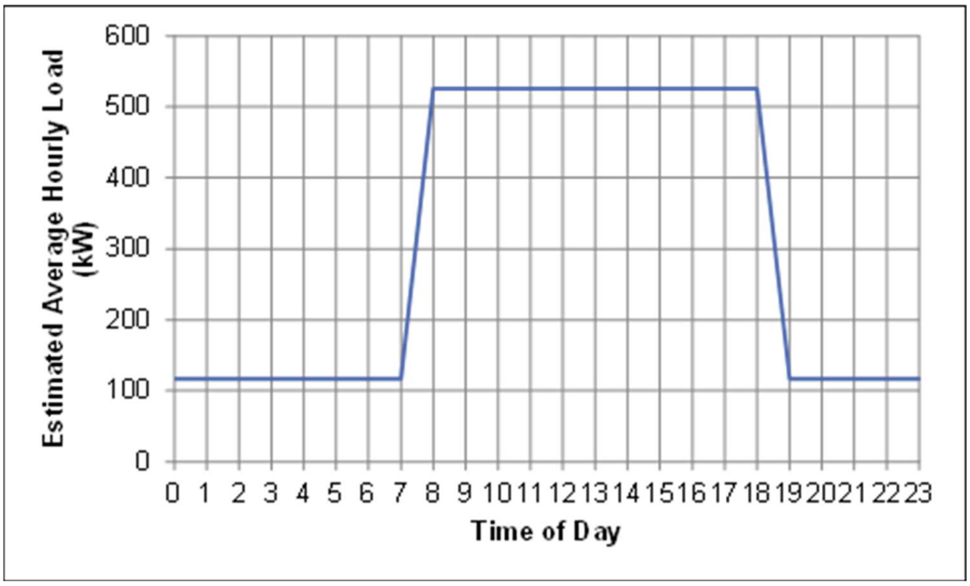


Figure 4.35 Estimated Daily Power Profile, Paris Pilot Site (O'Connell et al., 2016)

The load, storage and generation systems identified from the design drawings and documentation included internal and external lighting, plug loads, AHUs chillers, pumps, exhaust fans, electric DHW water heaters, PV and ICT loads.

4.7.2.2 Step 2: Flexibility Characterisation

Of the systems identified in Step 1, only the battery system was found to meet the sheddable, controllable, acceptable criteria for flexibility. Therefore, the flexible system identified at the Paris pilot site were:

- 2nd life battery storage with an installed capacity of 22 kWh.

Table 4.10 Battery System Flexibility Technical Specification, Paris Pilot Site

	Battery System [Renault Kangoo]			DT3
	Type	***Description***	***Unit***	***Value***
Specifications	No. of Batteries		-	2
	Capacity		kWh	11 x 2 = 22
	Max Charge Rate	At DC side of charger	kW	3 x 2 = 6
	Max Discharge Rate	At AC side of Inverter	kW	12 x 2 = 24
	Min Charge Rate	At AC side of charger	kW	0.85
	Min Discharge Rate	At AC side of Inverter	kW	1.2
	Min Stage of Charge (SOC)	N/A		
	Min time between charging & discharging	Cold start to discharging	s	60
		Cold start to charging	s	20
		Charging to Discharging	s	25
		Discharging to Charging	s	20
		Standby to Charging	s	20
		Standby to Discharging	s	25
	No. of cycles/day	Full charge/discharge cycles	-	2
Efficiency & Losses	Inverter Efficiency	Lower limit for Efficiency TBD	%	Up to 96
	Battery System Energy Efficiency	Approximate value 75% for a system of 3 batteries; shall be lower for a system of 2 batteries	%	75
	Fixed Power Consumption	Industrial PC, ventilation etc. Estimated value. Actual TBD	kW	0.3
Communications	Web Services API	Between UTRCI EBEMS and BYES ESMS	-	
	OPC-UA			
	IEC 61850			
	Delay		s	TBD
Control Parameters	Charge Power rate	Confirmed	kW	0.85 – 6.0
	Discharge Power rate	Confirmed	kW	1.2 - 24
Flexibility	Max	0.92 hour	kW	24
	Min	18.33 hour	kW	1.2
	4 Hour Min		kW	5.5

The maximum flexibility the battery system at the Paris site can offer is 24 kW. Therefore, if the battery was fully charged to 22 kWh and discharged at the maximum rate, it has the capability to provide 24 kW over 55 minutes.

The minimum flexibility the battery system can offer is 1.2 kW. If the battery was fully charged to 22 kWh and discharged at the minimum rate, it has the capability to provide 1.2 kW over 18.33 hours duration.

Longer flexibility events may last three to four hours. If a four-hour request was sent to the battery system, and it was fully charged to 22 kWh, it would have the capability to provide 5.5 kW of flexibility over four-hours duration.

4.7.2.3 Step 3: Scenario Generation

Scenario modelling was conducted for the Paris pilot site. A one-hour scenario with the battery storage system is shown in Figure 4.36. This uses the estimated load profile which may differ from a typical actual load profile. The precited load reduction was 5% based on a power discharge from the battery system of 22 kW over a one-hour period.

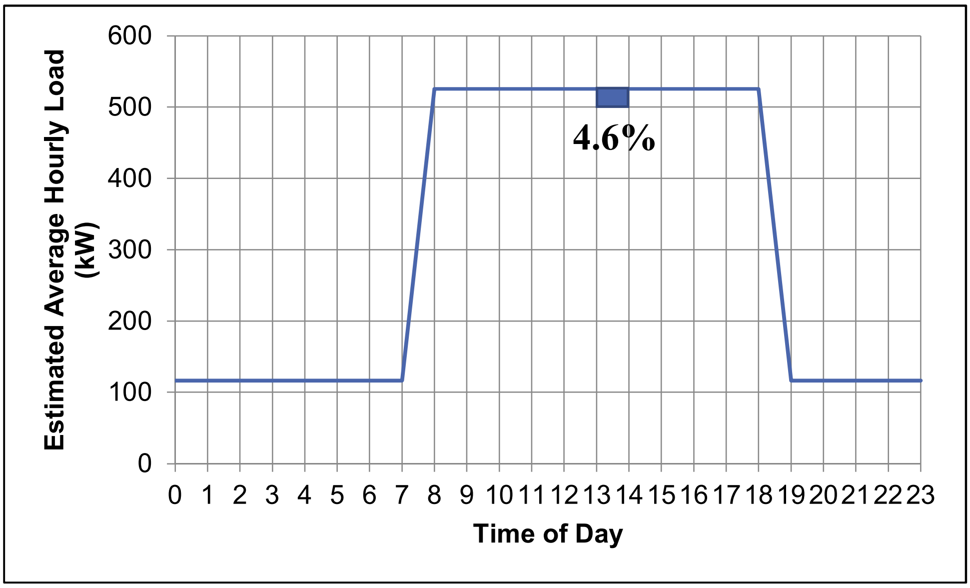


Figure 4.36 One-hour Scenario Generation, Paris Pilot Site (O'Connell et al., 2016)

4.7.2.4 Peak Shaving Use Case Verification

Peak shaving was the use case demonstrated at the Paris pilot site. The deep retrofit of the building was completed in 2017 and actual power load data became available in 2018. The actual peak load for the building was 250 kW. This was significantly lower than the peak load estimated from design data which was 525 kW. The predicted load reduction for the use case was calculated based on the actual peak load of 250 kW. Thus, the target reduction for peak shaving was 9% of peak load.

Experimental results from the peak shaving use case, implemented on 22nd June 2018 at the Paris pilot site are included in Figure 4.37 below. The actual power profile for the building is shown in red in the top graph. The vertical red dashed line indicates the maximum power demand peaks for the building. Battery system discharging is shown in blue on the lower graph.

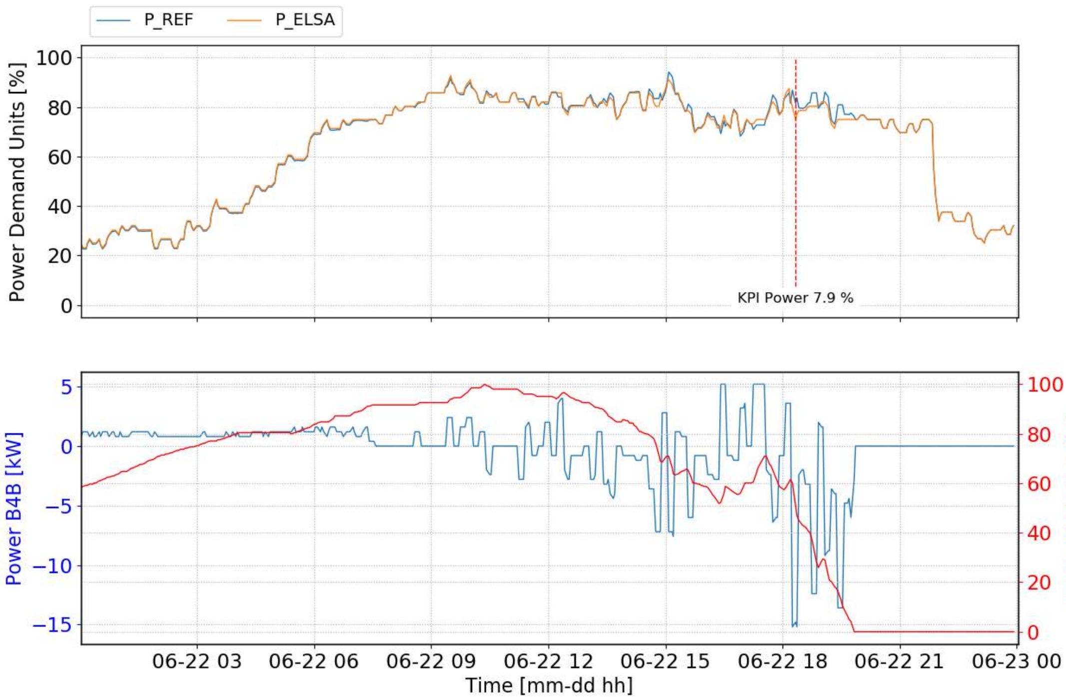


Figure 4.37 Peak Shaving Use Case Results, Paris Pilot Site (Lapedra et al., 2018)

The actual maximum peak load power reduction achieved was 8%, as a result of the battery system discharging at 15 kW. This was 1% lower than the predicted flexibility of 9%.

The difference between the predicted and actual flexibility was due to the battery system not discharging at maximum capacity. As highlighted previously, the 2nd life battery system is a TRL5/6 prototype and requires further development to mature the battery management system technology to TRL 9. In addition, for the Paris Pilot site, the control signal to the battery management system was generated by a UTRC algorithm, an experimental implementation which continuously changed the set point. This may have also contributed to the result being lower than expected.

In the experiment shown in Figure 4.37, the battery system state of charge is approximately 90% at 12:00 noon and 0% at 20:00 in the evening. Thus the battery discharged over a duration of 8 hours. Peak capacity of the battery system was 22 kWh, of which 90% was 19.8 kWh. For the 8 hour discharge average power reduction was 2 kW.

Compared with the scenario generation prediction of 5%, the achieved load reduction of 8% was higher. This was due to the measured peak load of the building being lower than that estimated from design data. When the flexibility assessment was performed in 2016, the building was in the process of being renovated and measured load data was not available. Peak load was estimated at 525 kW based on electrical specifications from the design team. The actual measured peak load of the building in June 2018 was 250 kW. Occupancy levels in the building in 2018 were approximately 50%. As occupancy levels increase, the peak load may also increase.

4.7.2.5 Step 4: KPI Label

The flexibility capability of the pilot site is represented on the KPI label in Figure 4.38.

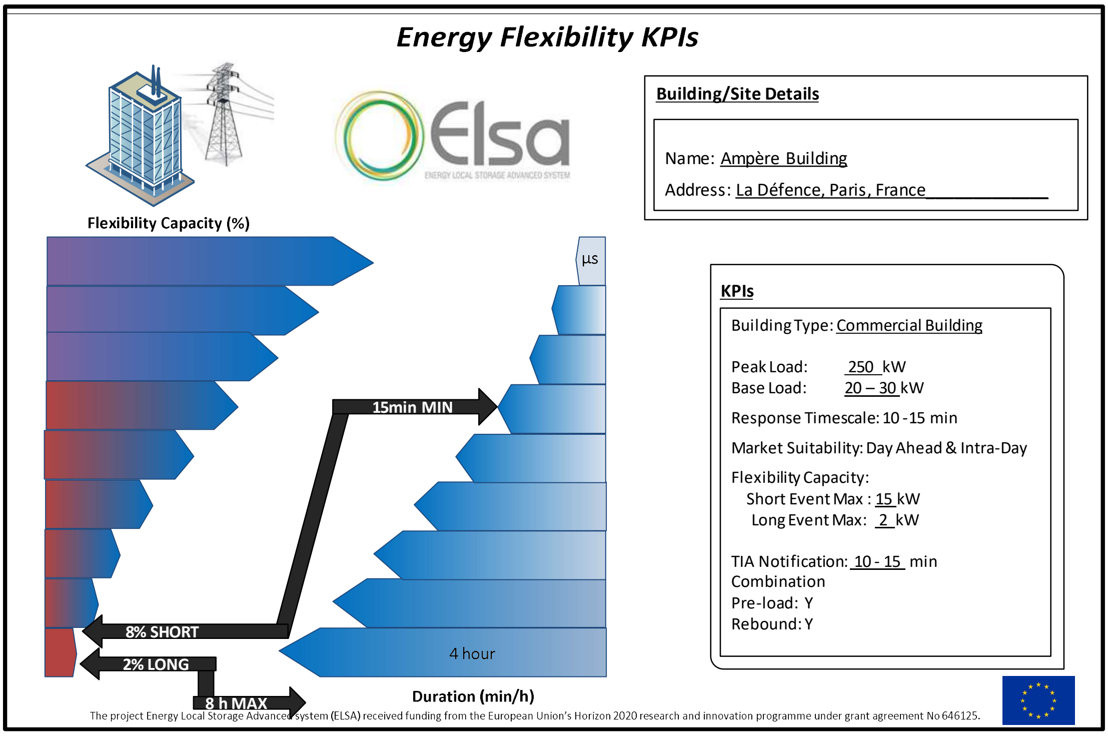


Figure 4.38 KPI Label, Paris Pilot Site

4.7.3 Aachen Pilot Site

The building used for the Aachen pilot site was the E.ON ERC building located on the RWTH university campus. It is a 650 m^2 building consisting of office and laboratory space.

