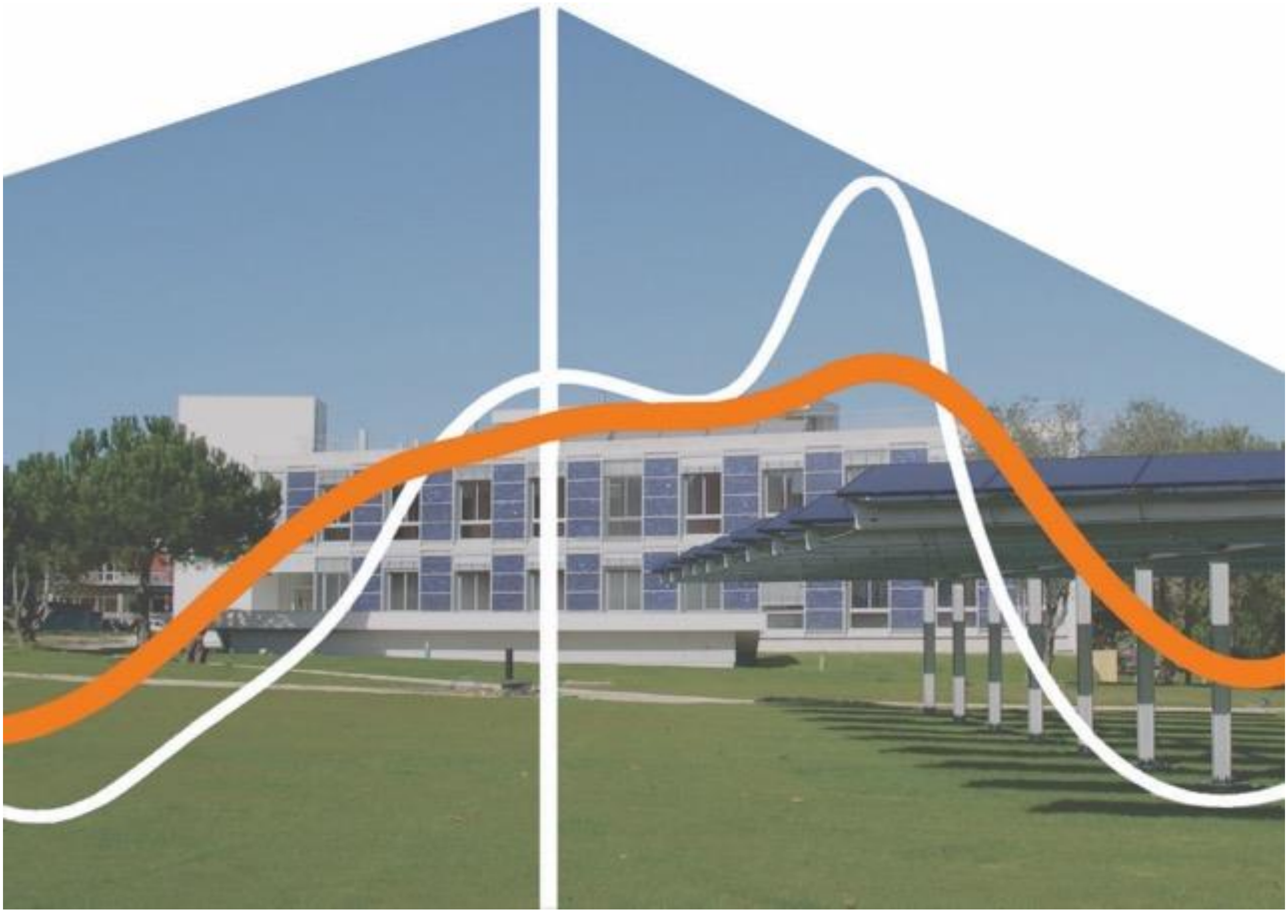
Energy in Buildings and
Communities Programme

International Energy Agency

Principles of Energy Flexible Buildings

Energy in Buildings and Communities Programme
Annex 67 Energy Flexible Buildings

December 2019



Technology Collaboration Programme
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International Energy Agency

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Annex 67 Energy Flexible Buildings

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Published by Danish Technological Institute, Denmark

ISBN: ISBN: 978-87-93250-08-6
ISSN: 1600-3780

Participating countries in EBC:

Australia, Austria, Belgium, Canada, P.R. China, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Poland, Portugal, Singapore, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

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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 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 the electrical energy systems. 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. However, 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 to specific cases when evaluating and/or quantifying energy flexibility.

Although the concept of energy flexibility of buildings is relatively simple to understand, its application in reality can be complex and difficult to explain in simple terms. This complexity is not helped by the myriad of ways in which energy flexibility can be achieved or the wide range of stakeholders involved; especially when many stakeholders have very little understanding, or interest, in the supply and demand of energy in buildings.

There was, thus, a need for increasing knowledge on, and demonstration of, which services energy flexibility buildings can provide to the energy networks. At the same time, there was a need for identifying critical aspects and possible solutions to manage this energy flexibility, while maintaining the comfort of the occupants and minimizing the use of non-renewable energy.

Based on the above the Executive Committee of the IEA Technical Collaboration Programme (TCP) Energy in Buildings and Communities (EBC) decided to initiate Annex 67 Energy Flexible Buildings in June 2015 with an end date of November 2019.

The objectives were:

- development of a common terminology, a definition of 'energy flexibility in buildings' and a classification method,
- investigation of user comfort, motivation and acceptance associated with the introduction of energy flexibility in buildings,
- analysis of the energy flexibility potential in different buildings and contexts, and development of design examples, control strategies and algorithms,
- investigation of the aggregated energy flexibility of buildings and the potential effect on energy grids, and
- demonstration of energy flexibility through experimental and field studies.

The work of IEA EBC Annex 67 has been documented in 7 deliverables reports; the titles of these reports are:

- **Principles of Energy Flexible Buildings** (the present report) 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** describes the terminology around energy flexibility, the existing indicators used to evaluate the flexibility potential and how to characterize and label energy flexibility.
- **Control strategies and algorithms for obtaining Energy Flexibility in buildings** reviews and evaluates 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.
- **Stakeholder perspectives on Energy Flexible buildings** considers the view point of different types of stakeholders towards energy flexible buildings.
- **Examples of Energy Flexibility in buildings** summarizes different examples on how to obtain energy flexible buildings.
- **Project Summary Report** contains a very brief summary of the outcome of Annex 67.

The main findings of the five key deliverables are included in chapters 3-7 of the present report. The five key deliverables are: Characterization of Energy Flexibility in Buildings; Control strategies and algorithms for obtaining Energy Flexibility in buildings; Experimental facilities and methods for assessing Energy Flexibility in buildings; Stakeholder perspectives on Energy Flexible buildings; and Examples of Energy Flexibility in buildings.

The third chapter of the present report unfolds the characterization methodology, terminology and definition developed by the Annex and the possible application of the methodology.

The fourth chapter is devoted to the control of energy flexible buildings, which is the core of this concept. It demonstrates which control strategies and algorithms can provide energy flexibility from buildings and identifies critical aspects and possible solutions to manage energy flexibility.

The fifth chapter gives the overview of the existing test facilities located in Belgium, Canada, Denmark, Finland Germany, Norway, Spain and Switzerland, which are designed and constructed to test different control strategies and combination of components, and thus evaluate the energy flexible building under realistic conditions.

The sixth chapter provides the feedback on energy flexible buildings from the perspective of nine types of stakeholders. It presents and discusses their roles, motivations, and potential barriers to energy flexible buildings. The chapter closes with recommendations for how the different types of stakeholders should be approached and motivated in order to become an active part of the energy flexible concept

The seventh chapter summarizes the good examples of energy flexibility collected during Annex 67. It describes the scope and focus of the examples, followed by a more detailed description of a sample of specific examples that describe the different sources of flexibility. It ends by evaluating the statistical range of the described examples.

It is hoped that the present report will not only provide an impression of what energy flexibility in buildings is and how it can be obtained, but also be a source of inspiration for future research and development in this area.

For more detailed information on the work carried out in IEA EBC Annex 67 please refer to the above mentioned deliverables (on annex67.org/Publications/Deliverables) or the many technical reports, articles and papers produced by the participants of IEA EBC Annex 67 (on annex67.org/Publications).

Table of content

Abbreviations

Abbreviations	Meaning
AC	Air Condition
ADR	Automatic Demand Response
AHU	Air Handing Unit
ANN	Artificial Neural Network
BESS	Battery Energy Storage System
BIPV	Building Integrated Photovoltaic
BMS	Building Management system
BRP	Balance Responsible Party
C_{ARD}	The amount of heat that can be added to the storage in the time frame of an ADR event
CES	Cumulated Energy Consumption
CHP	Combined Heat and Power
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand Site Management
DSO	Distribution System Operator
EE	Energy Efficiency
EFSI	Energy Flexibility Saving Index
EM	Energy Management
EMPC	Economic Model Predictive Control
EPBD	Energy Performance of Buildings Directive
EV	Electric Vehicle
FCU	Fan Coil Unit
FF	Flexibility Function
GA	Generic Algorithm
GSC	Grid Support Coefficient
HiL	Hardware-in-the-Loop
HVAC	Heating, Ventilation and Air Condition
KF	Kalman Filter
MEF	Marginal Emission Factor
ME	Marginal Emissions
MOGA	Multi-Objective Generic Algorithm
MPC	Model Predictive Control
NZEB	Net Zero Energy Buildings
η_{ADR}	The storage efficiency is defined as the fraction of the heat that is stored during the ADR event that can be used subsequently to reduce the heating power needed to maintain thermal comfort
PC	Probabilistic Classification
PCM	Phase Change Materials
PV	Photovoltaic

Abbreviations	Meaning
PWM	Pulse Width Modulation
RBC	Rule-Based Controller
RC	Resistance Capacitance
RES	Renewable Energy Sources
RL	Reinforced Learning
ROI	Return of Investment
SC	Self-Consumption
SH/SC	Space Heating/Space Cooling
SS	Self-Sufficiency
TES	Thermal Energy Storage
TSO	Transmission System Operator
VAV	Variable Air Volume
VSHP	Variable Speed Heat Pump

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 perspectives 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' abilities to provide energy flexible services to the grid. The available energy flexibility is often defined by a set of generally static Key Performance Indicators like amount of energy or power that can be shifted in time. 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 viewpoint 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. How may energy flexibility in buildings help the future energy networks?

Søren Østergaard Jensen and Anna Joanna Marskal-Pomianowska

The development in building technologies has during the last decades been concentrated on obtaining sufficient indoor comfort and on increasing the energy efficiency of buildings including the energy service systems. This has in many countries been forced by a continuous strengthening of the building regulations – e.g. in the EU regulated via the Energy Performance of Buildings Directive (EPBD). Buildings have up to now mainly been considered as passive consumers (and in the later years also as passive producers) of energy where the surrounding energy networks ensure a sufficient energy supply to the buildings. This has started to change. The stability of the energy networks are today mostly ensured by central fossil-fuelled energy plants, which many countries have decided to phase out and be replaced with renewable energy sources (RES), which have an intrinsic variability that will seriously affect the operation and stability of the energy networks. Therefore, there is a need for a transition from generation on-demand to consumption on-demand to match the instantaneous energy supply. This means in practice that the energy consumption needs to become flexible.

As buildings account for approximately 40 % of the annual energy use worldwide, they need to go from being passive to active consumers/producers, which can adjust their energy consumption according to the needs the energy networks – e.g. consume more during period with much RES in the networks. Thus, 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.

The present report summarizes the extensive work done in IEA EBC Annex 67 energy flexible buildings and is an introduction into the topic of energy flexible buildings – both residential and non-residential. For more information the reader is referred to the five more detailed Annex 67 reports (mentioned in section 1.1.4) and the many technical reports, article and papers produced during the duration of Annex 67 – please see http://annex67.org/publications/.

2.1. Energy flexibility of buildings

Energy flexibility buildings is typically obtained by decoupling energy demand and energy delivery by using storage in the building to shift the energy use e.g. from periods with a high price for the energy to periods with a low price. Energy flexibility can also be obtained by reducing the energy demand without a later need of restoring the situation with extra use of energy – e.g. dimming of lights or switching off an appliance. This latter case is not dealt with in the present report.

Different ways of obtaining energy flexibility are illustrated below in Figure 2.1.

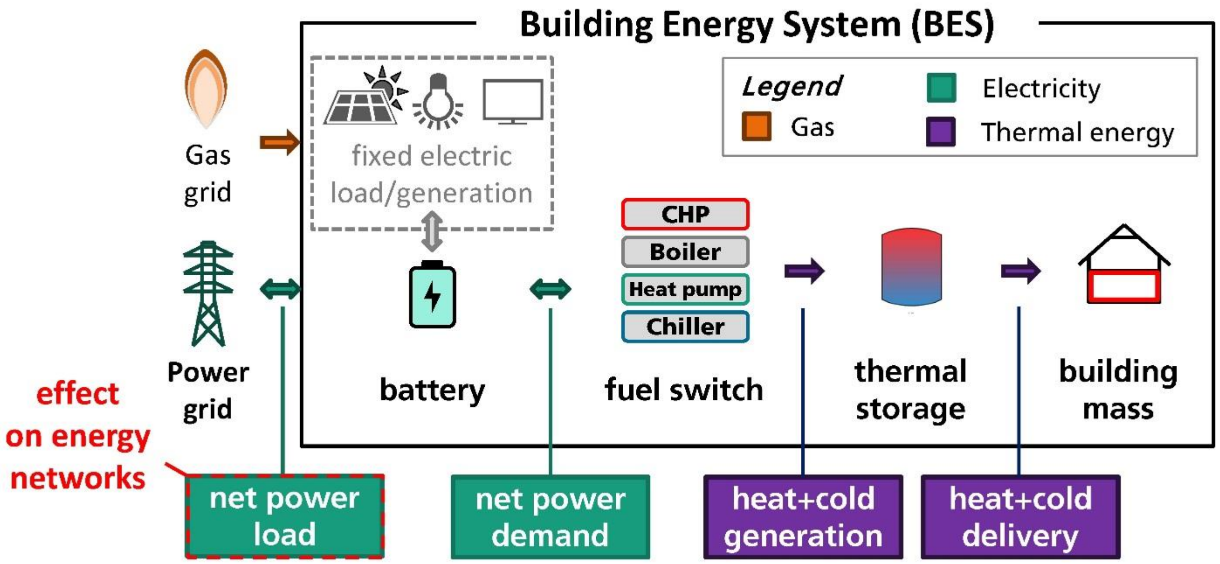


Figure 2.1 Sources for obtaining energy flexibility (Klein et al., 2017).

Seen from the right in Figure 2.1:

Building mass: walls, floors (especially underfloor heating), ceilings and furniture of buildings contain a certain mass and thereby a certain thermal (storage) capacity, which can be utilized to store energy. During a shortage of energy, the heating or cooling system can, therefore, be switched off for a period without decreasing the comfort of the users. The possible duration of such a period depends on the thermal mass and the heat loss of the buildings but can range from a few hours up to a couple of days. However, care should be taken, as the storage is directly connected to the indoor climate and the thermal comfort must not be jeopardized.

Thermal storage: this refers to active storage that are not part of the buildings' thermal mass. This can be water in domestic hot water (DHW) storage, buffer tanks between supply and delivery e.g. a heat pump and the space heating system (radiators or underfloor heating) but can e.g. also be indoor swimming pools. The storage can also use PCM (phase change materials) as storage medium.

Fuel switch: if a building utilizes different fuels (e.g. a gas or biomass boiler and a heat pump) energy flexibility may be obtained by using the boiler during periods where the electricity price is high (or, for example, when the production from wind turbines is low), while using the heat pump when surplus electricity is available in the grid.

Battery: here electricity is directly stored8 on site. Batteries can either be the battery of an electrical vehicle or the battery of a PV system. The battery is charged during periods when there is plenty of electricity in the grid and discharged during periods when there is a shortage. The battery can also be used for increasing self-consumption of electricity from a PV system.

Generation: many buildings are becoming prosumers – i.e. they no longer only consume energy, they also produce energy through PV, a solar thermal system, a micro wind turbine or a CHP (combined heat and power production) plant – this is not shown in Figure 2.1.

Networks: a building may be connected to one or more energy networks. Buildings are typically connected to a power grid (electricity) but may in many countries also be connected to a district heating/cooling or a gas network. The energy flexibility services needed by these three types of energy networks are different. The power grids need very fast, medium- and long-term services: ranging from fast voltage control to load shifting. District heating systems have large inertia in form of the water in the network and are thus rather slow reacting, however, these may need peak shaving of the morning and evening peaks. The gas grids have traditionally large built-in storage capacity and do not need flexibility services from buildings. However, switch between gas consumption and consumption of electricity/district heating will increase the energy flexibility, buildings may offer the power grid and district heating/cooling networks.

In order to take advantage of the aforementioned sources for energy flexibility efficiently, there is a need for preferably automated control. Different types of control may be utilized for obtaining energy flexibility from buildings. This control can be very simple like a heat pump being switched off every day during a predefined period, or more complex rule-based control where several constraints are included (e.g. that the heat pump is switched off during high price periods unless the indoor temperature is too low), or be advanced model-based control including forecasts of weather, occupancy behaviour (these two provide a forecast of future demand) and energy prices.

2.2. Examples on utilization of the energy flexibility from buildings

To illustrate how energy flexible buildings may support the surrounding energy networks, two examples are given in the following (Figure 2.2 and Figure 2.3).

Figure 2.2 shows an example of how the flexibility of houses with heat pumps may decrease the need for reinforcement of the local 0.4 kV power grid, where the houses are situated. Figure 2.2 shows a winter situation for a small Danish feeder with only single-family houses:

a) the existing situation with oil or gas fired boilers. The peak from 17:00 to 20:00 is called the cooking peak due to people coming home from work and start cooking. The peak also is due to switching on other appliances.

Heat pumps are then installed in all houses in order to support the transition from a fossil-based energy network to a RES based network. 40 % of the households additionally purchase an electrical vehicle (EV).

b) business as usual: the heat pumps and the electrical vehicles (EVs) in the system will demand a reinforcement of the grid as the demand exceeds the maximum allowed load.

c) a Smart Grid solution where the buildings prior to the cooking peak (17:00-20:00) are excess heated within the comfort band of the room temperature (red circle). The buildings are mainly free floating during the cooking peak (blue circle) but need extra heat after the cooking peak (orange circle). The charging of the EV's is controlled intelligently in order to keep the demand below the maximum allowed load (black circle).

Figure 2.2 shows a situation where the energy flexibility in the houses is obtained by heating up the constructions (floor, walls and ceiling) of the houses prior to a peak situation – red circle in Figure 2.2c. In order to store heat in the constructions, the air temperature is increased slightly by e.g. 1-

2°C for a period before the peak situation, however, still inside the comfort range of the users of the houses. This allows most of the heat pumps to be switched off during the peak situation (blue circle in Figure 2.2c) without the indoor temperature being outside the comfort range. Some heat pumps may need to be turned on during the peak situation in order not to jeopardize the thermal comfort. In spite of this an overall large reduction (also called peak shaving or load shifting, as the energy consumption is moved to later) in the energy demand during the cooking peak is possible. The charging of the batteries of the EVs is further controlled in order to keep the total electrical power demand below the allowed limit of the feeder – black circle of Figure 2.2c.

