Energy in Buildings and Communities Programme

International Energy Agency

Characterization of Energy Flexibility in Buildings

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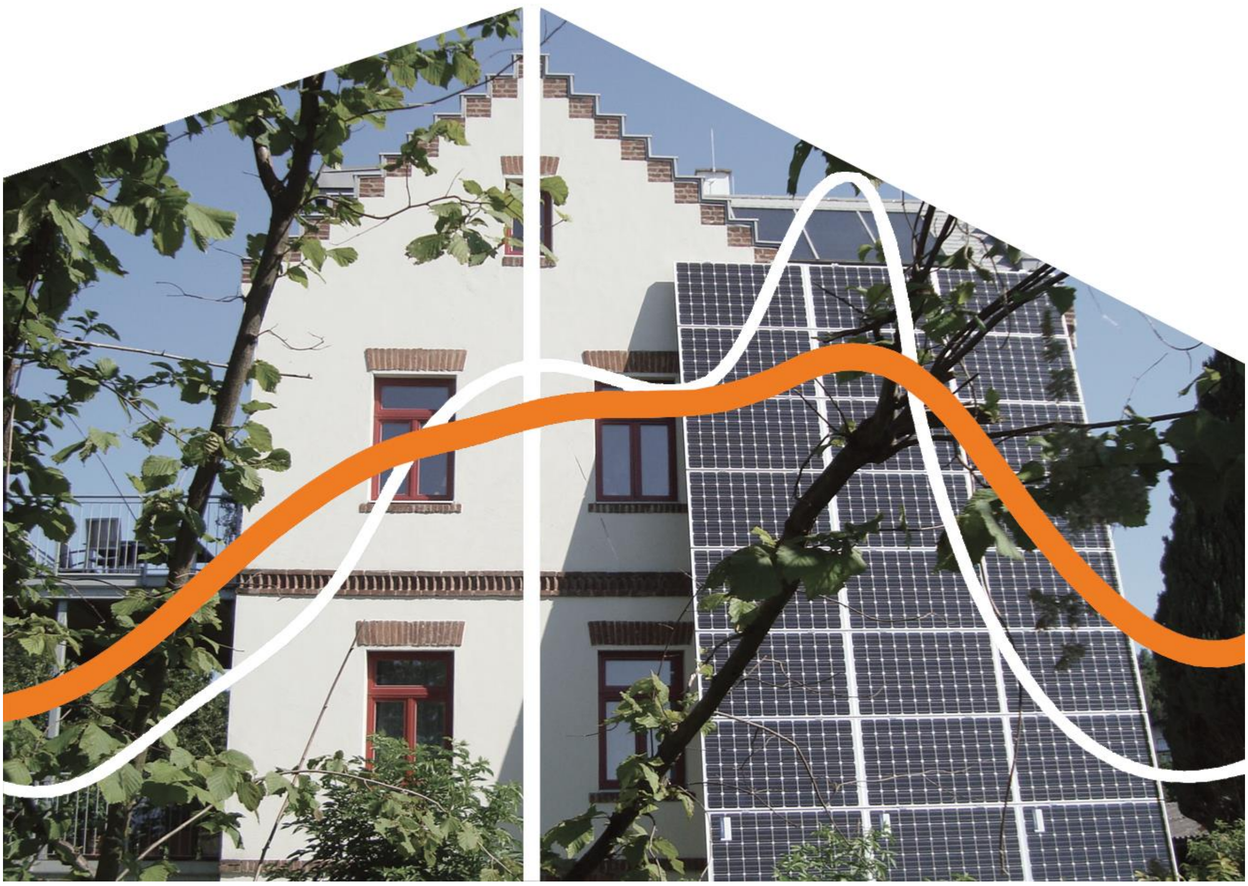
Annex 67 Energy flexible buildings

December 2019



Technology Collaboration Programme
by iea

International Energy Agency

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 28 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates research and development in a number of areas related to energy. The mission of the Energy in Buildings and Communities (EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the IEA-EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the IEA-EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. The research and development (R&D) strategies of IEA-EBC aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas for R&D activities:

– Integrated planning and building design
– Building energy systems
– Building envelope
– Community scale methods
– Real building energy use

The Executive Committee

Overall control of the IEA-EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA-EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA-EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)

Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy & CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy & CO_2 Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling & Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building & Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Energy Principles (*)
Annex 65: Long-Term Performance of Super-Insulation in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behaviour in Buildings
Annex 67: Energy flexible buildings

Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Building Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Public Communities
Annex 74: Energy Endeavour
Annex 75: Cost-effective Strategies to Combine Energy Efficiency Measures and Renewable Energy Use in Building Renovation at District Level
Annex 76: ☼ Deep Renovation of Historic Buildings towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy flexible buildings towards resilient low carbon energy systems

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings
Working Group - Cities and Communities
Working Group - Building Energy Codes
Working Group - International Building Materials Database

Management Summary

Energy flexibility represents a key building feature for the future energy systems, where the deployment of renewable energies will increase and the possibility to adapt the energy loads according to the requirements of the grid will be needed. Nevertheless, despite the given attention, a uniform understanding and a commonly accepted definition is still not in place for this building concept. The lack of a clear international framework for the requirements and properties of energy flexible buildings leads to numerous definitions that are being developed in parallel and are applied in the context of specific case studies when evaluating and/or quantifying energy flexibility. In this regard, the report aims to provide a unique and shared vision about energy flexibility, starting from the adoption of a common definition and terminology and from the analysis of the indicators currently available in literature than can be used for quantifying flexibility. According to these first achievements, a common methodology for quantifying and labelling energy flexibility has been defined and tested, in order to complete the general framework on energy flexibility. The report is structured into a series of chapter which are summarised in the following paragraphs.

Chapter 1 gives an overview of Annex 67, with the presentation of the main tasks and objectives and the general structure of the work.

Chapter 2 gives a specific introduction to the report, with an overview of the European context, the main aspects and boundaries of the energy flexibility and the general position of the Annex 67 members for addressing the topic.

Chapter 3 aims to introduce the definition and the main terminology for describing energy flexibility, in order to provide the basis for a common understanding of this rather novel concept. It commence with a detailed literature review of the current vision of flexibility and related control strategies, analyzed according to a set of criteria dealing with the implemented control signal and impact on the buildings and on the grid. A literature review is coupled with an internal survey among IEA EBC Annex 67 experts, in order to outline the main terminology to present the full scope of the energy flexibility concept, which is classified in eight categories: driving forces, definition, method, energy demand, infrastructure, stakeholders, technologies, control.

The overview about energy flexibility is in Chapter 4 completed by a detailed analysis of the indicators available in the literature for the assessment at the level of component, single building and at cluster of buildings. The identified flexibility indicators have a different focus, but three general properties of energy flexibility emerged as follows:

i) the time over which energy and power can be shifted or shed;
ii) the amount of energy or power that can be shifted or shed;
iii) the associated cost or efficiency loss at the building level that result from activating this flexibility.

Chapter 4 introduced also the concept of cluster of buildings, defined as a group of buildings interconnected to the same energy infrastructure or same aggregator, such that the change of behaviour/energy performance of each building affects both the energy infrastructure and the other buildings of the whole cluster and reports a set of indicators used for the cluster level analyses. This chapter highlights, from existing literature, how fragmented the definition of suitable indicators for energy flexibility is, and the needs for identifying a replicable and shared methodology to be widely applied

To understand and integrate the potential of energy flexible buildings in future energy systems, a holistic approach is needed harmonizing not only building and energy (both electrical and thermal) system engineering but also energy market design and even occupant interaction. As building engineers are often not familiar with all technical aspects of energy networks and vice versa, IEA EBC Annex 67 proposes a shared definition and an operative approach for evaluating energy flexibility. This approach facilitates design and operational decisions on both building and energy system level, taking into account the complex interactions between building, energy system, occupants and other boundary conditions (e.g., RES availability, weather conditions).

Taking this into consideration, Chapter 5 describes a methodology to characterize the energy flexibility available in buildings and districts (i.e. demand side), which is based on the assumption that energy flexible buildings can adjust their demand in response to penalties imposed over time with the main objective of reducing the resulting cumulative penalty (e.g. energy cost or CO_2-content of energy). In the case of the applied electricity rate, which can vary throughout the day and season to reflect specific needs (e.g. reduce demand peaks), will be referred to as a Penalty signal and the energy flexibility would be used to reduce the monthly energy bill (i.e. the resulting cumulative penalty). Therefore, in more general terms, this methodology also assumes that the time-varying needs of the power systems can be translated to Penalty signals, which are developed in order to induce the desired energy consumption patterns. This relation between Penalty signal and demand response is described here by the concept of a Flexibility Function (FF), and constitutes the core of the proposed methodology. The methodology is generic and is, thus, not only applicable for power systems, but can be utilized for all types of energy networks including district heating. In addition, the chapter describes the utilization of the Flexibility Function for the assessment of the Flexibility Index and introduces the approach for labelling energy flexibility, also coupled with the description of the Annex 67 harmonised visualization and communication tool.

Chapter 6 gives an overview of the main findings of an extensive testing phase that was carried out to evaluate and exemplify the constraints and applicability of the characterization methodology outlined in Chapter 5. The focus was primarily on evaluating the potential and interpretability using simulations and a step change of the Penalty signal – i.e., the direct approach. The chapter reports the results of a set of simulations from different modelling teams on different case studies. The aim is to identify the influence of boundary conditions on the energy flexibility, to assess the dependence of the flexibility characteristics from the Penalty signal and from the starting and boundary conditions, to evaluate the anticipation effect of model predictive control. The results show a preliminary validation of the methodology and provide an effective and practical example for the implementation.

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Abbreviations

Abbreviations	Meaning
C_{ARD}	The amount of heat that can be added to the storage in the time frame of an ADR event
CC	Collaborative Consumption
CHP	Combined Heat and Power
DER	Distributed Energy Resources
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand Site Management
DSO	Distribution System Operator
EE	Energy Efficiency
EFSI	Energy Flexibility Saving Index
EH	Electric Heater
FET	Flexible-Evaluation-Tool
FF	Flexibility Function
FI	Flexibility Index
FIR	Finite Impulse Response
HP	Heat Pump
HVAC	Heating, Ventilation and Air Condition
KPI	Key Performance Indicator
LTI	Linear and Time-variant
MPC	Model Predictive Control
NZEB	Net Zero Energy Buildings
NZEC	Net Zero Energy Communities
η_{ADR}	Storage efficiency
PSE	Power Shifting Efficiency
PV	Photovoltaic
Q_s	Power shifting capacity
RBC	Rule-Based Controller
R3C3	RC thermal network model
RES	Renewable Energy Sources
SBC	Smart Building Cluster
SOC	State Of Charge
STES	Structural Thermal Energy Storage
TABS	Thermal Activated Building System
TES	Thermal Energy Storage
VPP	Virtual Power Plant
VRES	Variable Renewable Energy Sources

1. Introduction to Annex 67

Substantial and unprecedented reductions in carbon emissions are required if the worst effects of climate change are to be avoided. A major paradigmatic shift is, therefore, needed in the way heat and electricity are generated and consumed in general, and in the case of buildings and communities in particular. The reduction in carbon emissions can be achieved by firstly: reducing the energy demand as a result of energy efficiency improvements and secondly: covering the remaining energy demand by renewable energy sources. Applying flexibility to the energy consumption is just as important as energy efficiency improvements. Energy flexibility is necessary due to the large-scale integration of central as well as decentralized energy conversion systems based on fluctuating renewable primary energy resources, which is a key component of the national and international roadmaps to a transition towards sustainable energy systems where the reduction of fuel poverty and CO_2-equivalent emissions are top priorities.

In many countries, the share of renewable energy sources (RES) is increasing parallel with an extensive electrification of demands, where the replacement of traditional cars with electrical vehicles or the displacement of fossil fuel heating systems, such as gas or oil boilers, with energy efficient heat pumps, are common examples. These changes, on both the demand and supply sides, impose new challenges to the management of energy systems, such as the variability and limited control of energy supply from renewables or the increasing load variations over the day. The electrification of the energy systems also threatens to exceed already strained limits in peak demand.

A paradigm shift is, thus, required away from existing systems, where energy supply always follows demand, to a system where the demand side considers available supply. Taking this into consideration, flexible energy systems should play an important part in the holistic solution. Flexible energy systems overcome the traditional centralized production, transport and distribution-oriented approach, by integrating decentralized storage and demand response into the energy market. In this context, strategies to ensure the security and reliability of energy supply involve simultaneous coordination of distributed energy resources (DERs), energy storage and flexible schedulable loads connected to smart distribution networks (electrical as well as thermal grids).

Looking further into the future, the ambition towards net zero energy buildings (NZEB) imposes new challenges as buildings not only consume, but also generate heat and power locally. Such buildings are commonly called prosumers, which are able to share excess power and heat with other consumers in the nearby energy networks. Consequently, the energy networks must consider the demand of both heat and electricity as well as the local energy generation. If not, it may result in limitations of the amount of exported energy for building owners to avoid power quality problems; for example, Germany has already enforced restrictions on private PV generation exported to the grid. Furthermore, today the distribution grid is often sized based on buildings that are heated by sources other than electricity. However, the transition to a renewable energy system will, in many areas, lead to an increase in electrical heating, by heat pumps for example, which will lead to an increase in the electricity demand even if the foreseen reduction in the space heating demand via energy renovation is realized. The expected penetration of electrical vehicles will increase the loads in the distribution grids, but they may also be used for load shifting by using their batteries; they could in effect become mobile storage systems. All these factors will, in most distribution grids, call for major reinforcement of the existing grids or for a more intelligent way of consuming electricity in order to avoid congestion problems. The latter approach is holistically referred to as a 'Smart Grid' (or as a Smart Energy Network, when energy carriers other than electricity are considered as well) where both demand and local production are controlled to stabilize the energy networks and thereby lead to a better exploitation of the available renewable energy sources towards a decarbonisation of the building stock. Buildings are, therefore, expected to have a pivotal role in the development of future Smart Grids/Energy networks, by providing energy flexibility services.

As buildings account for approximately 40 % of the annual energy use worldwide, they will need to play a significant role in providing a safe and efficient operation of the future energy system. They have the potential to offer significant flexibility services to the energy systems by intelligent control of their thermal and electric energy loads. More specifically, a large part of the buildings' energy demand may be shifted in time and may thus significantly contribute to increasing flexibility of the demand in the energy system. In particular, the thermal part of the energy demand, e.g. space heating/cooling, ventilation, domestic hot water, but also hot water for washing machines, dishwashers and heat to tumble dryers, can be shifted. Additionally, the demand from other devices like electrical vehicles or pool pumps, can also be controlled to provide energy flexibility.

All buildings have thermal mass embedded in their construction elements, which makes it possible to store a certain amount of heat and thereby postpone heating or cooling from periods with low RES in the networks to periods with excess RES in the networks without jeopardizing the thermal comfort. The amount of thermal storage available and how quickly it can be charged and discharged affect how this thermal storage can be used to offer flexibility. Additionally, many buildings may also contain different kinds of discrete storage (e.g. water tanks and storage heaters) that can potentially contribute to the energy flexibility of the buildings. A simple example of a discrete storage system is the domestic hot water tank, which can be pre-heated before a fall in available power. From these examples, it is evident that the type and amount of flexibility that can be offered will vary among buildings. A key challenge is, therefore, to establish a uniform framework that describes how flexibility can be offered in terms of quantity and quality.

Storage (thermal or electrical) is often necessary in order to obtain energy flexibility. However, storage has "roundtrip" energy conversion losses, which may lead to a decrease in the energy efficiency in the single building. But as energy flexibility ensures a higher utilization of the installed RES, the efficiency of the overall energy system will increase. A decrease in efficiency will mainly be seen in well-controlled buildings due to the conversion losses when storing energy. However, most buildings are not well-controlled. In this latter case, the introduction of energy flexibility may typically lead to a more optimal control of the buildings and in this way simultaneously increase the energy efficiency of the buildings and more than overcome the conversion losses when providing energy flexibility.

Various investigations of buildings in the Smart Grid context have been carried out to date. However, research on how energy flexibility in buildings can actively participate the future energy system and local energy communities, and thereby facilitate large penetration of renewable energy sources and the increasing electrification of demand, is still in its early stages. The investigations have either focused on how to control a single component - often simple on/off controlled - or have focused on simulations for defining indicators for energy flexibility, rather than on how to optimize the energy flexibility of the buildings themselves.

The concept of flexible loads, demand side management and peak shaving is of course not new, as demand response already in the 1970s was utilized in some power grids. Although the concept is not new, it has been understudied as compared to strictly building energy efficiency research.

This was the main, although not sole, reason why IEA EBC Annex 67 Energy Flexible Buildings was initiated.

1.1. IEA EBC Annex 67

The aim of IEA EBC Annex 67 was to increase the knowledge, identify critical aspects and possible solutions concerning the energy flexibility that buildings can provide, plus the means to exploit and control this flexibility. In addition to these technical aims, Annex 67 also sought to understand all stakeholder perspectives - from users to utilities - on energy flexibility, as these are a potential barrier to success. This knowledge is crucial for ensuring that the energy flexibility of buildings is incorporated into future Smart Energy systems, and thereby facilitating the transition towards a fossil free energy system. The obtained knowledge is also important when developing business cases that will utilize building energy flexibility in future energy systems – considering that utilization of energy flexibility in buildings may reduce costly upgrades of distribution grids.

The work of IEA EBC Annex 67 was divided into three main areas:

- terminology and characterization of energy flexibility in buildings
- determination of the available energy flexibility of devices, buildings and clusters of buildings
- demonstration of and stakeholder's perspective on energy flexible buildings

1.1.1. Terminology for and characterization of Energy Flexibility in Buildings

A common terminology is important in order to communicate a building's or a cluster of buildings' ability to provide energy flexible services to the grid. The available energy flexibility is often defined by a set of generally static Key Performance Indicators. However, the useful energy flexibility will be influenced by internal factors such as the form or function of a building, and external factors, such as local climatic conditions and the composition and capacity of the local energy grids. There is, therefore, a need for a dynamic approach in order to understand the services a building can provide to a specific energy grid. A methodology for such a dynamic approach has been developed during the course of IEA EBC Annex 67.

The findings in the area of terminology and characterization of energy flexibility in buildings are reported in the deliverable "Characterization of Energy Flexibility in Buildings" mentioned below.

1.1.2. Determination of the available Energy Flexibility of Devices, Buildings and Clusters of Buildings

Simulation is a powerful tool when investigating the possible energy flexibility in buildings. In IEA EBC Annex 67, different simulation tools have been applied on different building types and Common Exercises have been carried out on well-defined case studies. This approach increased the common understanding of energy flexibility in buildings and was useful for the development of a common terminology.

Simulations are very effective to quickly test different control strategies, among which some may be more realistic than others. Control strategies and the combination of components were, therefore, also tested in test facilities under controllable, yet realistic, conditions. Hardware-in-the-loop concepts were utilized at several test facilities, where, for example, a heat pump and other components were tested combined with the energy demand of virtual buildings and exposed to virtual weather and grid conditions.

The results of the investigations are described in several of the below mentioned publications by IEA EBC Annex 67.

1.1.3. Demonstration of and Stakeholders Perspective on Energy Flexible Buildings

In order to be able to convince key stakeholders such as policy makers, energy utilities, grid operators, aggregators of energy flexibility, building industry and consumers about the benefits of energy flexibility to the future energy systems, proof of concept based on demonstrations in real buildings is crucial. Example cases of obtaining energy flexibility in real buildings have, therefore, been investigated and documented in reports, articles and papers and as examples in the deliverables of IEA EBC Annex 67.

When utilizing the energy flexibility in buildings, the comfort, economy and normal operations of the buildings can be influenced. If the owner, facility manager and/or users of a building are not interested in exploiting energy flexibility to increase building smartness, it does not matter how energy flexible the building is, as the building will not be an asset for the local energy infrastructure. However, the involvement of utilities, regulators and other stakeholders, for example, building automation providers, can provide incentives and increase awareness of and thereby participation in providing energy flexibility. It is, therefore, very important to understand which barriers exist for the stakeholders involved in the energy flexible buildings and how they may be motivated to contribute with energy flexibility in buildings to stabilize the future energy grids. Investigating the barriers and benefits for stakeholders is, therefore, of paramount importance and work was completed in IEA EBC Annex 67 to understand these in more detail. Findings from this work are described in the report “Stakeholder perspectives on Energy Flexible Buildings” mentioned below.

1.1.4. Deliverables from IEA EBC Annex 67

Many reports, articles and conference papers have been published by IEA EBC Annex 67 participants. These can be found on http://annex67.org/publications/.

The main publications by IEA EBC Annex 67 are, however, the following reports, which all may be found on http://annex67.org/publications/deliverables/.

Principles of Energy Flexible Buildings summarizes the main findings of Annex 67 and targets all interested in what energy flexibility in buildings is, how it can be controlled, and which services it may provide.

Characterization of Energy Flexibility in Buildings presents the terminology around energy flexibility, the indicators used to evaluate the flexibility potential and how to characterize and label energy flexibility.

Stakeholder perspectives on Energy Flexible Buildings displays the view point of different types of stakeholders towards energy flexible buildings.

Control strategies and algorithms for obtaining Energy Flexibility in buildings reviews and gives examples on control strategies for energy flexibility in buildings.

Experimental facilities and methods for assessing Energy Flexibility in buildings describes several test facilities including experiments related to energy flexibility and draws recommendations for future testing activities.

Examples of Energy Flexibility in buildings summarizes different examples on how to obtain energy flexible buildings.

Project Summary Report brief summary of the outcome of Annex 67.

2. Need for Characterization of Energy Flexibility from Buildings

Armin Knotzer and Roberta Pernetti

2.1. Introduction

In recent decades the development in building technologies has been concentrated on obtaining sufficient indoor comfort and on increasing the energy efficiency of buildings including the energy service systems. This has been driven by an in many countries continuous strengthening of the building regulations. In e.g. EU it is regulated via the Energy Performance of Buildings Directive (EPBD). However, buildings have up to now mainly been considered as passive consumers (and more recently also as passive producers) of energy where the surrounding energy networks ensure a sufficient energy supply to buildings. As explained in the former chapter, this has started to change as the stability of the energy networks traditionally was ensured by central fossil fuelled energy plants, energy plants which many countries have decided to phase out and replace with renewable energy sources (RES), which have an intrinsic variability that significantly will affect the operation and stability of the energy networks. There is, therefore, a need for a transition from “generation on-demand” to “consumption on-demand” to match the instantaneous energy generation. In practise, this means that the energy consumption needs to become flexible.

As buildings account for approximately 40 % of the annual energy use worldwide, there is a need to go from being passive to active consumers(/producers), which are capable of adjusting their energy consumption according to the actual level of energy in the energy networks – i.e. consume more during period with much RES in the networks e.g. by storing energy and opposite reduce the energy consumption during energy shortages in the networks. Therefore, buildings need to become energy flexible. As energy flexibility of buildings is a underexplored area, there is a need for knowledge increase and transfer on how to obtain and characterize energy flexibility from buildings. There is further a clear need for a common way to characterize the energy flexibility that a building or a cluster of buildings can provide to the energy networks so this energy flexibility becomes an asset for the energy networks. The development of a methodology for characterization of Energy Flexibility has, therefore, been an important task of IEA EBC Annex 67.

2.2. The Work carried out in IEA EBC Annex 67

This report describes the results from the definition and characterization activities in IEA EBC Annex 67. Detailed literature reviews have been carried out, accompanied by simulations on different case studies to investigate existing indicators and for developing ideas for characterization and labelling methods. Furthermore, IEA EBC Annex 67 has been a stakeholder in the EU studies on Smart Readiness Indicators, and has developed a position paper on this (Pernetti, Reynders and Knotzer, 2017).

The “Clean Energy for All European” package (EC, 2016a) of the European Commission sets out the energy policy framework towards 2030 and treats buildings as an essential part of the clean energy transition of Europe. The principle “energy efficiency first” (EC, 2015) drives the transformation of the conventional centralized energy system based on fossil fuels towards a decentralized system powered by renewable energy sources. In a similar way the Pan-Canadian Framework on Clean Growth and Climate Change (Environment and Climate Change Canada, 2016) targets to develop and adopt increasingly stringent building codes, starting in 2020, with the goal that provinces and territories adopt a “net-zero energy ready” model building code by 2030. Also in China the Future Energy Roadmap foresees an energy consumption limitation, the electricity proportion is supposed to increase from 20 % to 60% and renewable energy proportion from 26 % to 55 % (Wang, 2019). In the U.S. ongoing activities like the GridOptimal™ Initiative, supported by different energy supplying companies, uptake grid resiliency goals and recognise that operation patterns will increasingly drive building system selection preferences (Miller, 2018).

Energy systems based on variable renewable energy sources (VRES) are characterized by intermittent generation, and their rapid increase challenges the stability of both thermal and electric grids (Whiteman et al., 2016). A mitigating effect of the stress put on the grid by VRES penetration can be provided by buildings, which are gradually moving from standalone consumers to interconnected prosumers (both producers and consumers) able to provide and often store renewable energy while actively participate in demand response.

Despite the fact that the Energy Performance of Buildings Directive (EU, 2010) and the Renewable Energy Directive (EU, 2009) have stimulated the deployment of on-site renewable energy systems, the onsite (or nearby) renewable energy production and self-consumption in European countries are not at their full potential. This is partly due to rigid regulatory frameworks and lack of investments. The instantaneous sharing of produced energy among buildings is allowed or encouraged only in a few member states and currently the storage technologies are too expensive for massive application. Therefore, it is necessary to identify solutions aimed at changing the relationship between the grid and the consumers. Future buildings should adapt their energy demand to the needs of the grid and the renewable production, while maintaining high comfort standards and low operating costs.

In this regards, the research conducted by IEA EBC Annex 67 emphasizes energy flexibility of buildings as part of the solution for the problem, and acknowledges that the interactions between buildings and the energy infrastructure in time and scale should be fostered. The use of energy flexibility in the interaction of the building with the grid will increase the potential exploitation of renewables and mitigate CO_2-emissions on an aggregated level for achieving the intended de-carbonization of energy services by 2050. On one hand, each building should ensure a certain level of flexibility and, on the other hand, building design and control should go beyond that of individual buildings and it is important to investigate novel approaches for fostering the interaction of buildings, by introducing the concept of building cluster.

To understand and integrate the potential of energy flexible buildings in future energy systems, a holistic approach is needed to harmonize building and energy (both electrical and thermal) system engineering but also energy market design and even occupant interaction. As building engineers are often not familiar with all technical aspects of energy networks and vice versa, IEA EBC Annex 67 proposes a shared definition and an operative approach for evaluating energy flexibility that are easy to understand by both parties. This approach facilitates design and operational decisions on both building and energy system level, taking into account the complex interactions between building, energy system, occupants and other boundary conditions (e.g. RES availability, weather conditions) (Junker et al., 2018).

As a first step, this report presents the terminology and definition of energy flexibility (Chapter 3) in order to set-up a common language and enable the reader to understand the main features and the potential benefits associated to energy flexibility.

The second part (Chapter 4) reports an overview of the approaches and the indicators developed in the past recent years to represent the building features related to energy flexibility at the level of single buildings and clusters of buildings. This literature review highlights that, although a clear need for assessing energy flexibility, the evaluation approaches are still fragmented.

The knowledge background on definition, evaluation approaches and indicators described in Chapters 3 and 4 fostered the definition of a quantitative methodology for evaluating and labelling energy flexibility within IEA EBC Annex 67 (Chapter 5). In particular, the methodology takes into account not only the technical aspects or services on a building level, but also the interaction with the energy system, occupants and other boundary conditions. While studies demonstrating the potential of energy flexibility through case studies are manifold, a literature review in the framework of IEA EBC Annex 67 concluded that limited methodologies exist aiming at a direct prediction of the amount of energy flexibility a building can offer to the grid. Such a uniform and direct quantification method – which starts from what a building may offer rather than how much flexibility is harvested in a specific case study – is a prerequisite to establish a common basis for comparison of the flexibility potential of different buildings (and technologies) between studies and applications. Hence, this bottom-up viewpoint, supported by IEA EBC Annex 67, opens the path towards labelling of energy flexibility, as a part of smartness, in buildings.

Energy flexibility is obtained by the level of controllability of the system taking into account its technical constraints, storage options and interaction with its surroundings. Therefore, it is evident that a direct prediction of the actual, instantaneous energy flexibility that a building can offer to the energy system requires a case-specific analysis. Similar to the prediction of the actual energy use of buildings, predicting energy flexibility requires a detailed dynamic modelling of the system, its constraints and its boundary conditions, and would result in a flexibility profile that varies in time (Stinner et al., 2016; De Coninck et al., 2016; Oldewurtel et al., 2013; Reynders et al., 2017). As these profiles or their underlying models are often difficult to communicate – and interpret – between stakeholders at different levels and sides of the energy system, IEA EBC Annex 67 focussed on characterization and labelling of energy flexibility by energy flexibility indicators.