Figure 4.39 Aachen Pilot Site (RWTH, 2019)

4.7.3.1 Step 1: System, Load, Storage and Generation Identification

Typical daily load profile is shown in Figure 4.40. The power characteristics of the site are:

- Peak load 220 kW
- Base load 62 kW.

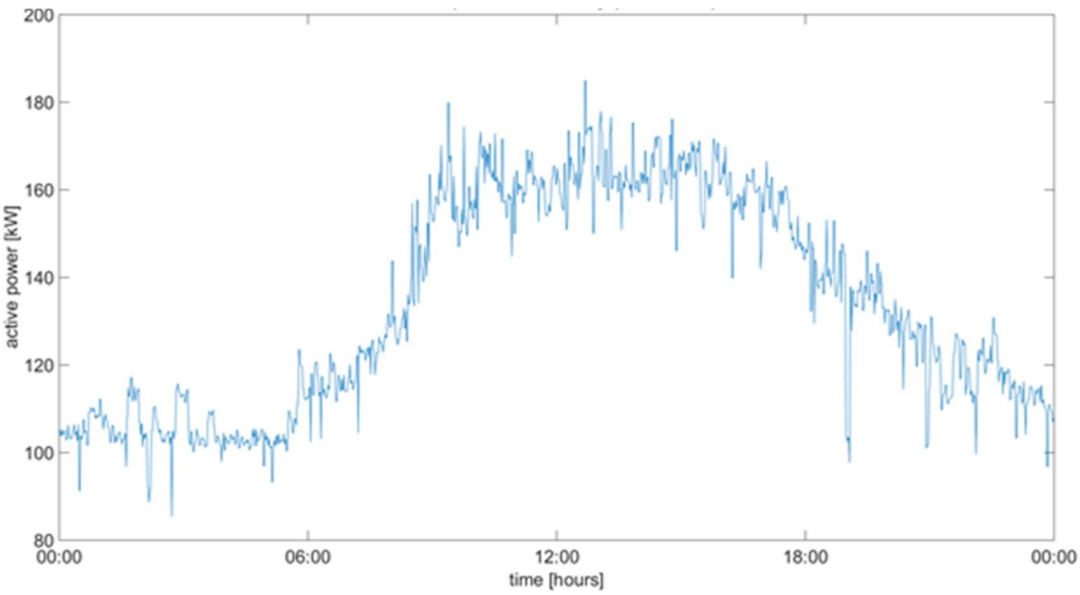


Figure 4.40 Typical Daily Power Profile, Aachen Pilot Site (O’Connell et al., 2016)

4.7.3.2 Step 2: Flexibility Characterisation

Flexible systems identified for the building in Aachen were:

- AHU Fans;
- Heating Rod;
- 2nd Life Battery System.

A number of other systems were assessed for flexibility but found, ultimately, to be not flexible. This was due to a lack of controllability and acceptability. These included PV, CHP unit, Heat pump, Sorption supported air conditioning, Chiller, Glycol Cooler, Condensing Boiler, Heating buffer storage and Cooling buffer storage. A 500 kW virtual wind turbine was also included in the initial assessment.

Table 4.11 AHU Fans Flexibility Technical Specification, Aachen Pilot Site

	Fans			
	Type	***Description***	***Value***	***Unit***
Specifications	Electrical Consumption		0 – 23	kW
Communications	BACnet	Communication via the AHU interface		
Control Parameters	Fan speed	The fan speed can be changed through the BEMS		
	Load can be varied continuously within the operating range.			
Flexibility	Max	Flexible power: the increase or decrease of the power from the baseline during the action	23	kW
	Min	Flexible power: the increase or decrease of the power from the baseline during the action	0	kW
		Flexibility	37.1	%
	Rebound effect			
	Upward flexibility			
	Downward flexibility			

Table 4.12 Heating Rod Flexibility Technical Specification, Aachen Pilot Site

	Heating Rod			
	Type	***Description***	***Value***	***Unit***
Specifications	Electrical Heating Rod	Capacity of 0 to 9 kW in 3 kW steps	3 -9	kW
Communications	BACnet	Communication via the BEMS of main building		

4.7.3.3 Step 3: Scenario Generation

Scenario models were not generated for the Aachen building using step 3 in the methodology. Some relative frequency percentage graphs were produced which incorporated all of the theoretical systems, the majority of which were ultimately not flexible. Thus, the flexibility available at the site for the available flexible systems was not represented in scenario generation.

4.7.3.4 CO_2 Minimisation Use Case Verification

For the CO_2 minimisation use case, average CO_2 emissions per kWh were estimated based on the 2017 generation mix for Germany (ENTSO-E, 2019). This consisted of:

- Average CO_2 emissions per kWh: 416.58 g/kWh
- Maximum CO_2 emissions for one hour: 11.261 g/kWh

The battery system charge and discharge cycles were assessed to determine if the total round-trip CO_2 emissions avoided by use of the battery were greater than the converter losses incurred in charging and discharging. It was found that use of the battery system increased the overall CO_2 emissions and therefore, it was not selected as a suitable system for the CO_2 minimisation use case.

Load shedding was deemed the optimal means of avoiding CO_2 emissions. The AHU fans and heating rod were selected as the most suitable loads to shed. This resulted in a CO_2 emissions reduction target of 3% when rounded to the nearest percentage.

A number of use case experiments were conducted for 30-minute time periods in June 2018. The CO_2 minimisation input signal is shown in Figure 4.41.

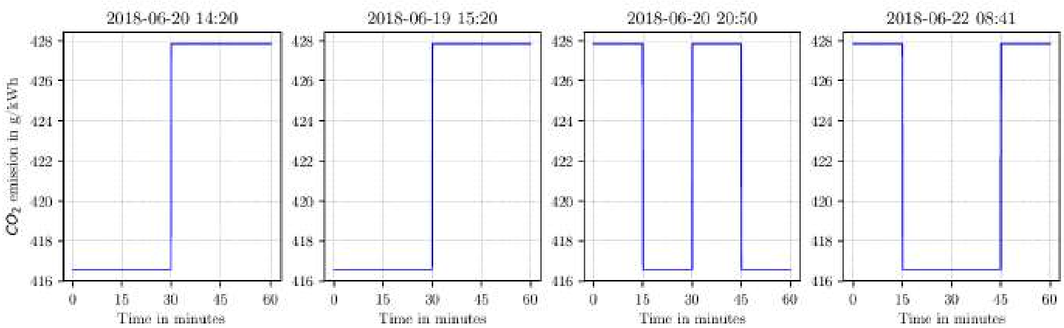


Figure 4.41 CO_2 minimisation use case input signal (Lapedra et al., 2018)

The average percentage of CO_2 emissions reduction was 3%, rounded to the nearest percentage. Comparing this with the predicted value of 3% for the peak shaving using case the prediction error is 0%. However, as the predicted value is so small, errors at the sub 1% order of magnitude are not reflected.

4.7.3.5 Step 4: KPI Label

The flexibility capability of the pilot site is represented on the KPI label in Figure 4.42.

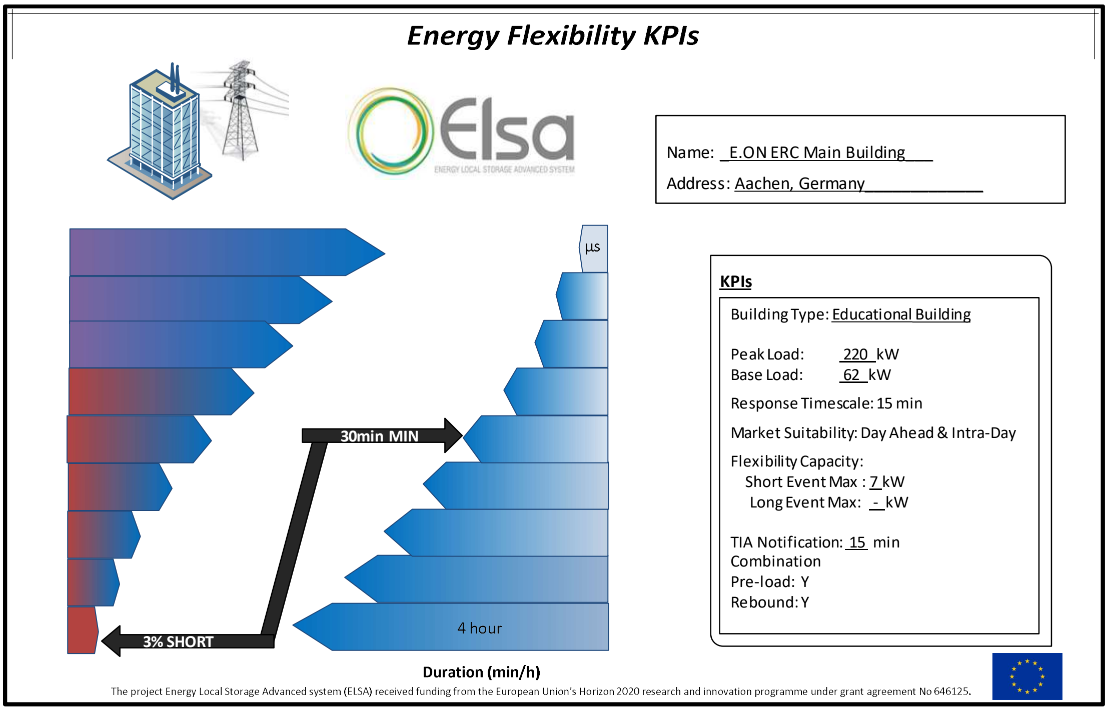


Figure 4.42 KPI Label, Aachen Pilot Site

4.7.4 Kempten Pilot Site

Residential District, Kempten, DE: The test site of Kempten consists of six apartment buildings with a total of 81 apartments located in the residential area of Auf dem Bühl. PV arrays were installed on three of the apartment buildings in the district with a combined installed capacity of 37 kWp. The residential district hosts a 2nd life battery storage system in the transformer station consisting of 66 kWh installed capacity.

Figure 4.43 Kempten Pilot Site (with transformer station hosting the battery storage system in the foreground and apartment buildings in the background) (Lapedra et al., 2018)

4.7.4.1 Step 1: System, Load, Storage and Generation Identification

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.

Space heating and hot water are not provided from electrical sources hence the electrical load is low compared with the pilot sites which are commercial buildings.

The peak load and base load of the Kempten pilot site are:

- Peak load of standard load profile: 33 kW
- Base load of standard load profile: 10 kW

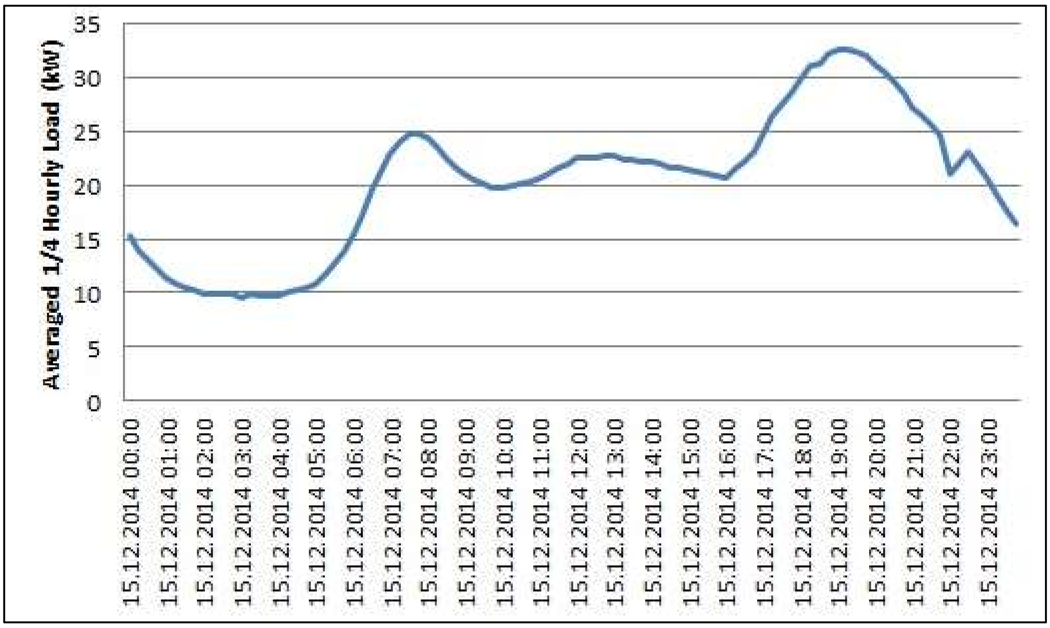


Figure 4.44 Typical Daily Power Profile, Kempten Pilot Site (O'Connell et al., 2016)

4.7.4.2 Step 2: Flexibility Characterisation

Step 2: Flexibility Characterisation was then implemented using the process in Chapter 3. It was applied to the loads, storage and generation sources identified.