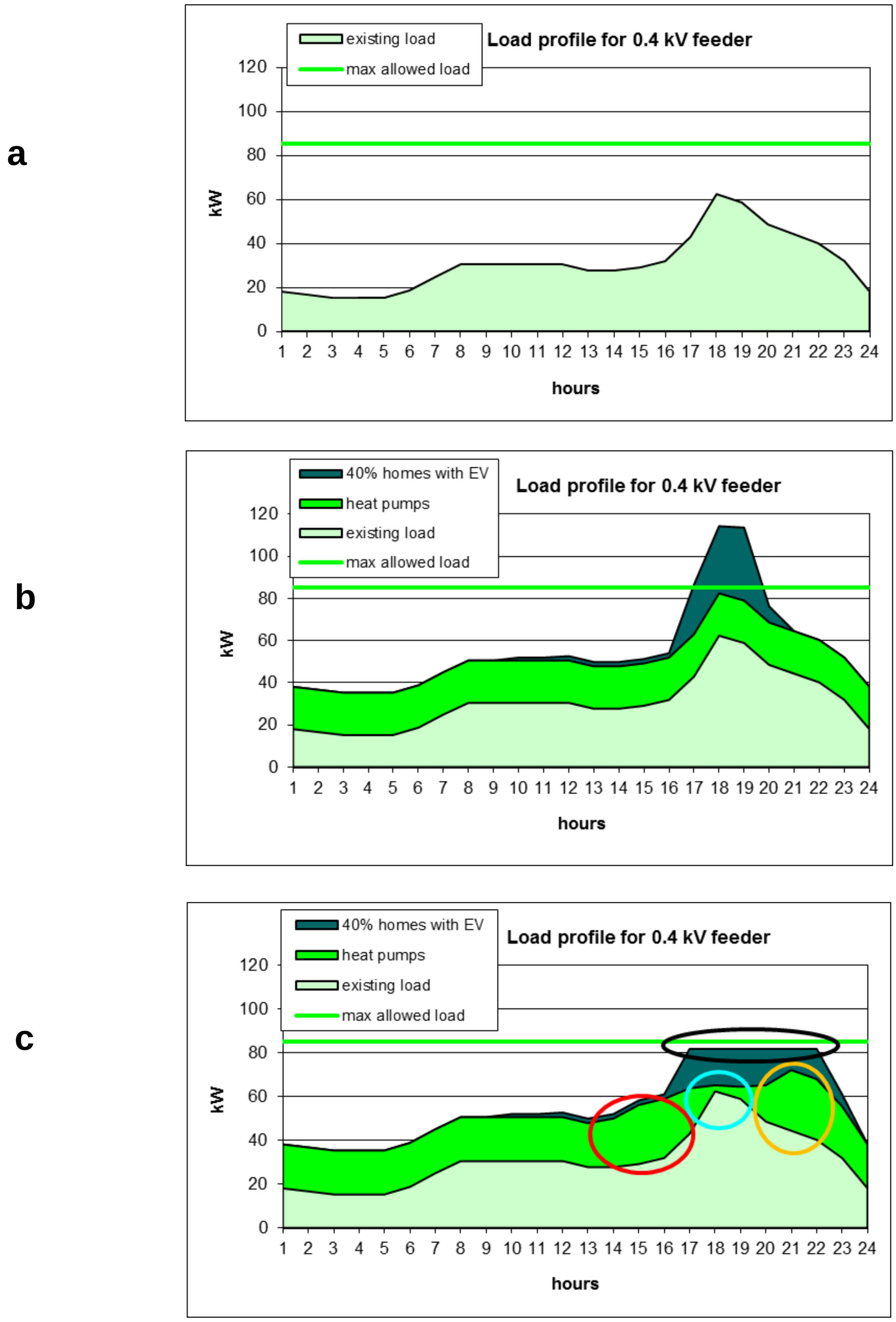


Figure 2.2 The graphs show an example of the introduction of heat pumps and electrical vehicles in a 0.4 kV outlet/feeder (Jensen et al., 2017).

After the peak period there is a need for restoring the indoor temperature to the desired level, so there is during a period need for an increased electricity supply to the heat pumps to reheat the building (orange circle in Figure 2.2c). This is called the rebound effect – see Figure 3.1. During the rebound period care should be taken in order not to create a new peak situation. This means that the heat pumps should not start simultaneously and not at full speed, however, prioritising the houses which are closest to the lower level of the comfort range of the indoor temperature. This of course makes a central control at the level of the 0.4 kV feeder necessary.

The same principle as shown in Figure 2.2 may also be utilized in district heating networks, which typically have a morning peak that often may be expensive to cover by backup boilers. Storing excess heat in the constructions or in the domestic hot water tanks of the buildings may even out these peaks.

Figure 2.2 shows a Danish case, however, the situation differs from country to country, both with building tradition and with the anticipated mix of RES in the energy networks. In order to gain an overview of the need for flexibility for different countries an analysis of the expected residual load in the power grid in 2030 was carried out for 14 European countries together with Alberta in Canada (Klein et al., 2016). The residual load is defined here as the electric load minus the generation of intermittent renewable plants (wind and PV). Therefore, the residual load is the electric power that needs to be provided by conventional dispatchable plants in order to balance generation and demand and can be used as an indication of the relative demand for conventionally-produced electricity.

The residual loads shown in figure 2.3 have been calculated based on assumed installed wind and PV plants in 2030 mostly based on (Agora, 2016) and on the numerical weather model COSMO-EU. For further details please see (Klein et al., 2016). Figure 2.3 shows daily mean values for four months. During the day the residual load of an actual day will of course fluctuate around the shown mean values, however, the shown patterns stay the same.

In most countries, the residual load shows its lowest values around noon as a consequence of peak solar and (on average) wind generation, as well as lower loads compared to the morning and evening. Even in the aggregated form shown in Figure 2.3, residual loads close to or below zero occur in Spain, Denmark, Greece and Italy. This means that during especially sunny and/or windy days, extreme surpluses of renewable electricity are expected. Storing this surplus or making it useful by demand response will be a major challenge and makes a strong case for considering energy flexibility in buildings.

Moreover, the residual loads in the analysed countries show significant seasonal differences: they are typically lower and more volatile during summer than during winter. This is largely due to higher solar and wind generation levels and lower electric loads in summer in the considered countries.

In order to show if buildings may help to stabilize the power grids, the heating and cooling demand has been calculated for a small office building equipped with a heating and cooling system. The heating system is based on a heat pump. For the weather conditions of each country the heating and cooling demand has been simulated and is shown in figure 2.4 – light red and blue curves. The two other curves show the result of a grid-optimal operation of the heating and cooling systems. The heating and cooling systems are 25% over-dimensioned and sufficient thermal storage capacity for intraday load shifting is assumed.

The grid-optimal energy loads in figure 2.4 are in most cases in reverse phase with the residual loads shown in figure 2.3. Thus, it is possible with an intelligent operation and utilization of the energy flexibility of the buildings, to make the buildings increase the energy consumption during periods with low residual loads (much RES in the energy networks) and store surplus energy to periods with high residual loads (low amount of RES in the energy networks).

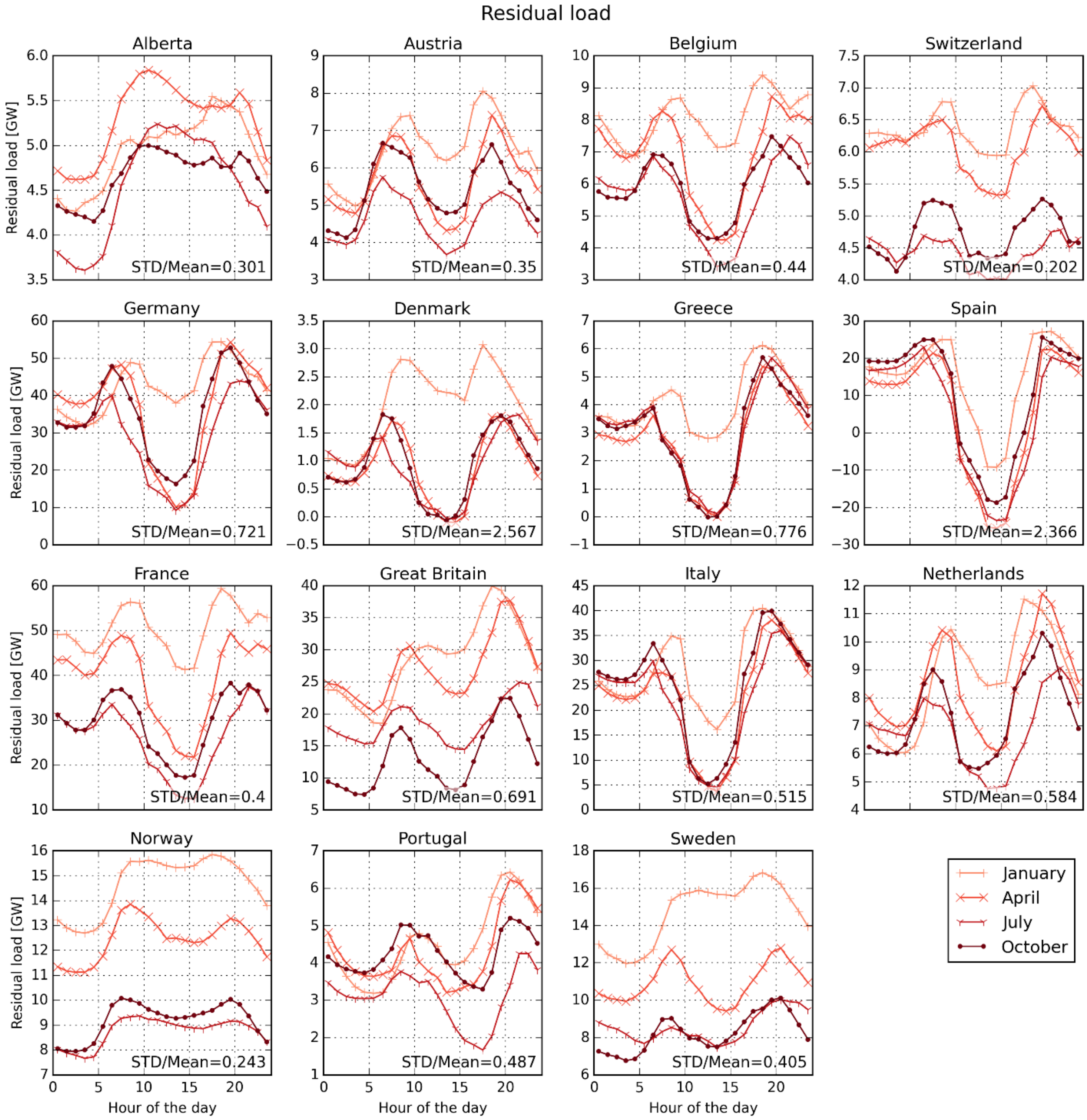


Figure 2.3. Aggregated daily profiles of the residual load in 2030 for January, April, July and October (Klein et al., 2016).

Figure 2.4 shows a simulated case that may or may not be realistic in all countries, however, figures 2.3 and 2.4 show the potential on utilizing the energy flexibility of buildings as part of a solution to obtain resilient energy networks based entirely on renewable energy sources.

The available amount of energy flexibility, however, depends on the type of building, the types of energy service systems in the building, the control possibilities, the climate, the time of day and year, the acceptance of the users and owners of the building, the state of the storage, etc. but also on the type of application as some energy use cannot be shifted e.g. electric to fire alarms. The actual useful energy flexibility is further determined by the needs of the surrounding energy networks to which the building provides flexibility services as indicated in figures 2.3 and 2.4.

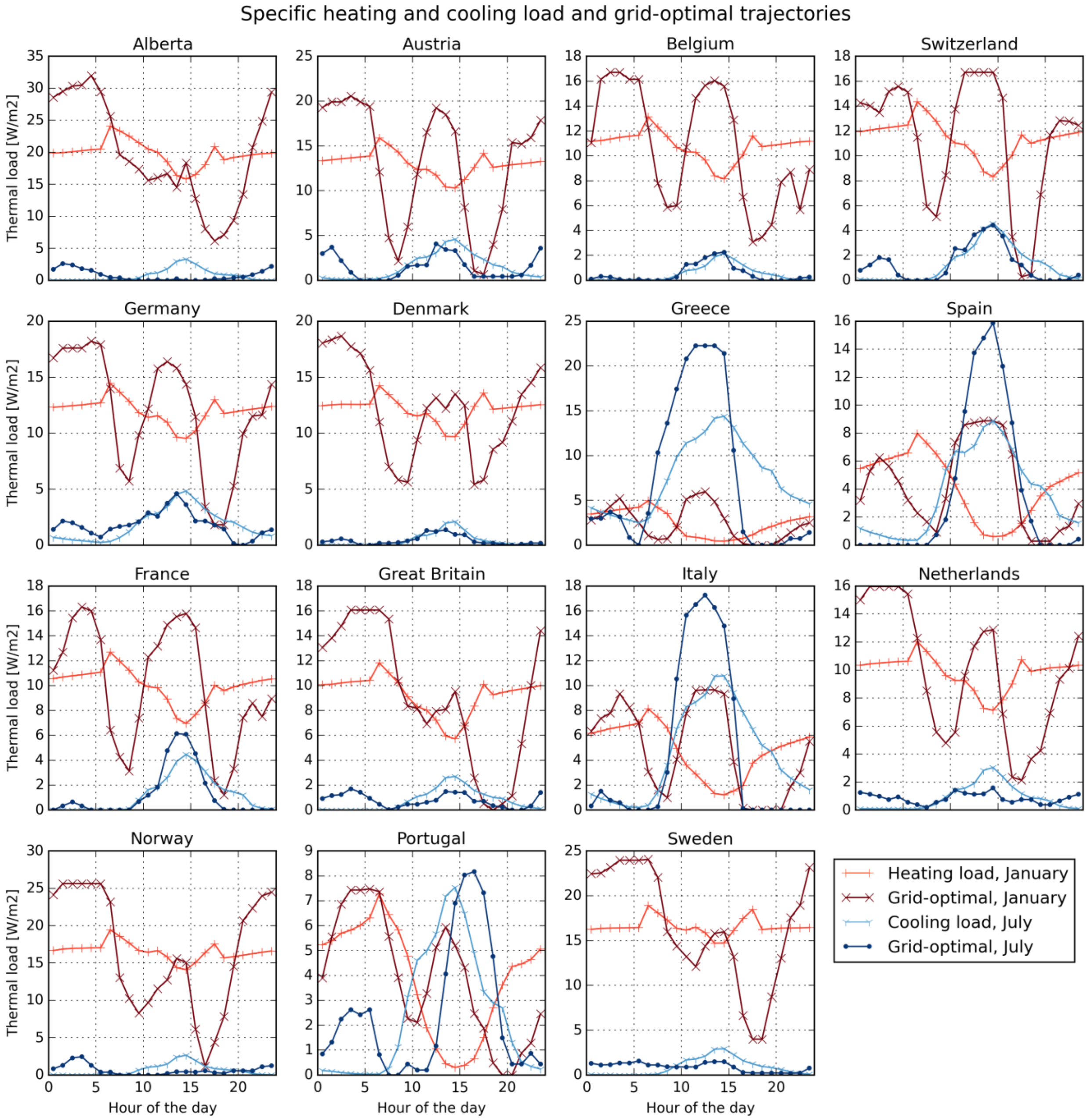


Figure 2.4. The daily thermal heating and cooling loads with and without grid-optimal operation of the heating and cooling systems for January and July (Klein et al., 2016).

2.3. Different energy networks have different needs

The flexibility of a building can be described by a dynamic Flexibility Function (FF) – see the following chapter (section 3.2), which describes how the building reacts to a Penalty signal. A Penalty signal may be a price signal, the CO_2 content in the grid or the amount of RES in the grid. Figure 2.5 shows the FF for three different buildings. Building 1 (black dashed line) has a large time constant e.g. a low energy building with a significant amount of thermal mass, which can stay without heating for several days without jeopardizing the thermal comfort, while building 3 (blue line) has a very low time constant e.g. a poorly insulated building with direct electric heating (without much thermal mass), which quickly can react to the needs of the grid, but also quickly needs reheating after a switch off, of the heating system. Building 2 (red dashed line) has a medium time constant.

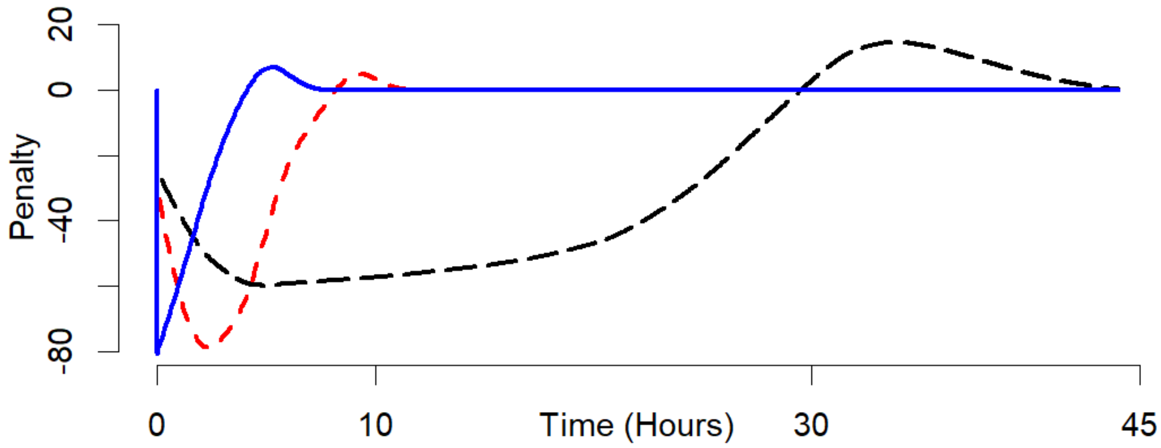


Figure 2.5. The Flexibility Function for three different buildings – heating case (Junker et al., 2018).
Black curve: a building with a large thermal time constant.
Blue curve: a building with a very low thermal time constant
Red curve: a building with a medium time constant.

The FF can be used to investigate how a specific building may support a specific grid. Figure 2.6 shows three different grids: one with a large amount of wind power, one with much solar power, and one with large peaks (Ramp) in the morning and afternoon (e.g. a district heating network). Figure 2.6 shows an example of dynamic Penalty signals for such grids, where a penalty of 1 means that there is little or no wind or solar power in the grid (i.e. periods with high residual loads in the grid as shown in section 2.2) or there are shorter periods with ramping (peak) problems (also typical for district heating networks).

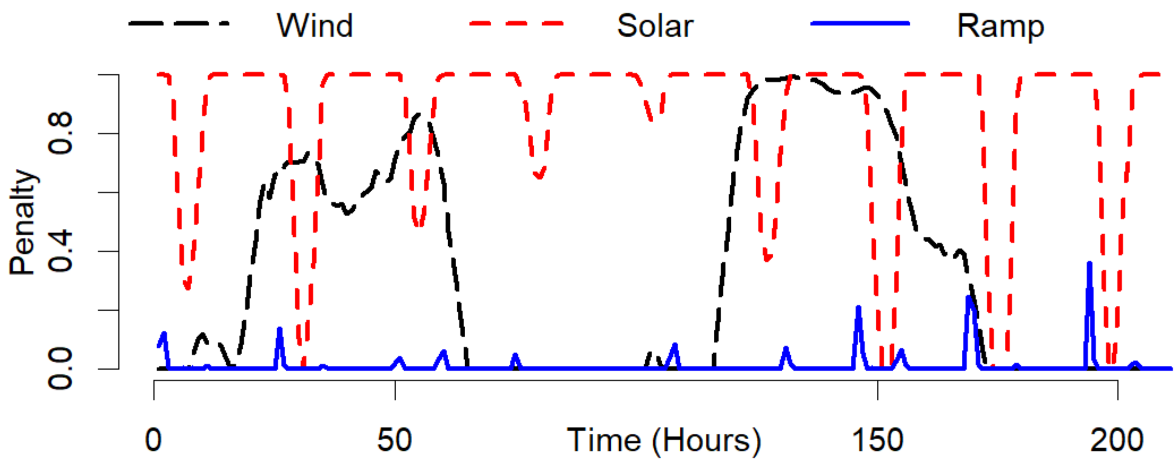


Figure 2.6. Penalty signals based on wind and solar power production in Denmark during 2017. Ramp penalty based on the electricity consumption in Norway during the same period (this situation is also typical for district heating networks) (Junker et al., 2018).