Through an extensive literature review (Reynders et al., 2018), and taking into account the interface between buildings and energy systems when dealing with energy flexibility, three general properties appear when communicating energy flexibility:

- Capacity (amount of energy that can be shifted, including any pre-or rebound effects)
- Time aspects (starting time and duration)
- Cost (potential cost saving or energy use associated to activating the available flexibility)

These properties generally follow from underlying definitions of energy flexibility as a change in power or energy compared to a reference scenario. The methodology introduced by IEA EBC Annex 67 represents energy flexibility by quantifying the amount of energy a building can shift according to external forcing factors, without compromising the occupant comfort conditions and taking into account the technical constraints of the building and of its HVAC system. In that, it acknowledges that forcing factors act as boundary conditions, which can change over the lifetime of a building and with different levels of frequency:

- **Low frequency factors**: climate change, macro-economic factors, technology improvement, energy costs, use of the building
- **High frequency factors**: energy mix/RES availability, energy prices, internal/solar gains, user behaviour, ambient temperature

Consequently, the energy flexibility of a building is not a fixed static value, but varies according to such forcing factors and control signals (henceforth called Penalty signal), which induce a system response (see Chapter 5). Hence, a building is able to shift and move part or all of the instantaneous energy demand minimizing the effect of and external control/Penalty signal. Among others the Penalty signal could be designed to 1) reduce the peak load of a specific distribution grid, 2) minimize the energy consumption, 3) minimize the cost, or 4) minimize the CO_2 footprint of the building – or a combination of those criteria. In order to enable a comprehensive understanding of the methodology proposed within IEA EBC Annex 67, Chapter 6 reports a set of implementation examples.

This report sets up a comprehensive framework for understanding and evaluating energy flexibility, representing a key reference for the relevant decision makers at different level, from the designers of the buildings towards the policy makers, as highlighted in Table 2.1.

Table 2.1 Overview of the beneficiary target groups.

Target group	Potential benefits from this report
Scientific community	Classification and evaluation of the indicators available in literature dealing with energy flexibility (Chapter 4 and Appendix A and B) Structured and replicable methodology for assessing energy flexibility (Chapter 5) Examples of implementation of the methodology (Chapter 6)
Building designers	Indicators and methodologies for assessing energy flexibility as a support for the adoption of technology fostering energy flexibility during the design phase (Chapters 4-5)
Grid operators	Indicators and methodologies for assessing energy flexibility (Chapters 4-5) by: • evaluating the impact of the building operation on the grids • promoting incentives and penalties fostering the adoption of building solutions that minimises the stress on the grid
Policy makers	General definition (Chapter 3) and approach for labelling energy flexibility (Chapter 5)

3. Energy Flexibility Terminologies and Definitions

Anna Marszal-Pomianowska and Søren Østergaard Jensen

3.1. Literature Reviews on Definitions

Energy flexibility of a building is really not a new concept. It originates from the demand side management regime, which for decades has been applied by the designers and operators to foster stable and bottleneck-free operation of electrical energy systems (Behrangrad, 2015; Delgado, 1985). However, as the transition of both the demand and supply side of the energy system imposes new challenges to the management of the whole energy system, such as the variability and limited control of energy supply from renewables or the increasing load variations over the day, the energy flexible building concept has gained more international attention. Nevertheless, despite the given attention, a uniform understanding and a commonly accepted definition is still not in place for this concept. The lack of a clear international framework for the requirements and properties of energy flexible buildings leads to numerous definitions that are being developed in parallel and are applied for a particular case when evaluating and/or quantifying energy flexibility.

In particular, the definitions and evaluation approaches vary according to the different components of a building structure and HVAC (Heating, Ventilation and Air Conditioning) system that can be activated to deliver energy flexibility. The adjustability/flexibility of the heating and cooling system has been the subject of many studies. Hewitt (Hewitt, 2012) illustrated that heat pumps and hot water storage together with a sufficient tariff system can significantly contribute to the integration of wind power into the electricity network in UK and Ireland. Arteconi et al. (Arteconi et al., 2012) presented different thermal energy storage (TES) systems within the building, which can be activated to shift electrical loads in time and thus become a powerful instrument for Demand Site Management (DSM) strategies. In their later study (Arteconi et al., 2013) the authors analyzed the flexibility potential of the TES systems coupled with a heat pump delivering heat to either radiators or underfloor heating in a residential house in UK. Hedegaard et al. (Hedegaard, K. et al., 2012) illustrated that individual heat pumps in combination with passive heat storage, i.e. building thermal mass, are an important step in cost-effective integration of wind power in the Danish energy system.

A number of studies have shown that the structural thermal mass can be easily activated and utilized for flexibility purpose, e.g. in both old and new residential buildings (Dréau, and Heiselberg, 2016; Pedersen et al., 2017; Reynders et al., 2013) and in non-residential buildings (Arteconi et al., 2014; Xue et al., 2014). Much of the research on utilization of the thermal mass of buildings describe different control strategies that can be applied to maximize benefits to the buildings and/or the grid (Hong et al., 2013; Oldewurtel et al., 2010; Široký et al., 2011; Tahersima et al., 2011). For example, it is demonstrated in a variety of studies that smart operation of heat pumps (Yu, 2013) e.g. with frequency control (Kim et al., 2016) or with use of model predictive control (MPC) (Halvgaard et al., 2012) can contribute to limit the peak power demand of a building and to maximize the self-consumption of the locally produced electricity (Fischer et al., 2017; Vanhoudt et al., 2014).

In addition to literature focusing on thermal loads, different studies demonstrate how much flexibility can be achieved by adapting the time of use of plug loads, such as washing machines, dishwashers and tumble dryers (Paatero and Lund, P. D., 2006; Widén, 2014), by application of an optimal charging schedule of electric vehicles (Clement et al., 2009; Mendaza, 2014), or by controlling and varying temperature between the cooling units of a commercial multi-zone refrigeration system (Hovgaard et al., 2013). Few publications have studied the effect of simultaneous utilization of more than one DSM strategy, e.g. PV panels in combination with electric vehicles, heat pump, plug loads, storage (battery and thermal mass) (Salpakari and Lund, 2016; Salpakari et al., 2017) or PV panels with air-water heat pumps in a zero energy building (Dar et al., 2014).

A large share of the identified papers do not explicitly define or focus on the concept of energy flexibility, yet deal with the development of control strategies and algorithms for specific case studies. Therefore, in order to synthetize the definitions about energy flexibility or energy flexible buildings, four main topics have been identified and analyzed based the literature review (Table 3.1):

- Time/duration of the change;
- Applied penalty/control signal;
- Possibility of compromising other building performance;
- Local energy infrastructure context

Although multiple definitions cover more than one of the identified topics, Table 3.1 shows that none of them gives a comprehensive definition to encompass all properties. Nevertheless, all definitions are built upon the basic concept that *energy flexibility represents the ability of a building to adapt its energy demand profile to provide specific services required by the local energy infrastructure.*

Table 3.1 Focus topics addressed when defining energy flexible buildings.

		Topics included in definition's body			
Reference	**Identified definitions and introductions to the concept of energy flexibility**	**Time/ duration of the change**	**Applied penalty/ control signal**	**Possi-bility of compro-mising other building perfor-mances**	**Local energy infrastructure context**
Hewitt (Hewitt, 2012)	"…the concept of using our building stock to effectively store energy for a number of hours prior to use is available…There are a number of methods available to balance the electricity network in times of high wind energy availability. It has been illustrated that the buildings themselves have some ability … "	x			x (power grid)
Hedegaard et al. (Hedegaard, K. et al., 2012)	"Flexible technologies such as large heat pumps, electric boilers, and heat storages in combined heat and power (CHP) systems, and electric vehicles can play a significant role in facilitating the integration of wind power… As such, ground heat pumps and air/water heat pumps can be operated flexibly by storing heat in the central heating system and in the construction. "				x (power grid and district heating)
Le Dréau et al. (Le Dréau,	"This (flexibility) factor illustrates the ability to shift the energy use from high to low price periods."	x	x price	x	

Reference	Identified definitions and introductions to the concept of energy flexibility	Topics included in definition's body: Time/ duration of the change	Applied penalty/ control signal	Possi-bility of compro-mising other building perfor-mances	Local energy infrastructure context
and Heiselberg, 2016)					
Reynders et al. (Reynders et al., 2013)	"... short-term flexibility is shown to shift the electricity use for heating without jeopardizing thermal comfort."			x	x (power grid)
Xue et al. (Xue et al., 2014)	"Buildings can help improving energy performance of an electrical grid (…). However, characterization of power demand alteration potentials of buildings and their collective effect (…)."				x (power grid)
Arteconi et al. (Arteconi et al., 2014)	"From the utility point of view, thermal activated building systems (TABS) represent flexible energy demand systems because they allow a significant load control without requesting for particular design specifications on the original systems."				x (energy system)
Oldewurtel et al. (Oldewurtel et al., 2010)	"… price information and economic incentive for end-consumers to react accordingly. This creates an important feedback in the system, acting against both peak grid loading and peak electricity demand, as grid-friendly consumer behaviour is rewarded."		x price $ incentive		x (power grid)
Tahersima et al. (Tahersima et al., 2011)	"... to deviate power consumption of the heat pump from its optimal value, in order to compensate power imbalances in the grid. The heating systems could be forced to consume energy, i.e. storing it in heat buffers when there is a power surplus in the grid; and be prevented from using power, in case of power shortage."	x		x	x (power grid)
Hong et al. (Hong et al., 2013)	"to maximize the time window within which the heat pump operating time could be shifted without significantly affecting comfort or the hot water supply temperatures to the end-user"	x		x	x (power grid)
Kim et al. (Kim et al., 2016)	"Additionally, the significant energy storage capacity inherent in building structures allows buildings to be exploited as distributed energy resources, providing demand-side flexibility in electrical grids. In particular, the flexibility provided by the building's thermal inertia can be achieved via ancillary services of heating,				x (power grid)

Reference	Identified definitions and introductions to the concept of energy flexibility	Topics included in definition's body			
		Time/ duration of the change	Applied penalty/ control signal	Possi-bility of compro-mising other building perfor-mances	Local energy infrastructure context
	ventilating, and air-conditioning (HVAC) systems."				
Halvgaard et al. (Halvgaard et al., 2012)	"In this paper, we use heat pumps for heating residential buildings with a floor heating system. We use the thermal capacity of the building to shift the energy consumption to periods with low electricity prices. In this way the heating system of the house becomes a flexible power consumer in the Smart Grid."	x	x price		x
Fischer et al. (Fischer et al., 2017)	"The most common parameters (...) characterizing the flexibility of a system are the amount of power change, duration of the change, rate of change, response time, shifted load and maximal hours of load advance. (...) it is suggested in this work that recovery time should also be included to the list of flexibility parameters, to know when a pool is ready to be used again by the operator after being used once."	x			x (power grid)
Dar et al. (Dar et al., 2014)	"Two leading scenarios in this aspect are identified: (i) where the energy system is promoting the building's own energy supply security, and (ii) where the building's energy system is actively participating to reduce stress on the grid. The gap between these two scenarios could be seen as the flexibility that an all-electric Net-zero energy buildings (NZEB could offer to the grid."				x (power grid)
Six et al. (Six et al., 2011)	"…flexibility, defined as the ability to shift the consumption of a certain amount of electrical power in time (number of hours or kWh). The flexibility of a heat pump in smart or intelligent grids can be seen in two different ways. Delay of (a part of) the electricity consumption of the heat pump over a limited period, although there is a demand for space heating and/or domestic hot water … Forced electricity consumption of the heat pump over a certain period although there is no or low demand for space heating and/or domestic hot water…"	x			x (power grid)
Nuytten et al., (Nuytten et al., 2013)	"The flexibility of the installation allows for changes in the energy use over time and is a valuable property when the supply of energy has an increasingly intermittent character"	x			x (power grid)

Reference	Identified definitions and introductions to the concept of energy flexibility	Topics included in definition's body: Time/ duration of the change	Applied penalty/ control signal	Possi-bility of compro-mising other building perfor-mances	Local energy infrastructure context
D'hulst et al. (D'hulst et al., 2015)	"For such consumption changes to be acceptable, they may not impact the correct functioning of the appliances, nor reduce the comfort level of the users. This is what defines 'the flexibility' of the appliances: the power increases and decreases that are possible within these functional and comfort limits, combined with how long the changes can be sustained."	x		x	x (power grid)
Linear (n.d.)	"…the electricity consumption of several appliances is shifted to a more beneficial moment in time."	x			x (power grid)
Šikšnys et al. (Siksnys et al., 2015)	"Flex-object is a multidimensional object capturing two aspects: (1) a time flexibility interval and (2) an amount profile with a sequence of consecutive slices, each defined by minimum and maximum bounds of the amount."	x			

Based on the definitions found in the literature, which can be seen in Table 3.1 and are often very purpose specific, IEA EBC Annex 67 developed the following definition, that in more overall terms hopefully is easy understood by all:

The energy flexibility of a building is the ability to manage its demand and generation according to local climate conditions, user needs and grid requirements.

Energy flexibility of buildings will thus allow for demand side management/load control and thereby demand response based on the requirements of the surrounding grids.

3.2. Common Terminology and Definitions

The literature review presented in Section 3.1 shows discrepancies in the flexibility definitions. The energy flexible buildings are on the boundary of many disciplines and within the scope of many interdisciplinary projects, in which the involved professionals have various backgrounds and might not have a mutual understanding of the concept.

Therefore, a study of the terminology used in practice were carried out based on scientific publications written by the IEA EBC Annex 67 participants and a survey among IEA EBC Annex 67 experts. In total more than 50 articles and papers were reviewed. 25 international experts responded to the following questions:

- What should be the final goal of energy flexibility in buildings?
- Have you ever considered (studied) building energy flexibility in your work?
- What are your experiences, coming from your own projects?
- Do you think energy flexibility should, beside the evident short time effects, say anything about long-term effects on the functions, design and facility planning of a building?
- Which influence should the market (and prices) have in the definition of building energy flexibility?

The results of the investigations are summarized in Figure 3.1 which outlines the main eight terminology categories to present the full scope of the energy flexibility concept. In the following section more explanation is given to the categories, which were additionally discussed in the publications or were given high priority by the experts during the survey.

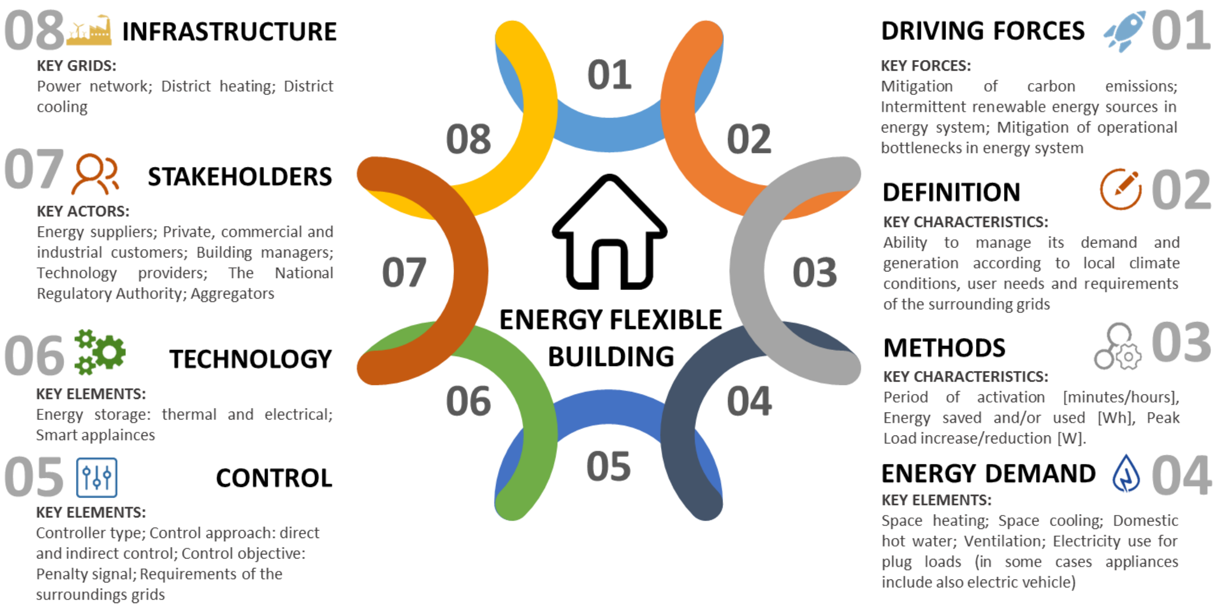


Figure 3.1 Key categories describing the scope of the energy flexible building concept.

3.2.1. Driving Forces

The main driving force behind the application of energy flexibility is the reduction of carbon emissions and thereby the mitigation of climate change effects. In order to achieve this ultimate goal, the research environment has developed a list of intermediate goals, which are often named as motivation for energy flexible buildings:

- Increase the use of intermittent renewable energy sources (RES) in the energy system
- Mitigate operational bottlenecks in the energy system and local energy infrastructure
- Reduce investments in the grid infrastructure, such like peak load power plants, cables reinforcement etc.

Additionally, the survey results indicated that experts perceive the ability to shift energy loads either as support to the energy infrastructure, or as an opportunity to optimize self-consumption and hence be more independent from the energy infrastructure.

Furthermore, the experts pointed out that although the energy flexible buildings can significantly contribute to accomplish these goals, the market addressing the flexibility service does not yet exist, thus it is difficult for the stakeholders, such like building owners or utilities, to see the potential and relate to the topic.

3.2.2. Definition

Section 3.1 describes the full literature study of the definitions used to outline the phenomena of energy flexible buildings – see detailed explanation of characteristics provided in Section 3.1.

3.2.3. Methods

How much flexibility can be delivered by the building and what is the best way to quantify it? As these questions have been discussed in numerous IEA EBC Annex 67 publications and a significant share of the IEA EBC Annex 67 work, project time has been dedicated to answer this question. Chapters 4 and 5 discuss in detail the key performance indicators (KPIs) for energy flexibility and propose a generic methodology to evaluate and quantify energy flexibility.

Based on the reviewed material it can be concluded that each KPI or method used to evaluate flexibility includes the following 3 characteristics:

- *Period of activation*: the time, when a building can either reduce or increase its energy use and thus shift energy consumption to another period. It can be expressed either in seconds, minutes, hours or even days depending on the context [sec/min/h/d].
- *Energy saved and/or used*: the amount of the energy that is moved to another period. It can be determined for a single activation event or for a certain period, e.g. day, week, month, year depending on the context [kWh]
- *Peak load reduction/increase*: the maximum change in demand. Similar to energy it can be determined for a single activation event or for the certain operation period, which is often dependent on the context [kW]

3.2.4. Energy Demand

Many types of energy loads have been investigated from the perspective of how much flexibility they can deliver. The choice of which energy load should be modulated is closely related to the local context and requirements of the surrounding grids. Of course, this choice depends on the building type, function, available HVAC technologies and control strategies.

3.2.5. Control

It is the crucial part of the energy flexible building concept and always a part of any investigation of energy flexibility potential of a building. The essential characteristics of control are:

- *Controller type*, which can be optimal control; rule based control (RBC); predictive rule based control; model predictive control (MPC)
- *Control approach*: direct and indirect control

- *Control objective*: energy efficiency; load shifting; peak shaving
- *Penalty signal*: marginal CO_2 intensity, average CO_2 intensity; electricity spot price; electricity balancing price; network tariffs for electricity and district heating
- *Requirements of the surroundings grids*: including services needed by the grid

More details on control issues can be found in the IEA EBC Annex 67 report “Control strategies and algorithms for obtaining energy flexibility in buildings” (Santos and Jørgensen, 2019).

3.2.6. Technology

Energy flexibility of a building can only be utilized if appropriate technology is present. In the literature, the associated technology is understood as:

- thermal energy storage in the building construction due to its thermal mass, building internal fabric (e.g., furniture) or in a water storage tank,
- electrical energy storage in batteries,
- smart appliances: heat pumps, white goods, electric vehicles,
- active technologies: photovoltaic panels.

3.2.7. Stakeholders

As energy flexible buildings exist in the space between the demand and supply side of an energy system, the group of interested stakeholders is multidisciplinary and includes actors from the building sector, energy sector, utilities sector, as well as occupants, building owners, business models developers and policy makers. Moreover, since the concept of energy flexible buildings is still developing, similarly the mix of stakeholders is under constant evolution.

More about the stakeholders can be found in the IEA EBC Annex 67 report “Stakeholders’ perspectives on energy flexible buildings” (Ma and Parker, 2019)

3.2.8. Infrastructure

In the research on energy flexible buildings, the electric power network is the pre-dominant energy infrastructure. This is comprehensively explained by the fact that the majority of renewable energy sources is integrated in the power grid resulting in operational bottlenecks such like large voltage deviations, phase unbalances, overloading of the current infrastructures, periods with negative prices or even forced losses of resources. District heating or cooling networks are mostly present with a European context. Nevertheless, they are getting more international attention, since they can offer new solutions for solving the issues of smart energy systems.

3.3. Conclusion

The eight categories shown in Figure 3.1 indicate that the buildings of the future will be even stronger than today, if integrated in the energy system infrastructure. It is likely that and new actors will be involved already in the design stage and that the design teams will need to have new additional competences and skills to address the emerging features of future energy flexible buildings. This also is a sign that interdisciplinary approaches must be an integral part of the building sector. What previously was a task primarily for civil engineers and architects has now become a task for grid and/or control engineers and even utilities.

4. State of the Art of Characterization of Energy Flexibility in Buildings

To complete the general overview of the terminology and definition, this chapter presents an analysis of the indicators often used for evaluating energy flexibility.

Generally, indicators can be categorized into three levels in accordance with their scope (illustrated in Figure 4.1): a building component, a single building, and a cluster of buildings. The different components include the on-site energy generation systems (thermal and electrical), energy storages (embedded in the building structure as construction components or as part of the energy system) as well as other technologies and devices providing various flexible loads. The aggregation of the interactions between building component's as well as the interactions of these with the building as a whole gives indicators for single buildings, and correspondingly, aggregation of single buildings gives indicators for clusters of buildings.

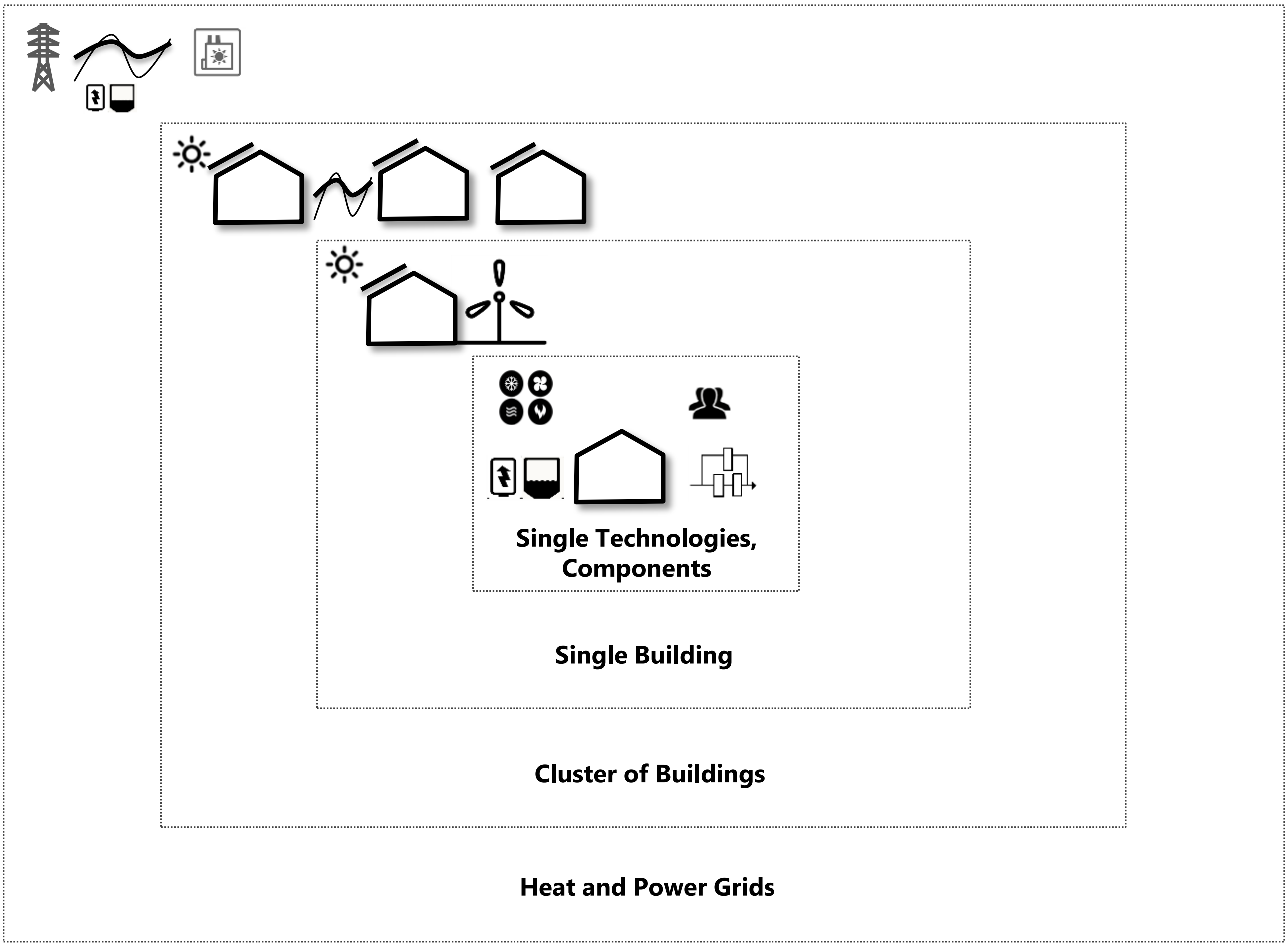


Figure 4.1 Possible energy flexibility interactions with the grid: a building technology or component, a single building and a cluster of buildings (Illustration by Tobias Weiss, 2019, based on Marszal et al. 2010).

4.1. Energy Flexibility Indicators for Single Buildings

Armin Knotzer, Minyan Lu, Ala Hasan, Tobias Weiss, Rui Amaral Lopes, Glenn Reynders, Anna Marszal-Pomianowska, Hicham Johra

The purpose of this section is to identify, investigate and review energy flexibility indicators for single buildings including indicators for different building components as well as for the whole service system. The section provides a brief overview of the indicator groups by their features and gives guidance on the literature about energy flexibility indicators in buildings. The investigated indicators are listed in Appendix A while selected indicators are analyzed and reported in Appendix B.

In the following sections, first a few words about the approach for quantifying energy flexibility in relation to single building indicators, then energy flexibility sources at the building level and finally an overview of the indicators found (Lu and Hasan, 2018) is given.

4.1.1. Energy Flexibility Quantification Approach for Single Building

Energy flexibility can be used to manage the load curve of buildings, such as shift demand in time (load-shifting), reduction of peaks in the energy demand (peak-clipping/load shaving/shedding) or temporarily increase of the load when the incentives are high or electricity prices are low (valley-filling) through Demand Side Management (DSM) – see Figure 4.2.

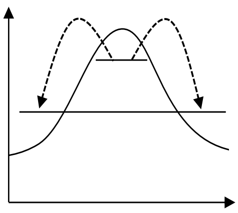
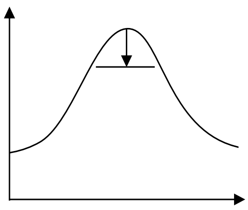
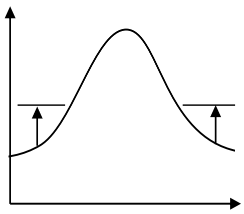
Load shifting	Load shaving	Valley filling
		
Moving loads from one time to another.	Cutting load at a certain instance (and not using it later).	Increasing load at certain instances (which normally is not active).
E.g. washing machine, or if electric heating: heating the building earlier or later.	E.g. turning off electric heating, and using gas or bio instead.	E.g. turning on electric heating if normally heated by gas or bio.

Figure 4.2 Flexible mechanisms: load shifting, load shaving and valley filling (Linberg, 2019).

DSM is defined from a utility perspective as “the planning and implementation of those electric utility activities designed to influence customer uses of electricity in ways that will produce desired changes in the utility’s load shape” (Gellings, 1985), and DSM can be divided into two categories as energy efficiency (EE) and demand response (DR) (Palensky and Dietrich, 2011). The benefit of DR strongly depends on the available energy flexibility and successful implementation of DR programs. Hence, most state-of-the-art literature focuses on demonstrating to what extent this can reduce energy cost, shift peak power, increase the use of local renewable electricity production, or achieve stability in the power grids by utilizing the flexibility of buildings.