No control system was installed to control loads in the apartment buildings; therefore loads, were not controllable. As no agreement was in place with the occupants or owners of the apartments it was not acceptable to control loads in the buildings. Consequently, there are no flexible loads in the Kempten pilot site.

Flexibility is provided by PV installation and the 2nd life battery storage system.

Flexible Sources:

- PV 37.1 kWp installation
- 2nd life storage system with an estimated capacity of 66 kWh

Table 4.13 PV System Flexibility Technical Specification, Kempten Pilot Site

	PV System			
	Type	***Description***	***Value***	***Unit***
Specifications	Panel Area		230,5	m^2
	Capacity		37.1	kWp
Efficiency & Losses	Inverter Efficiency		97,7	%
	Fixed Power Consumption	(if any)	0	kW
Communications	Electrical Meter	EasyMeter Q1D + egrid measurement box	kWh, kW, A, V, Hz	-
	Delay	Meter delay	15	min

Table 4.14 Battery System Flexibility Technical Specification, Kempten Pilot Site

	Battery System [Renault Kangoo]			
	Type	***Description***	***Value***	***Unit***
Specifications	No. of Batteries		6	-
	Capacity		11 x 6 = 66	kWh
	Max Charge Rate	At DC side of charger	3 x 6 = 18	kW
	Max Discharge Rate	At AC side of Inverter	12 x 6 = 72	kW
	Min Charge Rate	At AC side of charger	0.85	kW
	Min Discharge Rate	At AC side of Inverter	1.2	kW
	Min Stage of Charge (SOC)	N/A		
	Min time between charging & discharging	Cold start to discharging	60	s
		Cold start to charging	20	s
		Change to discharging (worst case)	25	s
		Discharge to Charging (worst case)	20	s
		Standby to Charging	20	s
		Standby to Discharging	25	s
	No. of cycles/day	Full charge/discharge cycles	2	-
Efficiency & Losses	Inverter Efficiency	Lower limit for Efficiency	Up to 96	%
	Battery System Energy Efficiency	Approximate value for a system of 6 batteries	80	%
	Fixed Power Consumption	Industrial PC, ventilation etc. Estimated value.	0.5	kW
Communications	Web Services API	BYES ESMS and Storage system controller		-
	Delay		TBD	s
Control Parameters	Charge Power rate	Confirmed	0.85 – 6.0	kW
	Discharge Power rate	Confirmed	1.2 - 24	kW
Flexibility	Max	0.92 hour	72	kW
	Min	60 hour	1.2	kW
	4 Hour Min		18	kW

4.7.4.3 Step 3: Scenario Generation

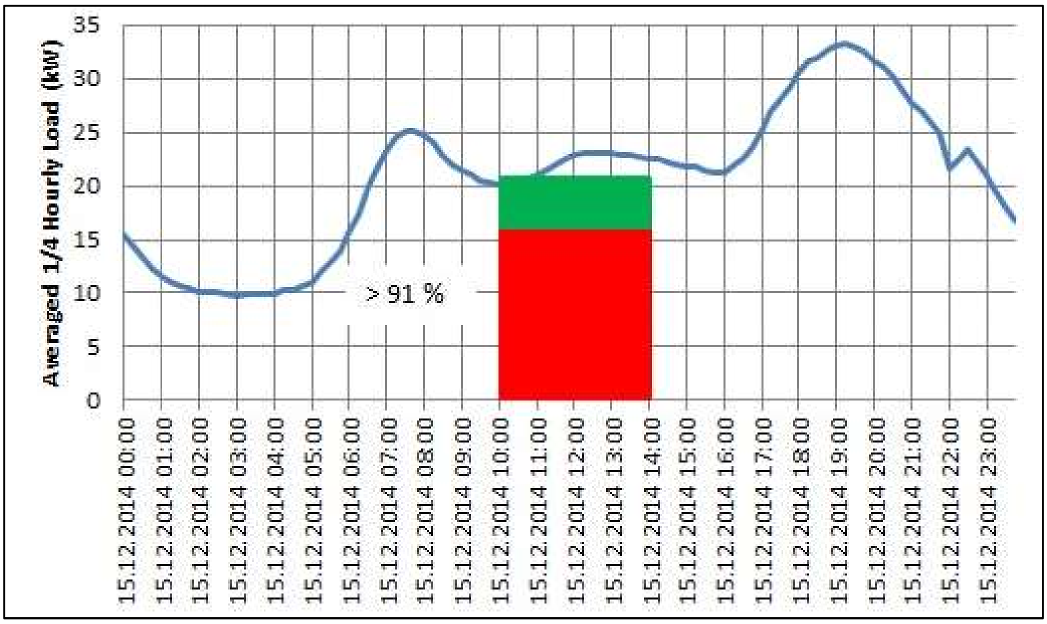


Figure 4.45 Scenario Generation, Kempten Pilot Site (O'Connell et al., 2016)

4.7.4.4 PV Power Smoothing Use Case Verification

Results from the PV power smoothing use case experiment on the 10th October 2018 is shown in Figure 4.46. It is a four-hour event from 18:00 to 22:00. Average meter readings are -8 kW. Battery system average discharge is 3.1 kW.

The battery system installed capacity at Kempten was 66 kWh which consisted of six second life batteries. However, only three of the 2nd life battery modules were available during the experiment, as was outlined in Section 4.6.3 and shown in Figure 4.28 Battery Management System Controller Showing Unavailable Batteries (**x**) (Lapedra et al., 2018). For the use case verification, actual battery capacity is used for the prediction calculation, as per the other pilot sites. With 33 kWh available capacity

The predicted load for this use case was -7 kW. Expressing this as a percentage of 33 kW typical peak load, the value is 103%. The actual load during the use case experiment was -8 kW. This gives 106 % when expressed as a percentage of peak load.

Comparing the use case experimental results with the scenario model, 106% is in excess of the predicted flexibility of >91% for a four-hour scenario.

Figure 4.46 Experimental Use Case, Kempten Pilot Site (Lapedra et al., 2018)

4.7.4.5 Step 4: KPI Label

The flexibility capability of the Kempten pilot site is represented on the KPI label in Figure 4.47.

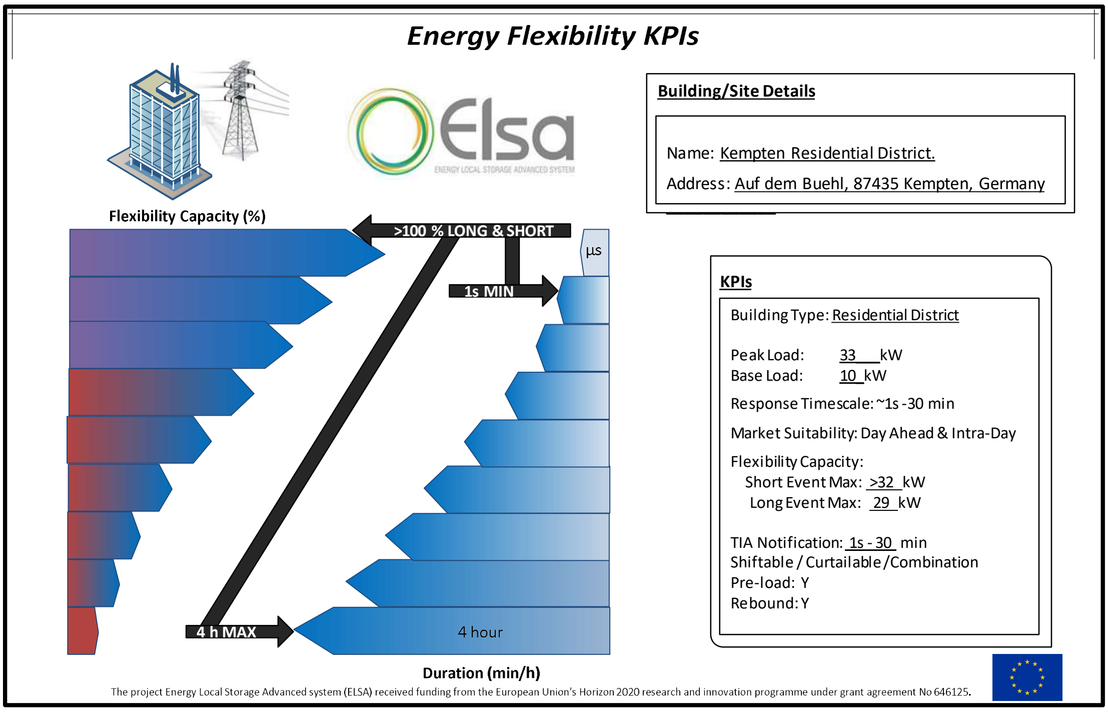


Figure 4.47 KPI Label, Kempten Pilot Site

4.8 Analysis of the Results

Actual results were compared with the predicted flexibility for each use case and both are shown for each pilot site in Table 4.15. 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 for each use case with the exception of the CO_2 minimisation use case. For CO_2 minimisation, use case flexibility is expressed as a percentage of total CO_2 produced by the electricity generation required to meet the electrical load consumption in the building.

4.8.1 Analysis

In Table 4.15, 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.

Table 4.15. Experimental Results for Pilot Sites

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	91%	81%	10%
Paris, FR	Building	F^{S}	Peak Shaving	9%	8%	11%
Aachen, DE	Building	F^{L}	CO_2 Minimisation[2]	3%	3%	-
Kempten, DE	Residential District	F^{RES}, F^{S},	PV Power Smoothing	103%	106%	3%

1. Use case flexibility is expressed as a percentage of typical peak load for each site, with the exception of CO_2 minimisation. 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.
2. CO_2 minimisation is expressed as a percentage of total CO_2 produced by the electrical consumption in the building.

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.

4.8.1.1 Quality of Flexibility

When considering the quality of the flexibility provided by the different sources, maintaining a stable and consistent load reduction during the use case implementation was best demonstrated by the AHU fans and the battery systems.

Other sources of flexibility, such as VRF heat pump systems, may have provided a deeper range of flexibility and a higher average load reduction but exhibited more volatility during the events. In order to achieve a load reduction of similar stability and consistency with a VRF system, direct compressor control may be required instead of temperature set point reduction or increase. Electrification of heating is predicated on increased installation of heat pumps as electric residential space heating is predicted to rise to 30% of total energy use by 2050 (Orths et al., 2019). Thus, the quality of the flexibility heat pumps can provide becomes more critical.

4.8.1.2 Maturing 2^{nd} Life Battery System

Lack of availability of all the battery modules due to issues with the battery management system was an issue in many of the pilot sites. Maturing the 2^{nd} life EV battery technology from TRL 5/6 to TRL 9 will remove the issues with the early stage prototype and provide a more reliable source of flexibility.

4.8.1.3 PV

While predicted average PV output was achieved during the experiments, it must be noted that PV output is volatile and large variations occurred which may adversely impact demand response events. PV output varies not only day-to-day but at the minute and even second scale. On a different day, the average PV output may not be achieved. Accurate forecasting of PV output at the building level will be required in future for PV to provide a reliable source of on-site flexibility.

PV power smoothing is one means of managing PV volatility. However, if the battery system is engaged in PV power smoothing then it may not be available for other flexibility events. For example, if PV power smoothing is continuously required when the PV panel is generating output then the battery system would only be available for other types of flexibility during the hours of darkness.

4.8.1.4 Use Cases

The different types of use cases influenced the sources selected and the range of flexibility delivered during the experiments. For example, at the Aachen pilot site, the CO_2 minimisation use case discounted the use of the battery system as the charging and discharging losses increased the overall CO_2 emissions for the event.

PV power smoothing has a different objective compared with peak shaving or a market based intra-day request in that it does not seek to maximise the flexibility provided but to smooth the load or generation profile at the point of common coupling, i.e. the utility meter. This removes the volatility produced by the PV and prevents it from entering the distribution grid. Even when on-site renewable generation is fully consumed locally, if it produces a highly variable output, the effect of this is transmitted to the grid due to the varying grid power import required. The measure of success for PV power smoothing perhaps should be how smooth the building load profile is rather than how much flexibility was provided as a percentage of peak load. The Kempten pilot site, at which the use case was implemented, may have greater potential flexibility than was demonstrated during the experiment.

4.8.1.5 Influential Factors

From the results it can be seen that the three factors which most influenced the flexibility of buildings or sites were:

i) number of available flexible systems
ii) size of installed renewable generation
iii) installed storage capacity.

4.8.2 Error Analysis

The error between prediction and accuracy for each pilot site is given on the right-hand side of Table 4.15. This shows 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 (Wang et al., 2018) that prediction accuracy improved when the number of sources, in their case dwellings, was increased, which correlates with the experimental results.