Based on the FF for the buildings and the dynamic Penalty signal it is possible to calculate an Energy Flexibility Savings Index (EFSI), which basically states the saving potential (cost or CO_2) of the three buildings when located in different energy networks with different needs. Table 2.1 shows the EFSI in % savings for the three buildings in Figure 2.5 when situated in the three grids shown in figure 2.6 – i.e. applying the dynamical Penalty signals shown in Figure 2.6.

Table 2.1 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 times 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 2.1. Expected EFSI for each of the three buildings based on the dynamical Penalty signal shown in figure 2.6 (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 2.1 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 2.5 and 2.6. However, Table 2.1 illustrates that different energy networks need different services from buildings.

The work of Annex 67 has mainly been concentrated on investigating the possible energy flexibility from single building and the characterization of this. However, work on clusters of buildings has also been carried out as there is a need for aggregation of the possible energy flexibility from buildings in order to make this available on a flexibility market. Less attention has at this stage been put on matching the possible energy flexibility with the different services needed by the energy networks in the form of frequency control, voltage control, primary, secondary and manual reserve, etc. This is aimed to be part of a proposed new IEA EBC Annex 82 Energy flexible buildings towards resilient low carbon energy systems, which will focus more on the interaction between buildings and the energy networks.

The outcome of Annex 67 is summarized in the following chapters.

3. Characterization of energy flexibility in buildings

Armin Knotzer, Roberta Pernetti, Rune Grønborg Junker, Rui Lopes, Henrik Madsen, Søren Østergaard Jensen

3.1. Introduction

To allow energy flexibility from buildings to be an asset for the energy networks, there is a need for a common way to characterize the energy flexibility that a building or a cluster of buildings can provide. The development of a methodology for characterization of energy flexibility has, therefore, been an important task of IEA EBC Annex 67. The developed methodology is documented in The Annex 67 report "Characterization of Energy Flexibility in Buildings" (Knotzer, Pernetti and Jensen, 2019). The following is a brief summary of this report.

3.2. Flexibility indicators

The concept of load flexibility by energy storage is not new, however, it is still not well explored. A literature review on existing methodologies for quantification of energy flexibility in buildings showed that the applied methods aimed at assessing the energy flexibility of buildings are diverse, but when implemented the methods can help match the energy demand to the production from renewable energy sources. The identified flexibility indicators were tested and compared in a single building case study (Reynders et al., 2018) and showed that although the quantification methodologies identified in different studies have different focus points, three general properties of energy flexibility emerge:

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 results from activating this flexibility.

Generally, indicators can be categorized into three levels in accordance with their scope: building component, single building and cluster of buildings. The different components include on-site energy generation (thermal and electrical), energy storage (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 components as well as the interactions of these with the building as a whole, gives indicators for single buildings. Similarly, the aggregation of single buildings gives indicators for clusters of buildings, defined within Annex 67 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* (Vigna et al., 2018).

As a general overview, it is possible to group the indicators according to the sources of energy flexibility:

- 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) or cooling system and its control; and
- Components of the local energy system, conversion (Combined Heat and Power plants (CHP), heat pumps (HP), electric heaters, etc.) and storage (hot-water storage tank, electric battery etc.).

The operation of these sources is highly affected by the implemented control method. In general, the literature review highlights that, although a clear need for assessing energy flexibility is seen, the evaluation approaches are still fragmented.

To understand and integrate the potential of energy flexible buildings in future energy systems, a holistic approach is needed for harmonizing building and energy (both electrical and thermal) systems but also for energy market design and even occupant interaction. As building engineers are often not familiar with all technical aspects of energy networks and vice versa, Annex 67 proposes a shared definition and an operative approach for evaluating energy flexibility that is easy to understand by both parties. This approach facilitates design and operational decisions on both building and energy system levels, 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).

The methodology introduced by 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 systems. It acknowledges that forcing factors, the so-called Penalty signals, act as boundary conditions, which can change over the lifetime of a building and with different levels of frequency (Pernetti et al., 2017):

- Low frequency signals: climate change, macro-economic factors, technology improvement, use of the building
- High frequency signals: 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 not only to the use of the building, the time of year and day but also to the forcing factors/external control signals (in the following called Penalty signals), which induce a system response. Hence, an energy flexible building is able to shift all or part of the instantaneous energy demand minimizing the effect of a Penalty signal. The following sections explain briefly the developed methodology for the characterisation of energy flexibility in buildings and an evaluation of its application.

3.3. The Flexibility Function

As exemplified in section 2.3, the potential of energy flexibility of a building differs depending on the local context, i.e. which type of energy networks the building is providing flexibility services to. Power grids and district heating/cooling networks need typically different flexibility services. And the mix of energy sources in the networks are very determining for the needed flexibility services. This fact calls for a characterization of the energy flexibility that is more than just a number, since two buildings may be equally flexible but in vastly different ways. The literature review (Reynders et al., 2018) shows that many flexibility indicators, each focusing on particular aspects of energy flexibility, have been proposed. While these provide valuable information about specific parts of the energy flexibility, they do so in a scattered way, and it is difficult to get an overview of the available energy flexibility.

When dealing with smart buildings that are being controlled in a penalty-aware way, the energy flexibility is contained in the relation between the penalty and the demand. This is what the Flexibility Function (Junker et al., 2018) utilizes to describe the dynamics of the energy flexibility in a condensed way. Examples of a Flexibility Function (FF) are shown in Figure 2.5 and more generically in Figure 3.1.

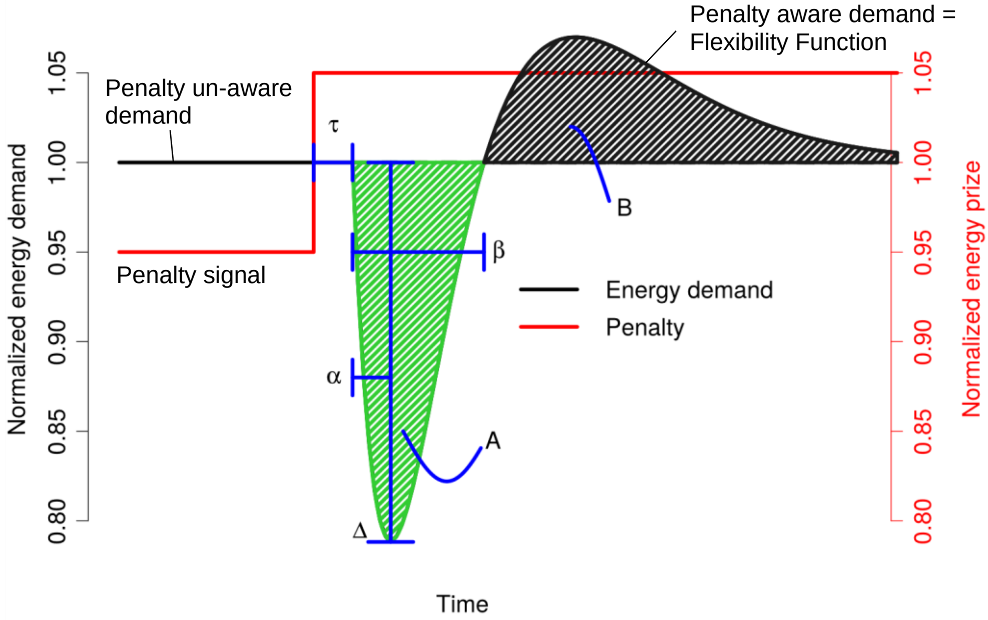


Figure 3.1. A Flexibility Function defined in terms of the change in demand, for a step increase in the energy prize. The flexibility characteristics are shown as well (Junker et al., 2018).

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 3.1. Figure 3.1 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:

- 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 controllers that are hesitant to turn off for too short a time.
- 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 increased of amount the 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 3.1 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 step 2

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 the 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 deviations from normal the 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 can be 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:

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

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):

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

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

The Penalty signal will in most cases not as shown in Figure 3.1, consist of only one single step increase/decrease. Figure 3.2 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 users (dashed lines in the top graph of Figure 3.2). The top plot of Figure 3.2 presents the room temperature in the building using both a penalty-aware controller that minimizes CO_2 emissions (green curve), and a traditional penalty-unaware controller that minimizes energy usage (red curve).

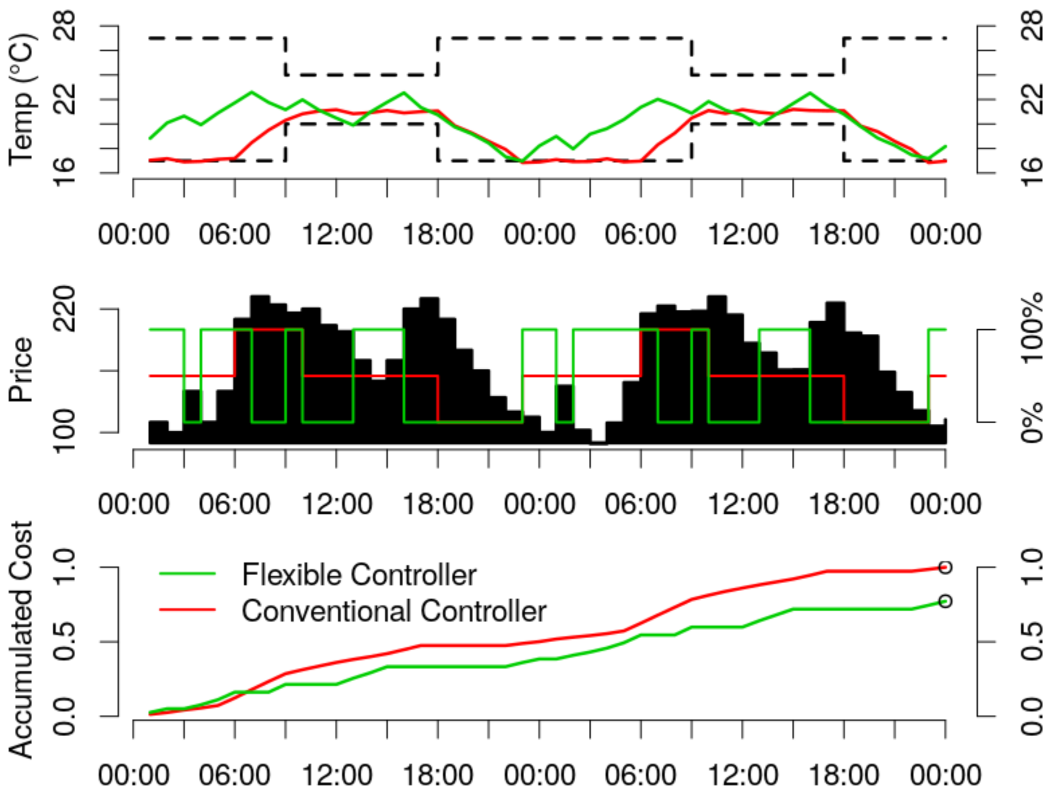


Figure 3.2 Top plot: The room temperature in a building is controlled by a penalty-aware controller (green line) or a conventional controller (red line). Both controllers are restricted to stay within the dashed lines (defined room temperature range).
Middle plot: The black columns give the penalty, while the green and red lines show when the two controllers activate heating (on/off right y axis).
Bottom plot: 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).

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 3.4 on how to deal with this situation.

In figure 3.2 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 3.1. Figure 3.3 shows the pattern of such a controller for a different example than shown in Figure 3.2 (see also section 6.3.3).

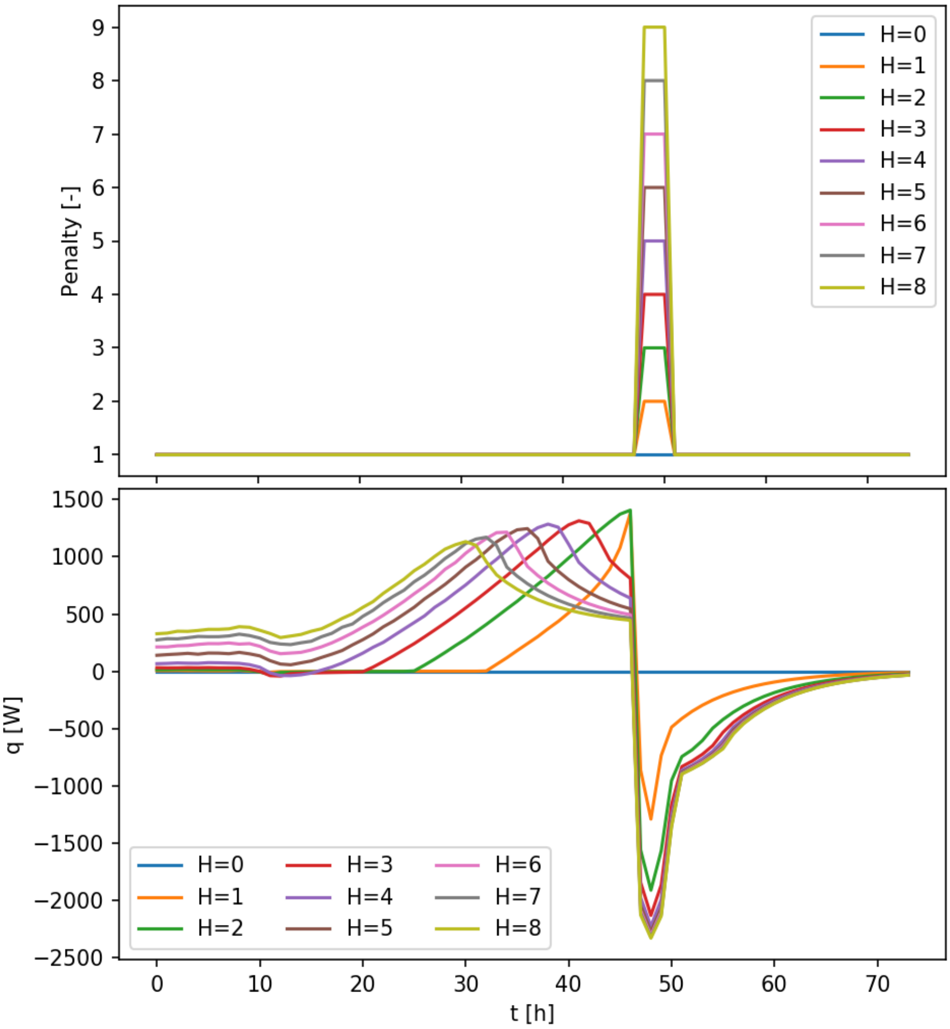


Figure 3.3 Impact of increasing amplitude of the Penalty signal (top) and the change in heating power profile using a MPC strategy compared to the flat price scenario H=0 (bottom) (Jensen, et al., 2019).

Figure 3.3 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.

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 3.3. 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.

3.4. Computing the Flexibility Function

For Figure 3.1 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.

3.4.1. Direct approach

The **direct baseline 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 3.1 (or two CO_2 scenarios as shown in Figure 3.2).

- 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 specific 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 simulation or test in hardware-in-the-loop test facilities (for the latter please see chapter 5 and the Annex 67 report “Experimental facilities and methods for assessing energy flexibility in buildings” (Salom and Péan, 2019)), where all boundary conditions can be kept identical for both cases. However, this is 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 baseline approach**, discussed below.

3.4.2. Indirect approach

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 3.1). This response is here called the **direct step 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 3.2 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 an 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 visualised as Figure 3.1 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 characterisation 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).

3.5. Evaluation of the approaches

Table 3.1 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 mainly have 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.

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 3.1.
- 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 3.1. 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).

Table 3.1 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 penalty-unaware	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**

3.6. Application of the characterization methodology

Table 2.1 shows one application of the methodology – i.e. determination of the Energy Flexibility Saving Index (EFSI) which basically states the saving potential of the three buildings when located in different energy networks with different needs.

3.6.1. Flexibility Index (FI)

Table 2.1 shows the potential savings in cost or CO_2 emissions depending on the applied Penalty signal. 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 2.5) and well-chosen Penalty signals similar to those shown in Figure 2.6 (Figure 3.7 shows the used simplified and more operational binary Penalty signals based on Figure 2.6 concentrating on when there is a need for support from the building(s)), the Flexibility Index (FI) may be calculated for the actual grid, describing the extent to which each of the buildings are able to solve the grid problems. Table 3.2 gives the FI as a percentage for the considered examples.

Table 3.2 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 2.1 and 3.2 are similar except that the values of Table 3.2 are approximately 3 to 4 times higher than in Table 2.1. 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.

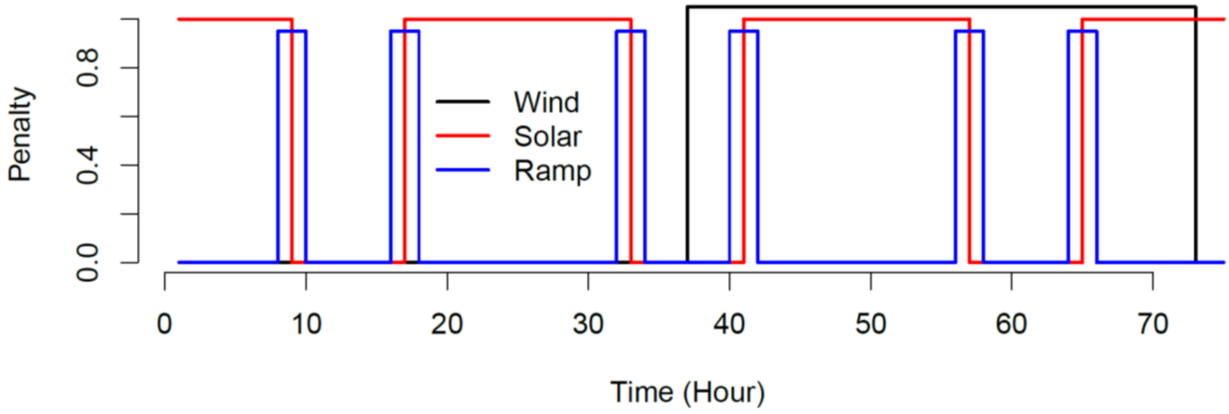


Figure 3.7 The Penalty signals from Figure 2.6 are simplified into more operational binary Penalty signals designed to obtain energy flexibility from the buildings when needed by the energy networks (Junker et al., 2018).

Table 3.2 Expected FI for each of the three buildings in Figure 2.5 based on the dynamical Penalty signals shown in Figure 3.7 (Junker et al., 2018).

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

3.6.2. 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.

3.7. Labelling

Tables 2.1 and 3.2 and the bottom graph of Figure 3.2 indicate 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 basis for labelling. However, here 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 that 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 like 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 Penalty signals, 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 the considered 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.

3.8. 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 et 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 via 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).