In general, the potential flexibility is mostly used to minimize energy cost or procurement cost of purchasing electricity and heat from the energy networks, increase the share of renewable energy sources (RES) in the distribution networks, or develop the ability of real-time matching of consumption and generation to keep the stability of the grid. Therefore, energy flexibility could be expressed as power [kW] and/or energy [kWh] that can be shifted - increased or decreased – in reaction to an external signal (within IEA EBC Annex 67 called “Penalty signal”) without jeopardizing the indoor comfort over a certain time span. Consequently, the pivotal challenge in characterizing flexibility is to find a common language to describe the shape, these energy or power shifts can take, while considering the objectives (activations), the constraints, the time period (minute, hour, month or year) and the corresponding optimal control strategies. D’hulst et al. (2015) described flexibility as the integration of the amount of power and time, which gives the amount of increased or decreased energy. Accordingly, a system shifting a high amount of energy has more flexibility compared to a system shifting a low amount of energy during the same period. Eid et al. (2015) defined flexibility as a “power adjustment sustained for a given duration in order to balance supply and demand at a given moment in time”.

The literature review on indicators showed that, although the focus of the quantification methodologies in the different studies varied, some general properties of energy flexibility were evident.

As a general outcome from literature, the flexibility potential can be identified as the amount of energy that is possible to shift or move, which is based on the information of capacity and direction (up/down) as well as time aspects. The cost is also an important element as the building capability, and hence its cost, to provide the flexibility in different hours of the day or seasons of the year.

The actual available energy flexibility is very dependent on the users of the buildings as it is often their comfort, which may be affected when energy flexibility is utilized, e.g. variation of the room temperature when the thermal mass of the construction is utilized as storage of heat or the start of appliances is postponed. The construction of the building (i.e. its thermal mass) is here an important aspect as it can be activated as a thermal storage. Likewise, the design of the building energy service systems including heating, cooling and ventilations systems, and energy technologies such as boilers, CHP (Combined Heat and Power generation), PV and thermal solar systems should also be taken into consideration. In addition to the thermal mass of the construction, storage in buildings also includes water tanks (e.g. domestic hot water (DHW) tanks) and batteries. In order to utilize the storage and the energy service systems for obtaining energy flexibility, there is a need for advanced control systems. A ‘smart’ energy management system can utilize the available energy technologies within the building in a least-cost way, but still such that the energy demand is met.

Hence, the available energy flexibility in a building is determined by:

- The building loads
- The building energy service system (i.e. the design, technologies and their capacity)
- The storage types and capacity, and their characteristics
- The controls applied to the energy service system

The available flexibility, however, varies over time, and depends on the state of charge of the storage and the actual energy demand of the building (Stinner et al., 2016). For example, if there is no heat demand (e.g. in summer), the offered flexibility of the heat storage will be zero, although it would be freely available. In addition, a sensitivity analysis of the influence of the main building characteristics on different aspects of energy flexibility may be found in Appendix B, where the indoor environment is utilized for storing heat.

4.1.2. Energy Flexibility Sources at the Building Level

Sources of energy flexibility in buildings include flexible distributed energy generation combined with storage systems (e.g. batteries), and thermal conversion in building heating/cooling systems coupled with thermal storage (Salpakari et al., 2016). In this section, a brief description of flexible loads, distributed energy generation and energy storage is given.

Building structure

The building itself can be utilized as thermal storage system where thermal energy is stored within the structure, i.e. walls, ceiling, floor and furniture. As emphasized by (Braun, 1990), both energy costs and peak electrical use can be significantly reduced through optimal strategies while considering the use for intrinsic thermal storage within the building structure. Some simulation-based and experimental results also show that model predictive control (MPC) strategies which take into account both the structural storage capacity of the building (i.e. the thermal mass embedded in the building structure) and the non-structural storage capacity (i.e. the storage capacity embedded in the energy system) may result in energy cost saving of 26 % up to 40 %, while maintaining or even improving thermal comfort (Reynders et al., 2013). These savings mostly come from the maximum use of solar and internal gains for passive heating, offsetting mechanical cooling with “free” cooling at night (such as night ventilation), or different prices of peak and off-peak period.

Reynders (2015) defines and quantifies several performance indicators to evaluate the potential flexibility of building structural thermal storage and concludes that the storage efficiency is strongly related to some building design parameters, i.e. the insulation quality of building, climatic boundary conditions, comfort requirements and occupant behavior (see Section 4.1.3).

Building energy loads

The loads can be classified into three categories based on the requirements and priorities to be changed/shifted or not:

1. <u>*Shiftable loads*</u> are those that can be rescheduled in accordance with the Penalty signal, e.g. when the energy is cheaper during off-peak hours or in a real-time pricing market, so that the peak demand is reduced (Belhomme and Bouffard, 2009; Hong et al., 2015). Examples of shiftable loads include dishwashers, washing machines, charging devices or electric vehicles. They can be applied to load shifting or interruption without influencing the occupant comfort and behavior pattern too much. Within this class, it is possible to distinguish between load, which can be shifted but the energy profile cannot be changed, and load where the total volume must be met over a set of time periods but the profile can change within limits (Ottesen and Tomasgard, 2015).
2. <u>*Non-shiftable loads*</u> are not flexible and are characterized by energy consumption profiles that cannot be modified, regardless of the energy cost and energy volume of the whole energy system. Examples are lighting, television and cooking.
3. <u>*Other controllable loads*</u> are shiftable loads that can be adjusted by optimal control strategies, like HVAC units whose consumed energy can be modified by dimming, thermostatic control, and by varying the fan speed. Depending on the load, this flexibility can be used to reduce consumption in peak periods and decrease procurement cost.

Distributed on-site generation and storage systems

The flexible use of PV and (small) wind turbines is closely linked to their coupling with storage systems (Belhomme and Bouffard, 2009). Certain available heating systems, such as heat pump (HP), electric heaters (EH) and combined heat and power (CHP), can meet the household demand by operating intermittently. The energy generation can be shifted, decreased, or increased by changing the operational pattern of the HP/EH/CHP according to the electricity price or the availability of energy supply from onsite RES. Six et al. (2011) demonstrated that an individual residential HP of 10 kW_{th} combined with a 400 litres water storage tank for space heating can offer about 1-hour flexibility per day with an average domestic heat demand. Masy et al. (2015) show that a smart grid control strategy can reduce procurement costs by 15 % and consumer costs by 13% using the flexibility offered by a HP and structural thermal storage of a building.

Some research studies model a building equipped with a HP or CHP and simulate their flexibility to satisfy the required heating/cooling loads or to charge/discharge a hot water storage tank. The offered flexibility is normally constrained by the capacity of the storage and the state of the thermal buffer. An electric battery can be used for the storage of imported electricity when the price is low in order to avoid times with high price or store onsite generated electricity. The interactions of a battery with the building's electrical loads and the imports/export to the grid can be complex and is highly affected by many parameters, e.g. the battery capacity, profile of electrical loads, tariff structure, and availability and profile of the onsite generations (Grantham et al., 2017; Stadler et al., 2009; Linssen et al., 2017).

For a comprehensive evaluation, the investment cost related to enabling the flexibility actions, such as IT equipment of each customer, should be taken into consideration (O´Connell et al., 2014).

Aggregated flexibility

Heussen et al. (2012) presented a holistic concept – namely the "power node framework" – to model the building coupled with renewable energy technologies, storage technologies, and demand response technologies as a virtual storage unit. In the power node framework, any power source or sink, connected to the electric power system, enables the virtual conversion of certain energy into electric power and vice versa. Each building can be lumped into a single "power node" (Figure 4.3) that contains the physical properties and internal composition of different processes.

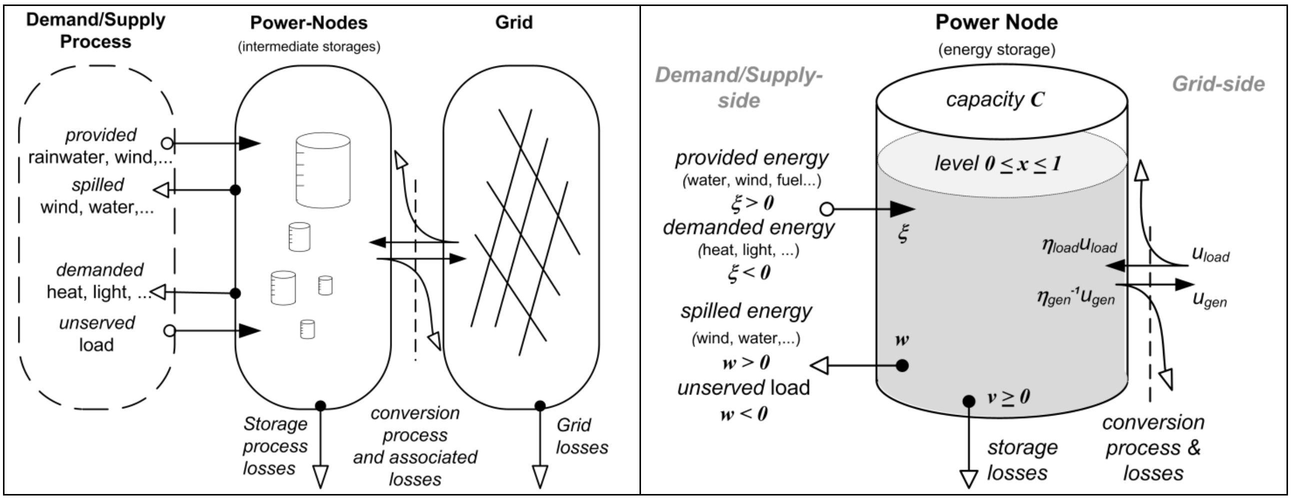


Figure 4.3 Power node domains (left) and notation for a single power node (right) (Heussen et al., 2012).

A similar concept to the "power node framework" is the "Energy Hub concept", introduced in the Vision of Future Energy Network project, which received more attention from energy market representatives. It is defined as a unit where multiple energy carriers can be converted, conditioned and stored (Geidl et al., 2007).

Both the above concepts have shown a strong potential to simulate and assess the operational flexibility in power systems (Reynders, 2015). Another benefit of considering the building as a "power node" or "Energy Hub" is that it helps the energy companies to aggregate the flexibility from smaller consumers and establish a "flexibility market" (Belhomme and Bouffard, 2009). Accordingly, not only large customers, e.g. industrial customers, but also individual residential customers can sell their flexibility to the market after they are identified and aggregated.

4.1.3. Energy Flexibility Indicators at the Single Building Level

The indicators found in the review reflect the extent to which any implemented flexibility action can affect the target objectives. The indicators can be used to describe and evaluate different control and operation strategies of energy flexible buildings. The indicators seek to be applicable to different energy systems and different types of building. Since the indicators are case dependent, the indicators were reviewed, classified, short-listed and selected according to the target physical quantities and intended impacts. A set of potential key performance indicators to characterize energy flexibility in buildings have been collected, grouped and their different characteristics outlined in the overview table in Appendix A. The following sections report a set of examples of flexibility indicators dealing with thermal storage, building loads and energy.

Example for thermal storage in building structure

Reynders (2015) suggests four indicators: available storage capacity (C_{ADR}), storage efficiency (η_{ADR}), power shifting capacity (Q_{δ}), and state of charge (SOC) – for energy flexibility and applies them to quantify the potential of structural thermal energy storage (STES) both under simplified (steady state) boundary conditions (Reynders et al., 2015) and dynamic boundary conditions (Reynders et al., 2016).

The definitions and quantification approaches for these indicators are based on simulations of demand response events and a comparison of resulting heating/cooling power to a reference with the building in normal operation. As schematically illustrated in Figure 4.4, the set point temperature for heating is slightly increased and used to activate the thermal mass that part of the heating energy can be stored within the building. Whereas, the reference control is assumed that a minimum temperature allowed by users thermal comfort would be maintained in order to minimize the energy consumption.

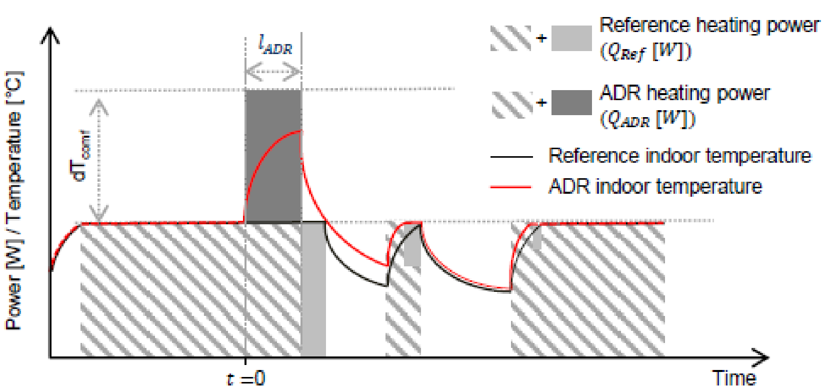


Figure 4.4 Scheme of the simulation experiment used to quantify the available storage capacity and the storage efficiency (Reynders, 2015).

Examples for building loads

Oldewurtel et al. (2010) introduced indicators like Power Shifting Potential ΔP and Power Shifting Efficiency (PSE), not only taking the constraints such as indoor comfort into consideration, but also regarding the minimum electrical cost as the objective function. The Power Shifting Potential ΔP of the building for providing a grid service at hour *i* is described as the amount of power the building can deviate when the price signal varies for the power consumption based on a constant electricity price. And PSE is the ratio of the maximum possible change in power consumption at hour *i* (without violating any constraints) to the additional energy consumption over a test period *T* compared to the baseline power consumption.

Tahersima et al. (2013) explored the flexibility criterion on flexible loads in a building and suggested a framework to measure the flexibility in terms of energy that can be shifted without violating its comfort. They assume a reference case where a nominal power with a constant value for space heating is consumed. Because of the contribution of the capacity of the building thermal mass (storage), the power consumption can fluctuate within a certain amplitude (e.g., from 0 to 2 Amps in Figure 4.5) during a given period compared to that in the reference case, with the goal to minimize the consumption cost in reaction to the electricity market price. At the same time, the indoor temperature stays within specific comfort boundaries pre-defined by a set point temperature profile and thermal tolerance level. As shown in Figure 4.5, the building shifts the load from the peak price period to an off-peak period. The shaded area i the graph for a single period T shows the maximum tolerable energy, which can be subtracted from or added to the normal power b so that the average power over time is the same as the normal power.

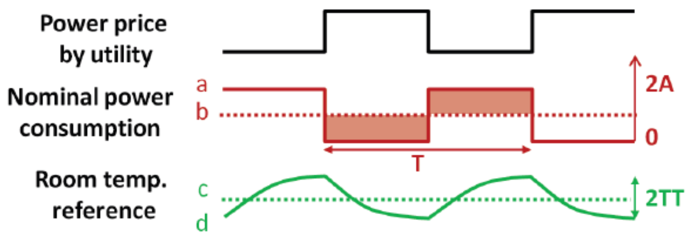


Figure 4.5 A hypothetical example which illustrates the flexible power signal (a), fluctuating between 0 and 2A around the nominal power (b). The shaded areas show the maximum energy varied to nominal value that can be tolerated by the system. (Tahersima et al., 2013).

Example for general building's energy related indicators

Six et al. (2011) discuss the flexibility potential of residual HP combined with thermal energy storage (TES) for space heating. Here, the flexibility resulting from the use of TES is quantified as the maximum time (number of hours) that the HP is delayed from starting or the HP is forced to operate. The former is under the circumstance that the HP is required not to start. The heat is instead provided by the surplus energy stored in the TES. The maximum hours the TES can deliver the necessary heating before the HP needs to be started is the potential flexibility of the systems.

From the Figure 4.6 it can be seen that the flexibility of a storage tank volume of 1,000 litre is 1.25 hours when consuming highest heat demand and approximately 2 hours for an average demand. The latter could mean that the HP is forced to operate at a lower heat demand, but also to charge the TES. The time period a HP can keep running to charge the TES from the empty volume to full is the maximum flexibility. For instance, the maximum flexibility of a storage tank of 1,000 litre with a capacity of 11.6 kWh is 1.16 hours when the HP provides a constant output power of 10 kW. The indicator invented is mainly to express the ramping up or ramping down ability of the TES.

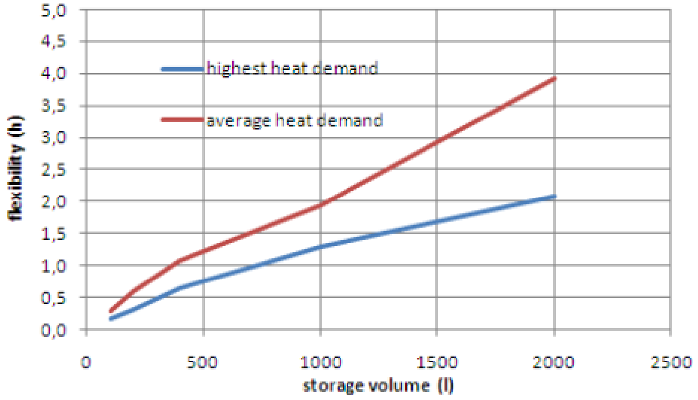


Figure 4.6 Flexibility as a function of the TES volume (ΔT=10K) (Six et al., 2011).

4.1.4. Conclusion

A majority of indicators illustrate how the amount of power or energy during a certain time interval can be altered and how long this defined power increase or decrease can be maintained. Indicators that measure the environmental and economic performance of buildings can also indirectly describe features of the energy flexibility. Generally, energy flexibility can be defined as the ability to deviate from a reference load profile (baseline power consumption or business as usual scenario) in response to requirements by the operation of the building or the grid.

Energy flexibility sources in buildings include the following:

- Electric loads, composed of shiftable electrical loads of wet appliances (dishwasher, washing machine etc.) and controllable loads (components of HVAC units and lighting);
- Thermal mass of the building, which is mainly affected by the used heating system (e.g. underfloor heating, radiator heating) and its control; and
- Components of the local energy system, conversion (CHP, HP, electric heater, etc.) and storage (hot-water storage tank, electric battery etc.).

The operation of these sources is highly affected by the implemented control method. Thermal comfort plays a significant role in limiting the offered flexibility, especially by building's thermal mass, and is, therefore, a constraint in many cases. For this, it is quite important to set the acceptable range as well as the rate of change of the indoor air temperature. Other common constraints are the time- or user-related restrictions on some appliances, air supply rates and the percentage of occupant satisfaction.

As already mentioned most indicators directly or indirectly give numbers of shiftable load or energy based on the energy flexibility sources from above in a specific time range together with price, CO_2 or efficiency reacting control systems. From the expert view of IEA EBC Annex 67 it was clear that all indicators addressing load or energy related values are closer to what is useful for the characterization of energy flexible buildings, instead of e.g. price or market related indicators. That is also one reason for the development of a harmonized visualization and communication tool in

Annex 67, showing the efficiency of flexible operation Eflex [%] and shifted flexible load Sflex [%] – see Section 5.6.

Further details on the investigated indicators are reported in Appendix A and a sensitivity analysis and classification of the indicators are reported in Appendix B.

4.2. Energy Flexibility Indicators for Building Clusters

Ilaria Vigna, Roberta Pernetti

As introduced in the previous section, the highest level for analyzing energy flexibility is represented by the building cluster. In order to address this topic, this section reports an overview of the benefits associated to the analysis at this level, the definition of cluster and a set of ancillary concepts and the description of the indicators found in literature (Vigna et al., 2018).

Utilities typically do not see the energy demand of single buildings but the aggregated energy demand of several buildings situated on a feather (outlet of a power line) or situated in a part of a district heating network. The relevance of the cluster level further comes from the introduction of prosumers, able to both consume and produce energy, that have changed the relation between the buildings and the energy infrastructure: the paradigm is shifting from single energy efficient units to interconnected active players that manage the energy flows.

Energy planning at the building cluster scale represents an effective strategy for providing local and low-carbon energy supply, through the enhancement of district energy systems and decentralized energy production. In the European context, the combination of energy efficiency improvement with renewable energy integration at the cluster scale has been investigated in a considerable number of strategically selected case studies, e.g. the BedZED eco-community in London or the Vauban in Freiburg, Hammarby in Stockholm (Williams, 2016). The results of these studies reveal that the management of a shared distribution network powered by solar thermal or CHP plants can bring several benefits to individual buildings in terms of increased efficiency, higher possibilities of storage and load complementarity due to different usage of the buildings, e.g. commercial and residential (IPCC, 2007).

Furthermore, the focus on cluster scale enables the development of a systemic approach in building design that considers, in an economy of scale perspective, factors such as retrofitting and adoption of technologies/strategies for increasing energy efficiency and minimizing CO_2-emissions, so as to reduce the unitary cost of investment and reach cost-optimality (Koch and Girard, 2013).

4.2.1. Definition of Building Cluster

Finding a common definition for the ‘building cluster’ concept is the starting point necessary for setting common rules and specific characteristics - e.g. size, composition, owner, type of connection with other buildings. In the literature it is possible to find several terms and definitions related to the cluster concepts according to different perspectives, even if there is not a univocal description of features associated with clusters of buildings.

In particular, urban social scientists introduce the concept of neighbourhood, focusing on its spatial attributes - geography, infrastructure and buildings - and on the social collective relations that characterize the space (Galster, 2001). The term community could identify, on one hand, a group of buildings located in the same area and, on the other hand, a "portfolio of buildings" geographically far but owned by a single person or set of occupants (Managan and Controls, 2012). Moreover, the definition of cluster can be linked to the concept of Net Zero Energy Communities (NZECs), characterized by a null or positive value in the difference between annual delivered energy and on-site renewable exported energy (He et al., 2016).The community can be considered the crucial scale for reaching the target of net zero energy, for improving energy interdependency and reducing maintenance and life-cycle costs. In fact, compared with a single building, the community level ensures a larger accommodation of RES supply systems and an easier flattening of load profiles due to highly varying occupancy patterns.

Thus, the building cluster concept will fundamentally transform the energy system by shifting on-site energy generation from a single Net Zero building to a system of "Net Zero clusters", able to freely share distributed power generation and storage devices, in order to achieve maximum energy efficiency (Li et al., 2014).

Starting from the literature review, a new definition of a cluster is suggested and adopted within IEA EBC Annex 67 (Vigna et al., 2018):

> *A building cluster identifies a group of buildings interconnected to the same energy infrastructure or same aggregator, such that the change of behaviour/energy performance of each building affects both the energy infrastructure and the other buildings of the whole cluster.*

This definition does not assign fixed dimension and boundaries to the building cluster scale, but it is based on building interconnection that could be physical and/or market related (Figure 4.7).

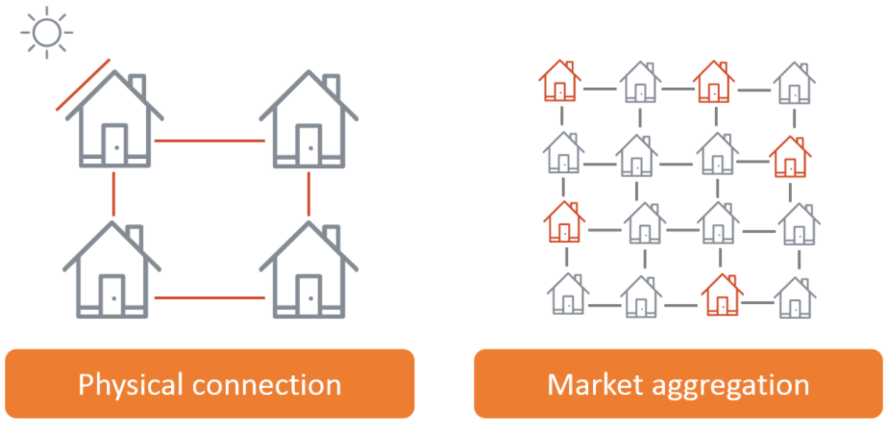


Figure 4.7 Scheme of the possible connection among buildings within a cluster

The physical connection to the same grid of building clusters allows the exchange of energy between buildings (e.g. PV panels installed in one building produce energy that can be used also by the other buildings) or from a central source toward the buildings (e.g., district heating).

The possible presence of market aggregation (Eurelectric, 2014) enables the management of the building cluster by a common agent or company who can potentially exploit the energy flexibility of the whole cluster (Langham et al., 2013). In general, different buildings can be treated as elements of the same cluster although they are not located in the same area (multi-site aggregation), e.g. different buildings with the same owner that can negotiate better energy tariffs with the DSO (Distribution System Operator), offering in exchange a reduction of the energy consumption when required by the grid.

4.2.2. *First Steps towards the Energy Flexibility Concept at the Building Cluster Scale*

One of the specific objectives of IEA EBC Annex 67 was the development of a common definition of 'energy flexible building clusters', in order to create a common basis for the work and to explain what energy flexibility is and how it can be evaluated.

As a general definition, starting from the approach set out for single buildings and reported in Section 4.1, energy flexible building clusters should have the capacity to react to forcing factors (Penalty signals) in order to minimize CO_2 emissions and maximize the use of Renewable Energy Sources (RES). Other objectives, which can be considered at the moment, like minimizing the electricity cost for the entire cluster, will come in parallel to minimizing of the CO_2 in the grids.

The absence of a consolidated definition requires, as a starting point, the analysis of some auxiliary concepts adopted so far in the literature used to describe the synergy of energy efficient buildings and renewable energy utilization at an aggregated level.

The identified auxiliary concepts are the following:

(i) Smart Building Cluster and
(ii) Zero Energy Neighbourhood concepts stressing the role of smart interaction between buildings and grid and underlining the importance of working at an aggregated level to reach the aim of Zero Energy Buildings;
(iii) Micro Energy Hub concept, representing the future behaviour of buildings, that will be able to consume, produce and store energy and will increasingly interact to reduce peak demand and grid stress;
(iv) Virtual Power Plant concept as a strategy for aggregating heterogeneous Distributed Energy Resources (DERs) to relieve the load on the grid by smartly distributing the power generated by the individual units during periods of peak load;
(v) Collaborative Consumption concept as a social agreement by users to share their energy sources;
(vi) Local Energy Community concept introduced by the European Commission in the document "Clean Energy for all Europeans" (EC, 2016a) as a new market players with the right to generate, consume, store and sell renewable energy.

It is important to refer to such auxiliary concepts, further detailed in the following sections, since they represent an expression of the market stakeholders and players involved in the ongoing energy transition towards the ambitious 100 % RES target. Policy makers should start from these auxiliary concepts in order to effectively promote energy efficiency in the current crucial transformation of market, building and infrastructure technologies, as well as in the EU legislative framework.

i. Smart Building Cluster. The concept of energy flexibility at an aggregated level can be linked to the definition of "Smart Building Cluster (SBC)", indicating "a group of neighbouring smart buildings electrically interconnected to the same micro-grid" (Ma et al., 2016). Considering the SBC scale, it is possible to obtain an improvement of the local use of renewable energy, a decrease in the cost of electricity consumption, and a larger load shift in time due to different occupancy patterns and varying load profiles within a cluster composed of mixed-use buildings.

ii. Zero Energy Neighbourhood. The "Zero Energy Building" concept still considers the individual buildings as autonomous entities and neglects the importance of reaching energy efficiency at a larger scale. In the future shift to NZEB 2.0 (D'Angiolella et al., 2016) the Zero

Energy Neighbourhood scale will take into account the numerous interactions between urban form, building energy needs and on-site production of RES (Marique and Reiter, 2014), in order to balance annual building energy consumption and individual transportation by the local production of renewable energy (Marique et al., 2013).

iii. Micro Energy Hub. In the framework of an energy flexible building cluster, buildings will increasingly interact with the energy systems and have the potential to take up an important role in the energy-supply-system stability by acting as micro energy hubs i.e. “multi hubs-generation systems, providing renewable energy production, storage and demand response” (Geidl et al., 2007). The key concept of the energy hub approach is the possibility to jointly manage the energy flows from multiple energy sources in order to improve the renewable energy sharing between different interconnected buildings (Darivianakis et al., 2014).

iv. Virtual Power Plant. It is possible to make an analogy between energy flexible building clusters (Carr, 2011) and virtual power plants. Virtual Power Plants (VPP) can be considered as “collective generators of renewable energy sources that can store and adjust energy output on demand and at will”. An aggregator can group different DER systems into a VPP in order to provide more energy flexibility than a single system and, in parallel, energy flexible buildings have the possibility to co-generate with current grids or operate solely to produce energy in a cost-effective way, while adapting/shifting the electricity consumption profile in time (De Coninck and Helsen, 2013).

v. Collaborative Consumption. In the current market, end-users hold only the role of final consumers and are not involved in the energy supply side. The community engagement to reach a suitable energy management framework represents an opportunity to increase social acceptance of distributed generation in smart grids (Ahmadi et al., 2015). Collaborative consumption (CC) is “a social-based agreement framework”, in which different consumers cooperate to share their resources and to create valuable services for the benefit of the whole community (Belk, 2010). Therefore, an active participation of residents into the energy market improves their inclination towards cooperation in order to reschedule their consumptions and generate more renewable energy so as to minimize energy cost, carbon emissions and primary energy consumption (Dai et al., 2015).

vi. Local Energy Community. The European Commission proposal for the recast of the International Electricity Market Directive (EC, 2016b) establishes a framework for Local Energy Communities aimed at improving energy management at the community level and empowering local participants. In such a geographically confined network, all consumers can have a direct involvement in energy consumption, storage and/or the sale of self-generated electricity to the market, and the up-take of new technologies and consumption patterns, including smart distribution grids and demand response, will get easier.