In the literature review in Section 2.5, it was found that prediction accuracy of +/- 10% is considered optimal (Borelli et al., 2018) (MacDougall et al., 2017) for grid applications but for heat pump prediction errors of up to 36% (Neupane, 2017) 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.

4.8.3 Scalability

The scalability of the assessment method was demonstrated by its implementation at five pilot sites. The types of sites ranged from commercial buildings to a cluster of buildings to residential districts and so cover a variety 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 implementation and verification of the methodology at five pilot sites demonstrates this, enabling roll out of demand response services to a wider spectrum of society.

4.8.4 Ease of Implementation

Flexibility 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 questionnaire was developed by the author and sent to the evaluators of the other four pilot sites. A number of questions were based on the Likert scale, providing a quantitative assessment of the ease of implementation (Cervera et al., 2015) of the methodology. The questionnaire is provided in Appendix C. This 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 (Santori et al., 2019). The evaluators found the level of training and support sufficient and would recommend the methodology to others (Santori et al., 2019).

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 (O'Connell, 2010a) (O'Connell, 2010b) (O'Connell, 2009), conducting energy audits for the pilot sites in this work would take approximately 3 to 4 weeks. 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, verification of the flexibility ranges predicted by the methodology did.

4.9 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 (Piette et al., 2006a). Benchmark 2 consisted of a demonstration project with similar sources of flexibility to the pilot sites, namely PV, battery storage and loads (Siebert et al., 2015). 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 4.16, 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 was due to the installed capacity of the PV and storage systems being 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.

Table 4.16. Benchmarking Comparison

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	<average	> max
Benchmark 2	~18	-	> max	> max	< max	< max	> max

4.10 Conclusions

Implementation and experimental verification of the early stage, four step flexibility assessment methodology was conducted at five pilot sites. A detailed implementation was illustrated using the Sunderland pilot site and summary results were included for the Paris, Terni, Aachen and Kempten pilot sites. Experimental implementation was performed 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.

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. Influential factors were multiple sources of flexibility and large storage or renewable generation systems which delivered higher levels of flexibility than sites with single sources.

The quality of flexibility, as measured by stable and consistent load reduction, was greatest for AHU fans and battery systems. Other sources such as heat pumps provided a deeper range but exhibited more volatility. Electrification of heating systems, primarily through heat pumps will mean that the quality of flexibility provided by these systems will become more critical.

Scalability and ease of implementation were demonstrated by the multiple implementations of the methodology at the five pilot sites. Durations of assessments may be reduced by 60% and cost by up to 80% compared with a bespoke energy audit implemented by an expert in energy efficiency or electrical engineering.

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.

Chapter 5: Future State

5.1 Introduction

The methodology developed and demonstrated in this work is targeted at an initial early stage site assessment for flexibility to enable contract negotiations for demand side services. However, it may also have future applicability in the development of online real time flexibility assessments whereby buildings and sites are continuously connected, and the implementation of flexibility has been fully automated from grid level through to building systems.

A number of possible future states, leveraging the flexibility assessment methodology developed, are postulated in Section 5.2. Future work to enable this would require automation of steps 3 & 4 in the methodology. Even with automation of the methodology, barriers such as resistance by site owners to automated control by aggregators and technology gaps relating to ICT would need to be overcome in order to realise this future state.

One approach to automating steps 3 & 4 of the methodology is to develop models for individual systems providing flexibility and input these into an optimisation algorithm. Potential models are proposed in Section 5.3 while potential optimisation formulations are discussed Section 5.4.

This chapter combines work done by the author in patent applications for:

a) managing flexible grid resources (Riverso et al., 2018);
b) method for controlling building power consumption (Riverso et al., 2019).

5.2 Online Real-Time Flexibility Assessment

Making buildings truly ‘smart’ for flexibility may be more cost effective if cloud-based solutions are utilised. Connecting multiples of buildings to a single cloud-based platform which implements the flexibility assessment methodology proposed in this work may accelerate roll out of flexibility for commercial and residential buildings as it will reduce cost by:

i) Achieving economies of scale;
ii) Minimising modifications to existing BMS systems.

Economies of scale would enable a single platform to compute flexibility for many buildings. Minimising expensive and time-consuming modifications to existing BMS systems in the buildings would reduce costs. These would enable online real time flexibility quantification for both buildings and aggregators. Two implementations are proposed:

- Aggregator based (Section 5.2.2);

- Building based (Section 5.2.3).

Occupant engagement in commercial buildings has the potential to increase the quantity of energy and power flexibility the building can offer. Crowdsourcing of flexibility is proposed as a means of engaging occupants in Section 5.2.4.

5.2.1 Barriers & Technology Gaps

One of the main barriers to online real time implementation is the reluctance of building or site operators to allow aggregators to directly control equipment in their building or site. At present, site operators prefer to permit each flexibility event through phone or e-mail authorisation (Liddy, 2016).

Two main technology gaps exist, one relating to ICT platforms and the other relating to BMS systems. If these technology gaps were to be overcome, the future states proposed herein may be realised.

ICT platform integration with existing building systems is bespoke, complex, time consuming and expensive as evidenced by the large numbers of research projects which require the development of dedicated ICT platforms (Monti et al., 2016) (O'Connell et al., 2019) (Valdivia et al., 2014) (Sterling, 2015) (Dinkelbach et al., 2018) (Foggia et al., 2014). Initial investment costs such as those relating to ICT platforms for flexibility have been identified as a barrier to demand response participation in stakeholder consultations by the IEA Annex 67 on Energy Flexible Buildings (Ma et al., 2019). Until ICT platforms for building flexibility reach plug-and-play capability at Technology Readiness Level (TRL) 9, implementation using physical surveys is required.

Modifying existing Building Management Systems (BMS) is expensive and time consuming, based on the author's experience during the ELSA project and previous projects (Valdivia et al., 2014) (Monti et al. 2017). BMS were originally intended to be a low-cost way of providing simple automation to schedule and manage building assets such as boilers, AHUs, fans etc. (Ghaffarianhoseini, 2016). While some manufacturers are moving towards systems with more intelligence (Schneider Electric, 2020), the price point for BMS systems (Bonilla et al., 2018) constrains significant investment at the building level.

5.2.2 Aggregator Based Implementation

Aggregators provide energy and power balancing services by acting as an intermediary between a contracting authority, typically a grid utility and buildings or sites connected to the electricity grid (Foggia et al., 2014). The aggregator puts together a portfolio of sites to meet the minimum power or energy participation criteria set by the contracting authority to provide flexibility services such as Demand Response (DR) to the grid (Østergaard Jensen et al., 2019b). Power and energy flexibility of grid connected loads, generation and storage has become increasingly important for grid utilities hosting larger capacities of renewable power generation on the grid (Orths et al., 2019). At the grid level, balancing non-dispatchable generation resources such as wind or solar requires flexibility on the demand side in order to match power generation to load (Davies & Madden, 2017). The role of the aggregator is to offer the increased or decreased load, quantified in terms of electrical power (in kW or MW) and duration (time) to the grid utility in return for a financial payment, so the grid utility can balance the grid, increase renewable hosting capacity and provide grid stability for the users of the electrical network (Aghaei and Alizadeh, 2013).

The methodology proposed in this work may be implemented automatically online and in real time if the barriers and technology gaps were overcome and Steps 3 & 4 in the methodology automated. Two possible implementations are proposed, aggregator based and building based. For the building-based application, the technology gap in relation to BMS systems would also need to be overcome.

A potential aggregator-based implementation is shown in Figure 5.1. The system would operate in an online real time manner and be hosted in the cloud. When a demand response request is received by the aggregator from a grid operator, the software automatically verifies flexibility contracts with the buildings in its portfolio to determine which are signed up to the particular demand response programme the request related to. The cloud based platform then contacts the BMS systems in the relevant buildings to read data from the systems in the buildings. The aggregator system then implements Step 1: Identification of flexible sources loads storage and generation on the data for each of the buildings individually. Step 2: Flexibility Characterisation is conducted in an automated manner to quantify the available flexibility at each building. Step 3: Scenario Modelling then outputs the available flexibility defined for the specific time period of the demand response request for each building. This is then input into the aggregator multi-building optimisation algorithm which selects the most appropriate building and sources for the event. The aggregator platform then decides to accept or reject the flexibility offered and a write signal to actuate sources is sent to the BMS systems in each building.

Step 4: KPI label may also be incorporated into the online real-time implementation of the methodology. The KPI label may change continuously in a dynamic way e.g. an animated version of the label. If the KPI label becomes widely accepted, this dynamic implementation may be a means of having an operational flexibility rating for the building.

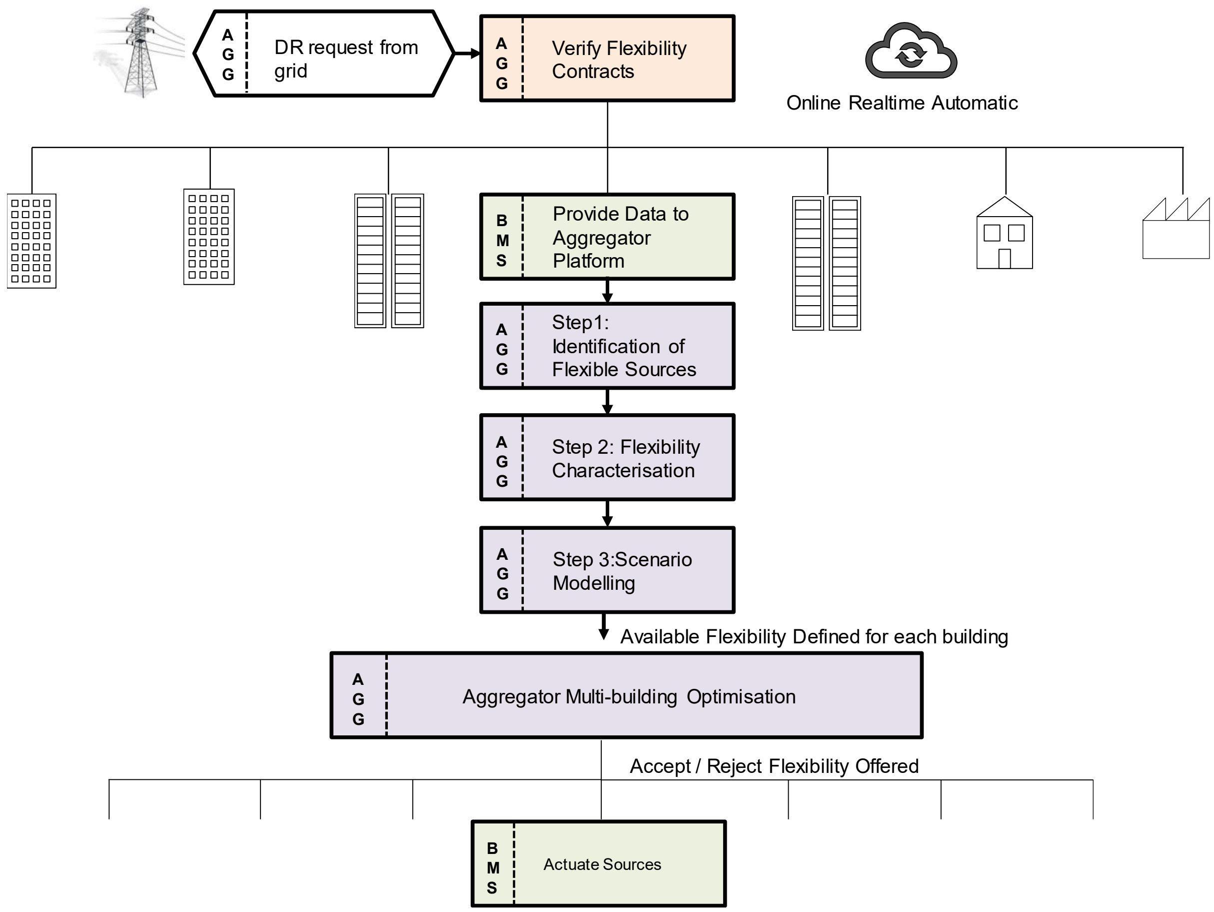


Figure 5.1 Aggregator Based Online Realtime Automatic Implementation of Flexibility Assessment Methodology.

5.2.3 Building Based Implementation

An alternative version where the aggregator interacts with the grid but the building operator controls flexibility quantification and activation is also proposed.

The system would operate in an online real time manner and be hosted in the cloud. When a demand response request is received by the aggregator from a grid operator, the aggregator's software automatically verifies flexibility contracts with the buildings in its portfolio to determine which are signed up to the particular demand response programme the request related to. The aggregator system may be located on a server on-site or in the cloud. The aggregator system then contacts the Building Energy Management Systems (BEMS) for each of the relevant buildings. The BEMS is more advanced than a traditional BMS system and has additional functionality, analysis and intelligence capability. The BEMS is owned or operated by the building operator. It may be a SaaS type service that is cloud based and or it may be physically located at the building. The BEMS reads data from the systems in the building and implements Step 1: Identification of flexible sources loads storage and generation. Step 2: Flexibility Characterisation is conducted in an automated manner to quantify the available flexibility for the building. Step 3: Scenario Modelling then outputs the available flexibility defined for the specific time period of the demand response request. This is then transmitted to the aggregator system for multi-building optimisation, the output of which is the selection of specific buildings. The selected buildings BEMS then receive a request to activate the defined flexibility previously transmitted.