The benefits of the tool:

- Evaluates energy flexibility with different time steps, timespans, Penalty signals (called cost function in the tool) based on a reference load profile, a load profile with flexible operation and a Penalty signal/cost function (Figure 3.8)
- 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 3.8 – 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

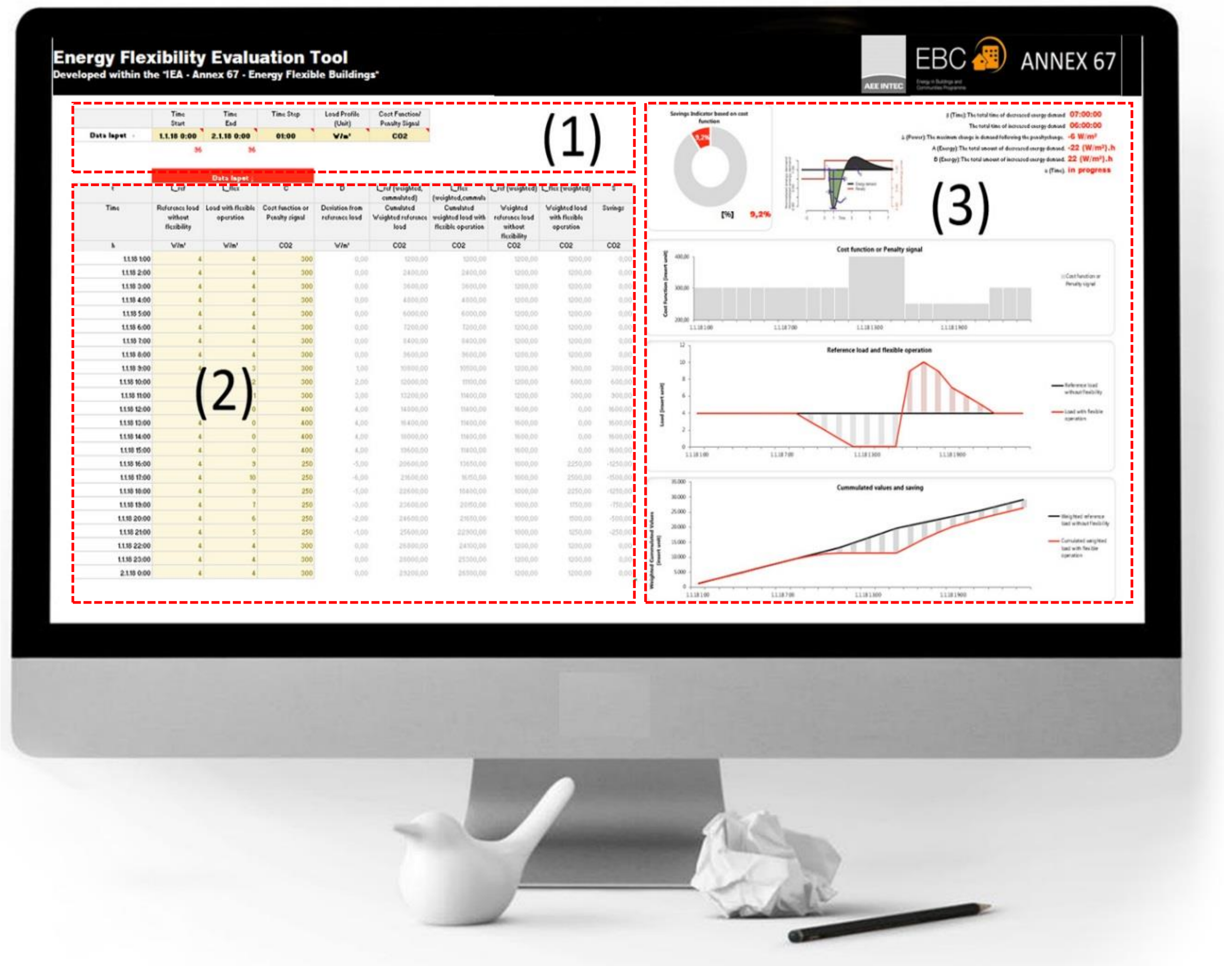


Figure 3.8 Energy **F**lexibility **E**valuation **T**ool (FET) - Overview of the interface (Weiss et al., 2019).

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 3.1in section 3.3:

- 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

3.9. 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.

4. Control of energy flexibility in buildings

Athila Santos, Bo Nørregaard-Jørgensen and Thibault Péan

4.1. Introduction

Today, buildings are controlled to obtain indoor comfort for the users, ideally without unnecessarily energy use. However, to provide energy flexibility to the surrounding energy networks it is necessary to consider additional factors such as occupant behaviour patterns, weather conditions, thermal properties and their complex interactions, without compromising occupant comfort. In order to use the potential of both commercial and residential buildings as providers of energy flexibility to smart energy networks, it is essential to redesign the way a building and its HVAC system is controlled.

For overall optimization of the energy performance of buildings, control architectures must be developed, which enables the estimation of weather, occupancy behaviour trends and energy consumption. More importantly, control methods should be multi-variable systems that can exploit the interactions between states to optimize performance, making buildings more adaptive to system variations and reducing the energy and environmental costs. In addition, the sensor information helps to better understand the building performance and the provided services, like air-conditioning, lighting and heating systems and their equivalent parameters, as well as the building's in-door environmental quality and comfort level in a real-time format.

Different studies described in this chapter investigate control strategies and efficient algorithm implementations for realizing energy flexibility in buildings, including strategies for storage capacities (thermal and electrical) and local renewables sources, like PV systems. Different control algorithms and strategies are introduced, ranging from simple low-level control of single devices over complex control of several devices to decision making based on different types of forecast (weather, prices, occupancy).

Currently, there is no overview or insight into the types and usages of control strategies on future energy systems. The aim of this chapter is, therefore, to increase knowledge on and demonstrate which control strategies and algorithms can provide energy flexibility from buildings, and to identify critical aspects and possible solutions to manage energy flexibility. The following is a summary of the Annex 67 report "Control strategies and algorithms for obtaining energy flexibility in buildings" (Santos and Jørgensen, 2019).

4.2. Example of a control strategy for obtaining energy flexibility in buildings

The Annex 67 report (Santos and Jørgensen, 2019) contains descriptions of 12 case studies (see section 4.4) carried out in Annex 67 to investigate different control possibilities for obtaining energy flexibility. One of these case studies is briefly described below.

The case study building in this example is a residential flat of 110 m^2, located in Terrassa (Barcelona), Spain and inhabited by a family of four people. The building comprises 4 bedrooms, a living room, kitchen and a bathroom. It was built in 1991 and forms part of a multi-family-dwelling over 4 floors. A model of the flat was created in the simulation program TRNSYS including a modelled retrofit measure for this analysis: a layer of 120 mm insulation is added within the external walls, bringing the U-value of these walls down to 0.20 from 0.60 W/(m^2 K). The occupancy of the four family members is modelled stochastically.

The building is conditioned by a circuit of Fan Coil Units (FCU), which are supplied by an air-to-water heat pump. The heat pump is reversible; thus, it can work in cooling mode in summer and heating mode in winter. Furthermore, the frequency of its compressor can be controlled within a certain range, thus it is a variable speed heat pump (VSHP). The indoor unit of the VSHP contains a 200 liter tank for storing domestic hot water (DHW).

The modelled control strategies apply to the whole HVAC system. The commands are sent directly to the heat pump, ordering it to function either for space heating/cooling (SH/SC) or for DHW production, and at which supply temperature. When the heat pump is activated for SH/SC, the same commands are sent to the FCU so that they run in a synchronized way. The control strategies for heating and cooling apply to the whole apartment. There are no independent, individual controls in the rooms.

4.2.1. Control strategy

A Model Predictive Control (MPC) strategy is implemented in the building to control the heat pump and the FCU systems. The present study focuses on the cooling mode, therefore, only results from the summer season are presented. The MPC control strategy intends to minimize the CO_2 emissions resulting from the electricity use of the heat pump system, hence aiming to reduce the impact of the HVAC systems use on the environment and climate change.

An external Penalty signal is utilized to inform the control decisions later applied to the heat pump. The signal represents the marginal CO_2 emissions of the electrical grid every hour. The marginal emissions factor (MEF) takes into account the merit order in which the plants are activated to supply the demand at a national scale (in Spain in the present case), and their respective emission factors. The Penalty signal is based on the hourly energy mix of Spain during one entire year (2016) and enabled to identify the CO_2 intensity of that grid, knowing the CO_2 emissions associated with each source of electricity.

The applied MPC strategy belongs to the class of indirect controls. It is provided with the above described external fluctuating signal and will intend to shift the loads to where this Penalty signal is the lowest. To achieve this objective, energy is stored in thermal form in the mass of the building and in the water tank for DHW. The MPC forecasts (in this case ideally) the ambient temperature, the solar radiation, the internal heat gains from the occupants and the DHW draw off. The applied MPC is described in more detail in (Santos and Jørgensen, 2019 - chapter 7).

4.2.2. Results and conclusion

The MPC CO_2 minimization strategy is tested by a simulation for three selected days of the summer 2016. Time series are presented in Figure 4.1, and summed indicators in Table 4.1, through a comparison with a standard thermostatic control case (Ref. case in figure 4.1).

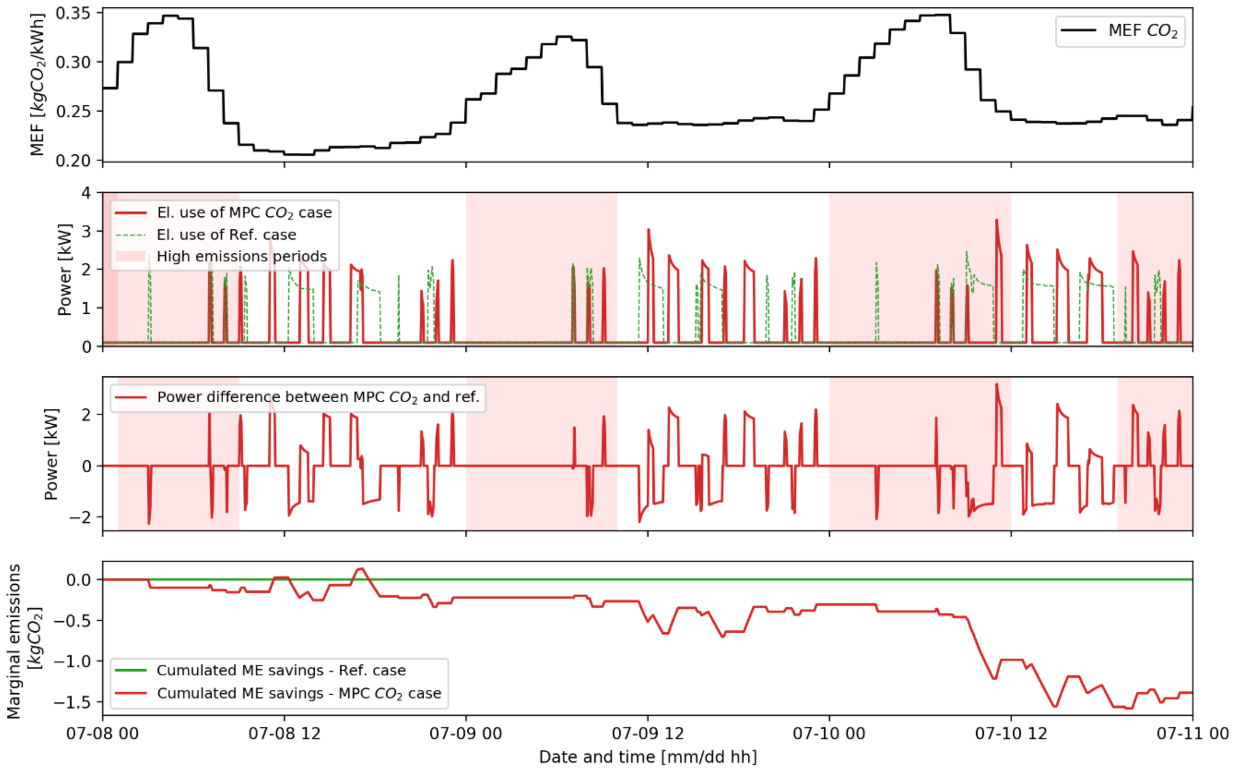


Figure 4.1 Time series of the MEF Penalty signal (top), the electrical use of the heat pump in the reference and MPC CO_2 case (second), power difference between these two cases (third), and finally the cumulated ME (marginal emissions) savings (bottom).

Table 4.1 Summary of the energy and emissions metrics of the MPC CO_2 case compared to the reference case with thermostat.

MPC objective case		**MPC CO_2**
Thermal energy use compared to reference case	[kWh]	-15.35
	[%]	-18.8%
Electricity used compared to the reference case	[kWh]	-5.15
	[%]	-16.6%
Average CO_2 emissions variation compared to the reference case	[$kgCO_2$]	-1.22
	[%]	-16.8%
Marginal CO_2 emissions variation compared to the reference case	[$kgCO_2$]	-1.39
	[%]	-19.1%
Flexibility factor (see chapter 7 of (Santos and Jørgensen, 2019) and below)	[-]	0.34

A certain amount of the load shifting occurred towards the periods of lower emissions, although the reference case already used little energy in the high emissions periods so there was little room for improvement. The flexibility factor (which should ideally be 1 if all the energy is used in low emissions periods and would take the value of -1 if all the energy is used in high emissions periods) was increased from 0.28 to 0.34. The amplitude of the load-shifting is thus rather small. The overall operation dictated by the MPC strategy resulted in 19.1 % savings in CO_2 marginal emissions. The MPC strategy lowers the delivered thermal energy to the building, leading to a small decrease of the occupants' comfort, as shown in in Figure 4.2 however the acceptable range (Category III) is naver exceeded.

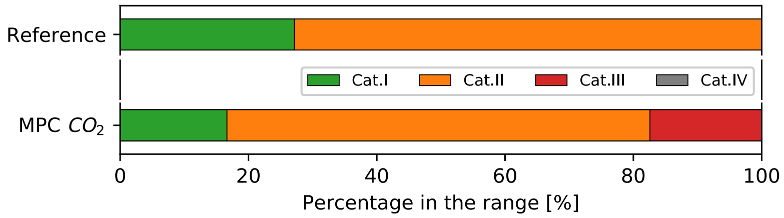


Figure 4.2 Percentage of times in the comfort ranges, as defined in the standard EN 15251 (CEN, 2007) by ranges of operative temperatures for the cooling season.

The development and computational burdens of the MPC need to be considered. Creating an MPC controller requires simplified models of the building and of the heat pump performance. These tasks require a lot of resources, since many adaptations are needed depending on the building typology, the HVAC systems in use, the season and other factors. Fine-tuning all the parameters of the MPC is very important for the good performance of the controller, therefore, this task need careful attention. This obstacle partly explains the low penetration of MPC controllers for HVAC control in existing buildings.

4.3. Terminology of control methods

Table 4.2 presents a summary of the most common control strategies that show potential for providing demand side flexibility in residential or commercial buildings. There are two main types of control: (1) control of a single component, also known as local control, and (2) control of a whole energy system, also known as supervisory control. The local controller makes sure that the process is stable and a proper set point is kept at all times, whereas the supervisory controller coordinates all the local controllers in a way that the overall operation of the energy system works smoothly.

Control methods can be divided into hard control, soft control and hybrid control. Classical control refers to the most commonly used control techniques, such as on/off control, P, PI or PID control. An on/off controller regulates a process within a predefined lower and upper threshold so that the process stays within these boundaries. P, PI and PID controllers modulate a controlled variable by using error dynamics, so that accurate control is achieved. Table 4.2 lists different available control methods and their maturity, while tables 4.5-4.6 briefly describe the control methods studied in Annex 67.

Table 4.2 Summary of the most common control methods.

Type of controller	Working principle	Implementation maturity
Thermostatic on/off control	Regulates a process within a predefined lower and upper threshold so that the process stays within these boundaries	State-of-the-art in buildings
P, PI, PID control	Modulates a controlled variable by taking into account error dynamics	State-of-the-art in buildings
Gain Scheduling PID	Controls non-linear systems by a family of linear controls which are used to control different operating points of the non-linear system	State-of-the-art for hydronic-radiator-based HVAC systems
Non-linear	A control law (derived from Lyapunov´s stability theory, feedback linearization and adaptive control techniques) for reaching a stable state of the non-linear system while keeping the control objectives	State-of-the-art for AHUs (Air Handling Units) and cross-flow water to air heat exchanger
Robust	Controller works well for changing parameters as well as time-varying disturbances. Considers model uncertainty and non-linearities of the system	State-of-the-art for supply air temperature, supply airflow rate and zone temperature control
Optimal	Solves an optimization problem (optimizing a cost function) → minimization of energy consumption and control effort, maximizing thermal comfort	State-of-the-art for active TES (Thermal Energy Storage), energy optimization for HVAC systems, VAV (Variable Air Volume) system control, building heating and cooling control
Adaptive	Controller learns to adapt to changes and learns from the characteristics of a building or/and environment by self-regulation	Used for single cases, but not widespread Used for AHUs with VAV
MPC	Applies a system model for predicting future system states and optimizes a cost function over a sliding planning horizon. Takes disturbances and constraints into account	Applied at building design stage, but not yet widespread for practical operation
Neural Network	A mathematical representation of neurons relating inputs and outputs as a huge network. Black-box modelling technique. A controller which is tuned/trained on the performance data of a system. Fits a non-linear mathematical model to the historical data	For fan control of an air-cooled chiller and for AC (Air Condition) setback time based on the outdoor temperature
Fuzzy Logic	Control actions as if-then-else statement. Methodology to represent human knowledge and reasoning by remembering rules and functions. Can be applied as supervisory control in combination with a local PID controller	Used in AHUs

4.4. Case studies

During Annex 67, twelve case studies in Denmark, Belgium, Finland, Spain, China, Germany, Norway, Netherlands, Ireland and Canada (listed in table 4.3) were developed in order to demonstrate control strategy and algorithm implementations that can provide energy flexibility in buildings. A description of the twelve case studies listed in Table 4.3 may be found in (Santos and Jørgensen, 2019).

Table 4.3 Case studies in IEA EBC Annex 67.

Case study	Name	Managed by	Location
1	Multi-objective genetic algorithm for model predictive control in buildings	University of Southern Denmark	Denmark
2	Deep reinforcement learning for optimal control of space heating	Enervalis and KU Leuven	Belgium
3	A Model Predictive Controller for Multiple-Source Energy Flexibility in Buildings	Technical Research Centre of Finland Ltd	Finland
4	Model predictive control for carbon emissions reduction in residential cooling loads	Catalonia Institute for Energy Research	Spain
5	Investigation of the energy flexibility of a residential net-zero energy building involved with the dynamic operations of hybrid energy storages and various energy conversion strategies	The Hong Kong Polytechnic University	China
6	Rule-based load shifting with heat pumps for single family houses	Fraunhofer IEE	Germany
7	Predictive rule-based control to perform heating demand response in Norwegian residential buildings	Norwegian University of Science and Technology	Norway
8	CO_2-aware heating of indoor swimming	Technical University of Denmark	Denmark
9	Economic model predictive control for demand flexibility of a residential building	Eindhoven University of Technology	Netherlands
10	Implementation of demand response strategies in a multi-purpose commercial building	University College Dublin	Ireland
11	Experimental assessment of energy flexibility potential of a zone with radiant floor heating system	Concordia University	Canada
12	Aggregation of energy flexibility of commercial buildings	University College Dublin	Ireland

The main features of the 12 case studies are listed (with an 'X') in Table 4.4. The features are grouped in five areas: Building typology, Energy system, Source of flexibility, Control system and what Results (are) based on. These five areas are further subdivided in to different technologies to help the reader in finding the examples of most interest. The icons in Table 4.4 are explained in Table 7.1. The examples describe results from investigations applying different boundary conditions (weather, energy prices, etc.) and constrains (use of buildings, comfort range, etc.) so the results may differ between the case studies.

Table 4.4 Examples of how to obtain energy flexibility from buildings.

	Building typology				Energy system				Source of flexibility				Control system		Results based on	
Case Study	Single-family house	Multi-family house	Non-residential building	Cluster of buildings	Heat pump	District heating	Other HVAC systems	PV	Constructions	Thermal storage	Batteries	Fuel switch	Rule based	Model based	Simulation	Measurements
1			X			X	X		X				X	X	X	X
2	X				X				X					X	X	
3	X				X	X	X	X		X	X		X	X	X	
4	X	X			X				X	X				X	X	
5	X				X			X			X		X		X	
6	X				X				X	X			X		X	
7	X						X		X	X			X		X	
8	X			X	X					X				X		X
9	X				X		X	X	X					X		X
10			X				X		X				X		X	
11	X						X		X				X			X
12			X				X	X	X		X		X		X	

4.5. Control strategies and algorithm implementation

The purpose of this section is to give an overview of the applied controls in the twelve studies, in order for the reader to be able to judge if a case study is of particular interest. The relevant case studies can be looked up in (Santos and Jørgensen, 2019).