4.2.3. Indicators for evaluating Energy Flexibility at the Building Cluster Level

Indicators are fundamental for quantifying the amount of energy flexibility that a building can offer, and measure how different aspects influence the sharing of renewable energies and the reduction of peaks of delivered energy in buildings. Indicators are also a way to effectively communicate the energy flexibility concept, provide a common language between energy players and support policy makers in the quantification of the actual impact of novel energy related policies. Chapter 5 presents the methodology to characterize energy flexibility. It can be applied to both single buildings as well as clusters. Nevertheless, having a comprehensive framework on the indicators available in literature dealing with energy flexibility is useful for further evaluations.

A literature review showed that the majority of existing indicators and approaches, related to energy flexibility quantification focuses on single buildings (Section 4.1), and there are no specific indicators for clusters. To address this, a set of potential key performance indicators that could be adapted to the cluster scale and used to characterize energy flexible building clusters was identified. The selected indicators have been classified into five different categories, as shown in Table 4.1.

Table 4.1 Indicators for energy flexible building clusters.

Indicators for energy flexible building clusters				
Costs	Spark Spread	Total Supply Spread	Specific Cost of Flexibility	Flexibility Factor
Thermal level	Available Storage Capacity	Comfort Index		
Electric level	Grid Control Level	Load Matching Index	Grid Interaction Index	
Thermal-Electric level	Maximum Hourly Surplus Maximum Hourly Deficit	Ratio of Peak Hourly Demand to Lowest Hourly Demand	On-site Energy Ratio	Annual Mismatch Ratio
Other relevant indicators	Homogeneity Index	Smart Ready Built Environment Indicator		

1. Cost *indicators*

The Cost level indicators focus on energy flexibility quantification with respect to costs.

The *Spark Spread* and the *Total Supply Spread* (Piacentino e Barbaro 2013) express the convenience of self-producing heat and electricity compared to energy purchased from the public grid. The *Specific Cost of Flexibility* (De Coninck and Helsen 2013) indicates how much the electricity price could change along with the change in load and the *Flexibility Factor* (Le Dréau and Heiselberg 2016) proves the ability to shift the energy consumption from high to low price periods.

2. *Thermal level*

The thermal level includes indicators related to energy flexibility of structural thermal energy storage and the thermal comfort aspects. The *Available Storage Capacity* indicator (Reynders 2015) quantifies the energy flexibility provided by the activation of the thermal mass of the building and the *Comfort Index* (Shen and Sun, 2016) calculates the thermal discomfort resulting from the cooling supply time failure of a cluster sized air-conditioning system.

3. Electric level

The electric level comprises indicators referred to the measure of electric grid control over the demand and to the relation between on-site generation and load for a specific temporal resolution. The *Grid Control Level* (Ahmadi, 2015) measures the capability of the grid to flexibly control the cluster energy demand according to availability of renewables and market prices. The *Load Matching Index* and the *Grid Interaction Index* (Voss, 2010) describe, respectively, the on-site renewable energy use achievable in a cluster and the grid stress in terms of energy exchange variation between a building cluster and the grid.

4 Thermal and electric level

The thermal and electric level encloses indicators related to cumulative energy demand/supply. The correlation between local renewable energy production and consumption at cluster scale can be calculated in terms of: energy-matching (*On-site Energy Ratio*), energy-mismatching (*Annual Mismatch Ratio*), surplus of on-site renewable generation (*Maximum Hourly Surplus*) and deficit of on-site renewable generation (*Maximum Hourly Deficit*) (Ala-juusela and Sepponen, 2014). The magnitude of the peak power demand of the cluster can be calculated as *Ratio of Peak Hourly Demand to Lowest Hourly Demand* (Ala-juusela and Sepponen, 2014).

5 Other relevant indicators

This level includes indicators related to other auxiliary issues that influence the energy flexibility, such as the influence of the typological composition of a cluster on energy consumption expressed through the *Homogeneity Index* (Jafari-marandi, 2016) and the readiness of a building to adapt its operation to the needs of the occupants and of the grid to improve its performance defined by the *Smart Built Environment Indicator* (De Groote, Volt, and Bean, 2017).

4.2.4. Conclusion

To conclude, the wider perspective of building clusters introduced an additional potential, since each building can take profit from the energy flexibility that can be offered by the surroundings. The relevance of this scale will be further increased in the next years since it will be enabled by the upcoming European Directives and national standards for energy sharing and aggregation. The analysis reported in the previous section represents a starting point for providing a comprehensive framework of the current approach for considering building clusters in terms of energy flexibility.

4.3. Conclusion

The foreseen large deployment of renewable energy sources may significantly affect the stability of energy grids and it will be necessary to control energy consumption in order to match instantaneous energy production. Energy flexibility in buildings will allow for demand side management and load control and thereby demand response according to climate conditions, user needs and grid requirements.

In the framework of IEA EBC Annex 67, a literature review was conducted to describe existing available indicators to quantify the energy flexibility at building scale. Moreover, the specific characteristics of an energy flexible building cluster have been outlined including the meaning of the word ‘cluster’ (definition), the working scale (composition), different levels of interaction among buildings (connections). Finally the reviewed indicators have been classified into different categories related to cost, thermal and electric features, cluster composition and smart readiness.

This chapter highlighted, from existing literature, how fragmented is the definition of suitable indicators for energy flexibility. There is the needs of identifying a replicable and shared methodology to be widely applied, and the following chapter, profits from the results of the performed literature analysis. The work in the present chapter is, thus, the initial knowledge framework for the definition of the quantification methodology for energy flexibility described in the following chapter.

5. Methodology to characterize Energy Flexibility in Buildings and Districts

Rune Grønborg Junker, Rui Amaral Lopes, Daniel Aelenei, Henrik Madsen, Tobias Weiss, Søren Østergaard Jensen

As presented in Chapter 1, power systems face important changes, both at supply and demand sides, resulting from the integration of energy conversion systems based on renewable primary energy resources and due to the increasing electrification of the energy demand. To address the resulting challenges, of always ensuring the instantaneous balance between supply and demand, energy flexibility available at both sides of the power system must be utilized. However, in some cases, like congestion problems at transmission and distribution levels, power systems have to rely mostly on energy flexibility available at the demand side.

Considering this, this chapter describes a methodology to characterize the energy flexibility available in buildings and districts (i.e., demand side), which is based on the assumption that energy flexible buildings can adjust their demand in response to penalties imposed over time with the main objective of reducing the resulting cumulative penalty (e.g., energy cost or CO_2-content of energy). A typical example where this type of mechanism is used to exploit demand side energy flexibility is indirect load control, where economic incentives and disincentives are imposed to encourage voluntary changes in customer electricity demand profiles. In this case, the applied electricity rate, which can vary throughout the day and season of the year to reflect specific needs (e.g., reduce demand peaks), will be referred to as a Penalty signal and the energy flexibility would be used to reduce the monthly energy bill (i.e., the resulting cumulative penalty). Therefore, in more general terms, this methodology also assumes that the time-varying needs of the power systems can be translated to Penalty signals, which are developed to induce the desired energy consumption patterns.

Energy flexible buildings present a certain degree of smartness as they react to the imposed Penalty signals while respecting the comfort of all users. Additionally, it is important to note that the internal dynamics of energy flexible buildings and districts can vary greatly, with vastly different sources of energy flexibility present in for example the heating systems or charging of electric vehicles. Similarly, the performance of the necessary controllers, which are used to correctly exploit the energy flexibility sources also impact the available energy flexibility, as discussed in the Annex 67 report “Control strategies and algorithms for obtaining energy flexibility in buildings” (Santos and Jørgensen. 2019).

For this reason, a method to characterize energy flexibility that can span across all these different systems has been developed. A method that tackles the problem at its roots, namely, the relation between a Penalty signal and the response to this signal. In the end, this is what matters for both the consumers, since it decides their energy bill, and for the utilities, since it offers the possibility to adapt the consumption and load profiles that are of interest to them.

This relation between Penalty signal and demand response is here described by the concept of a Flexibility Function (FF), which is presented in Section 5.1, and constitutes the core of the proposed methodology. The methodology is generic and is, thus, not only applicable for power systems, it can be utilized for all types of energy networks including district heating. An important aspect of the Flexibility Function relies on the possibility to aggregate responses from different energy flexible buildings, or even from individual controllable systems like wastewater treatment stations, thereby offering the possibility to characterize energy flexibility at both component and district levels. Following the description of this core concept, Section 5.2 describes how to compute the Flexibility Function, Section 5.3 evaluates different approaches to define the Flexibility Function and Section 5.4 discusses how to utilize the Flexibility Function for obtaining knowledge on how specific buildings perform in actual energy networks and briefly how to control the available energy flexibility. Section 5.5 discusses how the methodology can be utilized for labelling of buildings, while Section 5.6 briefly describes a software tool for characterization of energy flexibility. Section 5.7 concludes the chapter.

5.1. The Flexibility Function

The methodology for characterization of energy flexibility described here assumes that the energy flexible buildings under consideration integrate penalty-aware controllers, as described and analysed in the Annex 67 report “Control strategies and algorithms for obtaining energy flexibility in buildings” (Santos and Jørgensen, 2019). These controllers have the capacity to adapt the energy consumption in response to changes in the imposed Penalty signal. The Flexibility Function can be defined as: “the expected change in demand due to a Penalty signal”. As a result, the Flexibility Function describes the energy flexibility, and can be estimated based on a Penalty signal as input and consumption as response, as sketched in Figure 5.1.

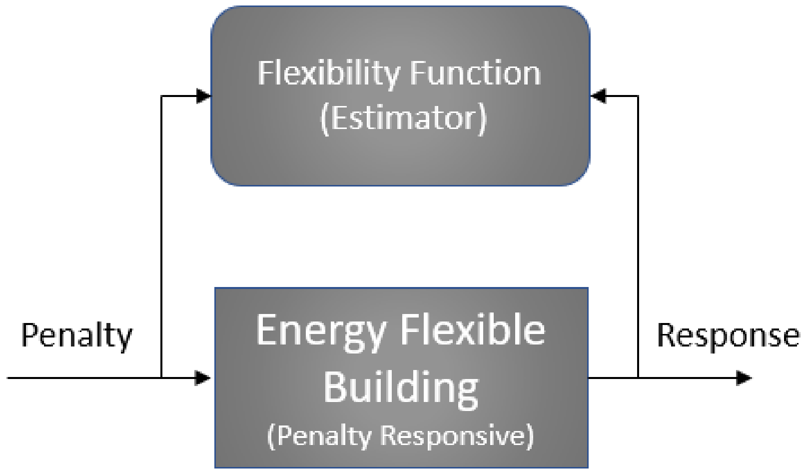


Figure 5.1 Signal flow for estimating a Flexibility Function of an energy flexible building responding to a Penalty signal.

For linear and time-invariant (LTI) systems, a step-response, i.e. the response to a step increase in the Penalty signal, characterizes the system uniquely. Furthermore, the characteristics of the step-response can be analysed and used to assess the energy flexibility. If the step increase is not predicted by the building controller, then the overall step-response is always the same for penalty-responsive systems, namely a drop in consumption that will gradually go back to normal, possibly with a rebound effect, to bring the state of the system back to normal as well. Thus, the Flexibility Function can be defined as the response to a step-response, with the general shape shown in Figure 5.2. Figure 5.2 shows the response of a system without forecast – i.e., the system has no knowledge about that the penalty will be increased at that specific moment. From this response to the Penalty signal, a number of important energy flexibility related characteristics/parameters can be obtained:

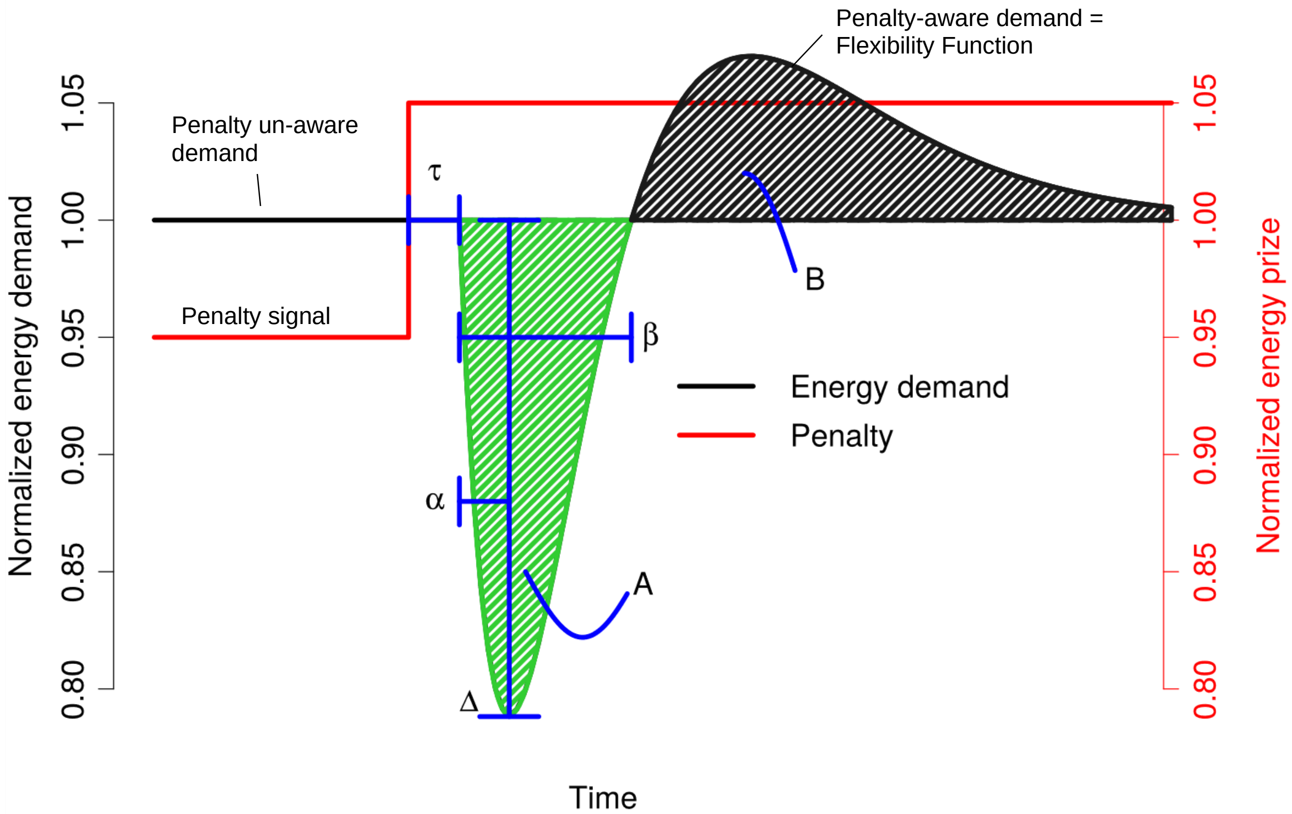


Figure 5.2 The expected response of some energy flexible buildings (without any prior knowledge regarding changes in the Penalty signal) exposed to a step increase in the Penalty signal, termed as the Flexibility Function.

- τ (Time): **Delay from step increase (or a decrease) to initial response**. This could be caused by communication delays from the grid operators to the penalty-aware system. In some cases, it could also be due to heavy computations in the penalty-aware optimization.
- Δ (Power): **Maximum change in response**. This characteristic describes the capacity of the energy flexibility and is important if it is to be used for problems that require large effects, such as voltage regulation. It is mostly related to the magnitude of the flexible energy demand.
- α (Time): **The time it takes from the start of the response to the maximum response**. This is caused by equipment that takes time to turn off, or equipment that have just been turned on and need a certain on-time before being switched off.
- β (Time): **The total amount of time during which the consumption is reduced**. This is important if the energy has to be shifted far in time. Especially heavy buildings will be able to have large values especially if they are well-insulated, while lighter buildings cannot change their demand for long.
- A (Energy): **The total decrease in the amount of energy demand during the response** (could also be an increase in energy demand if the Penalty signal was opposite). This is important if the task requires the shifting of a lot of energy, e.g. load matching in grids with a lot of renewable energy sources.
- B (Energy): **The total increase in the amount of energy consumption – also called rebound**. This can be caused by penalty-aware controllers that allow violations in comfort, but only for limited amounts of time. For temperature control, it could be that temperature is allowed to drop for a short period of time, but afterwards it will have to be increased to the original temperature again, regardless of whether the penalty is still high.

The Flexibility Function (FF) as shown in Figure 5.2 is determined in the following way:

1. Impose a flat Penalty signal in order to obtain the reference energy demand scenario – often called the baseline
2. Impose a step shaped Penalty signal. It induces the use of the available energy flexibility to decrease the resulting cumulative penalty over the period of analysis
3. To obtain the Flexibility Function, subtract the energy demand profiles from step 1 from step2.

The advantage of a Flexibility Function (FF) as compared to a single number describing the flexibility, is that while a single number might be able to explain one of the flexibility characteristics, it is not able to describe the full dynamic behaviour of the energy flexibility. Ignoring the dynamics leads to characterizations that are only valid when the systems are in particular states. An example is temperature control of buildings, where static descriptions are only valid as long as the temperature is kept at a fixed value. This is paradoxical to the point of energy flexibility, since the very nature of using energy flexibility implies deviation from normal operating set points, e.g., room temperatures away from business as usual values. Thus, static characterizations of energy flexibility is less useful. On the other hand, the dynamic behaviour can be explained by the Flexibility Function that describes how the energy flexibility changes when it is being utilised.

In practice energy flexible buildings will not act linearly to Penalty signals, but will have nonlinear dynamics as well. However, a large part of the energy flexibility can still be well-described by linearity assumption, especially for Penalty signals that do not vary too much. A first approach of modelling the non-linearities can be found in (Dominkovic, et al., 2019). It is clear that the energy flexibility is not time-invariant either. For example, there is a vast difference between energy consumption during day and night. The seasonality of the weather conditions represents another major change as well. Fortunately, this is dealt with rather easily, by including the relevant external variables in the flexibility function. If the time-invariant flexibility function is given by

$$D_t = \sum_{k=0}^{N} h_k \lambda_{t-k} \,, \tag{5.1}$$

where D_t and λ_t are demand and penalty at time t, and h_k are the parameters of the Flexibility Function. This expression can easily be extended to the time-invariant case by estimating the parameters as a function of the relevant external inputs (such as time of the day and ambient temperature):

$$D_t = \sum_{k=0}^{N} h_k(\theta_t) \lambda_{t-k} \,, \tag{5.2}$$

where θ_t is a vector of the relevant external inputs at time t.

The Penalty signal will further in most cases not, as shown in Figure 5.2, consist of only one single step increase/decrease. Figure 5.3 shows an example of the reaction of a specific building to a varying Penalty signal over a 48 h period. In this case, the Penalty signal refers to the emission of CO_2 per unit of energy consumed, which is dependent on the power system production mix over time. The energy flexibility is in this case provided by the heating system and controlled to respect the temperature comfort boundaries defined by the user (dashed lines in the top graph of Figure 5.3). The top plot of Figure 5.3 presents the room temperature in the building using both a penalty-aware controller that minimizes CO_2 emissions (green), and a traditional penalty-unaware controller that minimizes energy usage (red). The middle plot shows the Penalty signal (black columns) and the heating operation of both controllers. In this example the traditional controller keeps the temperature just above the minimum required room temperature, while the penalty-aware controller tends to heat when the penalty is low, which results in the temperature varying more. The lower plot shows the accumulated penalty, and as expected, the traditional controller accumulates more CO_2

emissions than the penalty-aware controller, despite consuming less energy (not shown in the graph, but indicated in the top graph as a higher mean room temperature). The FF can be obtained by subtracting the energy demand profiles of two control systems (flexible (penalty-aware) and conventional (penalty-unaware)). However, as both the energy demand of the building and the Penalty signal vary, the FF is not directly obtained by this subtraction – see Section 5.2.2 on how to deal with this situation.

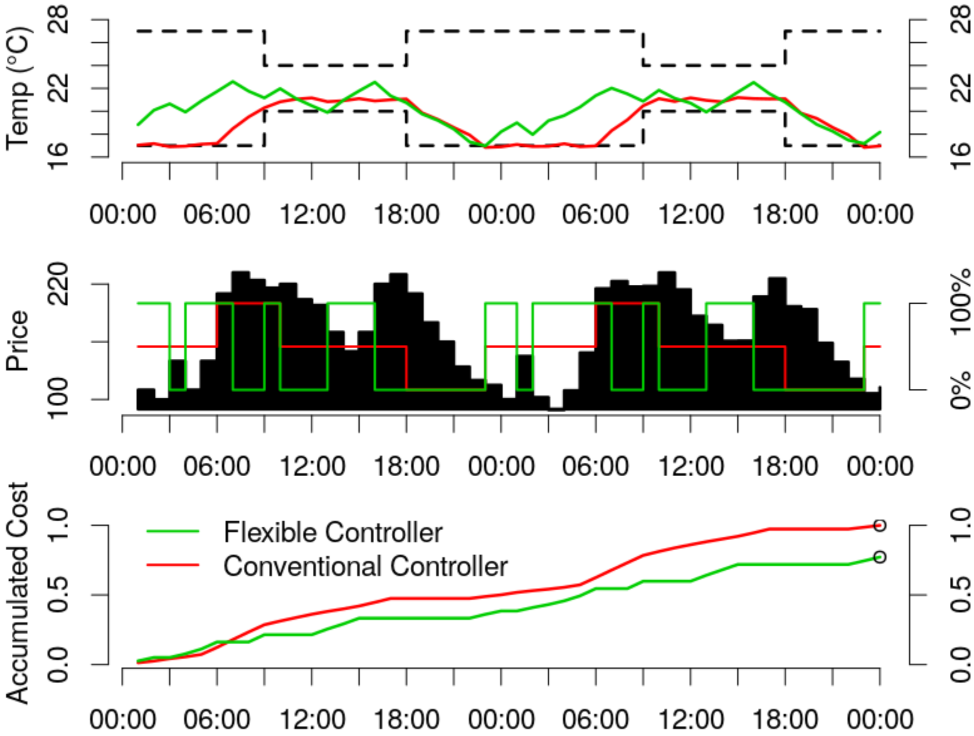


Figure 5.3 Top: The room temperature in a building is controlled by a penalty-aware controller (green line) or a conventional controller (red line). Both controllers are restricted to stay within the dashed lines (defined room temperature range).
Middle: The black columns give the penalty, while the green and red lines show when the two controllers activate heating (on/off – right y axis).
Bottom: The accumulated CO_2 emissions of the heating system caused by the two different controllers. The penalty-aware controller results, for the considered period, in 20 % less emission of CO_2 compared to the traditional controller (right y axis). (Junker et al., 2018).

In Figure 5.3 a Model Predictive Controller (MPC) was applied. This controller is capable of forecasting the future demand and receives forecast of the energy prices within a certain time span. The controller, thus, starts to increase the room temperature in the building before a high CO_2 Penalty signal. The reaction of the controller to the Penalty signal is, therefore, different to the pattern shown in Figure 5.2. Figure 5.4 shows the pattern of such a controller for different example than shown in Figure 5.3 (see also Section 6.3.3).

Figure 5.4 shows the profiles of the heating power (bottom plot) for increasing amplitude of the Penalty signal (high price period – top plot). The figure clearly shows that as a result of the temporary increase in the penalty, the model predictive control tries to reduce as much as possible the heating power during the high-price period. In order to be able to manage that, the model predictive control pre-heats the building prior to the high price period leading to a pre-bound instead of rebound effect in this example.

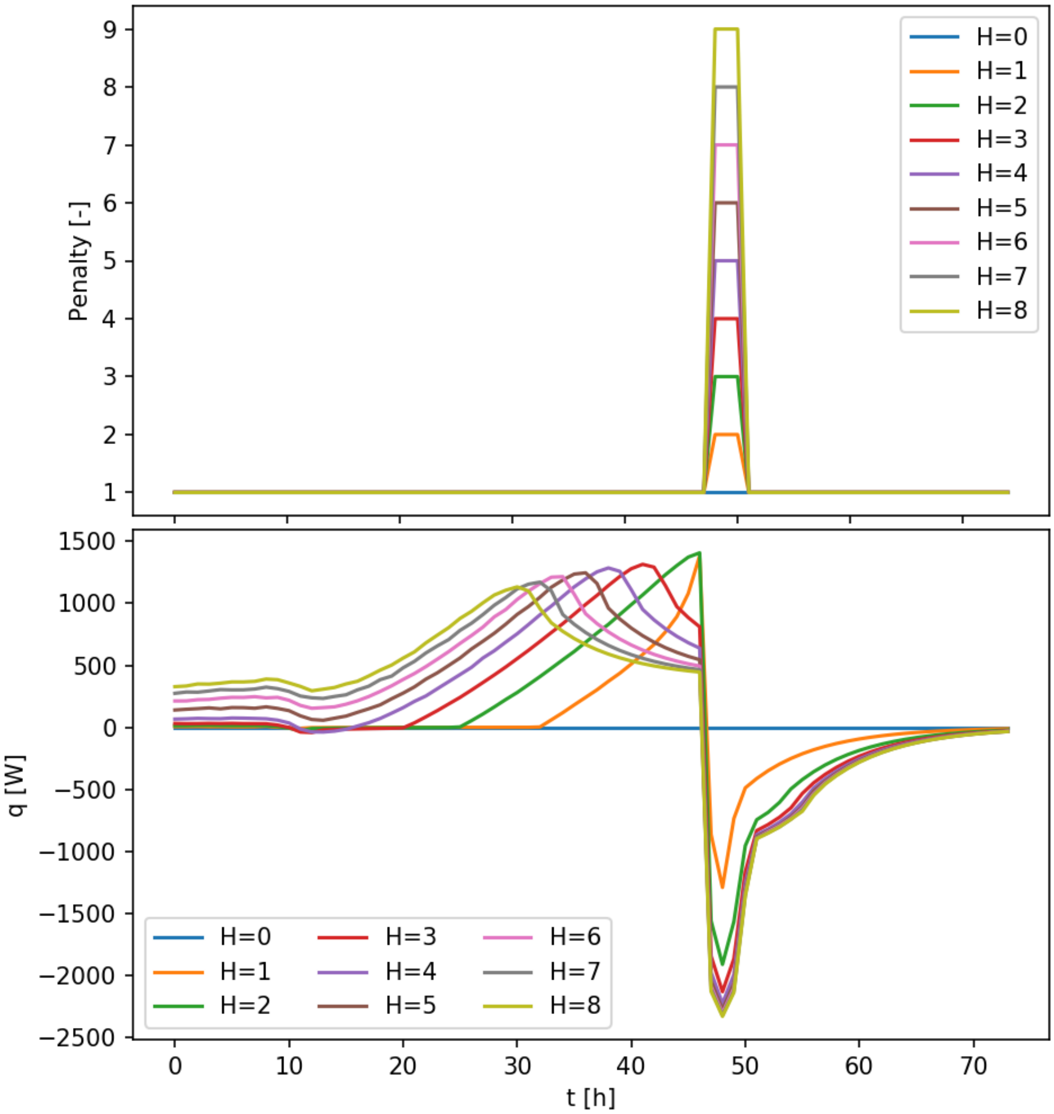


Figure 5.4 Impact of increasing amplitude of the Penalty signal (top) and the change in heating power profile using a MPC strategy compared to the flat price scenario H=0 (bottom) (Jensen, et al., 2019). See also Section 6.3.3.

The example shows that an optimal control strategy (e.g., like MPC) reacts to the anticipated step-change in the Penalty signal by pre-conditioning (e.g. pre-heating). The example further shows that the response of the flexible building cannot be assumed to increase linearly with increasing amplitudes of the step function. A saturation effect is seen at high amplitudes of the Penalty signal. An increase from H=7 to H=8 does nearly not lead to an extra reduction in the energy demand during the high price period – bottom plot of Figure 5.4. This clearly shows that buildings are not linear or time-invariant systems.