5.2.4 Crowdsourcing of Flexibility

Occupant engagement in commercial buildings has the potential to increase the quantity of energy and power flexibility the building can offer. Crowdsourcing of flexibility may involve occupants communicating preferences or pre-defining limits within which they will accept changes to their environment e.g. climate settings, lighting levels, availability of equipment. Additionally, occupants may be surveyed when the building receives a demand response request and would be given the option to provide greater or lesser levels of flexibility for different systems. This may be done in a dynamic way through a smartphone, web application or PC installed software. Incentives may increase participation, for example providing virtual credits, vouchers for coffee or communicating the climate change benefits of flexibility. In the climate change incentive example, occupants could have personalised targets for avoided CO_2 emissions or energy savings equivalent to planting a tree, powering a specific device or other analogous activity.

The flexibility assessment methodology developed in this work may incorporate pre-defined and/or real time user preferences as part of Step 2: Flexibility Characterisation. This would be implemented as part of an automated system managing the flexibility in the building using either of the aggregator based or building based platforms in Sections 5.2.2 and 5.2.3. Flexible loads identified in Step 1: Identification of Flexible Sources, would have additional dynamic variables assigned in Step 2 associated with their flexibility characterisation related to Shedability, i.e. the quantity of power reduction permitted for that load.

An example of implementation for the pre-defined limits is as follows: if a number of occupants select a flexibility option that includes dimming of lights in a controllable lighting system, a power set point for the lighting system that takes into account both the occupant preferences and a predetermined operating condition e.g. lux levels to remain between 300 and 500 lux in occupied areas, is generated.

An example of implementation for a dynamic demand response request is shown in Figure 5.2. Occupants have specified pre-defined temperature preferences of 20 - 21°C but have indicated that they may be willing to accept comfort conditions outside these bounds for short durations during flexibility events. A demand response request is received by the building. The online real-time automated system managing flexibility surveys the occupants to ask if they will accept a temperature set point of 18°C for a 30-minute interval. Occupants then opt in or out of this. If they opt in, they receive 3 green credits which go towards the incentive reward in the crowdsourcing programme e.g. free coffee or savings equivalent to planting a tree.

In addition to occupant preferences, Step 2: flexibility characterisation may also take into account the number of building occupants or the location of the occupants within the building, where devices are in place to measure these variables.

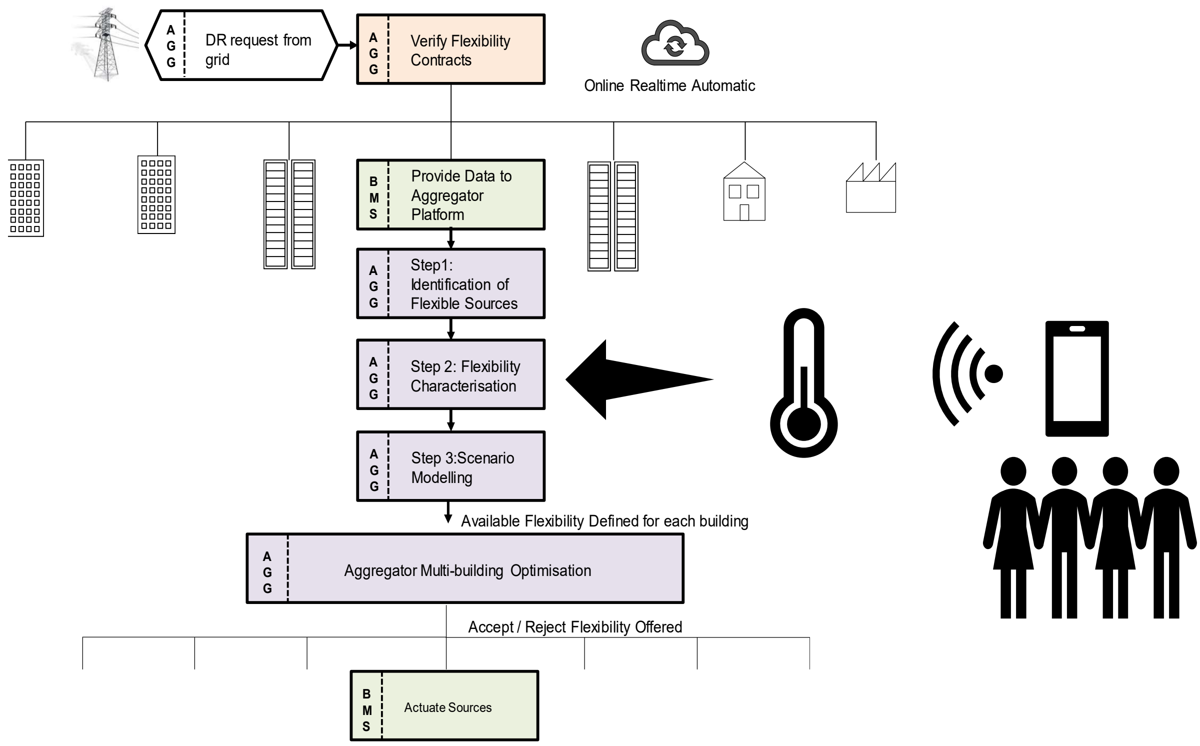


Figure 5.2 Crowdsourcing of Flexibility – Dynamic Implementation Example

5.3 Models for Automation

Automating the generation of models for Step 3: Scenario Modelling and the calculation of maximum and minimum flexibility for Step 4: KPI Label have been identified as future work if the methodology is to be implemented in an on-line real time way. To automate the methodology one possible approach may be to utilise models for specific building systems in conjunction with an optimisation formulation.

A number of potential modelling approaches were identified for the flexible systems present in this work. These include:

- physics based model with parameter estimation - PV
- mathematical model – Battery system
- greybox model - Thermal building systems
- Data Driven predictive model - AHU fan control.

In an online real-time scenario, when a signal is received from an aggregator requesting to be informed of the available flexibility, the models are activated (or are continuously predicting) and the outputs are input to the optimisation algorithm. The model outputs consist of the available power flexibility for the time period of the demand response request for each system. The optimal combination of systems is then selected by the optimisation algorithm.

The models have been selected to minimise data gathering requirements both in number of variables and in length of time series required for prediction. For example, it is not necessary to model the internal power electronics of the battery system as this will have very little impact on the available flexibility provided by the battery and would make for a computationally expensive model. Modelling using charging and discharging efficiencies will account for losses in the internal system.

Interactions between systems would need to be accounted for either in the models or at the optimisation stage. For the combination of systems under consideration in this work, there may be interaction between the thermal system i.e. Heat Pump VRF, and the AHU fans. Decreasing the AHU fan speed may increase the heating load for the VRF system in winter and increase the cooling load in summer. This may be accommodated by using the predicted fan speed as an input to the greybox model for the thermal building system. There would then be two model outputs for the thermal system, one with standard fan speed and one with modified fan speed.

Occupant comfort requirements may be incorporated in the greybox thermal model. Indoor air temperatures are required to stay within adaptive comfort boundaries as defined in ASHRAE 55 and EN15251 or maximum CO_2 levels may be specified in accordance with CIBSE guidelines (CIBSE, 2016).

5.3.1 PV model

A physics-based PV model such as that developed by Zhou et al. (2007) may be used to predict the output of the PV installation. The key inputs are solar irradiance and peak installed capacity. The model incorporates the PV curve with thermal drop off effect and a number of characteristic parameters of PV modules. Parameter estimation was included.

Forecasts for solar irradiance may be obtained from subscription services such as Weather Analytics (now Atlas) https://www.athenium.com/products/atlas/, or using freely available training data: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php

Another option for the PV model may be learning algorithms based on weather forecasts (Barbato and Capone, 2014). For both model types, the key to accurate prediction is solar irradiance forecasts.

Accuracy of prediction of PV output depends on the accuracy of forecasting for solar irradiance at the exact location of the PV installation. Ito et al. (2018) adopted a geographical area approach for predicting the output from large scale grid connected PV (e.g. one prediction point for a county). However, for individual buildings, particularly in temperate northern European climates, extremely localised effects may impact the PV installation's output e.g. cloud passing over the building, as was found during the experimental work in this thesis.

Control variable: N/A (Not controllable)

Objective: Determine the power output of the PV installation for a given predicted solar irradiance.

The model proposed by Zhou et al. (2007) determines the power output for a array, P_A, based on the number of modules connected in parallel N_p and the number connected in series N_s.

$$P_A = N_s \, . N_p \, . P_M \qquad (5.1)$$

P_M, the maximum power output from a PV module for a given solar irradiance, G, is defined as

$$P_M = \frac{v_{oc} - \ln(v_{\infty} + 0.72)}{1 + v_{oc}} \, . \left(1 - \frac{R_s}{V_{oc}/I_{sc}}\right) . \frac{V_{oc0}}{1 + \beta ln \frac{G_0}{G}} \, . \left(\frac{T_0}{T}\right)^{\gamma} . I_{sc} \left(\frac{G}{G_0}\right)^{\alpha} \qquad (5.2)$$

Where R_S is the series resistance of the PV module (Ω), V_{oc} is the open circuit voltage (V) under normal solar irradiance G (W/m^2), while V_{oc0} is the voltage under the standard solar irradiance G_0. I_{Sc} is the short circuit current (A) and I_{sc0} the short circuit current under the standard solar irradiance G_0. T is the PV module temperature (K) and T_0 the module temperature under standard solar irradiance G_0. α, β and γ are constant parameters for the PV module. v_{oc} is the normalised value of the open circuit voltage to the thermal voltage:

$$v_{oc} = \frac{V_{oc}}{nKT/q} \qquad (5.3)$$

n is the ideality factor, K is the Boltzmann constant (1.38×10^{-23} J/K) and q is the magnitude of the electron charge (1.6×10^{-19} C).

The angle of installation at which the PV panel is installed must be considered. It is assumed that the solar irradiance, G_H, is measured on the horizontal by a pyranometer located near the PV array.

$$G_M = \frac{G_H .\ Sin(A + B)}{Sin\ A} \quad (5.4)$$

Where A is the incident angle of the solar radiation (angle of declination) and B is the angle of installation of the solar panel.

The angle of declination, A, will change during the day as the sun rises and falls and over the year as the sun declines or rises in the sky and can either be calculated or taken from a look up table for a particular geographical location (Honsberg and Bowden, 2019).

Parameter estimation for α, β, γ, R_S and n at the maximum power point (MPP) was conducted using experimental data and the values determined (Zhou et al., 2007). $\alpha = 1.21$, $\beta = 0.058$, $\gamma = 1.15$, $R_S = 0.012\ \Omega$ and $n_{MPP} = 1.17$.

From the PV manufacturer's datasheet for the detailed case study building the Sunderland Pilot site, the following were identified:

$P_{max} =$ 250 Wp when $G = G_0$

$V_{oc0} = 37.8$ V

$I_{sc0} = 8.28$ A

$G_0 = 1000$ W/m2

$T_0 = 25$ °C.

5.3.2 Battery Model

A mathematical model for a lithium ion battery system was developed by Berrueta et al., (2018). Starting from a physics-based model, an electrical model was derived that provides a prediction of electrical output. The level of detail in this model may not be required for a model applied for flexibility. For flexibility the main priorities are accounting for the round-trip efficiency losses in charging and discharging the battery system. Modelling the internal workings of components such as the inverters may not be required. A simplified version of the model is proposed here.

Two types of efficiency are to be considered, η_c = colulombic efficiency (Discharging) and η_e = energy efficiency (Charging). Charging voltage is higher than discharging voltage due to non-ideal processes, therefore the efficiency losses are different.

Control variable: Charging or Discharging rate (kW/ kVA)

Objective: Determine the maximum power increase or reduction the battery system can provide for a specified time period. Assume constant rate of discharge over the time period.

The flexibility of the battery system, f_B may be modelled as follows:

General form:

$$f_B = \frac{C\ .\ SOC\ .\ \eta}{t_j} \qquad (5.5)$$

Charging:

$$f_B = \frac{C\ .SOC\ .\ \eta_e}{t_j} \qquad (5.6)$$

Discharging:

$$f_B = \frac{C\ .\ SOC\ .\ \eta_c}{t_j} \qquad (5.7)$$

Where C is the capacity of the battery system, SOC is the state of charge, η_e is the energy efficiency related to charging of the battery system, η_c is the coulombic efficiency related to discharging of the battery system and t_j is the time period of the demand response event.