Table 4.5 summarizes the control strategies applied in each case study of Table 4.4, as well as the controlled target system. The same is done in Table 4.6 regarding the algorithms used to achieve the desired control strategy.

Table 4.5 Summary of case studies regarding control strategies.

Case Study	Target	Control strategies
1	Ventilation dampers, radiator valves, set points for the air pressure in the ventilation duct system, ventilation air temperature (heating only), and light systems.	• Pre-ventilation or postponed ventilation • Pre-heating and utilization of thermal mass • Night-time free cooling (using ventilation) during summer • Decreased ventilation rate in low occupancy periods • Passive heating (absorption of solar heat gains into thermal mass for later use) • Light dimming
2	Heat pump thermostat control.	• Reduce energy demand for space conditioning by automatic control of the heating equipment while respecting occupant defined comfort bounds • The building is reheated while optimizing towards a secondary objective such as reducing costs
3	Energy storage (electricity in a battery and heat in a hot-water storage tank), operation of a Ground-Source Heat Pump (GSHP), electric heating element and, onsite PV panels, wind turbine and solar-thermal collectors.	• Optimal interaction of a building with the energy networks • Best management of the import and export to the electricity grid and the district heating network • Reduce the energy cost for electricity and heating of a residential building • Best management of the renewable electricity and heat generated by onsite PV panels, wind turbine and solar-thermal collectors, as well as import and export to the electricity grid and the district heating network.
4	Residential building equipped with a reversible heat pump, Fan Coil Units	• Reduce the operational CO_2 emissions • External Penalty signal is utilized (CO_2) • Focuses on the cooling mode • Shift the loads to where this Penalty signal is the lowest • Energy is stored in thermal form in the mass of the building and in the water tank for DHW.
5	Hybrid thermal storage systems, thermal mass of the building, building integrated photovoltaics, micro-wind turbine, electric vehicles	• Managing the on-site surplus renewable energy and investigate the impact of different energy sources • Renewable energy-to-demand control strategy vs Battery-to-demand control strategy • Peak load shaving and valley filling via the hybrid energy storages
6	Thermal energy storages (space heating and domestic hot water), heat pumps	• Aims at increasing the consumption of RE during peak periods with predefined rules • Load shifting potential of decentralized heat pumps • Energetic and economic aspects in comparison to the conventional heat pump operation (heat-driven) with heat pump blocking times
7	Electric radiators applied for space heating in a single-family detached house, domestic hot water in a storage tank using a electric resistance heater	• The main objective of the controls is shifting loads away from peak hours. • Reduce costs and/or carbon emissions • CO_2 based controls vs Price-based control

Case Study	Target	Control strategies
8	Heating of indoor swimming pools using heat pumps	• The objective is to minimize the CO_2 emission caused by the power plants producing the electricity used by the heat pumps of the swimming pools • Controller is used to control the temperature of the swimming pools according to Penalty signals • CO_2-intensity vs price Penalty signals
9	Room temperature controlled by one thermostat, heat pump, photovoltaic panels	• The objective is to optimize demand flexibility. For this approach, operational costs of energy usage are associated with demand flexibility, which is represented by the flexibility indicators: flexibility factor, supply cover factor, and load cover factor
10	Heating, ventilation and air conditioning equipment (thermal comfort and air quality). Chiller, fans and thermal mass of the building	• The main objective is to develop a demand response strategy selection scheme for commercial buildings, which employs the appropriate strategies as a response to varying utility/aggregator requests while maintaining occupant comfort • Investigate the capabilities and limitations of the various DR strategies to provide peak shaving and load shifting for different requests (activation time, event duration and season). • Create a repository of DR strategies based on simulated results for a representative winter and summer weekday for different activation times and event durations
11	Radiant floor embedded in a concrete slab via thermostat	• The thermostat controls the room air and floor temperature for a hydronic heating zone using Pulse Width Modulation (PWM) technology • The control of the system is based on an assumed price signal. Therefore, it is investigated how much flexibility can be obtained by modulating the air temperature set point from the baseline room temperature to the comfort limits of the zone • Load shifting based on price signal.
12	Water chiller, fans, battery	• Global Set point Adjustment • Chiller Water Temperature • Fan Modulation • Electric Battery

Table 4.6 Summary of case studies regarding algorithm implementation.

Case Study	Algorithm	Description
1	• Genetic Algorithm (GA) • Kalman Filter (KF) • Probabilistic Classification (PC)	• GA: used to estimate building specific steady state parameters of all zones and to optimize overall control strategy • KF: used to estimate specific transient parameters of the model (e.g. occupancy in rooms without cameras) • PC: used to predict indoor occupancy based on 3D camera data
2	• Rule-based control • Reinforced Learning (RL) • Model predictive control	• The reinforcement learning agent is expected to balance two reward streams. The first derives from respecting occupant comfort bounds while the second is to consume as little energy or money as possible while still meeting the first objective. • A model predictive controller is implemented which assumes full knowledge of system dynamics.
3	• Rule-based control • Model predictive control	• Nonlinear optimization-based model predictive controller, using successive linear programming, which makes continuous approximations of the discrete control variables.
4	• Model predictive control	• The MPC control strategy intends to minimize the CO_2 emissions resulting from the electricity use of the heat pump system, hence aiming at reducing the impact of the HVAC systems use on the environment and climate change. • external Penalty signal is utilized: this signal represents the marginal CO_2 emissions of the electrical grid every hour. • The MPC optimization model is a classical state-space model

Case Study	Algorithm	Description
		used to estimate the dynamics of the building envelope and was represented as a resistance-capacitance (RC) network with three states, the temperatures in the inside zone, at the surface of the walls and in the Thermal Energy Storage tank.
5	• Rule-base control	• The electricity generation from the hybrid renewable system is firstly used to cover the basic electric load • The surplus renewable energy is used to charge the electric vehicle before recharging the hybrid thermal storages • Whenever the basic electric load is higher than the renewable energy, the static battery is discharged before discharging the electric vehicle. • The rest of the electric load is covered by importing electricity from the grid. • Renewable energy-to-demand control strategy: basic electric load is firstly covered by the on-site renewable energy, and then it is covered by the electricity discharged from the battery. • Battery-to-demand control strategy: the battery is discharged to cover the basic electric load first, and then the remaining electric load is covered by the renewable energy.
6	• Rule-base control	• The local residual load is used as an external signal for the RBC and a flexibility strategy based on set-point modulation depending on the local residual load is applied to the heat pump control. • Heat pump blocking times: the grid operators can block the operation of heat pumps in order to avoid peak loads. • The RBC continuously receives the information about the electricity price from the outside of the building to make decisions in order to adjust to new set-point temperatures of the thermal energy storage • Based on the information about the electricity price signal, a new set-point temperature for space heating and hot water supply is defined by switching the heat pump operation from heat-driven to grid-driven operation.
7	• Predictive rule-based control	• Weather data and hourly day-ahead spot prices for each bidding zone are used as input signal for the price-based control and to calculate the heating costs. • Control strategy carbon a): aims at operating the energy system in times of lowest CO_2 intensities • Control strategy carbon b): charges the storages just before high-carbon periods in order to avoid the energy use during these critical periods • Control strategy price a): aims at operating the energy system in times of lowest price signals • Control strategy price b): charges the storages just before high price signals periods in order to avoid the energy use during these critical periods
8	• Economic model predictive control (E-MPC)	• The heat pumps are activated through temperature set points for the pool water. • The set points are set higher than the current water temperature to turn the heat pumps on and vice versa to switch them off. • The EMPC schedules the heating of the pool such as to keep the temperature within comfort boundaries as cheaply as possible • CO_2-intensity and price Penalty signals is send to the E-MPC, according to which it will minimize the operational costs. First used to minimize CO_2 emission, and later to improve grid balancing

Case Study	Algorithm	Description
9	• Economic model predictive control • Artificial neural network (ANN)	• An ANN-MPC approach is used to represent the dynamical behaviour of the heating system and the building. • Another ANN model is developed for weather forecasting to obtain global, horizontal solar radiation. • The validation of the ANN-MPC is conducted based on heating consumption. • The controller implements openings of windows, openings of curtains, and upper and lower comfort bounds, which are based on occupants' preferences • The EMPC assumes (1) the costs of consuming electricity from the grid, (2) the costs of consuming electricity from on-site PV power generation, and (3) the costs of delivering electricity from on-site PV power generation to the grid.
10	• Rule-base control • Case base reasoning	• Plant equipment (chiller) water temperature increase to target the chiller load; • Delivery equipment (fans) on/off control strategy and decreasing the supply air flow rate of variable air volume (VAV) unit; • Zone air temperature set point modification; • Decreasing the swimming pool zone air temperature and water temperature
11	• Rule-base control • Pulse Width Modulation (PWM)	• The control strategy is based on simple increasing and decreasing of the zone temperature by means of the zone thermostat. • The thermostat works based on pulse-width modulation. Therefore, the heating output of the heater is controlled via PWM. • The set point modulation strategy can be defined and applied to a price signal. Therefore, when there is a high price signal for a certain period of time in the forecast, the zone set point can be increased for a certain period and then get back to the normal operating condition.
12	• Rule-base control	• The temperature of the zones is controlled through a dual set point thermostat, one for cooling and one for heating. • Low-level controls to simulate certain closed-loop hardware controls, e.g. basic thermostatic control for zone heating and cooling • high-level controls to control the operation of large parts of the system and can coordinate control of the air system and the plant system.

4.6. Conclusion

The results and lessons learned from the case studies are very specific for each case. The results are based on different boundary conditions (weather, energy prices, etc.) and constraints (use of buildings, comfort range, etc.) so the results may differ between the examples or even be contradictive in some cases.

Since buildings are unpredictable consumers of energy, optimal control strategies are a key technology in next-generation energy efficient buildings. However, the case studies show that traditional control strategies are still being used in most of the buildings' subsystems even with the development of better alternatives presented over the past years. The reason for this is as explained at the end section 4.2, that the development of these more advanced controllers needs more time and skill than traditional controllers, and they are further still not well-known. So, business as usual is the easy way out.

In addition, the majority of studies focus on independent components of the building rather than building-wide optimization, neglecting the potential efficiency improvements to be exploited for the entire system in order to achieve significant energy flexibility.

Furthermore, the building-wide optimization is a non-linear and multivariate problem having no unique solution where competitive objectives arise in practice, involving interdependent issues distributed among multiple building climate zones. In this way, the coordinated operation of interconnected subsystems performing autonomous control is essential to achieve the overall system goals.

In this context, where the control process of buildings should be optimized, there is a need to seek new methods and technologies that provide fast and optimized management and control. Appropriate methods must be efficient and robust, performing inter-context considerations ensuring reliability and security in the operating conditions of the system.

5. Test of Energy Flexible components and systems

Jaume Salom and Søren Østergaard Jensen

5.1. Introduction

Test and demonstration in real buildings is preferable when evaluating new concepts like energy flexibility in buildings in order to convince the stakeholders of the validity of the concept. However, there are many non-controllable variables in a real building, which makes it difficult to draw reliable, significant conclusions - unless the concept is demonstrated in several buildings. Moreover, test and demonstration in real buildings can be time consuming and very expensive. Simulation is in comparison inexpensive and fast, so that parametric studies can be performed easily. However, since all inputs and the environment are often specified in a very simple way, this may lead to results that are not applicable to be found in real life.

Many components are exposed to certified tests in order to prove their performance. These tests in laboratories give insight into important parameters of the components, which are necessary inputs for simulations. However, the tests do not answer the question of how the component will perform in a building under realistic use, as the components are tested under standardized steady-state conditions, which often do not resemble the dynamic conditions that the components will be exposed to in real environments.

Hardware-in-the-loop (HiL) test facilities, where parts of a system are physical components while others are virtual, establish a bridge between the three approaches described above. Systems and energy flexibility strategies are usually developed through simulations, so there is a need for validation through tests under dynamic, real (or as close as possible to real) operating conditions. HiL represent, therefore, a necessary tool where researchers and industry can test, under controlled conditions, the performance of new systems before they are implemented in real buildings and/or field tests. Compared to field testing, dynamic tests in a controlled laboratory environment with a semi-virtual approach, offer the flexibility of imposing well-controlled and repeatable boundary conditions on the equipment, without waiting for given conditions to occur in the real world. The same system can be tested in different environments (e.g. connected to different building types, or exposed to different climatic conditions) quickly by reconfiguring the simulation of the virtual parts. Unwanted interferences (e.g. from users) can be avoided and the accuracy of measured data is generally better in a controlled laboratory than in a field study. Of course, field tests are still necessary for a complete performance assessment, but semi-virtual testing allows going further than conventional laboratory tests at a fraction of the cost of a pilot project.

5.2. Test facilities

During Annex 67, nine facilities in Belgium, Canada, Denmark, Finland Germany, Norway, Spain and Switzerland (listed in table 5.1) tested control strategies and the combination of components under controllable, yet realistic, conditions have been described extensively in the Annex 67 reports

(Péan and Salom, 2019, Salom and Péan, 2019). Eight out of the nine test facilities uses the hardware-in-the-loop concept while the last (the ZEB Living Lab in Norway) is a Living Lab being a zero energy house.

Table 5.1. Laboratories for testing energy flexibility in buildings hosted by participants in IEA EBC Annex 67.

Name	Managed by	Location
SEILAB	IREC - Catalonia Institute for Energy Research	Tarragona, Spain
Energy Smart Lab	IREC - Catalonia Institute for Energy Research	Barcelona, Spain
NZEB Emulator	Aalto University	Espoo, Finland
EnergyVille labs	EnergyVille (VITO, KU Leuven, IMEC)	Genk, Belgium
OPSYS test rig	Danish Technological Institute (DTI)	Taastrup, Denmark
ZEB Living Lab	NTNU / SINTEF	Trondheim, Norway
Semi-Virtual Laboratory	Polytechnique Montréal	Montréal, Canada
Energy Research Lab	Institute Energy in Building, FHNW	Muttenz, Switzerland
Test Lab Heat Pumps and Chillers	Fraunhofer Institute for Solar Energy Systems	Freiburg, Germany

Figure 5.1 shows the general operation concept of the NZEB emulator at Aalto University, Finland. The platform is designed to resemble a single-family house with respect to component sizing, but the operation can be scaled to match different building types. The actual building is a TRNSYS simulation running in a computer and the physical devices are operated according to electricity and heating demands given by the simulation at six-minute (changeable) intervals. The physical part of the system (composed by thermal and PV collectors, a micro wind turbine, one heat pump, water tanks and batteries) is operated in real-time and according to real weather conditions. The platform is equipped with an energy management system (EMS) which optimizes the energy use and flows by assessing the energy prices and weather.

A simpler set up is found in the OPSYS test rig at Danish Technological Institute, Denmark – Figure 5.2, where only the control of a heat pump in combination with the heat emitting system of a house is tested.

Figure 5.3 shows a photo of the ZEB Living Laboratory at NTNU/SINTEF, Norway, which is a single-family house with a heated floor area of approximately 100 m^2. It is different from the other test facilities mentioned in Table 5.1, in that people are allowed to live there for certain periods of time to investigate the interaction between users and the technology in low (zero) energy buildings. However, the ZEB Living lab has the common characteristic with the other test facilities that it can be managed and be forced to act under pre-defined conditions, by the controller of the building, for periods of time when tests are carried out. This of course excludes the outdoor boundary conditions, which are not controllable. Furthermore, the house can also run in a “fully virtual” mode (i.e. mimicking the presence of users even if no one is really in the building).

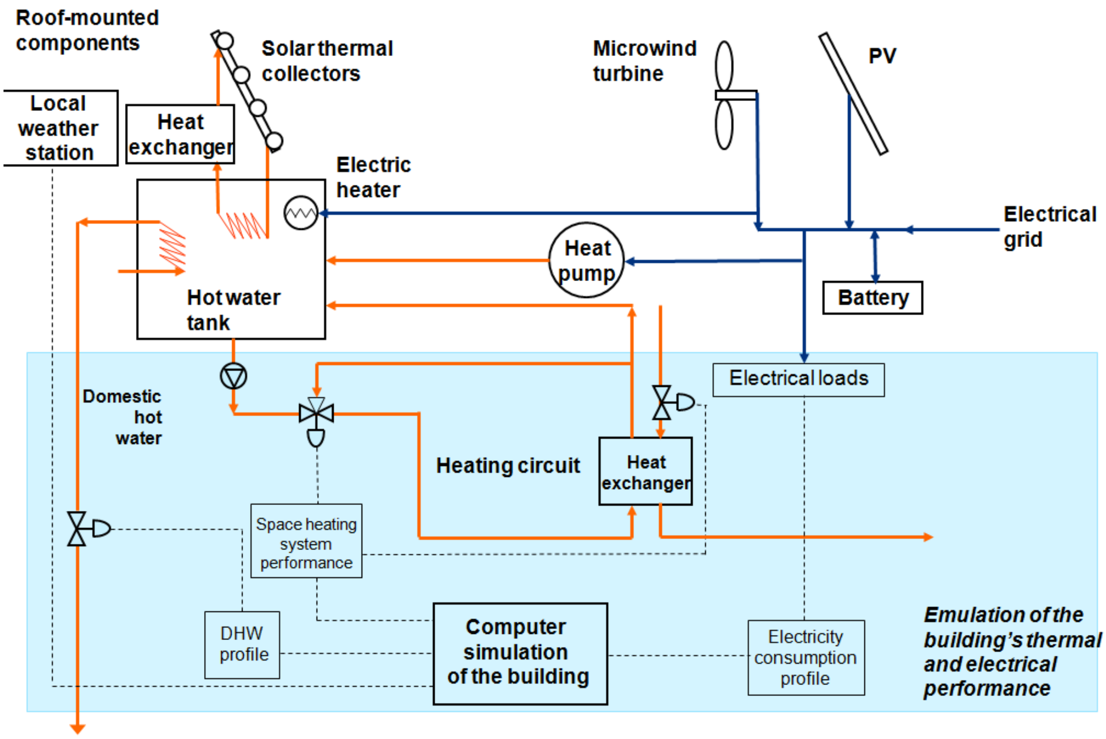


Figure 5.1. The general layout of the NZEB Emulator at Aalto University (Salom and Péan, 2019).

Figure 5.2. The OPSYS test rig at DTI, Denmark (Jensen, 2018).

Figure 5.3. The Living Lab house at NTNU/SINTEF, Norway (Annex 67, 2016).

5.3. Experiments on energy flexibility

During the course of Annex 67 experiments with the objective to test some aspect related to energy flexibility in buildings were carried out in six of the nine laboratories listed in Table 5.1. A common characteristic of the tests in the six test facilities is that the experiments are short tests lasting from days to 1-2 weeks. The aim of two experiments carried out in two test facilities (the OPSYS test rig at DTI and the semi-virtual laboratory at PLYMTL) is to quantify the amount of energy flexibility that can be derived from a building or a PCM (phase change material) tank respectively, comparing the performance of the system between a reference case and a case when energy flexibility is activated. The three experiments carried out in FHNW, Aalto and IREC aim to test how a certain flexible system behaves with an advanced control/management system in order to increase self-consumption or minimize energy costs or CO_2 emissions in comparison with a reference case when energy flexibility is not activated. The performed test in ZEB Living Lab at NTNU/SINTEF differs from the above as the aim here is the calibration of first-order reduced building models, which is a key aspect in the use of model predictive controller (MPC) to enhance energy flexibility in buildings. As a summary, Table 5.2 shows the main objective of the experiments developed in each of the test facilities, with the real elements controlled in the system and the length of the experiments which usually involves some warming-up days. For further information and results from the tests, please see the Annex 67 report “Experimental facilities and methods for assessing energy flexibility in building” (Salom and Péan, 2019). In each of the descriptions of the six tests mentioned above, the lessons learned from each facility when developing and running the experiments are also documented.

Table 5.2. Brief information on the tests carried out in the six test facilities.