The developed methodology is also able to handle such more advanced control strategies as seen in the following.

5.2. Computing the Flexibility Function

For Figure 5.2 the FF is most easily understood as the difference between the penalty-unaware and penalty-aware control of a building. While in principle this is easy to understand, in practice it is more complex than this. In most cases the Penalty signal is temporal and varying over time and for real buildings only the penalty-aware or the penalty-unaware are measured, as it is not possible to obtain both time series for exactly the same boundary conditions (weather, Penalty signal) and use of the building. This is a classic problem in controls. It is difficult to show the benefit of a strategy, because it needs to be compared with a hypothetical, non-existent baseline strategy. In other words, it is difficult to compare “what happened” with “what could have happened”. In this case the FF has to be estimated using time series analysis instead.

5.2.1. *Direct Approach*

The **direct <u>baseline</u> approach** to obtain the dependency on a Penalty signal of an energy flexible building, or any individual controllable system, assumes that the respective energy flexibility is given by the difference between two energy demand scenarios as shown in Figure 5.2 (or two CO_2 scenarios as shown in Figure 5.3).

- The first energy demand scenario, defined as the **reference/baseline scenario**, refers to the normal system operation, where the energy flexibility is not used to react against a Penalty signal. This is the “business as usual” or baseline situation, where e.g. heating of a building is done without considering that the energy price might be varying in time (in other words, the energy profile is obtained by applying a flat Penalty signal).
- The second energy demand scenario is where the **penalty-aware** controller is utilized, and represents, for example, the case where heating is primarily provided when the penalty is low. The difference between the energy demand for the reference scenario and the penalty-aware scenario is then used to assess the Flexibility Function of the given building.

It is easy to obtain time series for penalty-aware and penalty-unaware situations when performing simulations or tests in hardware-in-the-loop test facilities (for the latter please see the Annex 67 report (Salom and Péan, 2019)), where all boundary conditions can be kept identical for both cases. However, this not possible in real buildings and energy networks.

For real cases where only the energy demand of the penalty-aware control is available (no baseline is available) there is a need for an **indirect <u>baseline</u> approach**, discussed below.

5.2.2. *Indirect Approaches*

To understand the **indirect approach** it is necessary to first understand the **direct approach** where the FF is the response to one separate step change in the Penalty signal (Figure 5.2). This response is here called the **direct <u>step</u> approach** and is especially useful during a design phase of a building using simulations to investigate the possible energy flexibility of different components of the building. A step change in the Penalty signal may also be used for obtaining peak shaving during a known daily high load situation. However, in actual energy networks it is often more difficult to deviate from a temporal Penalty signal as this will disturb the operation of the network and possibly the comfort of the users of the buildings – i.e. a significant step change of the Penalty signal is often not possible. But, in some cases it may be possible to test the system by submitting a step change signal, which can be valuable for an aggregation, thereby gaining insight in the possible energy flexibility available.

However, in most cases the Penalty signal will be temporal (varying over time) as shown in Figure 5.3 and the energy demand is neither linear nor time-invariant (LTI). In this case there is a need for a more advanced approach based on system identification. Which in the following is called the **indirect step approach**.

The **indirect approaches** require more steps than the **direct approaches**. Firstly, the Penalty signal needs to provide the relevant statistical information, more precisely it has to be persistently exciting (More, 1983). To be persistently exciting, the Penalty signal must include the frequencies for which the buildings have dynamics. So, to estimate slow dynamics, such as those related to the thermal mass of building materials, the Penalty signal should include slow dynamics as well. While to estimate the fast dynamics of e.g. an electrical battery, the Penalty signal must include high frequency variations.

In contrast, real world Penalty signals (such as time-of-use tariffs) the Penalty signals are likely to have the same pattern day after day. This means that the only dynamics that can be estimated are those with similar time constants as the variations in this pattern. Furthermore, when the measured data is offered from real price signals and in-use buildings, then diurnal, weekly and seasonal patterns will be present, such as differences in demand throughout the day or year. Even worse, the Penalty signal is often correlated with the demand, since one of the reasons why there could be a large penalty is that the demand is large as well, since in this case it takes more expensive power generators to satisfy the demand. If left unchecked this results in estimates indicating that the demand goes up when the Penalty signal goes up, which is obviously not true. These natural patterns should not disturb the estimation of the Flexibility Function, and thus they should be filtered out. This process is called pre-whitening and is described in (Madsen, 2007).

Pre-whitening can be achieved in several ways, with the simplest approach being to subtract the average of the forecasted penalty from the current penalty, yielding a negative value when the current penalty is smaller than the forecasted penalty and vice versa when it is larger than the forecasted penalty. In summary, the steps involved in estimating the dependency of the energy demand on the Penalty signal are as follows:

1. Remove any trends from the measured demand. The most obvious one is the hourly mean value, while it is usually also required to filter it through a simple AR (Auto-Regressive) model. What is left is the flexible part of the demand.
2. Use the model from step 1 (e.g. the AR model) to filter the Penalty signal.
3. Fit a FIR (finite impulse response) model using either the filtered demand and penalty from step 1 and 2 or the original demand and penalty.
4. The (step-)response function is obtained by adding the coefficients of the FIR model, i.e. the cumulative sum of the coefficients of the FIR model.

The FIR model in step 3 constitutes the Flexibility Function and can be visualized as Figure 5.2 by finding the step response as described in step 4. If more advanced versions of the Flexibility Function are required, then the FIR model should be replaced by another dynamic model. How to choose the model is still an open research question. In the EBC Annex 58 report “Reliable building energy performance characterization based on full scale dynamic measurements” (Madsen et al., 2016), the principles needed for more advanced modelling and system identification is described. It is based on these principles that a non-linear description was developed in (Dominkovic et al., 2019).

5.3. Evaluation of the Approaches

Table 5.1 lists the different ways of obtaining the Flexibility Function.

When performing simulations for a building or a cluster of buildings it is very easy to obtain two time series for the energy demand: a penalty-aware demand and a penalty-unaware demand (**direct baseline**). This is why the Flexibility Function until now have mainly been investigated using simulation. In simulation it is also easy to introduce a well-defined step change of the Penalty signal (**direct step**).

However, for real buildings situated in actual energy networks only one time series of the energy demand is present – the penalty-aware demand (today, for most buildings only the penalty-unaware energy demand is available, however, this is of less interest when trying to determine the possible energy flexibility) – **indirect baseline**. When only having one time series of the energy demand, it is difficult to create time series for the dependency on the Penalty signal, as the energy demand is not only correlated with the Penalty signal, but also with the actual use of the building, the controller, the weather, etc. Further in real life, a well-defined step change of the Penalty signal is often not possible – **indirect step**. Normally only a temporal Penalty signal is available.

Table 5.1 Four different ways of obtaining the Flexibility Function dependent on if one or two time series are available (direct or indirect baseline approach) and the nature of the Penalty signal: step change or temporal (direct and indirect step approach).

Penalty signal	**Available time series**	
	Both penalty-aware and penaltyunaware	**Only penalty-aware**
Step change	Direct baseline } Direct step = **Direct approach**	Indirect baseline } Direct step = **Indirect approach**
Temporal	Direct baseline } Indirect step = **Indirect approach**	Indirect baseline } Indirect step = **Indirect approach**

Based on the above, two main approaches can be defined: direct and indirect approach:

- Defining the FF with two time series of the energy demand and with a well-defined step change of the Penalty signal is normally considered as the **direct approach**, as the FF directly is obtained by subtracting the penalty-unaware energy demand from the penalty-aware energy demand. This is shown in the top left corner of Table 5.1.
- When the baseline is indirect and/or the Penalty is temporal the determination of the FF is normally referred to as the **indirect approach** as time series analysis is necessary in order to derive the FF. This situation is shown in three of the possible scenarios as per Table 5.1. The **indirect approach** is more difficult to implement than the **direct approach** as it requires skills in time series analysis. For further details on time series analysis please refer to (Madsen, 2007) and (Madsen et al., 2016).

5.4. Utilization of the Flexibility Function

It has, in connection with Figure 5.2 been shown how a number of Energy Flexibility characteristics can be summarised in the Flexibility Function. Furthermore, it has been argued how these flexibility characteristics are important for different applications of energy flexibility. However, a formal quantification of the energy flexibility should be based on the value of using such flexibility. The value depends on the problems solved by using the energy flexibility, and thus it might vary both in space (from energy network to energy network) and time (of the day and season). Nonetheless, the value of the energy flexibility can be computed for a specific scenario of problems. Using the Flexibility Function for a building or a cluster of buildings the Expected Flexibility Saving Index (EFSI) and the Flexibility Index (FI) can be computed. EFSI and FI gives for a given Penalty signal the cumulated penalty by utilizing the energy flexibility of a building or a cluster of buildings. The applied Penalty signal should express the penalty related to consuming energy for the specific scenario of problems. In this way it is possible to investigate how a given building or cluster of buildings perform in a specific energy network.

5.4.1. Expected Flexibility Saving Index (EFSI)

Figure 5.5 shows the Flexibility Function (FF) for three different buildings. Building 1 has a large time constant (e.g. a low energy building with a significant amount of thermal mass), while Building 3 has a very low time constant (e.g. a poorly insulated building with resistive heating). Building 2 has a medium time constant. The FF can be used to investigate how a building may support a specific grid. Figure 5.6 shows examples of dynamic Penalty signals for three different grids: one with large amount of wind power, one with a significant amount of solar power, and one with large peaks (ramps) in the morning and afternoon. A penalty of 1 means that there is little or no wind or solar power in the grid or that there are ramping (peak) problems.

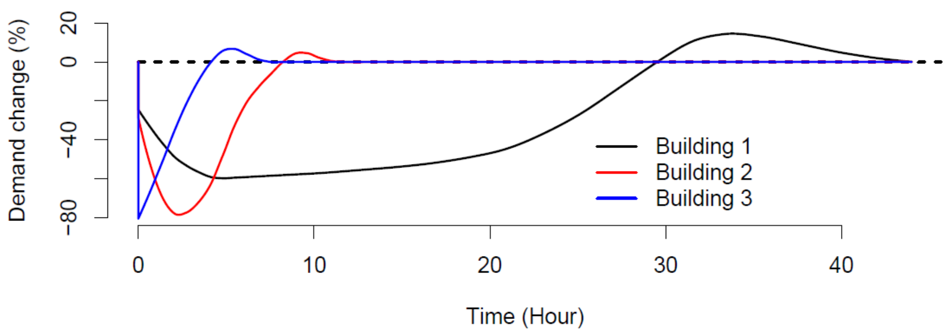


Figure 5.5 The Flexibility Function for three different buildings (Junker et al., 2018).

To obtain the Expected Flexibility Saving Index for a specific building and one particular series of the Penalty signal, the following steps should be followed after the FF has been determined either by the **direct** or the **indirect approach**:

1. Let λ_t be the penalty on the energy consumption at time t - one of the curves in Figure 5.6
2. Simulate the control of the building *without considering* the Penalty signal, and let u_t^0 be the energy consumption at time t.
3. Simulate the control of the building using the FF and thus *considering* the Penalty signal, and let u_t^1 be the energy consumption at time t.
4. The total operational cost of the penalty-ignorant control is given by

$$C^0 = \sum_{t=0}^{N} \lambda_t u_t^0 \tag{5.3}$$

5. Similarly, the operational cost of the penalty-aware control is given by

$$C^1 = \sum_{t=0}^{N} \lambda_t u_t^1 \tag{5.4}$$

6. Then the quantity

$$EFSI = 1 - \frac{C^1}{C^0} \tag{5.5}$$

gives the fractional amount of saved weighted penalty, which configures the suggested Expected Flexibility Saving Index EFSI.

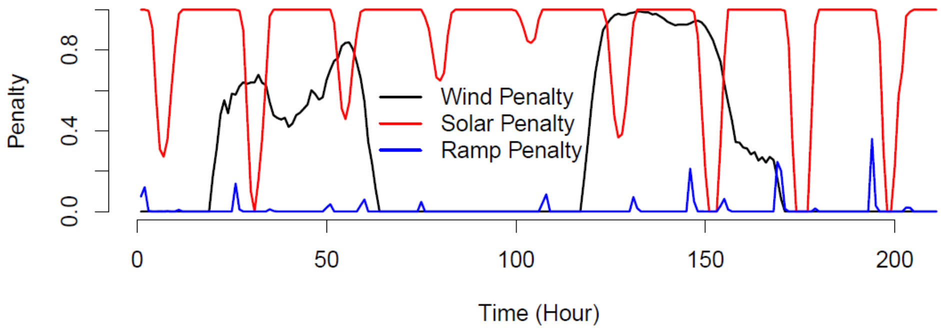


Figure 5.6 Penalty signals based on wind and solar power production in Denmark during 2017. Ramp penalty based on consumption in Norway during the same period (this situation is also typical for district heating systems) (Junker et al., 2018).

Based on the FF for the buildings and the dynamic Penalty signal, it is possible to calculate the Expected Flexibility Savings Index (EFSI) as described above. Table 5.2 shows the EFSI in % savings for the three buildings in Figure 5.5 when situated in the three grids shown in Figure 5.6.

Table 5.2 shows that Building 1 with the large time constant is best suited for a grid with much wind power - an EFSI of 11.8 % compared to 3.6 and 1.0 % for the two other buildings. The reason is that there often is wind or nearly no wind for several days, so energy needs to be stored for several days. Building 3 with the fast reaction is best suited for a grid with short peak problems, while Building 2 with a medium time constant best supports the grid with daily swings in the amount of RES (solar power) in the grid.

Table 5.2. EFSI for each of the three buildings based on the dynamical Penalty signal shown in Figure 5.6 (Junker et al., 2018).

Building	Wind (%)	Solar (%)	Ramp (%)
1	11.8	4.4	6.0
2	3.6	14.5	10.0
3	1.0	5.0	18.4

Table 5.2 shows the results of utilizing the energy flexibility from generic buildings in generic energy networks. The real world is much more complicated than shown in Figures 5.5 and 5.6. Nevertheless, Table 5.2 illustrates that different energy networks need different services from the buildings.

5.4.2. Flexibility Index (FI)

However, grid operators are typically more interested in knowing how buildings may help solve the problems faced by the grid. Again based on the FF (Figure 5.5) and well-chosen Penalty signals similar to those shown in Figure 5.6 (Figure 5.7 shows the used simplified and more operational binary Penalty signals based on Figure 5.6 concentrating on when there is a need for support from the building(s)), the Flexibility Index (FI) may be calculated for the actual energy network, describing the extent to which each of the buildings are able to solve the grid problems.

The Flexibility Index for a specific building is found in the same way as for the EFSI, where, however, the Penalty signal in step 1 is replaced with a Penalty signal, which is designed to solve problems in the energy network rather than to create a saving as for the EFSI.

Table 5.3 gives the FI as a percentage for the considered examples.

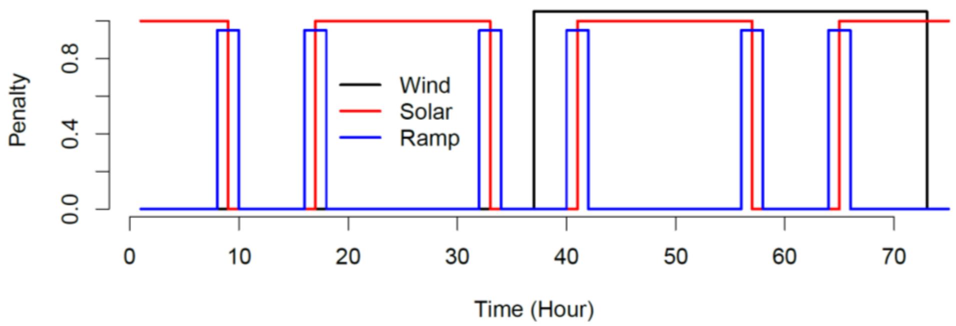


Figure 5.7 The Penalty signals from Figure 5.6 are simplified into more operational binary Penalty signals designed to obtain energy flexibility from the buildings when needed by the energy networks (Junker et al., 2018).

Table 5.3. Expected FI for each of the three buildings based on the dynamical Penalty signals shown in figure 5.7.

Building	Wind (%)	Solar (%)	Ramp (%)
1	35.1	7.2	18.9
2	10.2	24.0	37.5
3	4.9	11.1	71.0

Table 5.3 shows how much of the energy flexibility of the buildings which can be utilized for solving the problems in the grid. Building 3 is capable during 71 % of the time to help the grid with ramp problems, while Building 1 for 35 % of the cases can provide energy flexibility to a grid facing issues related to a high level of wind energy. It is further seen that the trend of Tables 5.2 and 5.3 are similar except that the values of Table 5.3 are approximately 3 to 4 times higher than in Table 5.2. This means that if a building performs well from the grid operator point of view is also gives the highest savings for the customer. This is a very encouraging result for actually getting consumers to accept participating in the stabilization of the future energy grids if there are mechanisms for appropriately compensating building owners for the services they can provide.

Exactly how the developed methodology may be applied in real energy networks is an issue for future research. However, this is one of the themes of a proposed new IEA EBC Annex: Annex 82 Energy flexible buildings towards resilient low carbon energy systems.

5.4.3. The Flexibility Function as the Core of a Controller

Since the Flexibility Function describes the relationship between a Penalty signal and the expected resulting energy demand of a building or a cluster of buildings the Flexibility Function can directly be applied in a controller of an aggregator for example. As the FF describes the possible energy flexibility from buildings, the FF may be utilized in a controller to define the Penalty signal which will lead to the required change in the energy demand. This was shown in (Corradi et al., 2013) and (Madsen et al., 2015). For a single building there is a large uncertainty as the available energy flexibility is dependent on the actual state of the building. E.g. if a heat pump has just started up, this needs a certain runtime before it can be switched off again in order not to increase the wear and tear of the heat pump. Conversely if the heat pump has just stopped it needs a certain rest period before it can be switched on again. However, the more buildings that receive the Penalty signal the more likely it is that the Penalty signal leads to the desired change in the overall energy demand. For clusters of buildings it was shown in (Junker et al., 2019), that the FF can be used to split electricity grid problems into sub problems suited for buildings with particular characteristics. This is of particular interest for DSOs and aggregators. From a TSO perspective it is expected that the flexibility function will be valuable at a market level as described in (Morales et al., 2014).

The Flexibility Functions is, therefore, not only valuable for characterizing the possible available energy flexibility, but it is also an important part of a controller which can generate appropriate Penalty signals.

5.5. Labelling

Tables 5.2 and 5.3 and the bottom graph of Figure 5.3 indicates that the developed methodology may also be utilized for labelling the energy flexibility of buildings. Especially the Flexibility Index (FI) has the potential to serve as the basis for labelling. However, it is important to remember that the energy flexibility is very much dependent on the use of the building, the weather and the energy networks it is connected to. Therefore, for identical buildings the useful energy flexibility of the building may differ significantly due to the location of the building.

During the design of a building or clusters of buildings the energy flexibility may be characterized and labelled as in the already existing certification schemes for the energy demand of buildings, where the buildings are exposed to standard values for weather and use - in order to determine if a building complies with the specifications of the national Building Code. On top of these standard values the buildings could be subject to a standard sequence of a Penalty signal, where the building is simulated with and without the penalty-aware controls. However, this will not give the grid operators and aggregators much information on how buildings will perform in their grid/portfolio. Alternatively, buildings could be subject to a number of Penalty signals typical for a given country with respect to weather conditions and the needs of the energy networks. This way, the available energy flexibility in different contexts can be obtained.

For buildings and clusters of buildings already in use, the measured energy demand and the applied Penalty signal may be utilized to characterize the buildings/clusters as described in the earlier sections. Here the result will be the energy flexibility for the actual use of the buildings/clusters located in an actual energy network.

During the course of Annex 67 the EU Commission proposed to include SRIs (Smart Readiness Indicators) in EPBD (Energy Performance of Buildings Directive -

https://smartreadinessindicator.eu/). The aim of SRIs is to rate the readiness of the building to adapt its operation to the needs of the occupant and the grid, and to improve its performance. This goal is clearly in line with the objectives of Annex 67. Annex 67 participated as stakeholder in the first study on SRIs and produced a position paper (Pernitti, Reynders and Knotzer, 2017). The position of Annex 67 is that there is a need for an approach that takes in to account the dynamic behaviour of buildings rather than a static counting and rating of control devices as proposed by the SRI study. Furthermore, it is important to minimize the CO_2 emissions in the overall energy networks rather than optimize the energy efficiency of the individual energy components in a building.

5.6. Harmonized visualization and communication Tool

This section describes a harmonized visualization and communication of the characterization work of Annex 67, including two key performance indicators developed by Annex 67, namely efficiency of flexible operation Eflex [%] and shifted flexible load Sflex [%] (Weiss el al., 2019).

An Excel tool, named Flexibility Evaluation Tool (FET) was developed and made available to the public via the Annex 67 website (http://www.annex67.org/publications/software/). FET is a tool to uniformly visualize, characterize and evaluate energy flexibility. The manual accompanying the tool can also be downloaded from the Annex 67 website. The manual provides a brief description of how to use the tool and gives an overview of the calculation methodology (Weiss et al., 2019).

To name some of the benefits of this tool:

- Evaluates energy flexibility with different time steps, timespans, Penalty signal called cost functions in the tool - based on a reference load profile, a load profile with flexible operation and a Penalty signal/cost function (Figure 5.8)
- Includes a reduced number of energy flexibility evaluation criteria and indicators
- Provides a way to compare results from both simulations and measured data

Explanation of the numbers represented in Figure 5.8 – for further information please see (Weiss et al., 2019):

(1) Overall inputs for timespan, time steps, cost-function/Penalty signal and units
(2) Input data about a buildings load profile, a flexible load profile and a cost function based on the time steps, timespan and units
(3) Evaluation charts and characterization

This Excel tool takes as input the time series data for:

- Penalty signal
- Reference load profile
- Load profile with flexible operation

In addition to these outputs an extra sheet has been added to document the boundary conditions and system properties used during the flexibility assessment process. As the energy flexibility is for most systems strongly dependent on – often time-varying – boundary conditions, this sheet takes time series input in order to document the boundary conditions in a uniform and unambiguous way.

Based on these time series data the following output is created also referring to Figure 5.2 in Section 5.1:

- Flexibility Function profile
- β Total time of decreased energy demand
- Total time of increased energy demand (rebound)
- Δ Maximum change in demand following the change of the penalty
- A total amount of energy decreased
- B Total amount of energy increased (rebound)
- Savings indicator (S) based on cost function: S = c(t)*(Lref(t) – Lflex(t)) - defines the “efficiency of flexible operation” and gives a percentage value of the savings in terms of costs, CO_2 or primary energy which can be achieved, compared to a baseline load profile without flexibility

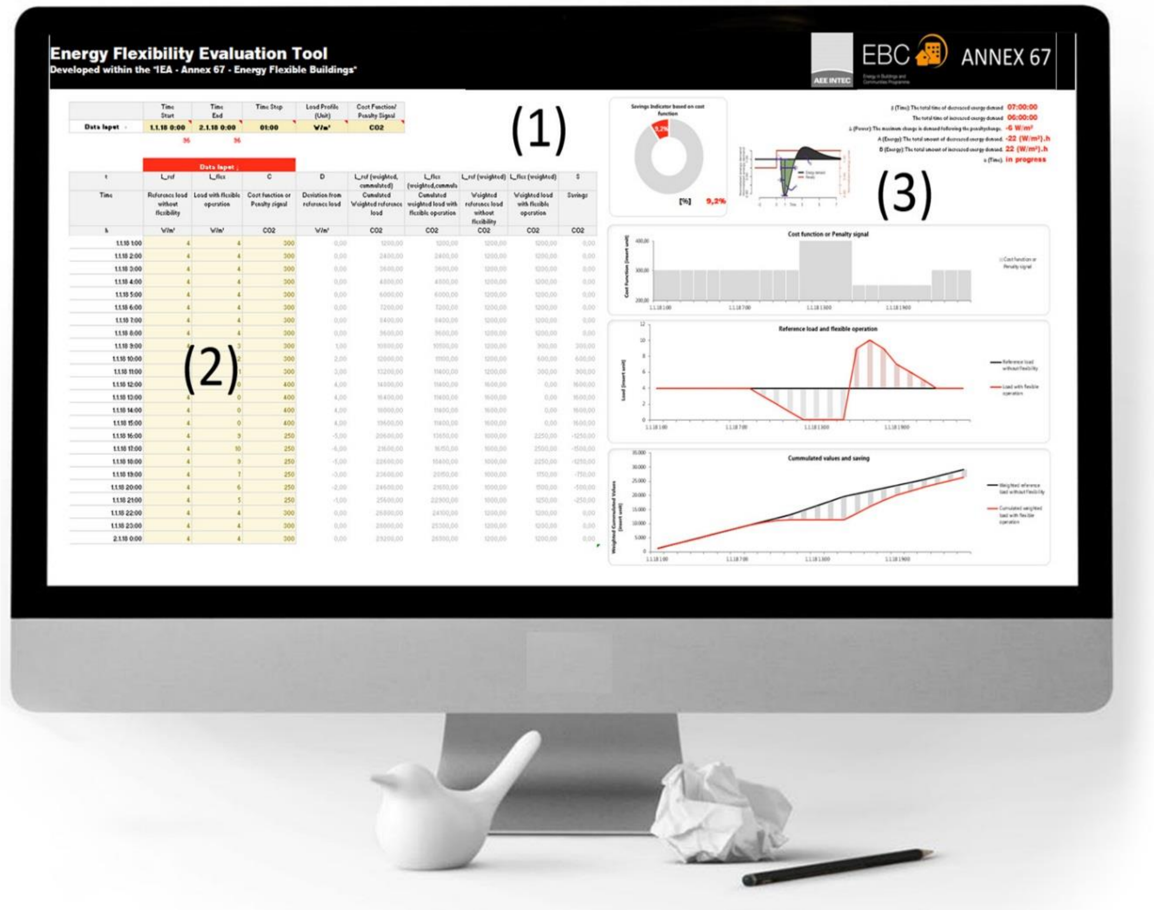


Figure 5.8 Energy **F**lexibility **E**valuation **T**ool (FET) - Overview of the interface (Weiss et al., 2019).

5.7. Conclusion

A methodology for characterization of the energy flexibility from buildings or clusters of buildings has been developed. The core of the methodology is a Flexibility Function which describes the response to a Penalty signal. The Penalty signal can either be a prize signal, the content of CO_2 or RES of the energy in the surrounding energy network.

Using the Flexibility Function for a building or a cluster of buildings the Expected Flexibility Saving Index (EFSI) and the Flexibility Index (FI) can be computed. EFSI and FI gives for a given Penalty signal the cumulated penalty by utilizing the energy flexibility of a building or a cluster of buildings. The applied Penalty signal should express the penalty related to consuming energy for the specific scenario of problems. In this way it is possible to investigate how a given building or cluster of buildings perform in a specific energy network. This gives important information to the DSO and aggregators of energy flexibility. It is further foreseen that the methodology may be the basis for a future labelling system concerning the possible energy flexibility from buildings.

6. Assessment of the Methodology to Characterize Energy Flexibility

Glenn Reynders, Jérôme Le Dréau, Krzystof Arendt, Rui Amaral Lopes, Kun Zhang, Tobias Weiss

6.1. Introduction

This chapter gives an overview of the main findings of an extensive testing phase that was carried out to evaluate and exemplify the constraints and applicability of the characterization methodology outlined in Chapter 5. The focus was primarily on evaluating the potential and interpretability using simulations and a step change of the Penalty signal referred to as the direct approach. Less focus was given to varying Penalty signals denoted the indirect approach.

Note that in theory, under the original assumption of linear and time-invariant systems, the outcome of both approaches direct and indirect would be directly comparable and equivalent. However, as buildings and their associated energy conversion systems often react in a non-linear way to changes of, for example, the heating or cooling power, Chapter 6 examines the comparability of both approaches in more detail.

The chapter is organized as follows: Section 6.2 commences by outlining a set of detailed research questions. Section 6.3 details the results of different studies that try to answer the research questions. Finally, Section 6.4 summarizes the main conclusions linked to the impact on the methodology as proposed in Chapter 5.

6.2. Outline of the assessment Procedure

The assessment of the characterization methodology that is presented in this chapter, was carried out as a set of common exercises in the context of the IEA EBC Annex 67 project. Throughout the IEA EBC Annex 67 project, these common exercises were used to formalize discussions and streamline the process of developing and evaluating definitions and quantification methods for energy flexibility. Early common exercises in the project aimed at applying many different characterization methodologies to the same case study building in order to compare properties of those characterization methodologies identified from literature or developed by participants. Those common exercises have supported the analysis presented in the literature review (Chapter 4) and are exemplified for instance in (Reynders et al, 2015). Findings from those common exercises supported the adoption of a unified methodology developed by IEA EBC Annex 67 as outlined in Chapter 5.