To take into account active states of the battery, i.e. if the battery is already in the process of charging or discharging and may continue to do so between the time of flexibility measurement and the demand response event, the following terms may be added to the model:

Battery is charging & flexibility event requests a discharge (negative flexibility):

$$f_B = \frac{(C\ .SOC\ .\ \eta_c)}{t_j} + \left(P_c\ .\ (t_0 - t_j)\right).\eta_e \qquad (5.8)$$

Battery is charging & flexibility event requests a charge (positive flexibility):

$$f_B = \frac{(C\ .SOC\ .\ \eta_e)}{t_j} - \left(P_c\ .\ (t_0 - t_j)\right).\eta_e \qquad (5.9)$$

Battery is discharging & flexibility event requests a discharge (negative flexibility):

$$f_B = \frac{(C\ .SOC\ .\ \eta_c)}{t_j} - \left(P_c\ .\ (t_0 - t_j)\right).\eta_c \qquad (5.10)$$

Battery is discharging & flexibility event requests a charge (positive flexibility):

$$f_B = \frac{(C\ .SOC\ .\ \eta_e)}{t_j} + \left(P_c\ .\ (t_0 - t_j)\right).\eta_c \qquad (5.11)$$

5.3.3 Thermal Systems

Modelling the electrical response of thermal systems in the building is a complex process which typically requires detailed thermal modelling of the building physics, known as white box models (Coakley et al., 2014). Data driven models, known as black box models, have also been used (Niu et al., 2019) but parameter identification may not map to real parameters in the building e.g. thermal conductivity and prediction is reliant on the quality and diversity of the data available. In recent years, a number of grey box modelling approached have been developed which combine knowledge of building physics with some data driven aspects.

The most common type is an R-C model, an analogy of the resistance capacitance approach of electrical circuits. An alternative is the state space model approach to thermal building modelling developed by Bacher and Madsen (2011).

Model libraries have been developed in the modelica modelling language by a number of research institutions (Wetter, 2011) (De Connick et al., 2016) (Halimov et al., 2019) (Wetter et al., 2015).

Other approaches start with complex whole building simulation e.g. EnergyPlus, and reduce model complexity incrementally until the model is computationally efficient (Reynders, 2015) (Kwak et al., 2015) and meets operating requirements, e.g. computation time required for prediction horizon. 80 hrs for full model reduced to 3 hrs for simplified model, would be too long for usable outputs (Li et al., 2017) for intra-day flexibility events.

Potential environments: R (greybox RC models), Modelica,

Control variable: Global indoor air temperature (set point) [°C]

Objective: determine the power reduction/ increase that can be achieved for a specific change in temperature set point.

Input parameters include OAT, and may include other weather related data e.g. solar radiation, wind, RH.

The state space model developed by Bacher & Madsen (2011) and implemented by Roels et al. (2015) uses a greybox approach based on the R-C principle. It starts with fitting a simple model and adding additional terms to simulate additional physical parameters e.g. solar radiation, wind etc. until the loglikelihood plateaus and residuals are equivalent to white noise. To implement this approach for power flexibility, the models would need to be adapted to focus on electrical energy instead of thermal energy.

$$dT = ATdt + BUdt + d\omega \qquad (5.12)$$

Where T is the state vector

U is the input vector

$$U = [T_a . \Phi_s . \Phi_h]^T \qquad (5.13)$$

And A and B are parameter vectors.

There are a number of possible approaches for deriving the power flexibility provided by the thermal system. Three potential solutions are listed below:

1) modify greybox model to have electrical power as the output. i.e. dP = AP dt + BU dt + CT dt + dw;
2) Use a greybox model to model internal air temperature & then use physics-based equations to calculate i) thermal energy ii) electrical energy based on COP;
3) data driven model which matches dT to a power reduction or increase. Using either the whole building meter (worst case) or meter for HVAC system (best case).

For option 2) if the temperature changes were determined from the state space model, then these could be input into the heat equation to calculate the heat reduction or increase:

$$Q = \dot{m}\, C_p\, dT \qquad (5.14)$$

The COP is then used to calculate electrical power from the heat equation:

$$COP = \frac{Q}{P} \qquad (5.15)$$

$$P = \frac{Q}{COP} \qquad (5.16)$$

For flexibility the change in power output is equivalent to the flexibility of the thermal system, f_T:

$$f_T = P = \frac{Q}{COP} \qquad (5.17)$$

Therefore, f_T is the thermal system contribution input into the objective function.

$$f_T = \frac{\dot{m}\,.C_p\,.dT}{COP_T} \qquad (5.18)$$

As COP varies with condenser and evaporator temperatures, heat pump or compressor power curves, see Figure 5.3, in look up table format are required to capture the relationship between COP and input / output temperatures.

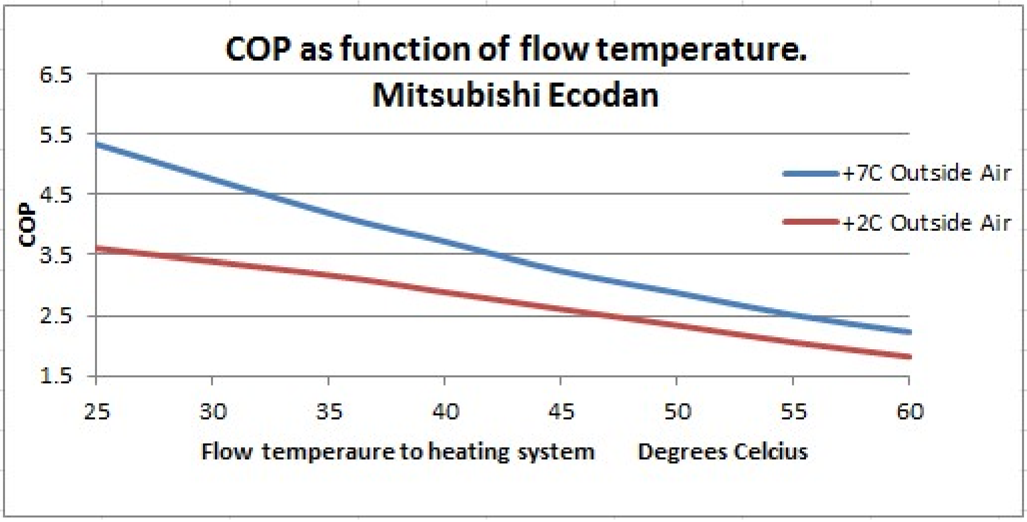


Figure 5.3 Example of Heat Pump COP Power Curve (Cantor, 2014)

5.3.4 AHU Fans

A data driven model may be suited to modelling the electrical power of an AHU fan to predict its flexibility. Ventilation rates are less complex than thermal systems and provided any change in fan speed is linked to the thermal system model, to ensure interactions are captured, the model may rely on data. Seasonal effects are not as impactful and a number of approaches are possible depending on the control variable for the fans.

Of the data driven modelling approaches available, ARX and ARMAX models are the most commonly used for energy use in buildings (Roels et al., 2015), (Niu et al., 2019). Other approaches include Box Jenkins (Jimenex and Madsen, 2008). A number of reviews of data driven modelling approaches in buildings have been conducted. A review of data driven for electrical load prediction in buildings (Zeng et al., 2019) focusing on regression models (Yildiz et al., 2017), review of data driven models for energy prediction in buildings (Bourdeau et al., 2019) and a review of data driven and large-scale modelling approaches for energy in buildings (Ahmad et al., 2018). Zeng et al. (2019) found that Multivariate Linear Regression (MLR) and Support Vector Machines (SVM) [non-linear] worked best, particularly for buildings with complex and unstable energy patterns.

Focusing specifically on the requirements for a data driven model of an AHU fan, a number of studies used CO_2 data to predict occupancy (Jung et al., 2019) or occupancy and ventilation rate to predict CO_2 concentration (Pantazaras et al., 2016). However, a model for flexibility would need to be different as the objective is to predict fan power from CO_2 data.

For the development of the model, if the fan is controlled by a set speed only, this may be reduced, subject to constraints and the model may be simple. If the fan speed is controlled by CO_2, a data model using CO_2 measurements as an input may appropriate, subject to the constraint of a CO_2 limit e.g. 1,000 ppm (CIBSE, 2016) may be developed. The data driven model may be correlated against occupancy to see if predicted fan speed 'learns' occupancy. To measure available flexibility the following formula may be used:

Fan flexibility (kW) = power @Current fan speed – power @ predicted fan speed.

Control variable: Fan speed [%].

Objective: Maximise the power reduction by the fans, subject to CO2 constraints.

Training data may be taken from representative days rather than all days (Paudel et al., 2017) e.g. weekdays with typical occupancy.

5.4 Optimisation

A number of approaches may potentially be used for optimisation. These include the flexibility formula proposed in Chapter 3, combined with the models above, multidimensional analysis or a mixed integer linear programming approach.

The formula for flexibility developed in Chapter 3 may be utilised as an objective function to maximise power flexibility for a given time period. Niu et al., (2019) applied models as constraints for the objective function. A similar approach may be applied for flexibility. The primary requirements for the objective function are that it be independent of use cases. Use cases would be addressed by varying constraints tailored that specific use case.

Formula for flexibility from Chapter 3:

$$\max \sum_{i=1}^{n} f_i(t_j) \qquad (5.19)$$

Subject to the constraints:

Flexibility may be positive or negative but not both at the same time.

Flexibility and flexibilities of systems are real numbers, $f_i \in \mathbb{R}$.

SOC of the battery can never be zero, set limit of x, e.g. 5%.

Indoor air temperature must be within with ASHRAE 55 / EN15251 adaptive comfort range.

CO_2 levels must be below 1,000 ppm.

Other model related constraints.

The flexibility matrix, as developed in Chapter 3, if applied to all the possible combinations and timesteps, is a multidimensional matrix. Multidimensional analysis may be suited to the generation of flexibility outputs for steps 3 & 4 in the methodology.

Optimisation using mixed integer linear programming (MILP) is the most commonly used approach for demand response applications (Niu et al., 2019) (Ottesen and Tomasgard, 2015) (Siebert et al., 2015).

Siebert et al. (2015) used Mixed Integer Linear Programming (MILP) to formulate objective functions for three distinct flexibility scenarios: maximising expected revenue, maximising bid duration and maximising peak power.

Maximising expected revenue:

$$\text{Max}\ \{\textstyle\sum_t \sum_r \text{Power}(t, r).\text{EnergyWeight}(t).\text{ut}\} \quad (5.20)$$

Maximising bid duration:

$$\text{Max}\ \{\textstyle\sum_t \text{BidActive}(t)\} \quad (5.21)$$

Subject to the constraint:

$$\textstyle\sum_r \text{Res}(t, r).\text{EventImpact}(t, r) \geq \text{BidActive}(t).\text{MinPower} \quad (5.22)$$

Maximising peak power:

$$\text{Max}\ \{\text{Max} \textstyle\sum_t \text{Res}(t, r).\text{EventImpact}(t, r),\ t \in T\} \quad (5.23)$$

Whereby:

Power(t, r) is the power flexibility provided by the resource r for the timestep t and Power(t, r) = Res(t, r).EventImpact(t, r)

Res(t, r) is a binary variable indicating if resource r is active during timestep t

EventImpact(t, r) is the amount of power variation that can be provided by resource r at timestep t. (kW)

EnergyWeight(t) is a unitless weighting factor for time step t, related to electricity price. on a scale from 0 to 2.5.

ut is the length of the optimisation step (s)

BidActive(t) is a binary variable indicating if the bid is active at time t.

MinPower is the minimum power that must be provided (kW)

T is the set of time steps between the bid start and end times.

Flexibility in these objective functions is not explicitly included but is expressed as EventImpact. Applying a unitless weighting factor for price, while it keeps it independent of currency, adds a level of complexity that may not be useful. The output of the cost function would then have to be converted to a financial cost. Using Booleans to switch on or off flexibility sources is an approach which allows the overall flexibility to be adjusted according to changing source availability. It could be argued that maximizing bid duration and maximizing peak power would be the same as maximizing revenue, if the grid signals were price based. Maximizing peak power may be required in a scenario where renewable penetration has increased to the extent that grid operators require the load to increase in order to balance the grid.

A stochastic approach, also using MILP was developed by Ottesen and Tomasgard (2015):

$$\min \sum_{s \in S} R_s \Bigg[\sum_{a \in A} \sum_{t \in T} P^{energy}_{a,t,s} x^{import}_{a,t,s} + \sum_{a \in A} P^{peak}_{a} x^{peak}_{a,s} + \sum_{o \in O} \sum_{y \in Y} \sum_{t \in T} G^{startup}_{o,y} \alpha^{start}_{o,y,t,s}$$

$$+ \sum_{d \in D^c} \sum_{y \in Y} \sum_{t \in T} X_{d,y,} \phi_{o,y,t,s} - \sum_{a \in A} \sum_{t \in T} P^{sales}_{a,t} x^{export}_{a,t,s} \Bigg] \quad (5.24)$$

The probability of scenarios is given by R_s. In order to change this to a deterministic approach, if all the information is known with certainty, then there will be only one scenario. P^{energy} denotes total load (kW) less flexibility (kW) while x^{import} is the cost of energy (€). The next term includes for a peak premium, for example in a Critical Peak Pricing (CPP) use case. $G^{startup}$ relates to a converter start-up cost; the X_d term incorporates losses due to disutility, such as loss of production or loss of worker productivity; while the final term includes for income from the sale of excess generation.

An advantage of this approach is that it is less tied to specific use cases than that used by Siebert et al. (2015). The pricing structure used in this cost function is more restrictive than the use cases in this project. It is well suited to Time of Use (TOU) or CPP fixed price structures but may not be adaptable enough for Real Time Pricing (RTP) or even intra-day demand response signals. Converter start up is not a significant issue with the battery, whereas it may be a consideration with on-site generators or fossil fuel power plants. Disutility is to be avoided where possible, but if there is a risk of it occurring, it is advisable to include it in the flexibility matrix. There may be sale of excess generation in some sites, upward flexibility where sites are requested to increase load, other sites may have spill to the grid with no payment while in some cases there may be a specific prohibition of net export.