Test facility	Main objective	Real controlled devices	Activated flexibility sources	Test length
IREC	Test MPC strategies to minimize energy costs or CO_2 emissions	Heat Pump	Building thermal mass DHW water tank	4 - 5 days
Aalto	Test EMS to minimize energy costs in a NZEB	Battery Heat Pump Electric heater in tank	Battery DHW water tank	1 week
DTI	Quantification of energy flexibility and validation of simulation tool	Heat Pump Thermostat (Sim)	Building thermal mass	1 - 2 weeks
NTNU/SINTEF	Parameter identification of a building control oriented model	Single electrical emitter following PRBS	(Building thermal mass)	6 - 11 days
FHNW	Test EMS to increase PV self-consumption	Battery Heat Pump	Battery DHW water tank	4 days
POLYMTL	Quantification of energy flexibility	PCM tank	PCM tank	3 - 4 days

5.3.1. Example of testing performance of advanced controls for energy flexibility

A series of dynamic experimental tests were carried out in the SEILAB facilities of IREC, which aimed at operating a real heat pump under a model predictive control framework and observing its performance in more realistic conditions than with only simulations. The dynamic tests evaluated the response of the heat pump to different configurations of the MPC. The benefits in terms of energy flexibility for different MPC configurations were assessed with the same heat pump operating in heating mode, in cooling mode and for production of domestic hot water (DHW) in both seasons. This range of combinations has been investigated to a low extent in the literature on MPC for energy flexibility, and few studies use a real heat pump system in an experimental setup. Furthermore, implementing such advanced control strategies on a real system helped to identify the bottlenecks that could hinder the deployment of MPC, propose solutions to improve them, and emphasize some lessons learned from the experiment.

For the dynamic tests, the experimental setup is presented in Figure 5.4. The tests consist of operating the heat pump (nominal heating power of 11 kW) during three consecutive days in real time and under dynamic conditions together with the virtual building model. The outdoor unit of the heat pump is located in a climate chamber, where the air temperature and relative humidity are controlled according to a predefined climate file. The indoor unit, with its integrated tank of 200 L for DHW, is placed outside the chamber.

The heat pump is “connected” to a virtual building model running on a pc in real time and emulated by the TRNSYS software. The supply water temperature and flow from the heat pump are measured and fed as information into the building model. TRNSYS then calculates the return temperature from the fan coil units (FCU), which is emulated as the actual water temperature returning to the real heat pump by means of the heat exchangers of the thermal benches. The DHW draw-offs follow a predetermined profile according to the European standard EN12976 and are reproduced in an additonal thermal test bench. The hot water flow is extracted from the tank following the programmed DHW tapping profile while the temperature of the cold water is controlled in an external tank of 1000 L, to emulate the conditions of the mains water according to the period of the year.

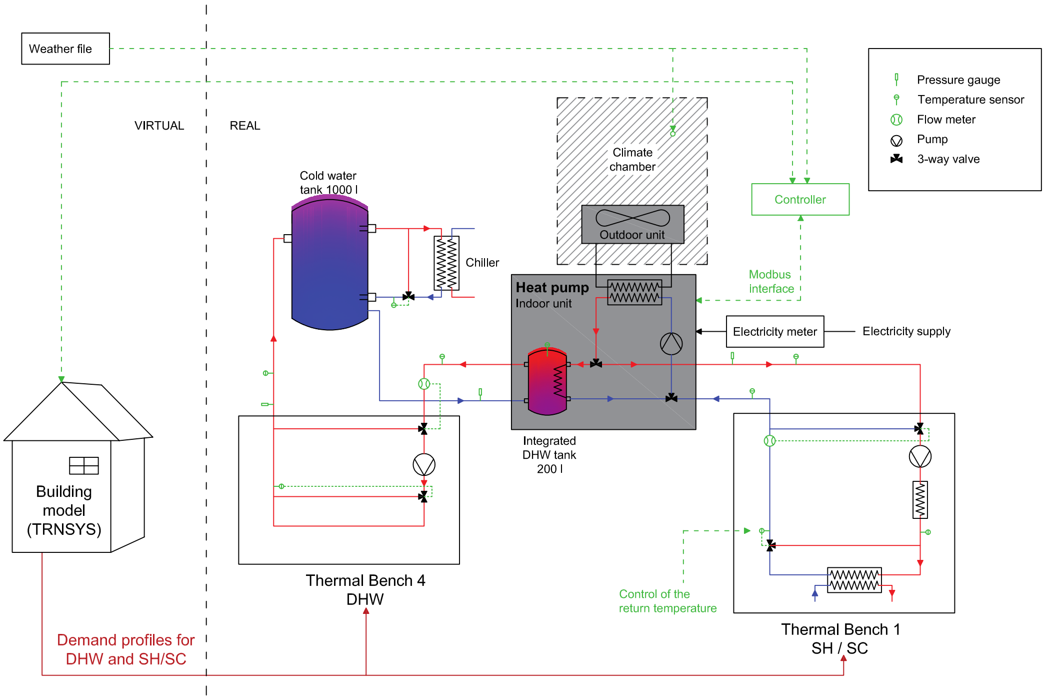


Figure 5.4 Scheme of the experimental setup used for dynamic tests.

All the systems are managed from a central interface programmed with the software LabVIEW. This interface communicates with the building simulation tool (TRNSYS), the heat pump (through a Modbus gateway), the controller (in Matlab), and the rest of the sensors and actuators in the climate chamber and the thermal benches. The MPC controller was designed and implemented in Matlab. Different configurations of MPC for energy flexibility were used and compared. A first one, called MPC ThEnerg, intends to minimize the thermal energy delivered to the building. A second one, called MPC Cost, minimizes the costs of the heat pump operation by reacting to an electricity price signal. A third one, called MPC CO_2, minimizes the CO_2 emissions by reacting to a CO_2 marginal emission factor signal.

Figure 5.5 shows the time series of several parameters recorded during the three days of one of the experiments with the MPC Cost configuration in heating mode.

On the top graph, the outdoor temperature set-point (from a climate file) is displayed, as well as the real air temperature measured in the climate chamber. On the second graph, the input price signal is shown. The periods where the price is considered high, hence when the MPC will tend to avoid operating the heat pump, are highlighted in red. The third graph shows the heat pump power consumption, i.e. when it was activated by the MPC. The last two graphs show the resulting temperatures in the indoor space and in the DHW tank, with their respective constraints. Savings in comparison with a reference case are quite small for that case (1%) compared with what is expected and reported by the literature. Further details regarding the effectiveness of different MPC strategies and other aspects related to the found bottlenecks in the implementation can be found in (Salom and Péan, 2019) and in (Péan et al., 2019).

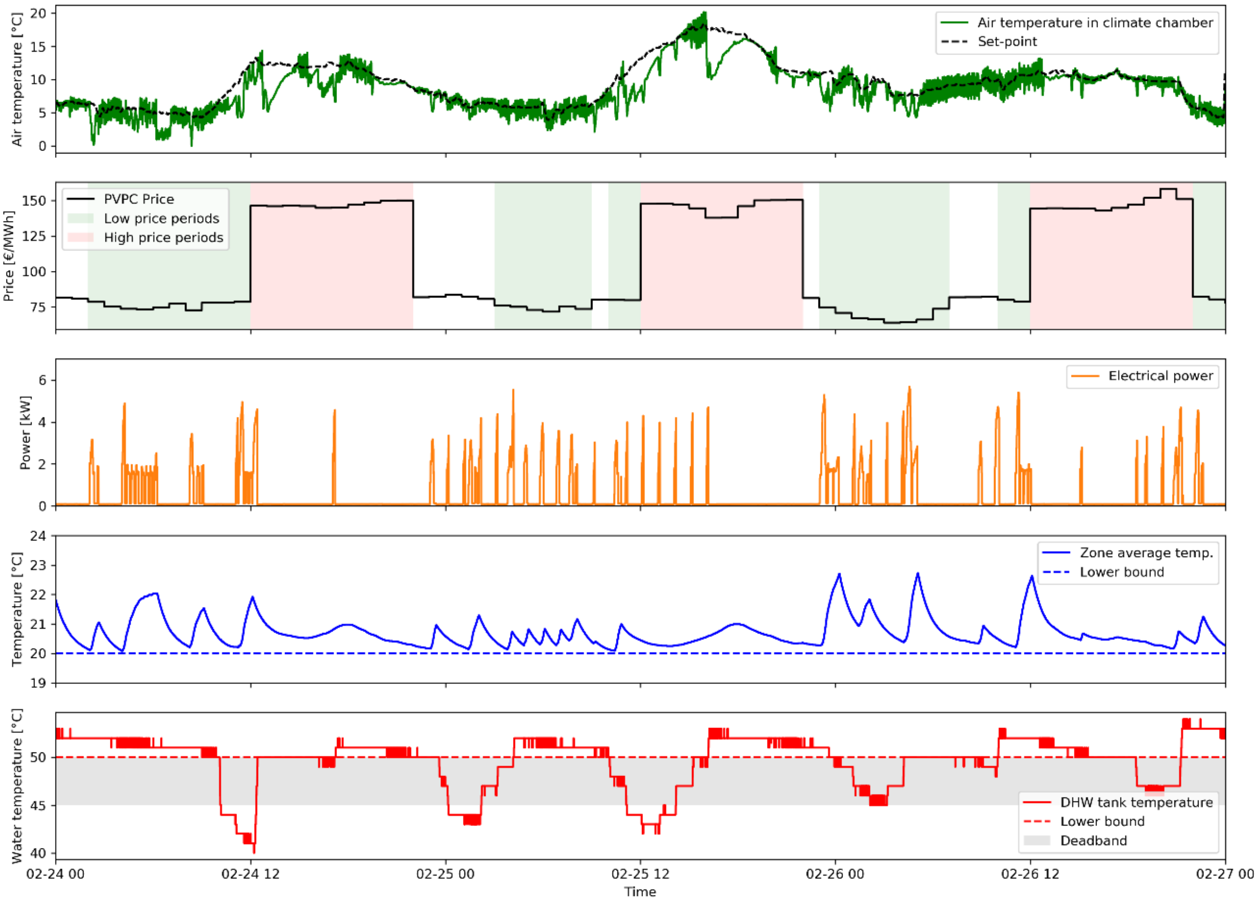


Figure 5.5. Time series of the 3-day experiment with MPC Cost in heating mode.

5.3.2. Example of testing characterization of buildings for energy flexibility

A study with a simple control for obtaining energy flexibility with the purpose of supporting grid operation has been conducted both in the OPSYS test rig and with the OPSYS simulation tool. The aim of the study was to determine if the OPSYS test rig and the developed simulation tool are suitable for research and development in the field of advanced controllers for obtaining energy flexibility from the combined system of a heat pump and a heat emitting system. The results of the simulations and the test in the OPSYS test rig have been documented in (Jensen et al., 2018). Only a brief summary of the results is given in this section.

The focus of the study was a Danish single-family house from the 1970's with a set point indoor temperature of 22°C during the day and a night setback at 19°C as shown in figure 5.6 (blue line). The aim of the tests was to study the obtainable energy flexibility if the set point for the room air temperature was decreased at the beginning of the cooking peak (red line after 17:00). The "cooking peak" (green box) is when people return home from work and start cooking and use other electrical appliances. This is the highest peak in the Danish power grid. To increase the obtainable energy flexibility, excess heating of the house before the cooking peak was also carried out by increasing the room set point temperature (red line before 17:00). Different scenarios were investigated with the OPSYS simulation tool, where different decreases and increases of the set point (1 K and 2 K) were investigated together with a variation of the length of the increase of the set point (one or two hours) before the cooking peak.

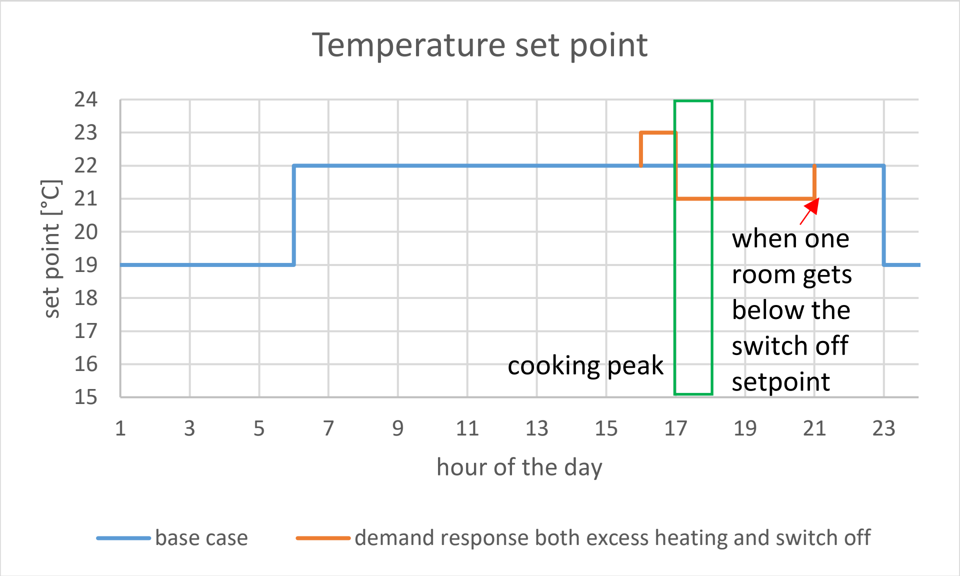


Figure 5.6 Variation of the room set point temperature during the study.

The main analysis was carried out with the fast OPSYS simulation tool as the OPSYS test rig runs at real time, which makes it less suitable for carrying out large series of parametric studies. One specific scenario was also carried out in the OPSYS test rig: the increase of the set point by 1 K one hour before the start of the cooking peak and a decrease by 1 K (2 K compared to the increased set point) at the start of the cooking peak. This scenario is illustrated by the red line in Figure 5.6. A comparison between the simulation and the measurements showed remarkably good compliance, as seen in Figure 5.7 comparing the room temperatures and the duration of the possible setback for one day. The test rig and the simulation tool give almost identical results and equal duration of the possible set back from the start of the cooking peak (black curve in Figure 5.7).

The simulation tool includes a rather simple model of a heat pump in order to make the simulations fast. The hydronic system of the simulation tool is also fairly simple. In comparison the test rig includes a real heat pump and a real hydronic system with all the complexity this involves. In spite of this, the two tools give rather identical room air temperatures and similar integrated power demands of the heat pumps, although the actual patterns of the power uptake of the heat pumps are somewhat different due to the simple model of the heat pump in the simulation tool. The set point responds as desired: it increases and decreases when asked to. More importantly, it is able to respond to the actual state of the house, i.e. return the set point back to the base case when, in this case, one of the rooms needs heating. Based on this it is assessed that the OPSYS tools will be valuable when developing more advanced controls for obtaining energy flexibility. Especially, where the control setup is developed using the simulation tool while the chosen concept is tested as hardware-in-the-loop in the test rig in order to determine if the developed control strategies will perform as expected in a more realistic environment.

Results for several combinations of set point increase before the cooking peak, time of the start of the increase of the set point, and decrease of the set point at the start of the cooking peak can be found in (Jensen, 2018).

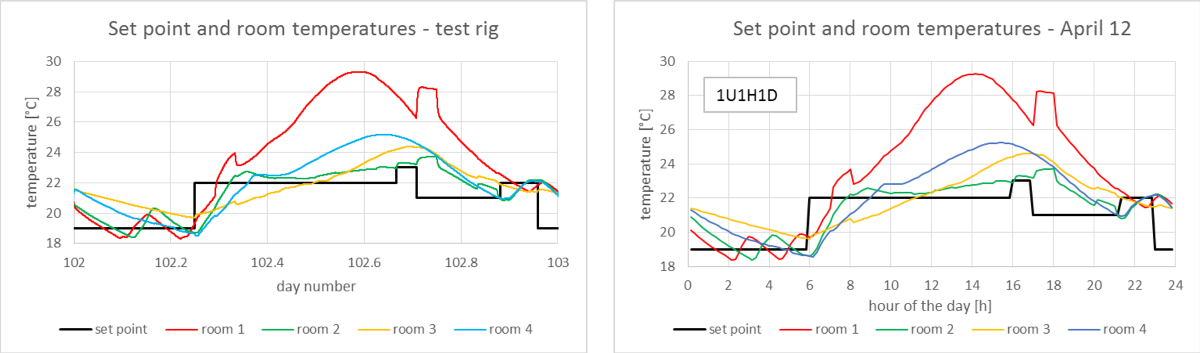


Figure 5.7 Room temperatures and set point from the test rig (left) and simulation tool (right). The more squared appearance of the set point curve from the test rig is due to measurements taken every 15 seconds while the time step of the simulation was 10 minutes.

5.4. Recommendations for experimental tests of energy flexibility

The take-home lessons derived are specific for each test and test facility, but quite a few common points exist as the test facilities have a common approach and the performed tests have strong similarities. A collaborative work among the researchers and the operators in charge of all the test facilities has lead to extract a set of practical reccommendations when planning or executing experiments with the objective to test energy flexibility in buildings. In addition, some more general aspects related to the planning and maintenance of the test facilities are also reported below.

5.4.1. Best practices for experiments

Experiments for testing energy flexibility are complex experiments that require close and dynamic interaction between the "real" hardware elements and the simulation of "virtual" elements. The lab setup not only involves the interaction of several hardware elements with the data acquisition, control and data storage systems (e.g. LabVIEW), but also the data exchange and communication between different simulation environments (e.g. IDA-ICE, Modelica or TRNSYS), hardware/data acquisition and even control systems running on different platforms (e.g. embedded PLC or Matlab). Energy flexibility tests based on semi-virtual test rigs thus present an additional complexity in terms of the general software tools capable of handling not only all the hydronic and electrical systems, but also the different and specific software environments necessary to control the different elements of the test rig.

Planning and preparing the experiment

- Plan the length of the experiment carefully. The minimum duration is imposed by the time constant of the tested systems, and in the reported tests it amounted to a few days (3 - 4 days) including a pre-conditioning period to place the system in the desired initial condition, especially when storage elements or high inertia systems are included in the test. Testing MPCs can require a longer test period depending on the prediction horizon. It is not recommended to extend the test duration much beyond the required length according to the objectives, thermal mass, and control horizon, in order to limit the time effort and reduce the likelihood of unwanted disturbances (hardware or software problems, loss of communication between elements, etc.). Several problems can appear during the experiments due the complexity of hardware and software pieces and their intercommunication. Plan the tests as short as possible, while focusing on the scope and expected results, without jeopardizing its usefulness and objective.

- Evaluate whether or not experiments should be compared with a reference case. If yes, an experiment will often consist of at least two tests: one reference case and the case when energy flexibility is activated.
- The real and virtual components of the system should be chosen according to the goals of the test and kept the same for all tests composing an experiment. Modifying some aspects of the platforms during the course of a set of experiments can make it difficult, if not impossible, to compare them.
- It is recommended not only to develop the numerical model of the virtual part of the test bed, but also to complete it with a model of the real part of the system (even if this is simplified). This allows having a “digital twin” of the complete system, which is extremely useful to select representative test periods or to fine-tune important parameters of the experiment prior to the run of the tests. The model is also typically used to warm-up the simulation before the start of the actual testing period.
- Before starting a test period, all the components of the system should be examined and debugged to minimize the potential for issues occurring during the actual test. Partial short tests on each subsystem are recommended before the complete experimental run takes place.
- Measure all the important values with a sufficient time resolution and accuracy. This is important for both the evaluation of the results from the hardware in the loop test and for a thorough comparison between measured and simulated results. Define and set control probes, and also consider adding additional sensors and/or double measurement of critical variables as they will help you to check if the experiments are running as they should.
- Check the stability and accuracy of the boundary conditions for the emulated variables (temperatures, flows, etc.) and fine-tune the control elements in the facility (i.e., PID) for a specific experiment, if needed.
- To evaluate the advantage gained when using a MPC, the results can be compared with implementing other simpler controllers in the simulation (e.g. compare with a rule-based controller).