To evaluate the robustness and application domain of the consolidated method presented in Chapter 5, IEA EBC Annex 67 participants applied the methodology outlined in Chapter 5 to different case studies. The first round of results showed significant discrepancies between the direct approach and the expected outcome from the indirect approach. Those discrepancies mostly resulted from different choices made by the modelling teams such as variance in assumptions, reference scenarios, boundary conditions, etc. Based on those intermediate findings, a list of detailed research questions was derived to structure the analysis of defining the application domain and interpretability of the characterization methodology.

Section 6.2.1 explains this list of identified research questions and provides some necessary background information. Section 6.3 describes the results obtained from the different case studies that are used to analyze the research questions.

6.2.1. Identification of Research Questions to assess applicability and interpretability of the Characterization Methodology

Whereas the theoretical framework behind the Flexibility Function is derived from system identification (see Section 5.2) and hence formulated for the “indirect approach” as defined in Chapter 5, most analysis to assess the characterization methodology were focused on the “direct approach”. This assessment approach was identified to result from the closer link to traditional building energy simulations that are generally used by the IEA EBC Annex 67 participants in their research domain. In contrast the system identification methodology and data-driven modelling, set up a mathematical relation between real data by measurements of the building system and the external inputs to the system, without going into details of what is actually happening inside the building system, which is somewhat strange for building physicists.

From the preliminary results, general findings are summarized in this section. These findings formed the basis for exercises to gain better insight in the applicability and limitations of the “direct simulation approach.” Note that the data-driven, indirect approach is only briefly addressed.

Table 6.1 summarizes the research questions that remain after the presentation of the preliminary results. The questions are arranged along different categories including boundary conditions, Penalty signal, periodicity and control formulation.

Table 6.1 Overview of research questions formulated to assess applicability and limitations of the flexibility characterization methodology.

Topic	Research question/ description of the problem	Discussed in section(s)
Boundary conditions	How do flexibility characteristics depend on boundary conditions?	6.3.1 and 6.3.2
Penalty signal	How do the flexibility characteristics depend on the amplitude of Penalty signal?	6.3.3
Control formulation	Anticipation effect of model predictive control in direct approach: can/should it be avoided?	6.3.7
Periodicity	How to deal with consecutive events?	6.3.6
Penalty signal	How do flexibility characteristics depend on starting conditions (state and time)?	6.3.4 and 6.3.5

How do flexibility characteristics depend on boundary conditions?

The available flexibility is known to depend significantly on the circumstances (boundary conditions). In this research question, the sensitivity of the characterization method to boundary conditions is analyzed. Specific attention is placed on weather conditions and occupant behavior (including comfort requirements).

How do flexibility characteristics depend on the amplitude of Penalty signal?

In the indirect approach the step response function is identified as a linear time-invariant transfer function, which can then be visualized for any step change in Penalty signal. For the direct approach, the Flexibility Function is obtained from comparison of a single realization of the step change. This question, therefore, polls to what extent the obtained flexibility characteristics are sensitive to different shapes (amplitudes) of the Penalty signal (step function).

Anticipation effect of model predictive control in direct approach: can/should it be avoided?

The current formulation of the direct approach to obtain the flexibility characteristics leads to an anticipation effect. As shown in Figure 6.1 an optimal control strategy (like MPC) anticipates to the step-change in the Penalty signal by pre-conditioning (e.g. pre-heating) moving the energy consumption for high-penalty periods to low-penalty periods.

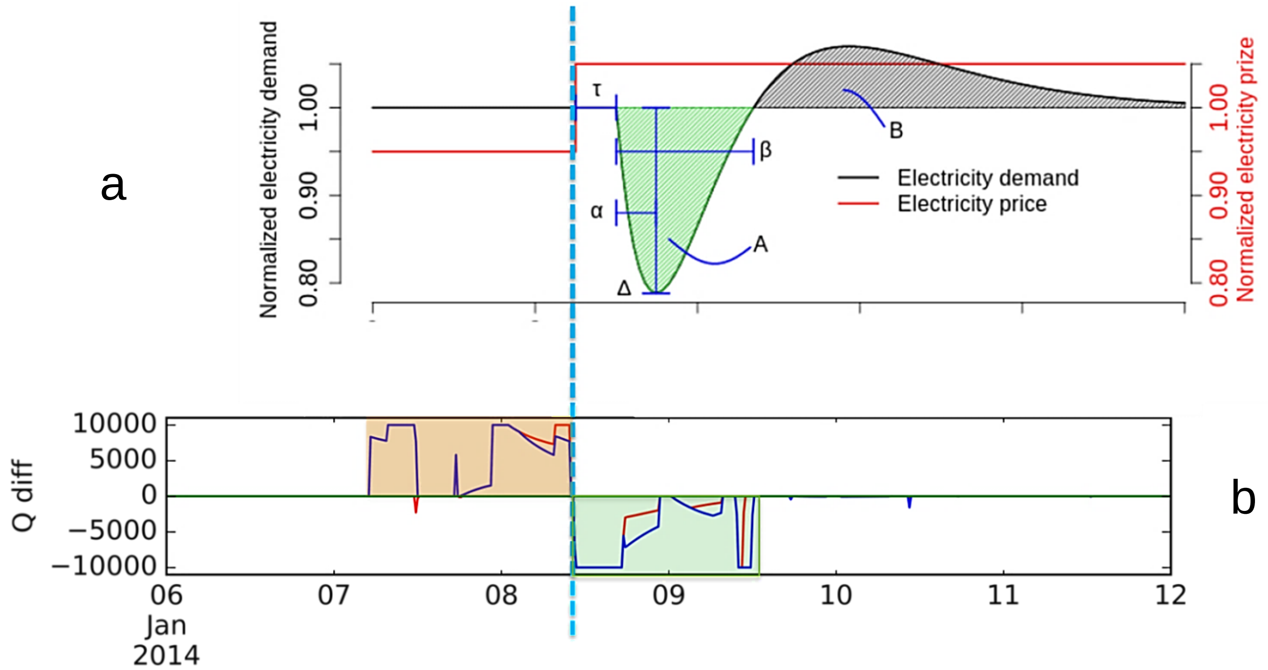


Figure 6.1 In the bottom graph (6.1b) an example is shown of the anticipation effect of energy demand in Watt as obtained when optimal predictive control of the building heating system is responding to a step change in price, introduced by dashed line coming from the top graph (6.1a), and compared to the change in energy demand obtained by a non-predictive controller (6.1a - top graph).

As this anticipation is not observed in the original definition of the FF (as represented in Figure 6.1a) the detailed question here is to analyze if an alternative formulation of the penalty function could result in a better comparability between the results from the direct and the indirect approaches. This does not mean it should be analyzed if this anticipation is needed/wanted but merely if an alternative formulation can bring both methods closer to each other.

How to deal with consecutive events?

The direct simulation approach is formulated based on the responses to a single step change in the Penalty signal. In practice, one may expect calls for flexibility occurring in consecutive events (few times a year down to few times per hour) or even continuously.

To what extent can the results for the single event within the direct approach be extrapolated to flexibility used in consecutive events?

How do flexibility characteristics depend on starting conditions (state and time)?

As only a single step change is simulated, this question polls to the sensitivity of the results to the exact starting conditions for which the simulation is performed. These starting conditions are described by the initial state of the system as well as the time in relation to the boundary conditions (e.g. at the start of a working day when office workers enter the building or during the night when the office is unoccupied).

6.3. Results of the verification Processes

Exercises were carried out in IEA EBC Annex 67 to answer the research questions identified in the previous section and the flexibility characterization methodology was subjected to different case studies during these exercises. It should be noted that all case studies investigated the direct simulation approach to characterize the energy flexibility and quantify the parameters of the Flexibility Function.

In this section the case studies are introduced together with their general findings related to the methodology described in Section 5.1. The case studies cover both the level of full buildings as well as the level of single building technologies, i.e. domestic hot water systems. They can be grouped into cases that implement a model predictive control as well as case studies in which rule-based control was used to respond to Penalty signals. Model predictive control relies on dynamic models of the process, most often linear empirical models obtained by system identification. It has the capability to include forecasts, anticipate future events and takes control actions accordingly. Rule-based control means that the accompanied algorithm relies on ‘if – then’ conditions to perform some reaction. This already indicates that the characterization method is applicable for both type of controls and only requires for the control to be able to react to a Penalty signal.

6.3.1. Influence of Weather Conditions – Rule-based control of a Residential House

Weather is a major cause of grid peak demands. The energy flexibility services that buildings can provide to the grid are also subject to the changing weather conditions because buildings constantly exchange heat with their surroundings. This section shows how weather impacts the amount of energy flexibility. The results are shown for a typical single family house situated in France, built according to the 2005 building regulation (Table 6.2).

Table 6.2 Thermal properties of the simulated building

	Building Regulation 2005
Insulation walls	10 cm IWI *(U=0.32 W/m².K)*
Insulation roof	16 cm *(U=0.23 W/m².K)*
Insulation floor	20 cm *(U=0.19 W/m².K)*
Windows	Double glazing *(U_w=1.6 W/m².K & g=0.60)*
C_m [Wh/K.m²$_{floor}$]	70 (heavy)
Mechanical exhaust ventilation [m³/h]	195
Infiltration [ACH]	0.18
HLC [W/K]	172
$Q_{heating\ needs}$ [kWh/m²$_{floor}$.y]	85

Figure 6.2 shows the total energy increase (in red) during the activation (as defined as A in Section 5.1) and the rebound effect (in blue), defined as B in Section 5.1. Activations are performed once a day by increasing the set-point by 2°C at noon for 6 hours (i.e., from 12:00 to 18:00). It corresponds therefore to a 6 hours anticipation period followed by a decrease of the heating energy use. The transition season shows a high variability in the different studied variables.

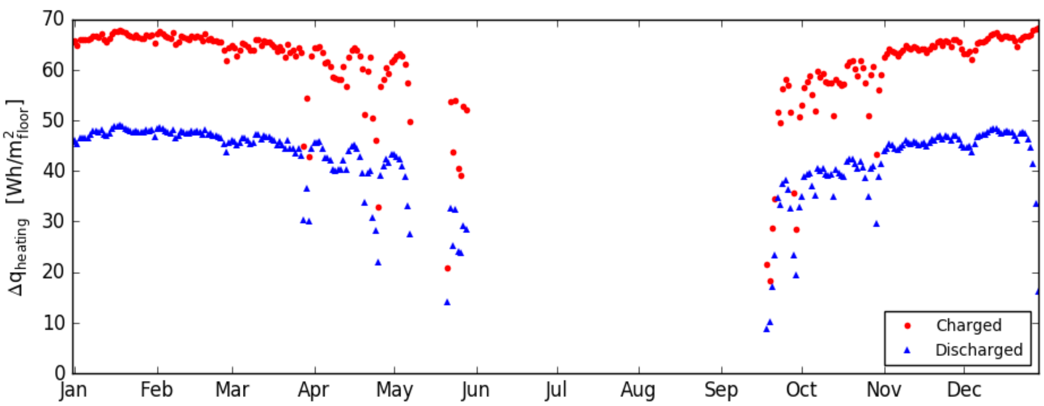


Figure 6.2 Influence of the outdoor conditions on the shiftable energy amount of A (red) = “charged” or “overheated” building by increasing the set-point by 2°C, and B (blue) = “discharged” or “cooling down” phase of the building - the transition season shows high variable values

When applying or interpreting the direct calculation approach, it is, therefore, critical to take into account the climatic boundary conditions to which the building is subjected. Clear documentation or even standardization would be needed to further improve the comparability of results between studies on the one hand, while on the other hand accurate climate predictions should be available to predict the flexibility of buildings in control applications. In the tool for quantifying flexibility developed in the IEA EBC Annex 67, dedicated columns have been foreseen to provide climate time series data and facilitate a clear communication of boundary conditions (see Section 5.6).

6.3.2. Impact of Occupant behaviour and Comfort requirements - Rule-based Control

A simplified semi-detached building was implemented using the IDEAS simulation library in Modelica. The building is heated using an air-to-water heat pump with low-temperature radiators, modelled as a power-limited ideal heat source. The building thermal characteristics correspond to a typical Belgian semi-detached dwelling constructed between 1990 and 2005. The floor is modelled in contact with the ground. The roof is a flat roof adjacent to the outdoor environment. The geometry is simplified to a shoe-box model with a ground surface of 125 m² and a single window, oriented south, is placed in the wall opposite to the partition wall, dividing the two dwellings. The model is described in detail in Reynders, 2015, and abridged data is summarized in Table 6.3.

For the case study, the building was subject to outdoor boundary conditions given by the Uccle (Belgium) TMY weather data. Occupants are assumed to be at home and active from 7:00 until 22:00, requiring a minimum indoor temperature 20°C and a maximum of 24°C. Night setback is applied, reducing the set point for heating to 16°C.

The resulting Flexibility Function and flexibility characteristics are known to depend significantly on user behavior and comfort requirements. For example in the case of thermal mass, comfort requirements directly affect the allowed temperature variations that are needed to activate the storage capacity. For domestic hot water storages, the hot water draw-off profiles will clearly influence the minimum amounts of hot water that should be available in the tank at specific times.

Table 6.3 Properties of the Belgian building

	Value	Unit
Floor surface area	125	m²
Volume	375	m³
Window to wall ratio	0.25	[-]
Effective ventilation rate	0.4	h^{-1}
Interior wall area	100	m²
Average U-value	0.24	W/m²K

As for the climate boundary conditions, clear communication of the occupant related boundary conditions is key to support comparability between studies. When aiming at comparative studies on energy flexibility, such as the comparison of building designs for their potential flexibility, standardization and simplification of occupant behavior can be used to allow for a comprehensive comparison of building design choices. To support this statement, Figure 6.3 shows the impact of occupant behavior and comfort requirements on the total increase in heating power corresponding to flexibility characteristic *A* in Section 5.1, denoted as C_{ADR} in Figure 6.3a, when increasing the temperature set point for heating to activate the flexibility of the thermal mass of a residential building. The black, blue and green lines correspond to scenarios whereby the temperature set point is increased for a duration of 1 h, 4 h and 8 h, respectively. Hence, direct control is used to activate the energy flexibility of the building thermal mass for 1 h, 4 h or 8 h, respectively, by increasing the heating power without anticipation. The results are shown as a function of time, meaning that each value shows the result of a charging event that starts at that specific point in time. Each point in time is hence obtained using a different set of simulations.

Figure 6.3b shows the minimum and maximum temperatures for a residential dwelling with night-setback, as well as the outdoor temperature during that winter period. During the day, occupants require a minimum temperature of 20°C, at night a temperature reduction to 16°C is allowed. The maximum temperature at all times is limited to 24°C.

Figure 6.3 clearly shows that as a consequence of the daily variation in comfort requirements (temperature set points), large variations in the increase of energy demand occur. With peaks in C_{ADR} in the evening when night-setback starts and minima of C_{ADR} in the morning when all heating power is already needed to recover from night-setback. Hence, in the morning, no additional power is available to provide flexibility.

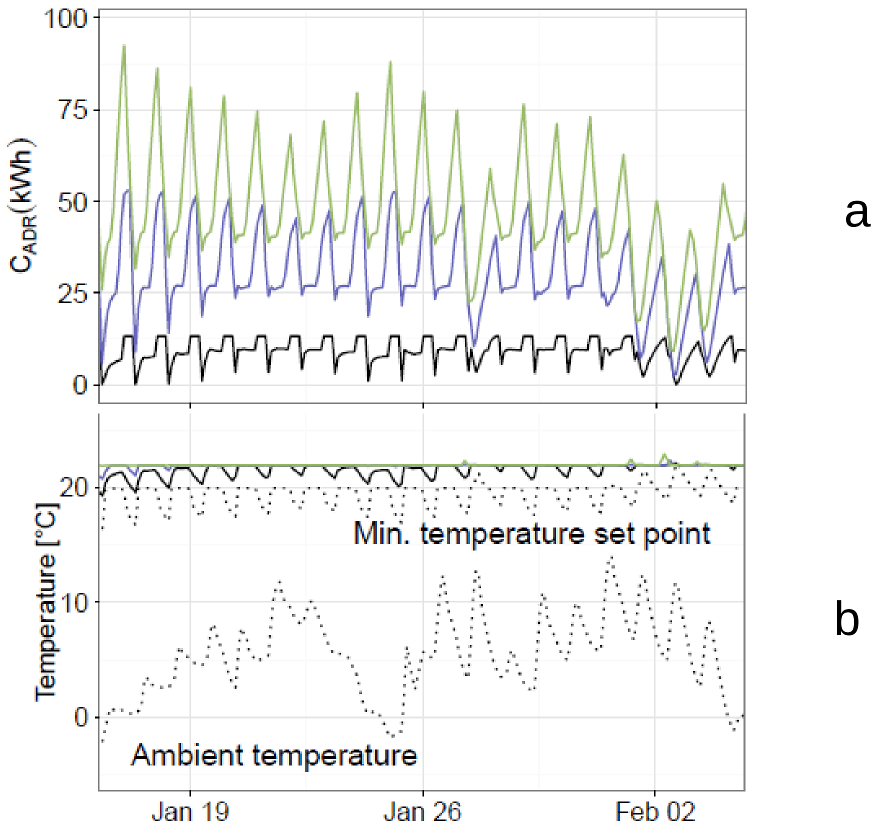


Figure 6.3 The top graph (6.3a) shows the impact of occupant behavior and comfort requirements on the total energy increase C_{ADR} (defined as A in Section 5.1) when increasing the temperature set point for heating to charge the thermal mass of a residential building. The black, blue and green line correspond to a charging time of 1 h, 4 h and 8 h, respectively. Each point in the curves shows the energy increase when the charging event starts at that given time. The bottom graph (6.3b) shows the ambient outdoor temperature, minimum (16°C) and maximum (24°C) temperature set points as dotted lines, as well as the resulting indoor temperatures, corresponding to the 3 charging time scenarios.

Based on this example, it can be concluded that when characterizing the flexibility of a single building, the available flexibility of a building provided by the structural thermal mass is highly time-variant as a result of the changing boundary conditions and comfort requirements to which the building is subjected. This affects both the direct and indirect flexibility characterization approach. For both methods, it is therefore key to apply them under realistic boundary conditions that are representative for the period during which flexibility is expected to be delivered. It is therefore advised to always include a detailed description of the boundary conditions for which the flexibility characteristics have been quantified.

6.3.3. *Influence of Penalty amplitude - Model predictive Control*

The Flexibility Function is defined in Section 5.1 as a step response function showing the response of the flexible system to a unit step function. Under the assumption of linear and time-invariant systems (LTI), the response of the flexible building is hence assumed to increase linearly with increasing amplitudes of the step function. This Section, therefore, analyses the impact of increasing the amplitude of the penalty function.

In this simulation study, model predictive control is used to optimize the heating power in response of an external Penalty signal. The model is a single-zone building modeled as a LTI state-space system representing a R3C3 thermal network, defined by 3 resistance and 3 capacitance parameters. External inputs are outdoor temperature, solar radiation, and number of occupants. The controlled input is the heating power and the model output is the indoor temperature. The model parameters are calibrated based on measured data from one of the zones of the OU44 building located at the SDU Campus Odense.

The goal of this case study is primarily to analyze the impact of the penalty function, simplifications to the boundary conditions that have been introduced. The outdoor temperature is fixed to 0°C and no solar radiation nor are occupants included in the model. These simplifications allow for a more comprehensive analysis of the results.

Figure 6.4 shows the profiles of the heating power (bottom plot 6.4b) for increasing amplitude of the penalty function. The figure clearly shows that as a result of the temporary increase in penalty, the model predictive control tries to reduce as much as possible the heating power during the high-price period. In order to be able to reduce the power during the high-price period, the model predictive control pre-heats the building prior to the high price period leading to no later rebound effect in this example.

Figure 6.4 shows the variation of the Flexibility Function parameters A and B (described in Section 5.1) deduced from the power profiles shown in Figure 6.4a. Figure 6.5 shows a clear non-linear relation between the amount of energy decrease (A) for increasing amplitude of the penalty function. As the flexibility provided by the thermal mass is bound by comfort ranges as well as thermal losses, the storage capacity gets saturated for increasing amplitudes, as it is physically infeasible to draw more heat from the thermal mass during the high-price periods. At the same time, for increasing penalties it is shown that significantly higher increases of B compared to increases of A are found.

6.3.4. *Influence of starting Conditions (state) - Model Predictive Control of a Domestic hot Water Storage Tank*

In this section the influence of the initial conditions is assessed. In this case, a single energy flexible system is considered, namely, a domestic hot water storage tank supported by an electric resistance heater, where the starting condition under analysis refers to the hot water temperature at t=0. The referred energy flexibility results from the thermal storage characteristics that enable temperature variations while respecting users comfort needs. Energy is provided by the electric resistance heater. The specifications guiding this assessment can be seen in Table 6.4.

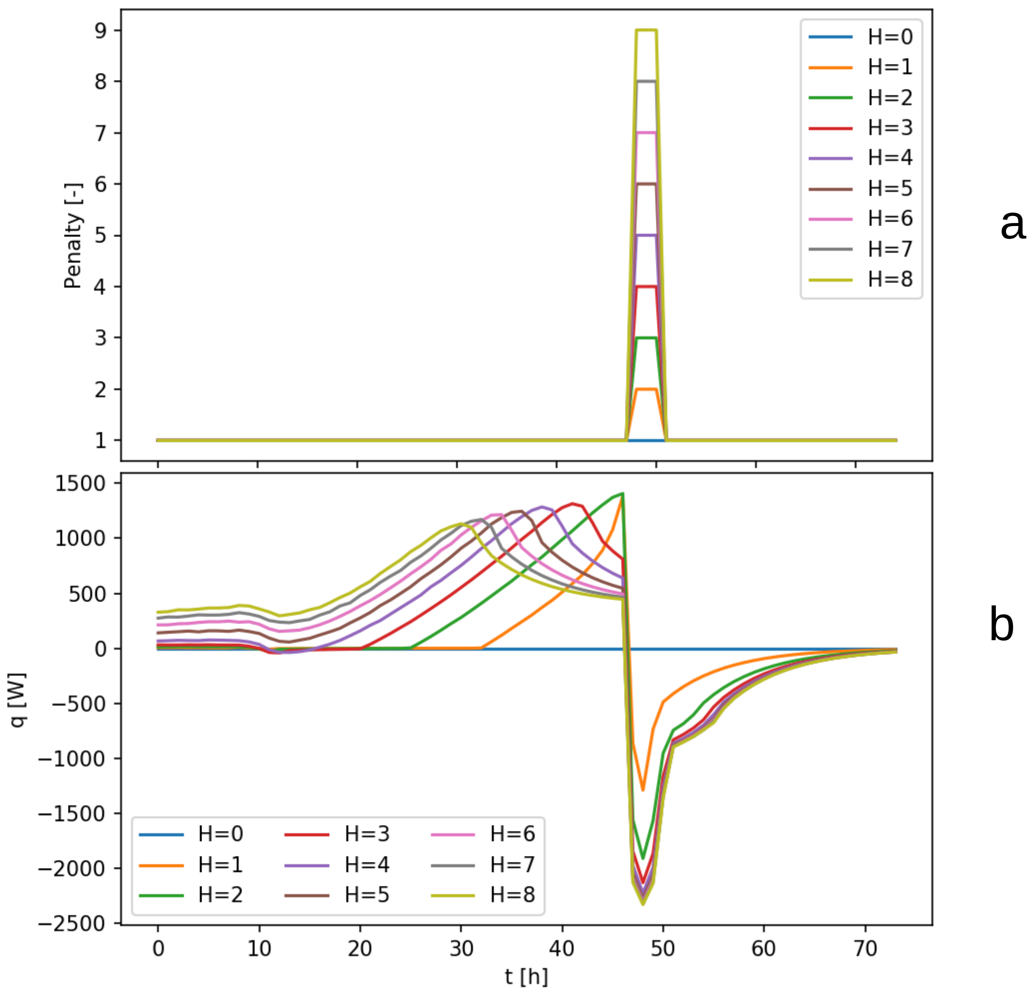


Figure 6.4 Impact of increasing amplitude of the penalty function (top) and the change in heating power profile compared to the flat price scenario (bottom).

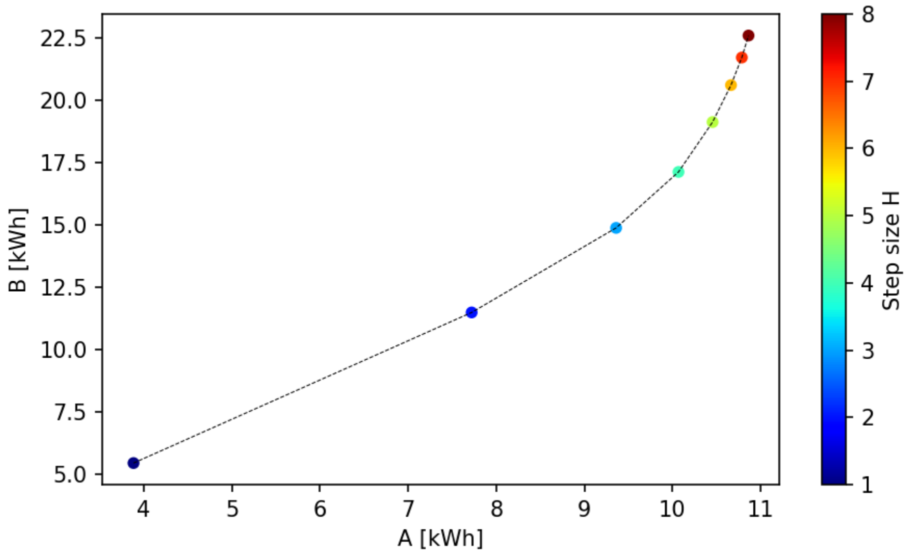


Figure 6.5 Decreased energy use (A) vs increased 'pre-bound' consumption (B) for different step sizes (H= 0 to H=8).

Following the assumption that energy flexibility reflects the difference between two distinct energy demand scenarios, this section aims to contribute to the assessment of the influence of the initial conditions (initial energy state) on the obtained results. The first scenario refers to the use of energy flexibility when a flat Penalty signal is imposed while the second scenario is associated to the use of energy flexibility when a time-varying Penalty signal is considered. Energy flexibility is here offered by a domestic hot water storage tank, supported by an electric resistance heater, where the water temperature can vary between 50ºC and 70ºC. Two initial hot water temperatures are considered, namely, 51 and 60ºC. Since the energy flexibility offered by a certain system depends on the adopted control strategy, both scenarios use a Genetic Algorithm (GA) that aims to minimize the penalty associated to the electricity consumption for the 24 h period.

Table 6.4 Assumptions of the assessment using a domestic hot water storage tank

	Value	Unit
Storage device characteristics:		
Size	150	litre
UA	1.96	W/K
Input Power	1000	W
Water Min. – Max. temperature	50 - 70	°C
Comfort needs:		
Hot water demand per day and user	40	litre
Number of users	4	[-]
Simulations:		
Resolution	15	min
Duration	24	h

Influenced by the user occupancy patterns, the hot water demand varies throughout the day. Figure 6.6 presents the hot water demand profile considered for four users.

Since energy flexibility is assessed by comparing two district energy demand scenarios, the following steps were implemented for each initial temperature considered in this study (51 and 60ºC):

1. The water temperature and electricity demand profiles were collected for a Flat Penalty signal;
2. The water temperature and electricity demand profiles were collected for a block pulse Penalty signal (see Figure 6.7), where the available energy flexibility is used to reduce the cumulative penalty over a 24-h period;
3. The use of energy flexibility is assessed at each time-step by subtracting the previous electricity demand profiles.

Figure 6.7 depicts the Penalty signal used in the simulations – a block pulse, which exhibits a sharp increase and decrease at 04:00 and 08:00, respectively. During the remaining day it presents a unitary value. The flat Penalty signal assumes a unitary value for all time steps.

For initial temperatures of 51 and 60ºC, Figures 6.8 and 6.9 respectively, show the hot water temperature of the hot water storage tank (top) and electricity consumption (bottom) profiles for half of the considered day. Regarding the results associated to the initial temperature of 51ºC (Figure 6.8), the impact of subjecting the system to the Penalty signals is evident. For a flat Penalty signal the hot water temperature is kept close to the minimal limit (i.e. 50ºC) so the resulting cumulative penalty is minimized, despite the changes in the hot water demand which are reflected in the associated electricity consumption. For the block pulse Penalty signal it is clear that the control strategy induces considerable changes in the temperature profile in order to minimize the associated cumulative penalty. More specifically, the hot water temperature is increased previously to the penalty increase in order to minimize the electricity consumption during the period with higher penalty.