An MILP objective function (Niu et al., 2019) combined with simple models of building systems and an ARX model of building thermal storage used a cost-based approach. The optimisation was implemented in Gurobi. The objective was to minimise electrical grid import costs, PV and cooling system maintenance costs. P denotes power (kW), Ep is the grid electricity price (€/kWh), ε is the expense of maintaining the PV and cooling systems (CS) respectively (€/kW installed), i is the number of chillers while Δτ is the length of each time step, one hour (h).

$$min \sum_{\tau \in T} P^{grid}.Ep\ .\Delta\tau + \left(\varepsilon^{PV}.P^{PV} + \varepsilon^{CS}.\sum_{i \in I} Q^{i}\right).\Delta\tau \qquad (5.25)$$

While cost may be a factor in many demand response events, it is not universally the case. CO_2 minimisation, for example, does not have a monetary cost factor. The maintenance cost of the PV system is independent of the time step and PV is not controllable, so it is not clear why it has been included. It is not clear how the maintenance cost of the chillers in the cooling system is impacted by participating in demand response. For split system heat pumps, the most commonly used type in office buildings, compressor cycling on part load is a routine part of their normal operation. Some types of large industrial chillers, e.g. ammonia chillers do require on/off operation at full load and cycling may have some slight impact their maintenance cycles. These chillers are installed for large loads e.g. chill warehousing or are coupled with purpose-built storage which dampen cyclic effects. It has not been established how significant the maintenance cost is for participation in demand response.

A more universal objective function for flexibility which is applicable to a wider range of use cases and includes only relevant variables would be required to automate the 4-step flexibility methodology developed in this work.

5.5 Conclusions

Initial scoping of a future state, adapting the methodology for on-line real-time applications, was outlined. The future state proposed requires acceptability barriers and technology gaps to be overcome before implementation would be possible. Aggregator and building based implementations were explored, with crowdsourcing of flexibility a possible sub-category of implementation. Mathematical models for automation, coupled with potential optimisation formulations were identified as a first step towards the potential future state. The KPI label, while developed initially for static implementation, may also be implemented in a dynamic way in the automated framework, providing a real time indicator of changing flexibility.

Chapter 6: Conclusions & Future Work

6.1 Conclusions

The specific contribution of this work is in the creation of a standardised 4-step flexibility assessment methodology which enables greater numbers of buildings and smaller sites to participate in demand response programmes, by overcoming the barrier of lack of consistency in assessment. Increased participation allows for higher levels of renewable integration for grid decarbonisation, to meet climate action targets. The methodology has been developed, implemented and demonstrated at multiple pilot sites, and through experimental demonstration verified its:

- Accuracy;
- Ease of implementation;
- Scalability.

The practical impacts of the methodology are that it:

- Reduces complexity and cost when assessing flexibility;
- Enables contract negotiations between building and site operators and aggregators.

A societal impact of the methodology is that it has the potential to operationalise the concept of building flexibility to a wider spectrum of society by providing an efficient, cost effective, repeatable and technically accurate method of assessing the flexibility of buildings and sites.

The overall conclusions and recommendations of this work are presented in this chapter with a particular focus on the novel aspects of the:

- Literature Review;
- Methodology;
- Detailed Case Study Implementation;
- Multiple Pilot Site Implementation & Results.

6.1.1 Literature Review

The literature review concluded that there is no early stage flexibility assessment methodology which explicitly includes source selection, is sufficiently adaptable to multiple sources of power flexibility or captures the key elements of flexibility in a comprehensive and systematic way. Several approaches reviewed required the installation of an ICT platform and extensive data gathering prior to implementation. This is a significant up-front cost investment for a building or site when the available flexibility is not yet known. Grid focused approaches omitted the needs of buildings while those tied to a specific price structure limit the applicability of the assessment outputs.

Stakeholder decision making currently relies on either a cursory assessment which may omit flexible systems, or a lengthy report which is bespoke to the building or site. There is no standardised, one-page, easily understood method of communicating the relevant technical information that characterises the Key Performance Indicators of flexibility for a building or site.

The literature review of benchmarking concluded that more published demonstration studies for flexibility will be beneficial for the development of standardised benchmarks similar to energy efficiency benchmarks for buildings and sites. From the available studies reviewed, benchmarks were created for the pilot sites in this work.

6.1.2 Methodology

A novel four-step flexibility assessment methodology was developed which fulfils an identified need for an early stage flexibility assessment that explicitly includes source selection. It is designed to be implemented in an off-line manner without the need for extensive real-time data acquisition, ICT platforms or additional meter and sensor installations. The four steps in the methodology consist of:

Step 1: Systems, Loads, Storage & Generation Identification;

Step 2: Flexibility Characterisation;

Step 3: Scenario Modelling;

Step 4: Key Performance Indicator (KPI) Label.

This standardised methodology addressed the gaps identified in the literature review as it:

- Explicitly includes source selection;
- Is designed to be implemented at an early stage, prior to any investment in ICT platforms, additional sensors or BMS system upgrades;
- Is not limited to loads but also includes storage and on-site generation;
- Utilises concepts from the literature review such as Shedability, Controllability and Acceptability but adapts them and applies them in a different way;
- Defines the variables and parameters for flexible sources and consistently applies these across all flexible systems;
- Has a systematic, standardised and technically robust approach utilising relevant elements of the ISO energy auditing standard.

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. The early stage flexibility assessment overcomes these barriers through a systematic, easy to implement methodology, to provide stakeholders with actionable information in a concise and relevant way, so they can quickly and cost effectively evaluate the flexibility of their building and negotiate with aggregators for demand response participation.

A KPI label is proposed in Step 4 which provides actionable information for decision makers in a concise, easily understood and targeted manner. By clearly defining the flexibility range, the novel KPI label enables contract negotiation between stakeholders for demand side services. The KPI label is a decision support tool for high-level decision-making such as demand side programme selection by site operators and portfolio creation by aggregators. By clearly defining the available flexibility ranges in a standardised way, it enables negotiation between building or site operators and aggregators or grid operators for demand side services contracts.

The KPI label is a decision support tool for high level decision making such as:

i) Building or site operator decision to participate in demand side services;
ii) Building or site operator demand side services programme participation selection;
iii) DSO or aggregator selection of appropriate sites or buildings for portfolios;
iv) Enable contract negotiation between building or site operators and aggregators (or grid operators) for demand side services;
v) Investment decisions in system upgrades, metering or ICT platforms to provide grid services.

The KPI label provides defined graphical and numerical information on the available power flexibility ranges and associated timescales, at a glance, for stakeholder decision making. Its effectiveness has been assessed using stakeholder feedback and a quantitative survey.

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. Flexibility may be well understood in the technical and scientific community but not in society as a whole. To meet renewable integration targets, power and energy flexibility will be required from smaller buildings and sites including residential buildings. The novel KPI label proposed in this work has the capability to operationalise the concept of flexibility to a wider spectrum of society, enabling smart grid demand side services roll out to residential and small commercial electricity customers. Participation from these sectors will be required in demand side programmes to balance the grid in order to achieve higher renewable integration targets.

Stakeholders were consulted on an early draft of the KPI Label and they found it relevant, specific to their needs and that it communicated the key metrics required based on a robust technical assessment process. The 4-step methodology was presented to the members of the International Energy Agency's Energy in Buildings and Communities Annex 67 – 'Energy Flexible Buildings' (Østergaard Jensen et al., 2017). Feedback from the members was very favourable and several partners requested the detailed structure and templates to apply the methodology at their own sites. Underpinning the methodology with ISO 50002 was viewed as a particular strength as it gave the approach a standardisation not always present in other assessments.

6.1.2.1 Limitations of the Methodology

The assessment methodology is targeted at a stakeholder need for an early stage assessment, before investment on site or contract negotiations take place. This results in a number of limitations in assessing the building or site flexibility. These include:

- Static assessment requires that scenarios are selected, and assumptions are made regarding the capacity and availability of the systems on site. By its nature, it does not represent all the possible dynamic scenarios that may present at a building or site. A dynamic assessment serves a different stakeholder need in that it is applicable after contracts have been signed and the building or site is actively participating in demand response services;
- Assumptions regarding renewable generation output are based on predictions or on historical performance. Actual output depends on weather conditions and may vary from predicted output;
- Storage capacity is assumed to be fully charged and the design rated capacity available. Actual storage state of charge and available capacity may differ depending on previous activities or technical issues with the system;
- Occupancy levels may change from those assumed at the time of assessment. This may be more relevant for buildings with variable occupancy e.g. public access sites such as museums or shopping centres. Other building types, such as offices, may have more consistent occupancy patterns;
- Availability of data for evaluating Shedability, Controllability and Acceptability may not always be present, and this may result in a partial assessment or exclusion of some sources;

- Novel sources of flexibility which may not have been documented in previous demonstration studies may require functional tests or models to assess their flexibility in addition to the site visit and flexibility characterisation;
- 5 pilot sites are considered a statistically small sample (i.e. <30) and the methodology may benefit from wider implementation in future;
- Three of the five use cases selected were for negative or delayed flexibility. While PV power smoothing and CO_2 minimisation have elements of positive or forced flexibility, the implementation of more use cases whereby the building or site is required to increase its grid import power and energy on demand would verify the capability of the methodology for a wider range of use cases.

The potential for overcoming these limitations may lead to future developments in demand response technology, particularly in the area of dynamic or real time flexibility assessment. The models for automation in future state in Chapter 5 and future work on an automation framework for aggregator-based demand response have the potential to address these limitations. Further implementation of the methodology by others on more buildings and sites with forced flexibility use cases would also be beneficial.

6.1.3 Detailed Case Study Implementation

A detailed case study for one building, with demonstration of actual flexibility through on-site experiments, verified the feasibility and accuracy of the approach. Benchmarking provided a performance assessment by comparing the site against other demonstration studies, giving an indication of how flexible it was.

The feasibility of the approach was demonstrated through the implementation of Steps 1 to 4 in a real site, the Skills Academy for Sustainable Manufacturing and Innovation (SASMI) building, in Sunderland, UK. Step 1: Systems Loads, Storage and Generation Identification involved a site visit to the building to identify the systems present. Step 2: Flexibility Characterisation applied the flexibility characterisation process and assessed the flexible sources using the filter or triage step of Shedability, Controllability and Acceptability. Flexibility Technical Specifications were then populated for each flexible source. Step 3: Scenario Modelling generated scenario models and Step 4: KPI Label created the KPI label.

The accuracy of the approach was verified by comparing the output of the scenario models in Step 3 with the results of the use case demonstration experiments. Scenario models for one-hour and four-hour events were generated. Use cases for peak shaving and a market based real-time demand response request were implemented on site using a remote access ICT platform to actuate the flexible systems in the building. These use cases were simulated using the OpenADR protocol. The resulting power flexibility of the building was recorded and compared with the scenario models. For the one-hour scenario, actual flexibility was 32% compared with predicted flexibility of 45%. The four-hour scenario actual flexibility was 23% compared with 27% predicted. However, if the technical issues with the early prototype 2nd life battery system were excluded, the variation between predicted and actual was 1%.

HVAC systems proved a more reliable source of flexibility than the battery storage. The HVAC sources used were AHU fans and a VRF heat pump system. The fans in particular provided an extremely stable load reduction. While predicted average PV output was achieved during the experiments, it must be noted that PV output is volatile and large variations occurred which may adversely impact demand response events.

Benchmarking the detailed case study building against demonstration studies, the case study building was within the range of Benchmark 1 and exceeded the range of Benchmark 2.

6.1.4 Multiple Pilot Site Implementation & Results

Implementation of the methodology at multiple buildings demonstrated its scalability and ease of implementation. Experiments were conducted at five pilot sites, in different geographical regions, activating a range of flexible sources through experiments on site. A diverse range of demand response use cases were used to activate flexibility in the sites and demonstrated the applicability of the flexibility evaluation method.

In common with the detailed case study implementation, it was found that the sites with loads, in particular HVAC loads, provided more reliable power flexibility than those with battery storage and/or PV. This was partly due to the early stage prototype at TRL 5/6 2nd life EV battery storage system which requires further technology maturation to TRL 9.

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

The scalability of the assessment method was 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 implementation and verification of the methodology at five pilot sites demonstrates this, enabling roll out of demand response services to a wider spectrum of society.

The ease of implementation of the methodology demonstrated through these multiple implementations will enable 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 (O'Connell, 2010a) (O'Connell, 2010b) (O'Connell, 2009). By comparison, the flexibility assessment methodology reduces the time for assessment to 1 - 2 weeks, a reduction of approx. 60%.

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.

6.2 KPI Label Dynamic Potential

Step 4: KPI label may also be incorporated into an online real-time implementation of the methodology as discussed in Chapter 5. The KPI label may change continuously in a dynamic way e.g. an animated version of the label. If the KPI label becomes widely accepted, this dynamic implementation may be a means of having an operational flexibility rating for the building.

This operational flexibility rating as represented by a dynamic KPI label may link to other energy related rating or evaluation systems such as the SRI (Verbeke et al., 2020), operational Building Information Modelling (BIM) (Patacas et al., 2020) or sustainability rating systems such as Building Research Establishment Environmental Assessment Method (BREEAM) assessment BREEAM In-Use (BRE, 2020) and the Leadership in Energy and Environmental Design (LEED) assessment LEED for Operations & Maintenance (USGBC, 2020).