<u>During the experiment</u>

- It is important to monitor the tests very closely in order to quickly detect and correct any problems. This will prevent valuable time being lost due to an otherwise necessary restart of a test. Regular visits to the lab and/or remote monitoring during tests and preliminary analysis of the results (at least daily) are strongly recommended.
- Enable remote visualisation (and if possible, control) of the main variables of the experiment from your office desk. When possible establish surveillance values to watch and alarms (e.g. e-mail messages) to warn the operator/researcher in case of anomalies.
- Perform a comprehensive check of the experiment during the first hours and react accordingly. Malfunctions can usually be detected at the very early stages of the experimental run.
- If a pre-warming method/period has been established to bring the storage elements (batteries, thermal storage) to a certain level of charge, check carefully that the initial conditions are reached. The same recommendation applies to the virtual/simulated part of the system.

After the experiment

- Often the aim of the experiment will be to develop or refine a model of the system being tested so that other operating conditions can be assessed in simulations. In that case, the model should be carefully calibrated based on experimental results and its range of validity should be clearly assessed. This is not an easy task and it is advisable to plan enough time for that task after the tests are completed.
- Be sure to carefully record and document any permanent change done in the test rigs during the test and/or its preparation. Additionally, write down the lessons learned when it comes to running of a test, so they will stay in the memory of the research group.
- Store the collected data and metadata in a structured repository, so they can be used for further analysis. Consider storing the data in an open access repository to be shared with other researchers.

5.4.2. Best practices for test facilities

The test facilities presented here are among the first world-class facilities for allowing investigation of energy flexibility in buildings. They were designed as flexible facilities to test new components and their integration and management involving electrical and thermal systems. Eight of the nine test facilities presented here have the common feature that they can interact with at least a virtual building model and virtual weather conditions, greatly expanding their flexibility and the range of testing conditions they can provide. This potential comes with additional large complexity due to the hardware and software elements that need to be in place. Practical advices when designing or maintaining these kinds of test facilities are:

- Look for a trade-off between flexibility of the elements in the lab and increased complexity according to the overall goals of the facility.
- Always calibrate and verify sensors and the entire acquisition chain thoroughly. A practical but effective approach is to acquire multiple values for the same physical quantity, especially for the important measured values during a test.
- Consider characterizing the elements and systems first in steady-state or predefined conditions before launching flexibility experiments. This provides a greater insight into the behaviour of the elements/systems and increases their controllability.
- As complex software environment is a key part of this type of test facilities, maintenance (software updates, etc.) and documentation, especially targeting new researchers, should be prioritized. Do not minimize the effort devoted to these tasks.

6. From the perspective of the stakeholders

Zheng Ma, Erwin Mlecnik and James Parker

6.1. Introduction

Stakeholder acceptance and behaviour is crucial to the success of strategies for energy flexibility in buildings. Without careful design and implementation, introducing energy flexibility has the potential to disrupt occupant lifestyles, building systems for thermal comfort and health, as well as potentially increasing cost or energy consumption. Stakeholder acceptance and behaviour may also be a barrier, but this can be mitigated, or overcome, if the related stakeholders are informed about flexibility measures, support any measures that are introduced and are given benefits in the form of a lower energy bill for example. Stakeholder acceptance and behaviour is, therefore, an important source of knowledge for the Annex 67 project as some solutions, although technically sound, may not be feasible as the consequences for the involved stakeholders may not be acceptable to them.

There is a wide range of different stakeholders who may be affected by energy flexibility measures: end-users (occupants of buildings), building owners, facility managers, Energy Service Companies (ESCOs), developers, architects, contractors, and product/system suppliers. The energy flexibility is ultimately useful for aggregators, DSOs (District System Operators for both the power grid and district heating/cooling networks) and TSOs (Transmission System Operators). It is important to establish a comprehensive understanding of acceptance, behaviour, and motivation at different levels of involvement for the relevant stakeholders.

6.2. Stakeholders and their roles in the energy flexible buildings

In the following, nine types of stakeholders with six types of buildings are presented and discussed, including their roles, motivations, and potential barriers to energy flexible buildings. A summary of stakeholders' definitions, business function in buildings, and roles in energy flexible buildings is collected in Table 6.1, and their motivations and barriers are listed in Table 6.2.

Table 6.1 A summary of stakeholders' definitions, business function in buildings, and roles in energy flexible buildings.

<table>
<tr><th>Stakeholders</th><th>Definition/note</th><th>(Building) Business function</th><th>Roles in energy flexible buildings</th></tr>
<tr><td>Energy managers in Campus buildings</td><td rowspan="2">Responsible for supervising the buildings' security, maintenance and repair in accordance with environmental and safety standards.</td><td>Campus buildings provide offices, classrooms, and other space types for education and research purposes.</td><td rowspan="2">The role of an Energy Manager (EM) involves facilitating energy conservation by identifying and implementing various options for saving energy, leading awareness programs, and monitoring energy consumption.</td></tr>
<tr><td>Energy managers in Retail buildings</td><td>Commercial supermarket type buildings selling a variety of products, which are owned or operated by the retailers.</td></tr>
</table>

Stakeholders	Definition/note	(Building) Business function	Roles in energy flexible buildings
Asset managers	Real estate asset managers are responsible for the strategic management of entrusted buildings and surroundings from the viewpoint of the total life cycle and value chain.	Asset is evaluated as buildings in operation within neighbourhoods and energy networks.	Asset managers are close to (specific types of) users, they can also influence strategy decisions and property developments and they can balance out the expectations and interests of investors and users within legal and marketing frameworks.
Households	A household consists of one or more people who live in the same dwelling	Residential buildings, e.g. single/multi-family home, condominium and, townhouse	End-users of energy in residential buildings.
Occupants in Office buildings	Employees, managers, interns, students, spend significant time seated at workspaces and at meeting rooms.	The main purpose of an office building is to provide a workplace and working environment primarily for administrative and managerial workers.	Consume energy for work related activities.
Occupants in Campus buildings	There are three types of occupants in the campus buildings: academics, students, and administration.	Occupants perform work and study activities in campus buildings.	Student occupants are the energy end-users, and they can provide feedback regarding the energy performance in campus buildings.
Electricity supplier	Electric utilities, system operators and local investors.	Invest in and operate the infrastructure for electricity generation and transmission.	Considers the interest of their stakeholders, the expected return of their investments and the balance of the grid.
District heating supplier	District heating suppliers are companies that mainly generate and distribute heat at the municipal level with often mixed cooperative, private and municipal ownership.	Suppliers interconnect single buildings by their energy networks, often forcing renewable energy. Invest in and operate the infrastructure for district heating generation and transmission.	District heating suppliers supply heat to the end users. They are an important player fin energy system development. They consider their customers' interest and are often committed (obligated) to ensure high security of supply and reduce the environmental impact of the production.
Industrial consumers	Companies and activities involved in the process of producing goods for sale, especially in a factory or special area.	A building or structure in use, e.g. for the purposes of a trade carried on in a factory or other similar premises.	The single largest electricity consumer. Industrial consumers have heavy energy use and have already begun to implement smart grid technologies for production purposes.
Aggregators	The act of grouping distinct agents in a power system (i.e. consumers, producers, prosumers, or any mix thereof) to act as a single entity when engaging in the power system markets (both wholesale and retail) or selling services to the system operator(s)	All buildings.	The role of an Aggregator involves pooling energy units, switch energy consumption due to market condition, and control of each unit due to individual settings and optimization of the end-users' energy usages.

Stakeholders	Definition/note	(Building) Business function	Roles in energy flexible buildings
Building automation providers	Providing building automation technology (sensors, actuators, software, and communication infrastructure).	All buildings	Increases the potential for energy efficient/flexible operation of buildings.
Energy consulting	A sub-discipline of environmental consulting that focuses on optimizing a business' energy usage, as well as the sources from which the actual energy is derived.	All buildings.	Consultancy services, including energy analytics and conducting innovative projects with illumination and documentation.
Energy analytics	Interdisciplinary stakeholder focusing on designing and optimizing energy market and helping customers to understand and reduce energy consumption.	All buildings.	Investigate and analyse the market condition. Set up interdisciplinary scenarios of the energy sector to find the most efficient solution.
The National Regulatory Authority	Stakeholder that make sure that the energy market is competitive and that the customers are treated fairly.	All buildings.	Responsible for creating a fair market for all stakeholders. They aim to make the market transparent for the customers and ensure that the methods which are used for the settlement of energy prices are consistent with the laws in force.

Table 6.2 A summary of stakeholders' motivations and barriers for energy flexible buildings.

Stakeholders	The motivation for energy flexible buildings	Barriers to energy flexible buildings
Energy managers in Campus buildings	Building automation and distributed energy resources create possibilities for buildings to provide energy flexibility to the grid.	Energy efficiency to be more important than providing flexibility to the grid; Many buildings are too old and need to be refurbished; The benefit of providing energy flexibility to the grid is not sufficient; Building management systems need to be either installed or upgraded to response to the demand from the grid.
Energy managers in Retail buildings	Ready to adopt the implicit demand response by manual energy control compared to the utility control or building automation: • The company goal influences the willingness of DR participation. • Related knowledge of energy flexibility influences the willingness of DR participation.	Significant concerns about: • Dynamic control can negatively influence the business operation • Dynamic control can negatively influence customer satisfaction (e.g. comfort) • Need to install new equipment or system • The company is Lacking knowledge • The ROI (Return on Investment) of installing the automatic control system
Asset managers	Integrating opportunities for efficient use of renewable energy and heat sources and for reducing CO_2 emissions and primary energy use.	Detailed planning of technical changes in buildings and grids and data management strategies are needed, as well as development within changing policy frameworks within cost efficiency boundaries. Special attention is needed for creating social engagement in neighbourhoods and co-creation for innovation.

Stakeholders	The motivation for energy flexible buildings	Barriers to energy flexible buildings
Households	The top three motivating factors for users adopting smart technologies were found to be: reduced the energy bill (strongly motivating), financial rewards from the energy supplier (motivating), and seeing the effects of energy use actions (motivating).	More than 60 % of the respondents were unaware of smart grids. Multiple control options should be included in the development of smart technologies to achieve high user acceptance and therefore realize the energy flexibility of home appliances.
Occupants in Office buildings	Economic savings, reduction in electricity consumptions and contribution in sustainability are most motivating factors to accept energy flexible usage in office buildings.	Concerns about smart control related to the possible risk of interference with work activities and with the privacy in office buildings.
Occupants in Campus buildings	'University plans to become a green intelligent university', 'University tries to reduce the energy consumption', 'University tries to reduce the energy bill, and will put the saved bill into campus facility improvement' can motivate students to accept the frequent indoor quality changes.	Student occupants believe the frequent changes in indoor comfort in classrooms can influence teaching and learning performance.
Electricity supplier	Reduce their need for new investments in the grid by load levelling and load shifting. Better control, better utilization of renewable energy and increased reliability of the grid.	Users lack knowledge and willingness to let their appliances and heating/cooling be shifted in smart grids. There is a need for political incentives. The initial investment in smart meters and smart appliances will take time.
District heating supplier	Integrating the load management and opportunities for the use of renewable energy like biomass and solar thermal energy. So reducing CO_2 emissions and exploiting local energy sources. Optimize production and distribution of district heating, while mitigating the need to invest in untimely network upgrades.	Uncertainties related to technological costs, lack of knowledge, incentives, and regulation framework currently hinders the use of energy flexibility of buildings in district heating grids, more than concerns on data privacy or security issues. Demand response is still considered an unproven method. The relatively high complexity combined with the uncertain estimates of impact is a significant barrier. Furthermore, it is not clear how appropriate incentive mechanisms can be established.
Aggregators	The increase of fluctuating renewable energy resources creates the need to balance the system with DR. This creates the business opportunity for a new market player, the aggregator to provide customers with a new service and controlling their devices.	Fixed energy prices or prices with a very small variation which do not create an incentive for end-users to change their consumption habits. The market structure needs to be redesigned for aggregators to take part. New technology like blockchain is a competitor to the aggregator.
Building automation providers	Additional functionality of their current product portfolio. Possibility for new markets, especially home automation.	No demand for energy flexibility functionality from society/consumers.
Energy consulting	Smart meters with two-way communication and half-hourly electricity pricing must be implemented to create an incitement for energy flexible buildings. Communication between energy suppliers and consumers is important.	The complexity of the energy system regulation makes the energy system very difficult to be more flexible. The requirement for providing energy flexibility to the grid is high and complicated. Tariffs and taxes associated with power production are a large barrier to energy flexibility. Unclear schemes for buildings to provide energy flexibility: either everyday flexibility or emergency.

Stakeholders	The motivation for energy flexible buildings	Barriers to energy flexible buildings
Energy analytics	More renewable energy in the system creates new opportunities for energy flexibility in buildings together with a rethink of the current energy system with a fixed tariff model and one-way communication.	Energy flexibilities access to the market. Regulation makes the system very complex, and service providers of energy flexibility need to be aware of all these regulation before entering the market. The incentive for providing energy flexibility in the building is low due to the relatively low savings it includes. The energy price is regulated by tariffs and taxes with needs to vary to reflect the market and grid situation. In reality, energy flexibility in buildings depends on a lot of stakeholders and other factors that need to be coordinated before it is a can be implemented in the market structure.
The National Regulatory Authority	Wants to create a fair and equal market for all stakeholders, which allows for more competition.	It is difficult for new stakeholders to enter the market, because stakeholders need to fulfil a lot of requirements.
Industrial consumers	Governmental incentives making energy flexibility more attractive; Some industrial consumers have installed distributed energy resources, it provides the opportunity of monetary gain for industrial consumers to participate in DR; Some industrial processes have the potential to provide energy flexibility, e.g. cooling; The desire to brand the company as "green". It impacts the inscription stage but interconnects customer focus.	A high priority of service quality and process improvement; The concern of return on investment; Not familiar with DR solutions, and concern about the ease of use of the DR solutions; Do not actively seek involvement in DR activities.

6.3. Case studies

To understand stakeholders' acceptance, behaviour, and motivation at different levels of involvement in energy flexible buildings, various methodologies, including questionnaires and interviews, have been carried out. These are all listed in Table 6.3. Summary of each case study including purpose, targeted aspects and results is listed in Table 6.4-6.10. For further information please refer to the Annex 67 report "Stakeholders' perspective on energy flexible Buildings" (Ma et al., 2019).

Table 6.3 Methodologies and stakeholders in studies cases.

Methodology	Types of stakeholders	Types of Buildings	Targeted countries
Case studies with interviews	Building managers	Campus buildings	Denmark
Questionnaire	Store managers	Retail buildings	Denmark and the Philippines
Questionnaire	Occupants	Campus buildings	Denmark
Interviews	Occupants	Campus buildings	Denmark

Methodology	Types of stakeholders	Types of Buildings	Targeted countries
Questionnaire	Occupants	Office buildings	Italy
Questionnaire	Households	Residential buildings	Netherland
Case study	Electricity supplier	Residential buildings	Denmark
Questionnaire	District heating supplier	N/A	Austria
Case studies with interviews	District heating supplier	N/A	Denmark
Interviews	Aggregators	N/A	Denmark
Experimental study	Building technology providers	Residential and commercial buildings	Denmark
Interviews	Energy consulting	N/A	Denmark and Austria
Interviews	The National Regulatory Authority	N/A	Denmark
Case studies with interviews	Industrial consumers	Industrial buildings	Denmark

Table 6.4 Summary of case studies regarding building managers.

Purpose	Targeted aspect	Result highlight
Building managers' activities and opinions	Building management system Energy consumption Energy purchasing strategy	• Building managers believe that buildings can provide energy flexibility by building automation and distributed energy resources; • Building managers consider energy efficiency to be more important than providing flexibility to the grid. • The main barriers for buildings to provide energy flexibility are 1) many buildings are too old and need to be refurbished, 2) the benefit of providing energy flexibility to the grid is not sufficient, 3) building management systems need to be either installed or upgraded to response to the demand from the grid.
	Energy control Energy technology adoption Employees' participation in an energy program Customers' concern	• Retail stores are much readier to participate in the implicit demand response by manual energy control compared to the utility control or building automation. Meanwhile, store managers have significant concerns about business activities and indoor lighting compared to other aspects • The statistically significant influential factors for retail stores to participate in the demand response are related to whether the DR participation matches the company goal, influences business operation, and whether the managers of retail stores lack the related knowledge • Managers of retail stores believe that stakeholders should be informed about the DR activities but not involved in these activities • There are significant differences regarding the energy control preferences and concerns between retail stores in Denmark and the Philippines, but no significant difference regarding the stakeholder engagement

Table 6.5 Summary of case studies regarding occupants.

Purpose:	Targeted aspect	Result highlight
Occupants' motivation and opinions	Occupants' awareness Occupants' satisfaction with the energy performance in buildings Occupants' acceptance of energy flexible buildings	• Occupants are satisfied with the indoor comfort • Occupants cannot tolerate frequent changes of indoor comfort • Occupants think that only the indoor comfort of hallway and canteen can be adjusted frequently • Occupants believe that the investment in solar panels and energy storages are feasible, but not combined heat and power. • Occupants believe that university plans for green image and energy saving can improve occupants' acceptance of frequent changes of indoor comfort
Energy Flexible office end-users, motivating factors	Perception of renewable energy usage Perception and attitude towards smart grid, smart appliances, and smart meters Willingness to use smart appliances in offices Motivation to accept a flexible energy usage	• The use of renewable energy instead of fossil fuels to fuel HVAC systems in office buildings is recognized as a very important action; • The smart grid concept is unfamiliar to almost half of the respondents; • The most suitable smart appliances accepted to be remotely controlled are the air conditioning and the heating system; • The possibility to override the control, not compromising the privacy and environmental advantages are the main motivating conditions for accepting the remote/follow the manual control of smart appliances; • The main motivating factors to accept a flexible energy usage are the possibility to see how much the electricity usage is minimized and the amount of saved money; • The most effective information to be displayed on a monitor is the amount of saved energy; • Half of the respondents think that smart grids will have a neutral influence on their work.
Residents ' perceptions	The willingness of occupants to use smart technologies and change their energy use behaviour How well building users are prepared to contribute to the energy flexibility of their buildings Building user perceptions of smart grids and their readiness to adopt smart technologies	• Awareness of smart grids is the highest among respondents aged 20–29 years • Willingness to use smart technologies and change energy behaviour are interdependent • 11 % of the respondents were found to be potential users of flexible building

Table 6.6 Summary of case studies regarding energy suppliers.

Purpose:	Targeted aspect	Result highlights
District heating suppliers	Challenges in district heating operation Opportunities for DR initiatives	• District heating suppliers consider flexible consumers a potentially valuable asset – but only if DR participation can be ensured through contractual means. • Energy flexible buildings compete with the less complex solution of centralized storage tanks. • There is currently no straightforward way of determining the economic incentive that could be provided to consumers. • There is a large potential for reducing the required heat generation capacity of the network by reducing the level of consumption during a relatively low number of hours: Removing 50 hours per year with the highest consumption reduces the required capacity by 14-17 %. • Reducing necessary pipe dimensions or supply temperature in order to reduce heat losses in the distribution network also hold significant potential.

Purpose:	Targeted aspect	Result highlights
District heating suppliers' activities and opinions	Smart operation of district heating grids Economic perspectives/ business and tariff models Drivers and barriers of using energy flexibility	• The relevance of smart district heating technologies and know-how is higher than expected • District heating suppliers believe that energy flexible buildings are important and allow for shifting heating peaks or for decentralized storage of heat from the grid, and for the control optimization for using the flexibility • There seems to be a relevant market for intelligent district heating concepts • Renewable energy use for district heating grids is of high importance • Cost, incentive and regulation related drivers and barriers are more important than data privacy or comfort issues

Table 6.7 Summary of case studies regarding aggregators.