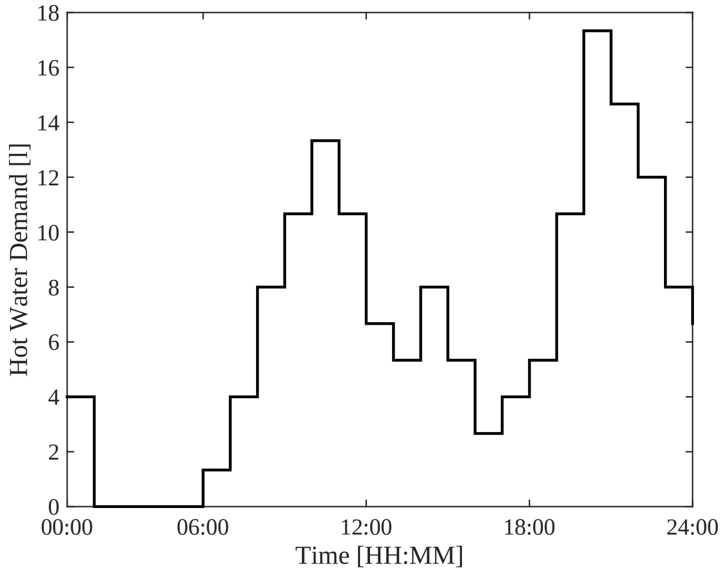


Figure 6.6 Hot water demand profile for four users (total hot water consumption of 160 litre per day).

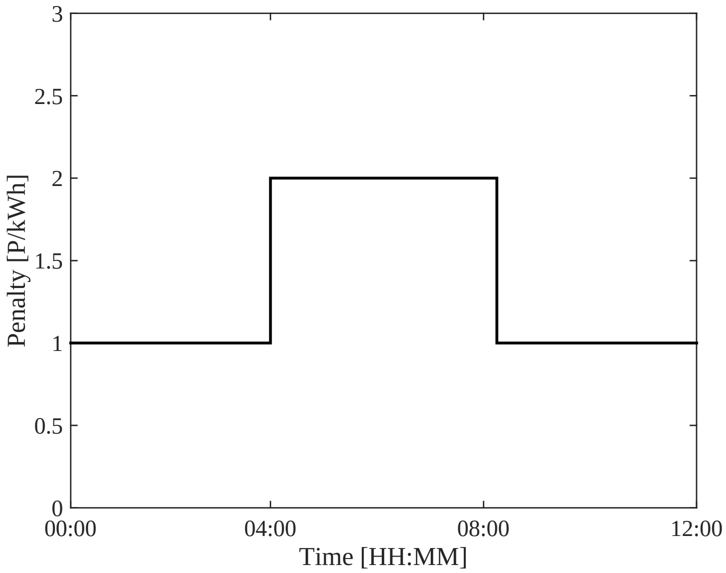


Figure 6.7 Block pulse Penalty signal.

For the initial temperature of 60ºC (Figure 6.9), the obtained results reflect the same behavior but with a lower temperature change previous to the penalty increase when the system is subjected to a block pulse Penalty signal. Such difference between the two scenarios reflects the higher initial temperature which restricts the tank charging before the penalty increase.

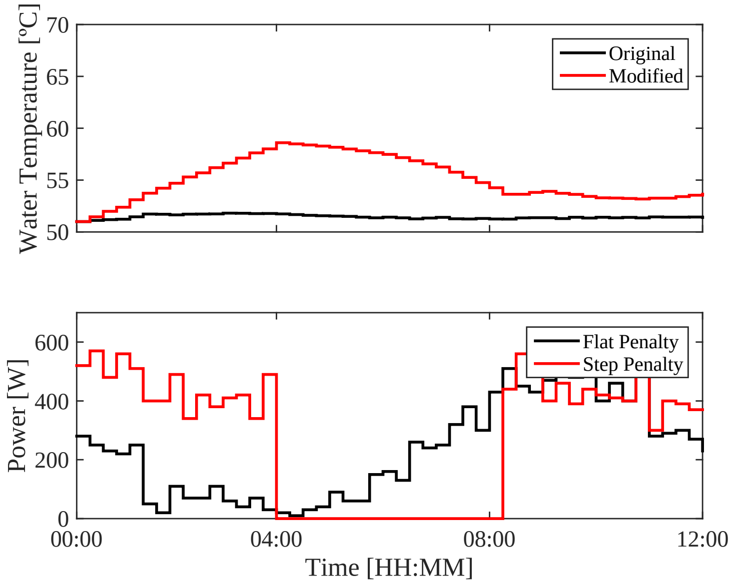


Figure 6.8 Water temperature (top graph) and power consumption (bottom graph) for both Penalty signals when the initial water temperature is 51ºC. The black line always represents the values of the original water heater, the red lines the modified values caused by introduced block pulse/step penalty.

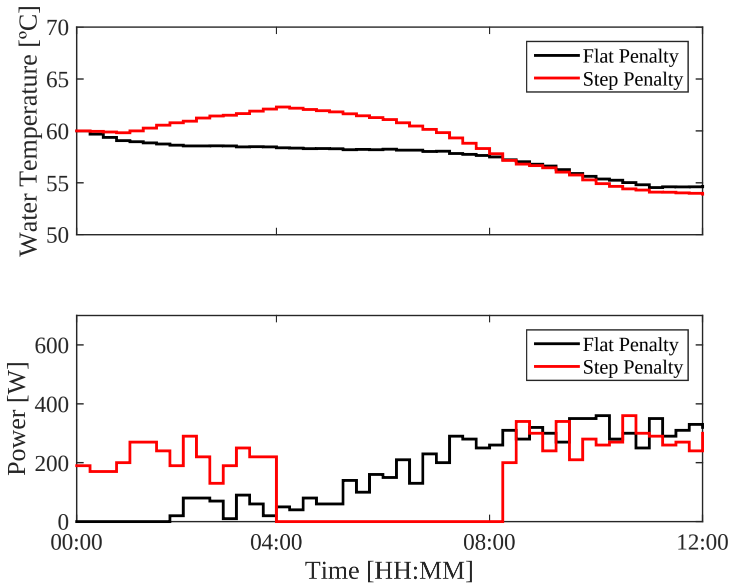


Figure 6.9 Water temperature (top graps) and power consumption (bottom graph) for both Penalty signals when the initial water temperature is 60ºC.

For each initial temperature considered in this study (51 and 60ºC), Figure 6.10 reflects the use of energy flexibility, which was obtained by subtracting the electricity demand profiles induced by the block pulse Penalty signal to the ones associated to the Flat Penalty signal. By comparing both profiles it can be concluded that, for the analyzed energy flexible system, a higher initial temperature results on a lower power increase before the Penalty signal increases.

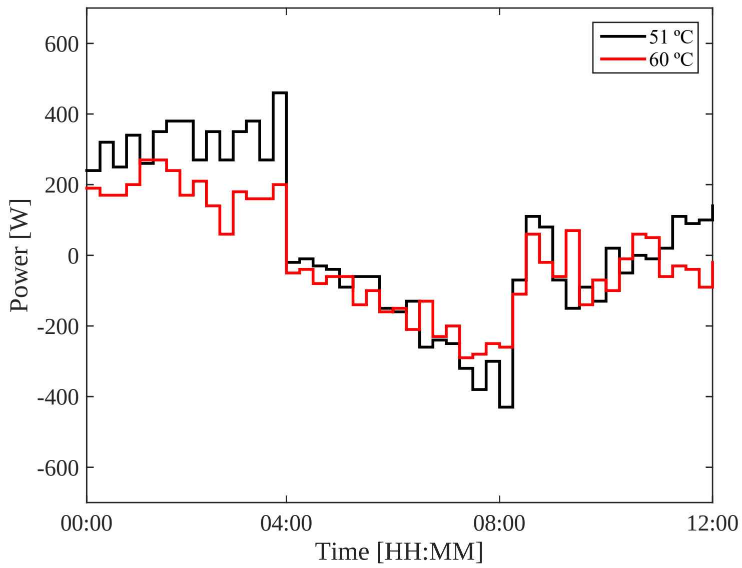


Figure 6.10 Flexibility Functions for initial temperatures of 51 and 60ºC.

6.3.5. Influence of initial Conditions: time - Rule-based Control

The selected residential buildings for this study are the twin houses at Canadian Centre for Housing Technology (CCHT) (Figure 6.11), which were built in 1998 according to the Canadian R-2000 building standard. The physical properties of the houses are given in Table 6.5.

They are three-story houses each with a basement, a first floor (living zone) and a second floor (sleeping zone). The construction is typically North-American with a wood frame structure and brick veneer as the exterior finish. The internal thermal mass is relatively low, and the time constant for a response to heating is of the order of 18 h. A brief summary of the CCHT houses are presented in Zhang et al. (2015). A home automation system is installed to simulate occupancy by activating appliances, lights, water valves and incandescent bulbs (for internal gains due to humans) based on repetitive daily schedules.

The starting time when the Demand Response (DR) event occurs may impact the building energy flexibility, because the building itself can be at different operation states, and its ambient environment such as outdoor temperature and solar radiation can also be significantly different at different time of the days. This was investigated by assuming that a DR event can only occur during one single hour over the course of a whole year. Therefore, 8760 simulations were necessary in order to investigate how the possible energy flexibility changes over the year.

The starting time impact on the building energy flexibility was investigated by controlling a space heating system in the Canadian CCHT residential building. The flexibility was realized by modulating the heating set point against the reference operation, specifically by increasing the heating set point by 2°C for the upward flexibility and decreasing the set point by 2°C for the downward flexibility.

Figure 6.11The investigated twin houses at CCHT, Canada.

Table 6.5 Properties of the CCHT house.

	Value	Unit
Livable area (2 stories)	210	m^2
Insulation (R):		
Attic	8.6	K/W
Walls (incl. basement)	3.5	K/W
Basement floor: concrete slabs	No insulation	
Windows: low-e-coated, argon filled	35	m^2
South facing	16.2	m^2
Airtightness: @ 50 Pa	1.5	h^{-1}

The power change during a 2 hour downward flexibility event on a typical day is shown in the Figure 6.12. In this case, the set point temperature decreases by 2°C from 7 am to 9 am during the Demand Response (DR) event. It can be observed that the total power demand decreases significantly when the set point drops by 2°C. The heating system is shut off during the first hour and then turned on with minimum power to maintain the set point. As a result, the zone temperature drops by 1°C after 1 hour and remains at the set point for the second hour of the event. When the event ends and the set points go back to normal, a power rebound (shown by the red curve) is observed. Since this is a simple thermostatic control and no strategy is implemented to counteract the rebound effect, as this consequence is expected.

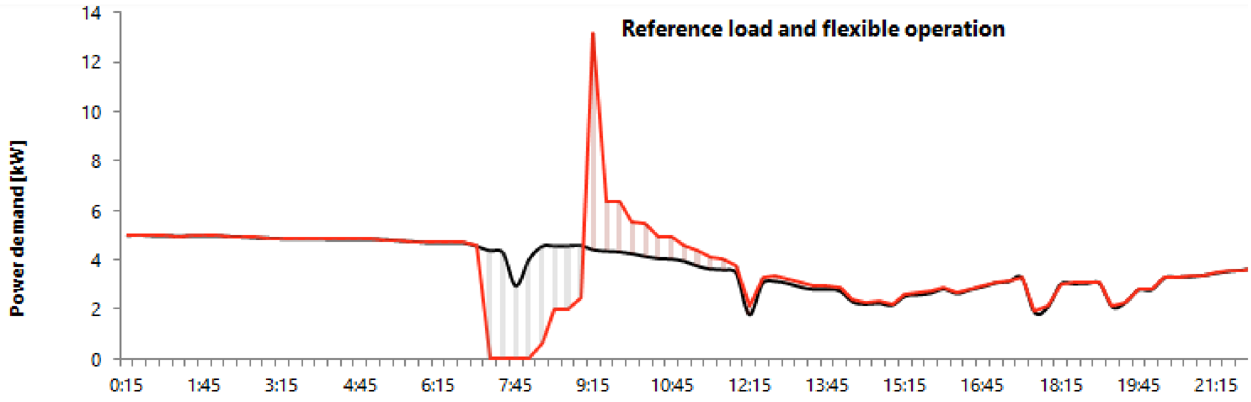


Figure 6.12 Reference load (black) and flexible operation (red) for a single downward flexibility event.

Figure 6.13 presents the downward flexible energy for 2 hour DR events occuring every hour for the whole heating season (the large blue dot in the middle shows the single case presented in Figure 6.13). It is assumed that the DR event happens at every hour of the heating season (space cooling is not included for the sake of simplicity). In addition, it is also assumed there is no periodic or consecutive event. Note that negative y-axis values are used to denote downward flexibility.

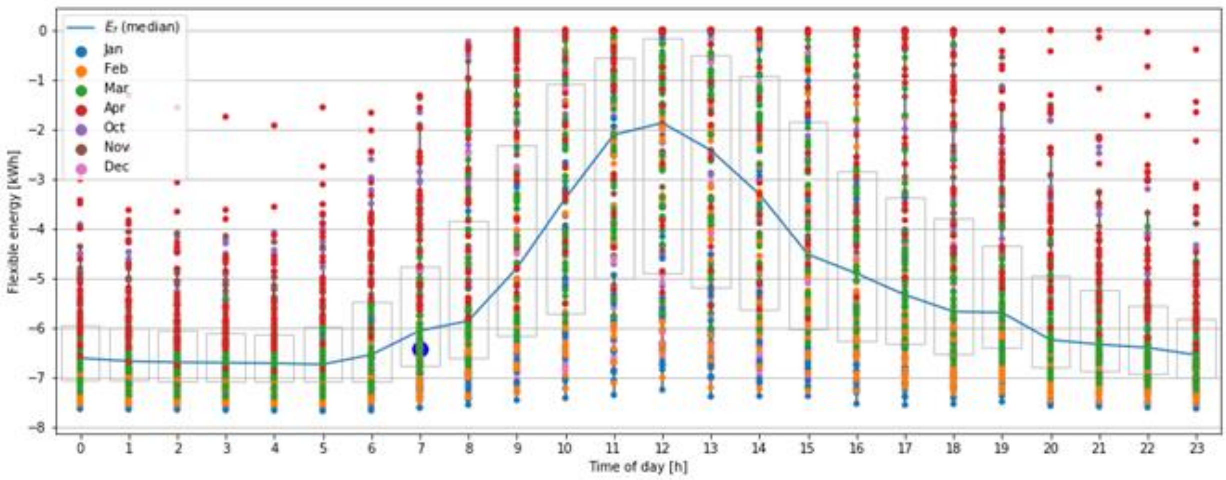


Figure 6.13 Downward flexibility of each single day during the heating season (October to April).

Each data point in the figure represents one simulation result, and all the data points were sorted by the hour of day as well as their corresponding months. The transparent boxes are the same as in boxplots with the top edge indicating the 75th percentiles and the bottom edge indicating the 25th percentiles. It can be seen that the flexible energy is largely spread out during the heating season, ranging from 0 up to almost 8 kWh. For same starting hour, but on different days, the flexible energy can also be significantly different. Moreover, the variation between hour to hour is even more pronounced.

Examining the median trend (blue curve in the middle of the graph), the amount of energy that can be shifted is highly correlated to the hour of day, i.e. the starting hour of the DR event. During the night time, the shifted energy is much more significant than the daytime with maximum value typically three times of the minimum. One of the main reasons is that the building generally experiences higher ambient temperature during the day and can have solar gains as well. This daily cycle of temperature results in a lower energy demand in the reference case and, therefore, exhibits a reduced DR potential.

6.3.6. Periodicity and consecutive Events - Rule-based Control

The reference case for the analysis is a single room model with a rectangular floor plan and a reference window 125 × 150 cm to the south, which is typical in Graz, Austria. Table 6.6 shows the details of the reference model. The primary construction has a specific heat capacity of 132 Wh/K related to one m^2 of its surface area and envelope U-values according to the minimum requirements of the Austrian national building regulations (Österreichisches Institut für Bautechnik, 2015). It is calculated by a steady-state approach where the boundary conditions such as outdoor temperature and internal loads are set constant in time. An ideal heating system of IDA ICE (EQUA Simulation AB, 2013) is used to condition the single room model. For the purpose of the sensitivity analysis, the heating system has no given physical location on any room surface. The default capacity of the ideal heater is large enough to heat the room under extremely cold conditions. The indoor operative temperature is set in a range of 20°C and 22°C according to the comfort limits of EN 15251, category II (Cen, 2007). A PI controller is used to keep the operative temperature at the heating set points.

Table 6.6 Characteristics of steady-state single room model of the reference case.

		Value	**Unit**
Floor area		25	m^2
U-value	Exterior wall	0.35	W/m^2K
	Windows	1.4	W/m^2K
Infiltration rate		0.4	1/h
Outdoor temperature		0 (constant)	°C
Envelope heat loss coefficient (UA)		0.65	W/m^2K
Interior walls		Adiabatic	
Internal gains		No	
Solar gains		No	
Heat distribution system		Radiator heating	
Primary construction and heat capacity of the surface area		Brick construction, specific heat capacity = 132 Wh/m^2K	
Thermal comfort		Allowed operative temperature range 20°-22°C	

An analysis was carried out on the Austrian example to determine the influence of periodicity and consecutive events on the energy flexibility potential of a heating system. Instead of switching off the heating system once - at time zero as in the previous case, a signal to switch off the system is given every 6 hours after the load shifting event (Figure 6.14). This is done in order to see the effect of consecutive events, whereby Figure 6.14 shows a reduction of the period during which the heating can be turned off (corresponding to β in Section 5.1) during consecutive events.

Compared to the first event the heat flexibility coefficient, the cooling-down timespan (Δt1, corresponding to β in Section 5.1) drops by approximately 1h to the previous event constantly if the heating system is switched off every six hours after a load shifting event. This reduces the timespan Δt1 to 2 hours at the end of the simulation period as it is seen in Figure 6.14. Even though the operative temperature of 22°C is reached in each cycle, the thermal mass of the building components is not fully charged at the end of each heating cycle, resulting in the decreasing cooling down periods. In other words, at the start of each consecutive cooling down cycle, the simulation model is not a completely steady state system like it was at the first event at time (i.e., not allowing for the thermal mass to fully charge).

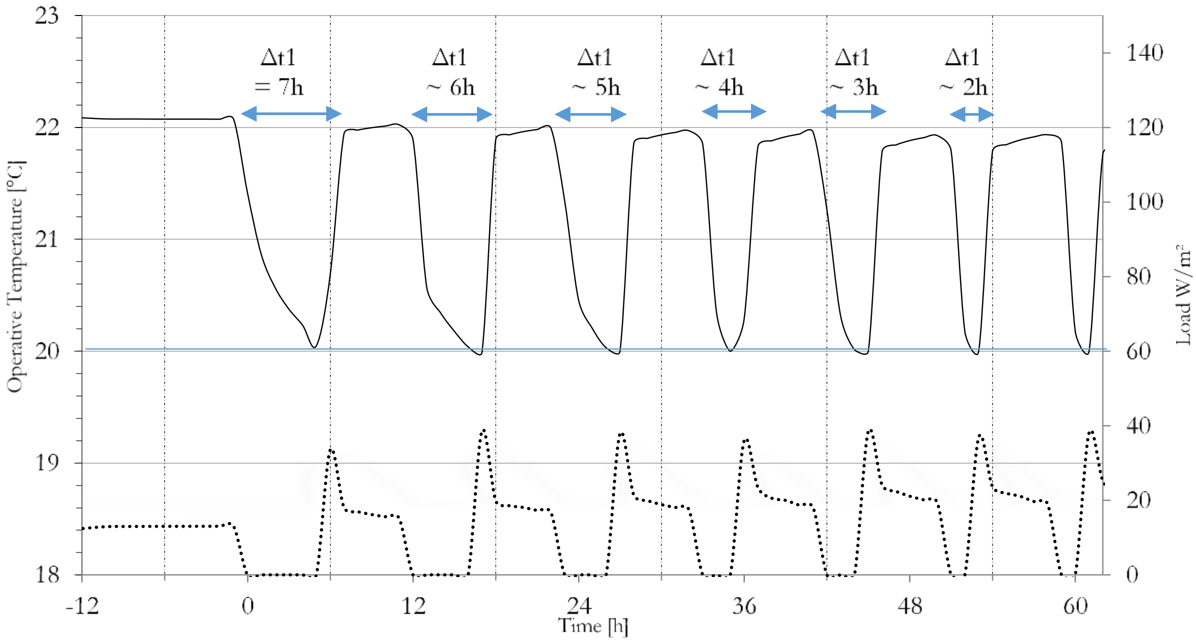


Figure 6.14 Periodicity and consecutive events, turning off the heating system every six hours: Top graph (full black line) shows the changes in the operative temperature while the bottom graph (black dotted line) shows the load changes.

The bottom graph of Figure 6.14 shows the increasing load during consecutive heating up events to hold the operative temperature limit.

On the other hand if single activations are performed independently for the three different days (i.e. allowing for the thermal mass to fully charge/discharge), little difference in Δt1 for the recurring events is seen (Figure 6.15).

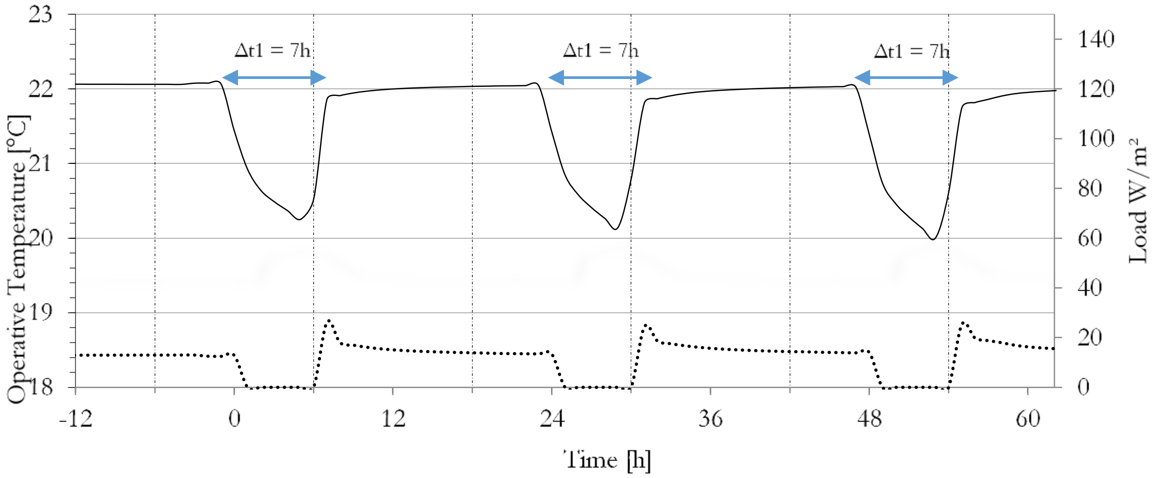


Figure 6.15 Periodicity and consecutive events, turning off the heating system every 24 hours: Top graph (full black line) shows the changes in the operative temperature while the bottom graph (black dotted line) shows the load changes.

From this example, it can be concluded that because of the generally high time constants of building thermal mass, the available flexibility provided by this thermal mass will reduce for consecutive events when those events follow each other closely. The timespan over which this interference is at play depends on the duration and amplitude of the flexibility event and differs from building to building as it is linked to the buildings time constant. When consecutive demands for flexibility can be expected, it is, therefore, advised to implement the direct approach as shown in this example whereby the consecutive events are included the simulation. Also note that this example confirms the importance of the initial state.

6.3.7. Anticipation effect

As shown in Figure 6.1, a deterministic optimal control strategy (e.g., Model Predictive Control (MPC)) anticipates the step-change in the Penalty signal by pre-conditioning (e.g. pre-heating) moving energy consumption for high-penalty periods to low-penalty periods. As this anticipation is not observed in the original definition of the Flexibility Function (as represented in the top graph of Figure 6.1), the question here is to analyze if an alternative formulation of the penalty function could result in a better comparability between the results from the direct and the indirect simulation method. This does not mean that it is analyzed if this anticipation is needed/wanted but merely if an alternative formulation can bring both methods closer to each other.

To analyze this research question two alternative Penalty signals are compared for the case of an optimal (flexible) control of a heating system coupled to the thermal mass of a dwelling.

The Penalty signals used for activating the flexibility are (1) a step change in line with the original definition and (2) a block pulse with a duration of 2 hours. Both signals are shown in Figure 6.16. To avoid the anticipation the time to the start of the penalty change is reduced to zero. These results are compared against the original formulation whereby 1 week with baseline penalty was included before the step/block-change.

The reference scenario in all cases is a minimum energy use on building level scenario (flat penalty). In the case of one week anticipation, the initial states (temperatures of all capacities) of the building were fixed, but given the long anticipation time (1 week) these do not affect the response at the step change. In the case no anticipation is allowed, the initial states for the step/block change are taken equal to the states of the reference scenario at that time. In other words, as the system is assumed not be have any up-front information about the coming step change, it is assumed it would have behaved as for the flat penalty.

Table 6.7 Overview of different anticipation cases.

Case name	Shape signal	Anticipation time allowed
Step Anticipation	step (+ 0.5)	1 week
Block Anticipation	block: (+0.5 ; 2h)	1 week
Step No Anticipation	step (+0.5)	no
Block No Anticipation	block (+0.5 ; 2h)	no
Block Anticipation neg	Block (-0.5; 2h)	1 week
Block No Anticipation neg.	Block (-0.5; 2h)	no

The hypotheses are the following:

- A step/block change that is announced upfront (represented by allowing a one week anticipation time) will always lead to anticipation.
- A *step change without allowing the anticipation* effect will not have any effect on the heating power (if the heating power is the only term in the cost function). If the step change occurs at time = 0, the optimization will perceive this again as a flat penalty and will try to minimize energy.
- A block change with positive amplitude at time=0, will not have any effect on the heating power, since we assume the building is already at minimum energy state, hence if the price is suddenly increased the building will not be able to respond.
- A block change with negative amplitude, results in a response with a similar shape as the step response function obtained from the indirect approach (only sign is opposite as now we have a decrease in price).

The results in Figure 6.16 confirm that both the step and block penalty change that are announced upfront results in an anticipation of the control, pre-charging the thermal mass prior to the high-penalty period. For the block penalty (red curve) the anticipation effect is much smaller as the controller only needs to shut down the heating for 2 h to overcome the high-penalty period. Also, it is shown that there is no significant rebound effect after the 2h period, since at the end of the high-penalty period the system is back at its minimum energy state. All rebound is translated to an anticipation.

Figure 6.16 also shows that indeed no effect of the step change is found in the case a step-penalty function is used and the step is introduced at t=0. However, for the block penalty with positive amplitude an increase of the heating in the night zone is found just after the penalty goes back to the reference value. This result is unexpected and should be further analyzed. This is most likely due to unstable behavior of the optimizer.

In case of the negative block there is no difference between the cases with or without anticipation. In both cases, the controller tries to maximize the heating power during the negative block period, whilst minimizing it before and after the block. As the reference profile is already the minimum energy scenario, the controller will follow that minimum energy profile before the decrease in penalty. After the block change, the controller will recover the energy stored in the structure by keeping the heating off until building is back in its reference minimum energy state.