6.3 Policy Implications

Potential impacts of the methodology at a policy level are specified below.

6.3.1 Renewable Energy Directive

The European Commission is currently reviewing its roadmap for the Renewable Energy Directive (RED II) (DG Energy, 2020). The key objective is to increase the use of renewable generation with a possible upward review of the 32% target for 2030 previously agreed by member states (European Parliament, 2018b). A element of the roadmap in which this methodology may have applicability is the establishment of a comprehensive terminology and robust certification system. If the standardised four-step methodology developed in this work were to become a regulatory requirement for all buildings and sites, as a driver for increased participation in demand response, it would have significant and far reaching benefits in creating a carbon neutral society for all.

6.3.2 EPBD

An alternative would be to include a mandatory quantitative flexibility assessment for buildings in any future recast of the Energy Performance of Buildings Directive (EPBD) (European Parliament 2018). The SRI included in the 2018 recast (European Parliament 2018) which is under development (Verbeke et al., 2020), is optional and is a qualitative assessment of a range of smart characteristics of which energy flexibility is only one. Having a dedicated standardised assessment for power and energy flexibility which produces measurable KPIs that are relevant for stakeholders assessing buildings for demand response participation, i.e. % of peak load and kW/MW power flexibility range, would increase demand response awareness and participation among building operators.

6.3.3 ISO Standards

The methodology developed in this work may have applicability in the development of a new ISO standard for flexibility assessment or as an addition to the existing ISO 50002 energy auditing standard. Energy audits were conducted for many years before an ISO standard was developed in 2014 (ISO, 2014). Prior to a standardised approach, energy auditing was in a state of the art similar to where flexibility assessment is now, with assessments being conducted in different ways by different industry professionals producing varying outputs. Having an ISO standard for flexibility assessment would enable all assessments to be implemented in a consistent manner, producing comparable outputs, thereby increasing the rate of roll out of flexibility and demand response participation among buildings and smaller sites. Initial discussion were held with Barry Smith of the National Standards Association of Ireland (NSAI) (Smith, 2019) and the next stage would be to engage with the ISOs Technical Council TC 301 on Energy Management and Energy Savings (ISO, 2020) through the NSAI.

6.4 Future Work

Potential future work to enhance the successful implementation of flexibility in buildings and sites was identified in a number of areas. These included:

- Control of Heat Pump systems at the compressor level;
- PV forecasting;
- Maturing 2nd Life EV battery management system;
- Automation of Steps 3 & 4 in the methodology.

Increasing electrification of heating is predicated on increased installation of heat pumps as electric residential space heating is predicted to rise to 30% of total energy use by 2050 (Orths et al., 2019). Thus, the quality of the flexibility provided by heat pumps, as measured by stable and consistent load reduction, becomes more critical. Deeper ranges of flexibility were provided by the VRF Heat Pump system but with more volatility than the AHU fans or the battery system. To achieve a more stable load reduction, working with manufacturers of these systems to enable direct compressor control rather than reducing load through room temperature set point reduction would be required.

Reliance on on-site renewable generation such as PVs to deliver flexibility on a consistent and reliable basis will require accurate forecasts of PV output. Work has been done on this at the grid scale (Ito et. al, 2018) (Haupt et al., 2019) and the building scale (El-Baz et al., 2018) but there is scope for further improvement, particularly for building scale perturbations such as clouds passing over the PV array.

The 2nd life EV battery management system was brought to TRL5/6 as per the EUs Research and Innovation Action (RIA) project funding criteria. Bouygues and Renault, the developers of the battery management system, intend to mature the technology to TRL 9.

Automation of Steps 3 & 4 in the methodology would enable it to be used in a future state with online real time flexibility assessments. Initial scoping for this future state was outlined in Chapter 5.

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Appendices

Appendix A – OpenADR Implementation

An example of the code used to implement the OpenADR protocol at the Sunderland pilot site is given below.

null, event_type, DR-Flexibility

null, t_rampup_start, 19-Aug-2018-22:45

null, t_event_start, 20-Aug-2018-10:15

null, t_event_end, 20-Aug-2018-12:45

null, t_recovery_end, 20-Aug-2018-13:15

20-Aug-2018-10:15,P_ref,80

20-Aug-2018-10:15,C_pen,10

20-Aug-2018-10:15,P_tol,10

null, event_type, DR-Flexibility

null, t_rampup_start, 20-Aug-2018-13:30

null, t_event_start, 20-Aug-2018-14:00

null, t_event_end, 20-Aug-2018-15:00

null, t_recovery_end, 20-Aug-2018-15:30

20-Aug-2018-14:00,P_ref,60

20-Aug-2018-14:00,C_pen,10

20-Aug-2018-14:00,P_tol,10

null, event_type, DR-Flexibility

null, t_rampup_start, 20-Aug-2018-15:50

null, t_event_start, 20-Aug-2018-16:20

null, t_event_end, 20-Aug-2018-17:50

null, t_recovery_end, 20-Aug-2018-18:20

20-Aug-2018-16:20,P_ref,40

20-Aug-2018-16:20,C_pen,10

20-Aug-2018-16:20,P_tol,10

Appendix B – Experiment Standard Operating Procedure

UTRC Ireland
Pilot Site Experiment Request - Standard Operating Procedure (SOP)

Site Name: SASMI, GCOL, UK

Site Contact 1: Paul Mitchell e-mail: [redacted] Phone: [redacted]

Site Contact 2: Geoff Watson e-mail: [redacted] Phone: [redacted]

Experiment Name: **Flexibility Validation** Request No.: 09

UTRCI Requestor: Sarah O'Connell e-mail: oconnesa@utrc.utc.com Phone: +353 (0) 21 4551212

Date of Proposed Experiment: Tuesday 31/07/2018 & Wednesday 01/08/2018

Permission Tracking:

Date of Request	*UTRCI PI Approval*	*Permission 1*	*Permission 2*	*Permission 3*
[30/07/2018]	M.T. 30/07/2018	[Initial/Date]	[Initial/Date]	[Initial/Date]

Description of Experiment

Overview: Flexibility Validation

For Deliverable D1.4 a flexibility assessment was conducted and flexibility ranges estimated for equipment in SASMI including AHUs, the VRF split system and the B4B batteries. See graphs below. UTRC would now like to validate these ranges by conducting 2 flexibility events, a 1 hour event and 4 hour event.

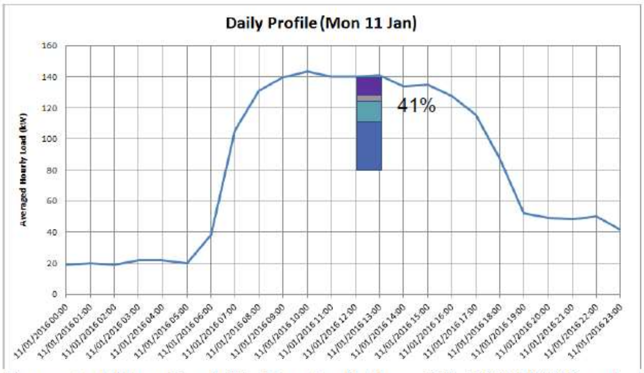


Figure 1. 1 Hour Flexibility Event – Battery, PV, 20% HVAC reduction.

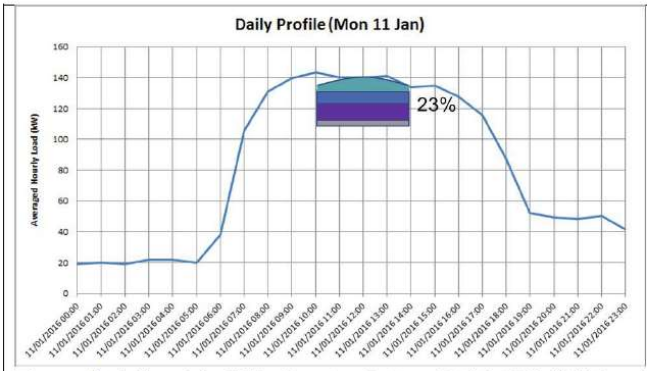


Figure 2. 4 Hour Flexibility Event – Battery & PV, 20% HVAC reduction.

Due to issues with data availability for the UTRC battery control system, we plan to do the experiment without the B4B system at this time. When Geoff returns, we can discuss with him doing a manual battery discharge of 1 hour and 4 hours.

At the end of the experiment, the systems will be reset to their original values.

Equipment: AHU01 (lecture theatre 1), AHU02 (general areas), AHU03 (workshop), AHU05 (changing areas), Carrier Toshiba VRF Split system, ~~B4B system~~

Set Points to be modified:
Global temperature set point increased by 3 deg C for 1 hour event and 2 deg C for 4 hour event.
AHU fan speed reduction by 20% on AHU 01, 02 & 05. Fan speed reduction by 50% on AHU 03 (Workshop).

~~B4B charge/discharge values.~~
~~*Ranges*: from **+9** kWh (charge) to **-36** kWh (discharge).~~

Duration: 1 hour on Tuesday 31st. proposed time 11am – 12 noon.
4 hours on Wed 1st August from 11am – 3pm.

Potential Impact on Building Occupants or Operations (if any)

Increasing the temperature set point and reducing air flow will cause the room temperatures in the building to get warmer which may impact occupants.

Operational impact:
BMS Matrikon Tunneller. GCOL intervention may be required to re-start the Matrikon Tunneller if it crashes prior to or during the experiment.

Completion of Experiment

Completed:	Yes/No	Date Complete:	[dd/mm/yyyy]
Previous set points re-instated:	Yes/No	Description:	[List set points re-instated]

Appendix C – Survey Questionnaire

Survey – implementation of standardized flexibility assessment methodology

1. At time of the flexibility assessment, would you describe your background as:

   - Technical background (e.g. engineering, computer science)
   - Non-technical
   - Expert in flexibility

2. How easy/difficult did you find the implementation of the assessment?
Very easy easy average difficult very difficult

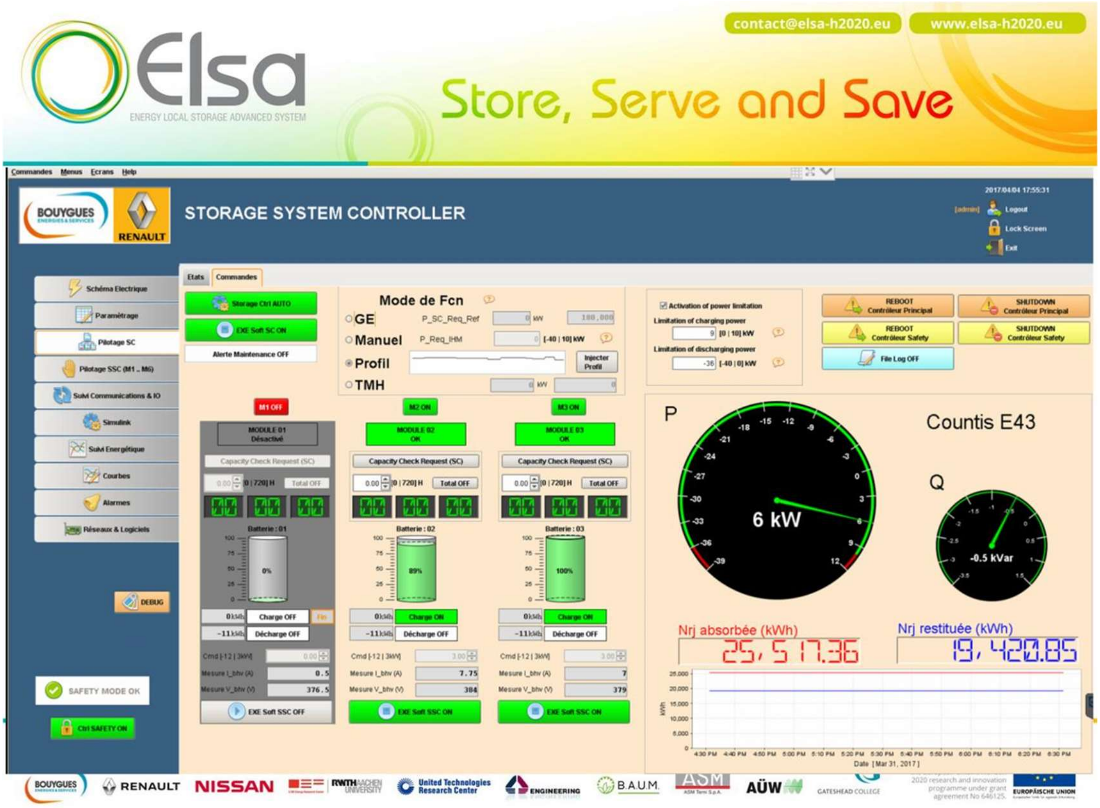
3. How much time did it take to do the assessment?
1-2 days 3-4 days 1-2 weeks longer _ please specify

4. Was sufficient training & support provided?
Yes No Partially

5. Would you recommend the assessment methodology to others?

6. Were there any improvements you would recommend?

Appendix D – Battery Management System GUI



Battery Management System GUI Sunderland & Paris Pilot Sites

Battery Management System GUI, Kempten Pilot Site