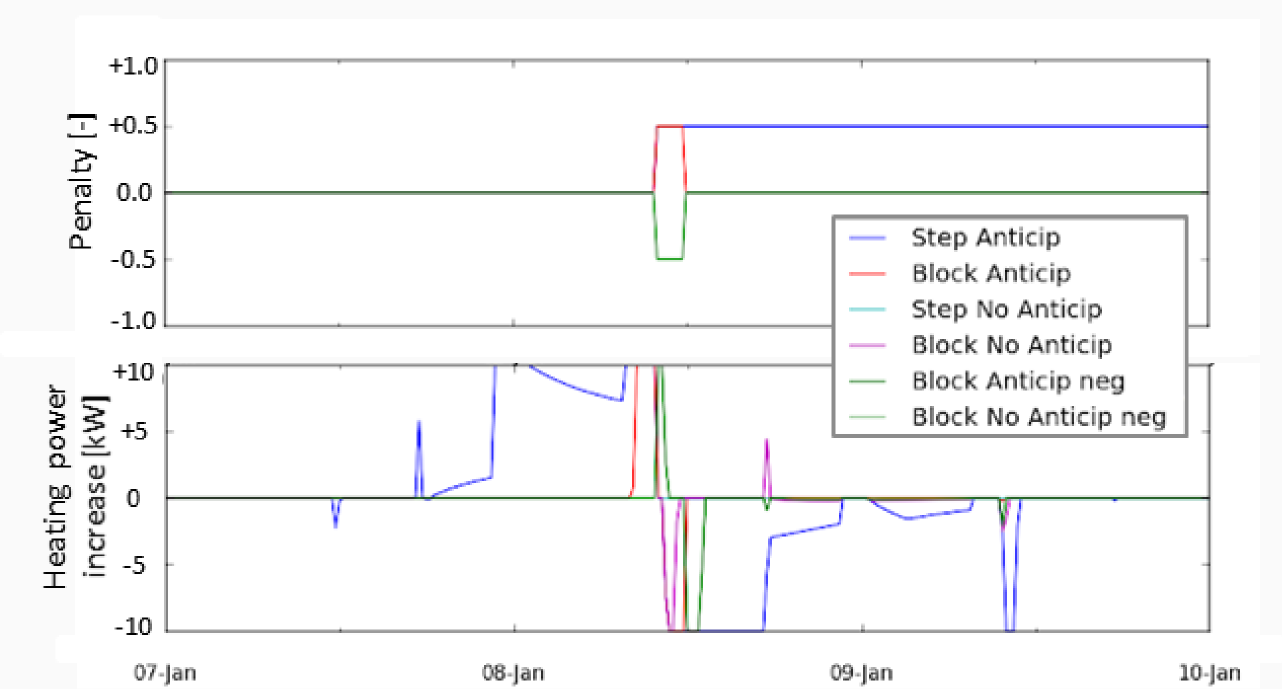


Figure 6.16 Evaluation of proposed penalty functions on a 2-zone building model, representing a typical Belgian detached single family dwelling constructed from 1990 to 2005 and equipped with radiator heating.

From this example, it can be concluded that it is technically feasible to remove the anticipation effect in the direct simulation approach with an MPC controller by shifting the starting time of the flexible control scenario using the initial states obtained from the reference control scenario. Despite this possibility, the obtained flexibility function still has a different shape compared to the flexibility function obtained from the indirect approach. Also, it is concluded that avoiding the anticipation may have a perverse effect (e.g., no flexibility available). Hence, in some cases it may be of interest to include a certain degree of anticipation. When applying the direct approach, it is key define up front the maximum anticipation time that would be allowed and formulate the flexible control scenario accordingly. Further research is needed to evaluate the predicted flexibility using both the indirect and direct approach for a concrete set of applications.

6.4. Lessons learned

The previous section detailed the results of the analysis of the research questions that were identified after the intercomparing of preliminary results of the different modelling teams. The goal of the tests was to exemplify the most important pitfalls when applying the “direct approach” from the characterization methodology outlined in Chapter 5. Note that this direct approach has been proposed as an alternative to the “indirect approach” for which the flexibility function was originally defined.

While further validation and field-tests of the characterization methodology using both direct and indirect approach are needed in order to evolve to a mature methodology, some important lessons have been drawn from the results.

Firstly, Sections 6.3.1 to 6.3.6 illustrate how the flexibility characteristics obtained by the direct approach are sensitive to the boundary conditions, the initial state of the system being analyzed and shape of the Penalty signal. Two approaches were proposed to deal with this sensitivity. The first approach is to standardize the boundary conditions and Penalty signal while prescribing initial states. As shown in Sections 6.3.2 and 6.3.5 such standardization can lead to a comprehensive basis for comparing different building designs. Note that such a standardization of boundary conditions is common practice in building energy evaluation where standard weather files or occupant behavior profiles are common practice. A second approach is proposed within the tool in Section 5.6, whereby the boundary conditions are not standardized but communicated in a standardized way. The developed visualization tool implemented (Flexibility Evaluation Tool) has shown to be a user-friendly solution that allows to both compute the flexibility characteristics directly from the time series data from the simulation tool, as well as provide a structure way of describing boundary conditions.

A second important finding from the direct simulation approach in comparison to the indirect approach was the appearance of an anticipation period whereby the penalty-aware control, being a deterministic model predictive control strategy, anticipates to the sudden increase (step-change) of the Penalty signal by pre-heating the building. Further research and real application examples for the methodology are needed to verify if such an anticipation effect is a desired effect or should be avoided.

Finally, as the direct simulation approach is defined for a single event, i.e. a step change in a penalty function, Section 6.3.6 evaluated the impact of periodicity and consecutive events. The results show limited impact of the flexibility characteristics, even when repeating long activations (up to 6 h) the influence of the periodicity on the heating demand is relatively small. Significant differences appear only in very-well insulated buildings, where the history of the charges/discharges on the thermal mass can be observed. Further research is evidently needed on a wider range of buildings and systems to better understand this relation.

The validation of the methodology developed in IEA EBC Annex 67 has shown that building experts are mostly familiar with simulation techniques. As a result, the direct approach to obtain the Flexibility Function was tested more than the indirect approach, which requires the use of system identification theory.

7. Conclusion and reach out

The foreseen large deployment of renewable energy sources is likely to have significant implications for the future operation of energy grids/networks. As a consequence, it will be necessary to define effective approaches to control the energy demand profile and evaluate the feasibility of installing storage systems (both active and passive – and thermal and electrical) in order to match instantaneous energy production, and to reduce the stress on the grid maximizing the integration and use of renewable energy sources. Energy flexibility of buildings represents one promising solution for improving the energy demand management and load control according to the external forcing factors such as weather conditions, availability of renewables, user needs and grid requirements.

In this perspective, finding approaches for the assessment of flexibility is crucial for designing efficient new buildings and to improve the operation of existing buildings.

In the context of IEA EBC Annex 67, a literature review was conducted to define and describe existing indicators to quantify the energy flexibility of single buildings and clusters of buildings. The properties found to be relevant for describing and defining energy flexibility in single buildings have been extracted from literature. A definition of different building clusters and possible different levels of building connectivity have been outlined, and first steps towards a definition of energy flexibility at a cluster scale have been setup. The reviewed indicators related to single buildings have been classified according to applied Penalty Signal, duration of the response/change, whether building functions have been compromised and the local energy infrastructure. The different categories of indicators found in building clusters are related to cost, thermal and electric features, cluster composition and smart readiness. All relevant indicators have been listed in Appendix A of this report and four main energy flexibility indicators have further been investigated in Appendix B.

Research within IEA EBC Annex 67 shows how the available energy flexibility of buildings and cluster of buildings not only relies on technical solutions or available services, but also depends on the integration and control of the systems, their interaction with occupants and energy networks as well as local climate and market conditions.

To account for these forcing factors and boundary conditions, a major outcome of IEA EBC Annex 67 is a common methodology, allowing for quantification and for communication of the possible energy flexibility of individual buildings and building clusters. The core of the methodology is a Flexibility Function which describes the response to a Penalty signal. The Penalty signal can either be a prize signal, the content of CO_2 or RES of the energy in the surrounding energy network.

Using the Flexibility Function for a building or a cluster of buildings the Expected Flexibility Saving Index (EFSI) and the Flexibility Index (FI) can be computed. EFSI and FI gives for a given Penalty signal the cumulated penalty by utilizing the energy flexibility of a building or a cluster of buildings. In this way it is possible to investigate how a given building or cluster of buildings perform in a specific energy network. This gives important information to the DSO and aggregators of energy flexibility. It is further foreseen that the methodology may be the basis for a future labelling system concerning the possible energy flexibility from buildings.

The work described in this report is intended to be a starting point for future research and gives an overview for policy makers that need to address the new topic of energy flexible buildings and clusters. The outcomes of the work have already been communicated to the EU study on Smart

Readiness Indicator (SRI) for implementation in the amended 2018 EPBD (Energy Performance of Buildings Directive). This study supports the assessment of smart technologies and strategies for the building's readiness to improve demand response.

Based on scientific evidence and following the outcomes of the work done by the experts, IEA EBC Annex 67 points out the importance to shift the attention from a static energy efficiency evaluation in single buildings to a dynamic CO_2-efficiency optimization in an enlarged (renewable) energy network context, using energy flexibility and control based energy performance labelling of buildings.

Tables 8.1 and 8.2 summarize what the Annex 67 found to be relevant to derive as advantages for the target groups and as main characteristics of energy flexibility in buildings.

Table 8.1 Target groups' view on energy flexibility.

For whom	What	Overall Effect
Building owner, user	Reduction of energy costs	Motivation to change behavior patterns
Network operators (TSO, DSO)	Stabilization of energy networks, especially under the strain of volatile energy generation from renewable sources	Reduce network infrastructure and network stabilization cost
Energy provider	Stable production/consumption	Reduce energy generation cost
Environment, society	Maximization of renewable energy sources used	Reduction of CO_2 emissions

Table 8.2 Main characteristics found for energy flexibility.

Main topics in the definitions	General properties of indicators	Energy flexibility determined by
Time/duration of the event	Capacity (amount of energy or power that can be shifted per time unit)	Building loads (shiftable, controllable, non-shiftable)
Applied control/ Penalty signal	Time aspects (staring time & duration)	Building energy service system (i.e. the design, technologies and their capacity)
Influence on building performance	Direction (upward/downward)	Storage types and capacity, and their characteristics
Local energy infrastructure context	Associated cost of the flexible action	Controls applied to the energy service system

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Appendix A: KPIs when using Energy Flexibility

In order to give an overview of the numerous different indicators found in literature during the Annex 67 and in addition to Sections 4.1 and 4.2, the following table was collected.

Indicator(s)	Unit	Author(s)	Links	Input parameter	Output
Storage capacity (E_{ADR}),	kWh	Reynders et al. 2013	https://www.sciencedirect.com/science/article/pii/S0360132313000905	Building physics' data	
Storage efficiency (η_{ADR})),	%				Energy flexibility of structural thermal energy storage for ADR (hours/day)
Power shifting capability (ΔP)	kW				
Flexible demand ($\Delta p_{k,w}$)	kW	Aduda et al. 2016	https://www.scopus.com/record/display.uri?eid=2-s2.0-84959336445&origin=inward&txGid=5cee66e09ddc8bd0bd30b8cc649adb7d	Consumed power of controllable loads such as ventilation system	Load reduction (by flexible load)
Power Shifting Potential (ΔP)	kW	Oldewurtel et al. 2013	https://opticontrol.ee.ethz.ch/Lit/Olde_13_Proc-CDC2013_submitted.pdf	Price signal and power consumption	Potential and efficiency for power increase/ decrease
Power Shifting Efficiency (PSE)	[-]				
The time (T) the building fluctuated from maximum to minimum power	h	Tahersima et al. 2013	https://ieeexplore.ieee.org/document/6662802/figures#figures	Nominal power with a constant value for space heating	Quantifies the flexibility in terms of time
Energy units model V(t,E)=(t_es,t_ls)	kWh	Pollhammer et al., 2011	-	Building loads, measured energy consumption	Energy consumption and shifting potential in time
Time flexibility tf(f), energy flexibility ef(f) , and combined vector v=(tf,ef)	kWh	Valsomatzis et al., 2015	http://vbn.aau.dk/en/publications/measuring-and-comparing-energy-flexibilities(68defc8e-465b-4286-9afa-bdfdb743defd).html	Energy consumption profile	Energy in each single time unit of a flexible service

Indicator(s)	Unit	Author(s)	Links	Input parameter	Output
Flexibility(k) as the difference between the upper and lower power consumption	kWh	Maasoumy et al., 2013	https://www2.eecs.berkeley.edu/Pubs/TechRpts/2013/EECS-2013-244.pdf	Power consumption, price signals/, energy rates	Rewarded down and upward flexibility
Flexibility cost	€/kWh	De Coninck et al. 2016	https://www.researchgate.net/publication/284122956_Quantification_of_flexibility_in_buildings_by_cost_curves_-_Methodology_and_application	Electric load profiles, electricity tariff	Flexibility in the form of cost functions/curves - how much the electricity price would change along with the change in load
Flexibility_{PC} as procurement costs avoided	€	Masy et al., 2015	https://www.researchgate.net/publication/281247066_Smart_grid_energy_flexible_buildings_through_the_use_of_heat_pumps_and_building_thermal_mass_as_energy_storage_in_the_Belgian_context	Space heating demand	Load volumes shifted and electricity cost
Delayed operation flexibility ($\Delta_{\text{Delayed},t}$)	h	Nuytten, Six et al., 2013	https://www.sciencedirect.com/science/article/pii/S0306261912008227	Combined heat and power system with thermal energy storage, central heating system	Thermal energy storage and effect on flexibility
Forced operation flexibility ($\Delta_{\text{Forced},t}$)	h	Nuytten, Six et al., 2013			
Power consumption increase (P_inc) and decrease (P_dec)	kW	D'hulst et al., 2015	https://www.researchgate.net/publication/278744325_Demand_response_flexibility_and_flexibility_potential_of_residential_smart_appliances_Experiences_from_large_pilot_test_in_Belgium	Data of smart household appliances and buffers	Minimum and Maximum curves in terms of energy and time
Spark Spread (SS)	[-]	Piacentino et al. 2013	https://www.sciencedirect.com/science/article/pii/S0306261913000706?via%3Dihub	Market price of electricity (expressed in €/kWh) and the cost of the amount of fuel consumed by the 'combined heat and power' (CHP) unit to	Convenience of self-producing heat and electricity compared to energy purchased from the public grid

Indicator(s)	Unit	Author(s)	Links	Input parameter	Output
				produce 1 kWh electricity	
Total Supply Spread (TSS)				It add t the previous indicator the cost to be sustained by a traditional boiler	
Flexibility factor	[-]	Le Dréau et al., 2016	https://www.sciencedirect.com/science/article/pii/S0360544216306934?via%3Dihub	Amount of energy consumed during low price and high price periods	Ability to shift the energy use from high to low price periods
Comfort index ($PE_{comfort}$)	[h]	Shen et al. 2016	https://www.sciencedirect.com/science/article/pii/S0378778816304418?via%3Dihub	Data on capacity of the cooling system and cooling load	Thermal discomfort resulting from the cooling supply time failure of a sized air-conditioning system
Grid control index (φ)	[%]	Ahmadi et al., 2015	refhub.elsevier.com/S2210-6707(17)31213-1/sbref0005	Loads of the buildings classified as first, second, and third priority load	Measure of the capacity of the central controller to flexibly delay the demand of the cluster and partly sell electricity to the grid if the market price is attractive
Load Matching Index ($f_{load,i,}$)	[%]	Voss et al. 2010	http://repositorio.lneg.pt/handle/10400.9/963	Energy generated by RES installed, stored in batteries and load	Amount of energy that can be generated by RES and stored with batteries in comparison to the load of the building
Grid Interaction Index	[%]	Voss et al.2010	http://repositorio.lneg.pt/handle/10400.9/963	Ratio between net grid metering over a given period compared to the	Average grid stress, through the variation of the energy exchange

Indicator(s)	Unit	Author(s)	Links	Input parameter	Output
				maximum/minimum value within an annual cycle	between a building cluster and the grid and it is defined as "
On-site Energy Ratio (OER)	[%]	Ala-juusela et al 2014	https://scholar.google.com/scholar_lookup?title=Defining%20the%20concept%20of%20an%20Energy%20Positive%20Neighbourhood%20and%20related%20KPIs&author=M.%20Ala-juusela&publication_year=2014	Ratio between annual energy supply from local renewable sources and annual energy demand	Annual loads covered by RES
Annual Mismatch Ratio	[%]			Energy demanded and supplied by RES	expresses the annual difference between demand and local renewable energy supply in a cluster of building
Maximum Hourly Surplus	[%]			Energy demanded, supplied by RES and stored by the storage system	Maximum hourly ratio of difference between on-site generation and load over the load for each energy type
Maximum Hourly Deficit	[%]			Energy demanded, supplied by RES and stored by the storage system	Storage discard rate
Homogeneity Index	[-]	Jafari-marandi et al. 2016	https://linkinghub.elsevier.com/retrieve/pii/S030626191501661X	Building energy profiles of the cluster	Average correlation of buildings' energy profiles within the same cluster
Smart Built Environment Indicator	[-]	De Groote et al. 2017	https://scholar.google.com/scholar_lookup?title=Is%20Europe%20ready%20for%20the%20smart%20buildings%20revolution%3F%20Mapping%20smart-	Features of the building cluster (e.g. share of energy from renewable sources,	Level of smartness of the building cluster

Indicator(s)	Unit	Author(s)	Links	Input parameter	Output
			readiness%20and%20innovative%20case%20studies&author=M.%20De%20Groote&publication_year=2017	smart meter deployment,access to demand response, etc.)	

A detailed overview of KPIs related to energy flexibility including formulas and methods is given in:

- Table 1 of (Clauß et al., 2017)! Clauß, J., Finck, C., Vogler-Finck, P., Beagon, P. (2017). Control strategies for building energy systems to unlock demand side flexibility – A review. IBPSA Building Simulation Conference 2017, San Francisco, USA, August 7-9, 2017, https://www.researchgate.net/publication/324877113_Control_strategies_for_building_energy_systems_to_unlock_demand_side_flexibility_-_A_review.
- Vigna I. et al. (2018) have shown an overview of flexibility indicators related to clusters of buildings. "New domain for promoting energy efficiency: energy flexible building cluster" (Article – Sustainable Cities and Societies). Vigna, I., Pernetti, R., Pasut, W., Lollini, R. https://www.sciencedirect.com/science/article/pii/S2210670717312131?via%3Dihub

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Appendix B: A Sensitivity Analysis and Key Performance Indicator Comparison

As indicated in Section 3.2.6 the energy flexibility can be achieved by utilization of various technologies and different building components. In Chapter 5 a generic methodology for evaluation of the energy flexibility of a building was introduced. To have a better understanding of which building component has a biggest impact, a sensitivity analysis concerning the influence of the main building parameters on different aspects of Energy Flexibility when using thermal storage in the built environment was carried out. The following four key components of the energy flexibility methodology were investigated:

- A and B - the total amount of energy decrease and increase, respectively, which represent the amount of energy shifted in time;
- Δ - the maximum change of power demand following the change of Penalty signal;
- β - the total time of decreased energy demand after the increase of the Penalty signal.

The analysis were expanded by including the load shifting ability index and an energy cost efficiency index from Weiss et al. (2019a).

The aim of this study performed by Johra et al. (2019a) is to review and compare different building energy flexibility indexes found in the literature. In addition, a sensitivity analysis is conducted to assess the influence of the main building parameters on different aspects of energy flexibility when performing thermal storage in the indoor environment. The authors hope to give a better insight to the building community about how to assess energy flexibility and how to optimize the design of buildings for that intent.

1. Comparison of KPIs for building Energy Flexibility

The main goal of energy flexibility is to ease the integration of fluctuating RES. However, it can also be used to minimize energy costs or CO_2 emissions, avoid peak power demands, optimize usage of locally-produced energy, or prepare a building for a forecasted grid deficiency. Regardless of how one could define energy flexibility, it can be expected that it will not be a constant value in time because of its dependency to the interaction with the building's indoor and external environment: building state, storage capacity level, local weather conditions, occupants' behaviour, grid state, energy price, etc. However, the main aspects of energy flexibility can be defined as follows (Jensen et al. 2017):

- **Capacity**: amount of power change or shifted energy load.
- **Temporality**: duration of energy flexibility event; by how long can be shifted the energy load.
- **Efficiency**: peak shaving or load shifting efficiency, accounting for pre or post-rebound effects.
- **Cost**: additional cost or cost savings generated by the activation of building energy flexibility.

- **Direction**: positive or negative alteration of the energy profile compared to non-flexible scenario; moving forward or backward in time energy load or power peak modulation.

In addition, one can imagine different types of Penalty signal generated by the Smart Grid for demand side control, which can also be used in the cost estimation of the flexible activation: energy spot price, current CO_2 intensity of energy production, local state of the grid, marginal cost of production, etc.

A review of the current literature on the topic reveals several key performance indicators (KPI), each related to one of the specific aforementioned characteristics of energy flexibility. However, no holistic KPI integrating all aspects of energy flexibility has been developed yet. Although the different authors of the reviewed studies are using various forms of equation, naming and definition for their flexibility indexes, clear similarities can be established in between them.

By studying the similitudes in KPIs' definitions and equations, the former can be classified in 4 distinct KPI categories (see Table B.1). One can notice that most of the KPIs focus on the global load shifting ability, capability of the building to alter its energy use profile and shift power load in time to minimize the Penalty signal, and the efficiency of such action, including its associated cost benefits or losses. In addition, the large majority of the KPIs makes use of a reference scenario without any energy flexibility activation.

The KPI is thus often formed as a ratio or a difference between one particular aspect of the building energy flexibility during the reference scenario without demand side management, and the scenario with demand side management. The use of a reference scenario is logical since energy flexibility implies some active effort from the building system to supply a service to the grid compared to a passive energy use profile with no influence from the grid.

2. Sensitivity analysis of building parameters on KPIs for building Energy Flexibility

In this section, are presented the results of a sensitivity analysis concerning the influence of the main building parameters on different aspects of energy flexibility when using thermal storage in the built environment. The former is performed by means of indoor temperature set point modulation. 6 result data sets have been collected from different numerical investigations (see Table B.2) and combined to obtain significant variations of the following building parameters and boundary conditions:

- **Type of building**: single family house or office building.
- **Insulation level**: can also be denominated as building envelope thermal performance, since it includes windows performance and air infiltration.
- **Thermal inertia**: effective thermal inertia of the indoor environment.
- **Heating / cooling system**: the type of heating / cooling system installed in the building.
- **Control strategy / Penalty signal**: different algorithms or rules are employed for the indoor temperature set point modulation controller. In addition, different Penalty signals are used to activate the building energy flexibility.
- **Outdoor temperature**.
- **Solar radiation**.

Table B.1 Classification of key performance indicators for building energy flexibility.

KPI category	KPI equation	Unit	Reference
Load shifting ability	$\frac{\sum_{i=1}^{n} \max(Q_{ref,i} - Q_{flex,i}\ , 0)}{\sum_{i=1}^{n} Q_{ref,i}}$	[-]	Weiss et al., 2019a
	$\left[\left(1 - \frac{\%High}{\%High_{ref}}\right) + \left(1 - \frac{\%Medium}{\%Medium_{ref}}\right)\right] \cdot \frac{100}{2}$	[%]	Johra et al., 2019a Loukou et al., 2019
	$\frac{\int_{low} Q_{heating} dt - \int_{high} Q_{heating} dt}{\int_{low} Q_{heating} dt + \int_{high} Q_{heating} dt}$	[-]	Le Dréau et al., 2019 Liu and Heiselberg, 2019
	$\frac{\int_{low} Q_{heating+cooling} dt - \int_{high} Q_{heating+cooling} dt}{\int_{low} Q_{heating+cooling} dt + \int_{high} Q_{heating+cooling} dt} \times \frac{Q_{ref}}{Q_{flex}}$	[-]	Liu and Heiselberg, 2019
	$C_{ADR} = \int_{0}^{ADR} (Q_{ADR} - Q_{ref})\, dt$	[Wh]	Reynders et al., 2017 Péan et al., 2018
	$\Phi_{\uparrow} = E_{max} - E_{ref} \geq 0$ $\Phi_{\downarrow} = E_{min} - E_{ref} \leq 0$	[Wh]	De Coninck and Helsen, 2016
	$\Delta_{Delayed,t} = t^{*} - t$	[hours]	Nuytten et al., 2013
	$\Delta_{Forced,t} = t^{*} - t$	[hours]	Nuytten et al., 2013
Power adjustement	$P_{difference} = P_{flexibility} - P_{ref}$	[W]	Liu and Heiselberg, 2019
	$Q_{\delta} = Q_{ADR} - Q_{ref}$	[W]	Reynders et al., 2017
	$\frac{P_{maxdaily}}{P_{continious}}$	[-]	Zilio et al., 2017
	$Flexibility(k) \triangleq P_f(e_k^u) - P_f(e_k^l)$	[W]	Maasoumy Haghighi, 2013
Energy efficiency	$\eta_{shifting} = \frac{-\Delta Q_{discharged}}{\Delta Q_{charged}}$	[-]	Le Dréau et al., 2019
	$\eta_{ADR} = 1 - \frac{\int_{o}^{\infty} (Q_{ADR} - Q_{ref}) dt}{\int_{0}^{ADR} (Q_{ADR} - Q_{ref}) dt}$	[-]	Reynders et al., 2017 Péan et al., 2018
	$Overconsumption = \frac{E - E_{int}}{E_{int}}$	[%]	Masy et al., 2015
Cost efficiency	$\frac{\sum_{i=1}^{n} C_i \cdot (Q_{ref,i} - Q_{flex,i})}{\sum_{i=1}^{n} C_i \cdot Q_{ref,i}}$	[-]	Weiss et al., 2019a
	$FI = 1 - \frac{c^1}{c^0}$	[%]	Junker et al., 2018
	$\frac{P_{el,max} - P_{el,avg}}{P_{el,max} - P_{el,min}}$	[-]	Masy et al., 2015
	$\frac{flexibility_{PC} - flexibility_{PC,ref}}{flexibility_{PC,ref}}$	[%]	Masy et al., 2015
	$\Gamma_{\uparrow} = J_{c,max} - J_{c,ref} \geq 0$ $\Gamma_{\downarrow} = J_{c,min} - J_{c,ref} \geq 0$	[¤]	De Coninck and Helsen, 2016

Table B.2 List of case study (CS) data sets used for the sensitivity analysis.

CS	Type of building	Parameters varied	Available data	Location	Reference
1	Single-family house	6	1 month	Denmark	Johra et al., 2019b
2	Single-family house	6	1 year	Denmark	Marszal-Pomianowska et al., 2019
3	Single-family house	2	1 year	France	Le Dréau and Heiselberg, 2016
4	Single-family house	1	1 year	Austria	Weiss et al., 2019b
5	Office building	3	1 year	Denmark	Loukou et al., 2019
6	Office building	4	1 year	Denmark	Liu and Heiselberg, 2019

4 result outputs are investigated here; the characteristics of the demand response of a building when subjected to an energy flexibility activation (for instance, increase of Penalty signal), as defined by Junker et al. (2018) Junker et al. (2018).

- **A** and **B**: the total amount of energy decrease and increase, respectively, which represent the amount of energy shifted in time.
- Δ : the maximum change of power demand following the change of Penalty signal.
- β : the total time of decreased energy demand after the increase of the Penalty signal.

In addition, a load shifting ability index and an energy cost efficiency index are calculated for the entire simulation period of each data set (see KPIs of Weiss et al. (2019a) in Table B.1). The sensitivity analysis is performed by means of consecutive Analysis of Variance (ANOVA) tests on linear regression models linking the aforementioned parameter inputs and result outputs.

Table B.3 Sensitivity ranking of the main building parameters with regards to energy flexibility.

General ranking	Parameter	A	B	Δ	β	Load shifting ability	Energy cost efficiency
1	Insulation level	1	1	1	1	1	1
2	Thermal inertia	2	2	2	6	2	4
3	Heating / cooling system	5	5	3	5	3	2
4	Control strategy / penalty signal	4	4	5	4	4	5
5	Building type	3	3	4	7	5	3
6	Outdoor temperature	6	6	6	3	6	6
7	Solar radiation	7	7	7	2	7	7

One can see in Table B.3 that the results of the sensitivity analysis clearly emphasize the preponderant influence of the building envelope performance on all the aspects of the energy flexibility. Secondarily, the thermal inertia also has a significant impact. These results are in agreement with previous studies (Johra et al. (2019b), Le Dréau Heiselberg, (2016), Masy et al. (2015). Those observations are in line with the current trend for improvement of the envelope thermal performance of new and renovated buildings. Therefore, buildings with energy efficient envelope and low energy needs for indoor environment conditioning will also be very capable of providing energy flexibility with indoor temperature set point modulation. Moreover, larger thermal inertia, which can be appreciated for lessening episodic overheating in buildings, will also increase the thermal storage capacity of the built environment and thus improve its energy elexibility.

3. Conclusions

To establish reliable energy grid systems with large share of RES, there is a crucial need to reduce the mismatch between power use and intermittent production of renewables. To that matter, buildings are a key active element of the future smart grids as they have a large potential for demand side management and energy flexibility by means of load shifting, power peak shaving and valley filing.

After reviewing the scientific literature, some KPIs have been classified into 4 main categories based on definition and equation similarities: load shifting ability, power adjustment, energy efficiency, cost efficiency. Most of the KPIs use reference scenario and focus on load shifting ability or energy / cost efficiency of the flexibility action. The sensitivity analysis performed in this study can be of interest for building designers willing to improve the overall energy flexibility or a certain aspect of it. Similarly to previous studies, this parametric analysis emphasizes the importance of the building envelope thermal performance and secondarily the building thermal inertia. Design recommendations for maximizing all aspects of energy flexibility in buildings using indoor temperature set point modulation are therefore in line with the ones for low energy buildings with high envelope performance.

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