Purpose:	Targeted aspect	Result highlight
Aggregators' activitie0s and opinions	Aggregator models Business opportunities	• Market stakeholders as TSOs (Transmission System Operators) and BRPs (Balance Responsible Parties) believe that aggregators will play a major role in the utilization of building flexibility and DR • The role of aggregators can be undertaken by suppliers, BRP's and third party. • The aggregation potential can be in industry, buildings, and smaller units with a battery or storage facility as electric vehicles and heat pumps. • The main influential factors for aggregators to enter the building flexibility are 1) a clear definition and standardization of the aggregators' role in the market structure, 2) the technological development of DR equipment, 3) energy price reflects the market price and distribution conditions.

Table 6.8 Summary of case studies regarding technology providers.

Purpose:	Targeted aspect	Result highlight
Technology providers: objectives and challenges	A prototype implementation of MPC (Model Predictive Control) schemes that enable flexible consumption	• The results indicate that technology providers already have the hardware needed for MPC. • More efforts should be put into the development of robust and reliable MPC algorithms. • Cost-efficient building automation hardware for non-commercial buildings (homes) should be developed.

Table 6.9 Summary of case studies regarding energy consultancy and analytics, and national regulatory authorities.

Purpose	Targeted aspect	Result highlight
Energy consultancy' opinions	Regulation and policies Tariffs and taxes Market condition and microgrids Stakeholders' collaboration	• The complexity of the energy system regulation makes the energy system very difficult to be more flexible. • The requirement for providing energy flexibility to the grid is high and complicated. • One large barrier to energy flexibility is the tariffs and taxes associated with power production. • Smart meters with two-way communication and hourly electricity pricing must be implemented to create an incitement for energy flexible buildings. • Unclear schemes for buildings to provide energy flexibility: either everyday flexibility or emergency. • Communication between energy suppliers and consumers is important.
Roles of energy analytics'	Regulation and policies Tariffs and taxes Market conditions and aggregators Stakeholders' collaboration	• The implementation of flex settlement need to be a reality for all, also consumers with a supply unit like photovoltaics (PV), to promote energy flexibility in buildings. • The access to data from the consumers is complicated. • Greater fluctuation of the electricity spot price will create an incentive to move consumption and save money. • The electricity price should reflect the grid and market condition instead of a price with fixed tariffs and taxes. • Collaboration between market stakeholders and consumers are important to success with the interdisciplinary implementation of energy flexibility in buildings.
The National Regulatory Authority	Opportunities Tariffs Market condition The potential for energy flexibility	• Consider the energy sources used in the grid to analyze the potential and need for energy flexibility. • Even when it is possible to control the energy sources and the need for energy flexibility are small, it still will create more competition in the market – which are good. • Blockchain can be used for energy flexibility instead of aggregators. • The rollout of smart meters makes real-time pricing possible. • Different tariffs due to the time of use create prices reflecting the grid condition and create an incentive to move consumption. • Easy access for smaller loads to be used as ancillary services is necessary. • Private customers need a service provider to control and perform energy flexibility for them. It needs to be easy.

Table 6.10 Summary of case studies regarding industrial consumers.

Purpose	Targeted aspect	Result highlight
Building-to-Grid participation	Regulation and policies Market conditions Energy prices Smart grid solutions	• Self-production of heat and some electricity, making them sensitive to changing electricity prices if flexibility cannot be achieved. • Not familiar to smart grid solutions, but positive towards net-based services if profit is maintained.
Acceptance of smart solutions	Energy transformation Shared support interaction Energy flexibility Smart grid solutions	• Electricity prices may vary in the future, making it crucial to have access to Nord Pool spot prices. • Heat from the cooling process is utilized to cover own heat consumption. • Do not proactively seek involvement in smart grid activities. • The desire to brand the company as "green". It impacts the inscription stage but interconnects customer focus.

6.4. Recommendations

If a market for energy flexibility is going to be developed, it is obvious that emerging business models need to incorporate demand side management (DSM) activities. DSM activities are typically classified into “Energy Efficiency (EE)” and “Demand Response (DR)” and DSM business models usually relate to segments of a typical electricity market: system operation, generation, transmission/distribution, energy retailing and load (Behrangrad, 2015). However, when considering the market development of energy flexible buildings, it becomes apparent that the heat market (district heating) and the engagement of the building stakeholders and end users also will play an important role.

Buildings can have an important role in energy flexibility due to their potential flexible energy consumption and distributed energy resources (Ma et al., 2016). Different types of building (residential, commercial, and industrial) can provide different energy flexibility, not only due to their energy profiles and DR opportunities, but also according to their potential for adopting energy and monitoring technology or HVAC (Heating, ventilation, and air conditioning) service solutions. The latter can be highly influenced by building and asset management strategies, for example timelines foreseen for maintenance or renovation of buildings. In this respect, there currently seems more potential for commercial and industrial buildings with higher energy consumption than for residential buildings with lower energy consumption.

The flexibility resources and potentials are different for different types of buildings. Building asset managers have different needs and behaviours compared to building owners, end users, electricity and heat providing stakeholders. Thus, it is essential to understand stakeholders’ needs and behaviour, not only regarding comfort and energy requirements, but also regarding their possible position within business models, in order to be able to develop feasible market access strategies for different types of actors. Meanwhile, incentive programs, national regulations, local policies, and energy and construction market characteristics are important to the stakeholders’ activation for continuing the development of business ideas.

General and specific laws and rules, specific exemptions, covenants and agreements can be deployed to engage building stakeholders to comply with energy stakeholders’ demands, or vice versa. These could, for example, include energy balancing targets, minimum renewable energy share standards, and requirements for energy efficiency or the promotion of technical solutions such as building energy management systems. Economic instruments can also be deployed, to help motivate stakeholders into action: grants, subsidies, beneficial loans, revolving funds and tax incentives for investments are all possible policy instruments that lead to an improvement in the adoption of energy flexible buildings. Also disincentives might be applied like tariff structures, where higher consumption of energy leads to higher tariffs, a mortgage system or real estate tax system.

In addition, the involvement of governments and regulators in aggregation can provide incentives and increase DR awareness and participation. However, the aggregation market is in many counties still immature, and the regulations and policies of aggregation markets vary across countries. For instance, in Europe, the countries Belgium, France, Ireland, and the UK have created a regulative framework to enable both DR and independent aggregators, whereas other European countries have not yet engaged with DR reforms, e.g. Portugal and Spain.

Furthermore, the European Commission recently proposed new Directives covering measures relating to energy efficiency, renewables, and also changes to reorganize the electricity market and tackle energy poverty (European Commission, 2018). It is expected that the upcoming Directives will support the implementation of energy flexibility. For example, the implementation of the revised European Performance of Buildings Directive already introduced the needed deployment of “smart grid ready" buildings in the Member states (Janhunen et al., 2019). Therefore, the business models exploiting aggregation potentials for buildings need to be based on emerging international policies, national regulations and visions regarding energy market restructuring.

The roles, motivations, and barriers for different stakeholders in energy flexible buildings have been discussed in the above sixteen cases. Based on the sixteen cases, the opportunities and barriers for energy flexible buildings can be divided into five dimensions as shown in Table 6.11.

By systematically studying the motivations and barriers discussed in the previous chapters and sections, suggestions for how to strengthen the motivations and how to eliminate or reduce the barriers have been developed. The recommendations for related stakeholders are presented in Table 6.12.

Table 6.12 shows that, although 'consumer driven/centred' approaches have been emphasized in recent years, policy makers are still the lead stakeholders for strengthening opportunities and eliminating barriers in the energy system. To establish and realize the markets for energy flexible buildings, decentralization of the power hierarchy is necessary, especially for international collaboration and trading.

Table 6.11 Business opportunities and barriers for energy flexible buildings.

Dimensions	Opportunities	Barriers
Climate and environment	• The use of renewable energy resources in the electricity grid is already high in some countries and will increase in others. • Reduction of CO_2 emissions and exploitation of local energy sources by using renewable energy like biomass and solar thermal energy will be gradually strengthened	• The use of renewable energy resources in buildings is challenged by building characteristics. The use of renewable energy resources in district heating systems is currently low and requires a shift to next generation heating grids • The CO_2 reduction and local energy use strategies are not necessarily deployed in buildings
Societal culture	• Environmental awareness of climate change and access to low-carbon solutions is increasing • Many consumers are ready to adopt the implicit demand response • Green image encourages companies' DR participation • The increase of fluctuating renewable energy resources in the energy system creates the need to balance the system with DR • Renewable energy communities are rapidly emerging • Innovators and intermediaries provide opportunities to shift the market to the development of strategic niches	• Majority of stakeholders are unaware of energy flexibility • Constraints of indoor comfort and working performance • Constraints of daily business and energy usage pattern • Users lack knowledge regarding DR solutions and willingness to DR participation • Concerns regarding the ease of use of the DR solutions • City densification and network expansions in district heating • Many buildings are too old and need to be refurbished; different buildings have different maintenance and renovation needs • Lack of social engagement in neighborhoods and co-creation for innovation • Lack of communication and collaboration among related stakeholders • Only a few demonstrations show viable market perspectives • Building stakeholders can perceive their relative advantage lower compared to energy stakeholders
Technology	• Building automation and distributed energy resources create possibilities for buildings to provide energy flexibility to the grid • Windows of opportunity for realising energy flexible buildings appear when district heating networks are revised or buildings are renovated • Technologies provide better control and better utilization of renewable energy • DR increases the reliability of the grid • Integration of load management provides opportunities for the use of renewable energy •	• Building management systems need to be either installed or upgraded to respond to the demand from the grid • The revision of district heating systems and the provision of thermal retrofit requires a high investment • High complexity of orchestrating demand response in district heating; changes are also needed within buildings • Needs for detailed planning of technical changes in buildings, grids and data management strategies • Multiple control options should be included in the development of smart technologies to achieve high user acceptance •

Dimensions	Opportunities	Barriers
	• Optimization technology for production and distribution of district heating • Some industrial processes, larger non-residential buildings and districts show good potential to provide energy flexibility	• The relatively high complexity combined with the uncertain estimates of the impact • Concerns on data privacy or security issues
Economy and finance	• Reduction of the energy bill • Financial rewards from the energy supplier • Reduce the need for new investments in the grid by load leveling and load shifting • Create business opportunities for new market players (e.g. aggregators) • Governmental incentives • Possible monetary gain for industrial consumers that have installed distributed energy resources • Price for delivered heat at a defined temperature is high. That give opportunities to converting excess low-price electricity into high-temperature stored heat • Reduce cost by reducing the supply temperature in the district heating grid	• Limited monetary benefits for both electricity and heating DR • Slow Return on investment (ROI) (e.g. smart meters and smart appliances) • Insufficient investment support • Expenses associated with establishing or modifying district heating networks are extremely high • The insufficient benefit of providing energy flexibility to the grid • Uncertainties related to technological costs • Unclear incentive mechanisms
Policies and regulations	• National/regional climate and energy goals • Installation of smart meters and hourly electricity pricing are ready in some countries and progressing in other countries • There are DR markets in some countries	• Needs for market structure redesign for DR opportunities • Lack of policy incentives and instruments • The complexity of energy system regulation hinders the use of energy flexibility of buildings • Fixed energy prices or prices with a very small variation do not create an incentive to change energy usage habits • The requirement for providing energy flexibility to the grid is high and complicated. • Tariffs and taxes associated with power production is a large barrier to energy flexibility • Unclear schemes for buildings to provide energy flexibility: either everyday or emergency flexibility and either as short or permanent terms • Energy flexibility is not a stakeholder's sustainability goal and energy efficiency is more important than providing flexibility to the grid

Table 6.12 Recommendation for stakeholders of energy flexible buildings.

Lead stakeholders	Related stakeholders	Strengthen opportunities	Eliminate barriers	Dimensions
Policy makers	• All stakeholders	• Implement policies regarding energy transition	• Encourage more renewable energy resources, CO_2 reduction and energy efficiency in an integrated energy and building value chain	Climate and environment
Policy makers	• Consumers • Solution providers (technology and consulting providers) • Energy suppliers	• Strengthen regulatory and economic policy instruments; learn from frontrunners • Deploy organisational and communication policy instruments to create energy use awareness and easy access to low-carbon solutions • Strengthen the use of voluntary or mandatory certificates for energy-efficient solutions, nearly-zero energy buildings and 'smart grid ready' buildings	• Regularly evaluate policy instruments regarding: • Analysis and service (including training) regarding consumer energy behaviours • (Software support for) forecast and analysis. • Engagement and collaboration among stakeholders • Efficient and easy solutions	Societal culture
Solution providers (technology and consulting providers)	• Policy makers • Consumers • Energy suppliers	• Develop DR strategies and packages of the control system and DER equipment • Deploy and evaluate easy and user-friendly control systems	• Develop and implement DR solutions; assess feasibility to integrate in electricity services • Propose integrated solutions for specific types of stakeholders • Manage cost for system updating and building renovation • Optimize for multi-inputs, controls, and uncertainties • Develop and communicate solutions and strategies for data use taking into account privacy and security	Technology
Policy makers	• Solution providers (technology and consulting providers) • Financial parties	• Identify specific financial incentives (sticks and carrots) • Provide an easy solution for upfront investment (for example loan or mortgage)	• Develop clear monetary benefits and incentives • Encourage incentives from regulators, TSOs/ DSOs • Strengthen ROI perspectives, for example by communicating a clear time path for deployment of energy flexibility	Economy and finance

Lead stake-holders	Related stake-holders	Strengthen opportunities	Eliminate barriers	Dimensions
		• Lower cost of solutions and equipment, for example by standardising and determining larger quantities for application	• Financially support the (collaboration for developing) equipment control system (e.g. loans, renting, innovation funding) during an innovation phase	
Policy makers	• Aggregators • Consumers	• Detail clear climate and energy initiatives and policies into SMART action plans • Implement flexible energy price schemes	• Facilitate market structure change to support active energy consumers and renewable energy communities; communicate clearly for stakeholders to participate in the DR market • Lower requirements and thresholds to allow smaller consumers to participate in the DR market • Restructure tariffs and taxes to increase the financial benefits of DR participation • Support introducing energy flexibility in aggregator goals and building regulations • Support policies for deployment of smart metering, not only in electricity grids, but also in district heating	Policies and regulations

7. Examples of the energy flexibility buildings may deliver

James Parker, Søren Østergaard Jensen, Hicham Johra, Hussain Kazmi, Laura Aelenei, Daniel Aelenei, Lilli Frison, Konstantin Klein and Peter Engelmann

7.1. Introduction

Although the concept of energy flexibility of buildings is relatively simple to understand, its application in reality can be complex and difficult to explain in simple terms. This complexity is not helped by the myriad of ways in which energy flexibility can be achieved or the wide range of stakeholders involved; especially when many stakeholders have very little understanding, or technical interest, in the supply and demand of energy in buildings. In addition to this, there is no common framework on how to evaluate and assess the energy flexibility of buildings.

Given the emerging nature of this subject and the breadth of its potential applications and actors, it is useful to describe practical examples of how energy flexibility in buildings can be achieved, evaluated and measured. Therefore, this chapter provides a sample of the more comprehensive Annex 67 report "Examples of Energy Flexibility in Buildings" (Jensen et al., 2019) in which 33 examples of energy flexible buildings are described in detail. This chapter is intended to cover the key themes of these examples to aid understanding of this subject and to build upon the theoretical concepts and exploratory work described in previous chapters.

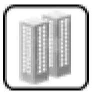
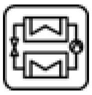
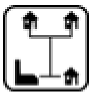
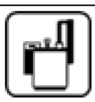
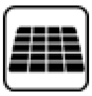
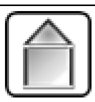
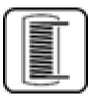
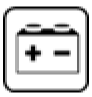
The remainder of this chapter is divided into three sections: the next section describes the scope and focus of the examples that have been part of Annex 67; the following section provides more detail for a sample of specific examples that describe the different sources of flexibility; and the final section then presents the statistical range of the described examples.

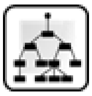
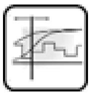
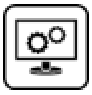
7.2. Scope and focus of examples

Researchers from organisations in 16 different countries contributed to Annex 67 and at least one practical example of how to achieve energy flexibility was provided for each country. In addition to the geographical spread of examples, there are also a range of characteristics that will have an impact on how energy flexibility is explained and understood. As already established in the previous chapters, there are various means to achieving flexibility, these include: passive thermal storage (in the building's thermal mass – referred to as 'constructions' in Table 7.1); active thermal storage (in hot water tanks for example – referred to as 'thermal storage' in Table 7.1); battery storage; often in connection with local power generation (either on-site or building integrated) (in Table 7.1 referred to af 'battery'); fuel switching between different HVAC systems or alternating between networks (for instance, the electricity grid and a district heat network) (in Table 7.1 referred to as 'fuel switch).

In keeping with the above, and to help the reader navigate the different strategies and methods available, the "Examples of Energy Flexibility in Buildings" report categorises the different cases using a set of common characteristics. As well as being categorised by the source of flexibility, the examples are also grouped by building typology (residential or non-residential), the energy system(s) used in the building, the control system employed and also whether the results are based upon simulated or measured data. These different categories and the assoicated technologies used to subdivide the categories are defined below in Table 7.1.

Table 7.1. Features of the cases included in the “Examples of Energy Flexibility in Buildings” report

	Icon	Technology	Explanation
Building typology		Single-family house	Only one single house or a flat is considered
		Multi-family house	The considered building is a multi-family building with a number of flats
		Non-residential build-ing	These buildings are in this report offices or multi-use e.g. university buildings
		Cluster of buildings	The flexibility of several buildings are considered at an aggregated level. The buildings can either be lo-cated physically next to each other or not be physi-cally connected but have the same aggregator con-trolling their energy flexibility – e.g. buildings with the same type of heating system e.g. a heat pump, and are controlled as a group
Energy system		Heat pump	The utilized heat pumps are located in the buildings and may both be ground source or air source heat pumps
		District heating	Is considered in the sense, that the building(s) heat demand is covered by district heating via typically a heat exchanger in the building
		Other HVAC system	This includes any other ventilation and/or cooling systems
		PV	PV systems located at the building make the building a prosumer, which may put extra stress on the grid when they export electricity to the grid
Source of flexibility		Constructions	The thermal mass of the building (walls, floors, ceil-ings but also furniture) are utilised for storage of heat
		Thermal storage	Thermal storage are here both DHW tanks, buffer tanks in space heating and cooling systems but also swimming pools or PCM storage
		Battery	Batteries may both be a stationary battery in the building (e.g. in connection with a PV system) or the battery of an electrical vehicle owned by the user of the building
		Fuel switch	Energy flexibility obtained in a building, which has two or more energy systems covering the same de-mand – e.g. a gas boiler and a heat pump

	Icon	Technology	Explanation
Control system		Rule based	Traditional control where the energy service systems are controlled by a set of predefined rules. A traditional PI thermostat is a simple rule based controller
		Model based	The controller is based on a model of the energy demand of the building in the form of a white box model (e.g. TRNSYS), a grey box model (typically a low order RC (resistance-capacitance) model) or a black box model (where the model is generated from measurements and the parameters of the model have no direct physical meaning). Model based controllers give the possibility of applying forecasts and can thereby make them more efficient but also more complex
Results based on		Simulations	The results of the example/teaser are based on simulations using typically white box modelling but can also be based on grey and black box models
		Measurements	The obtained results are from measurements on real building or from test facilities utilizing hardware-in-the loop where parts of the test are real physical components while the building and weather are simulated

The 33 cases are in the Annex 67 "Examples of Energy Flexibility in Buildings" report (Jensen et al., 2019) subdivided in the following chapters:

- Chapters 3-18 are short descriptions (typically 10 pages) of the results from research projects dealing with different ways of obtaining energy flexibility from buildings. These are further subdivided into examples describing:
    - Residential buildings – chapters 3-11
    - Non-residential (office or multi-use e.g. university) buildings – chapters 12-18
- Chapters 19-30 are brief summaries of more detailed descriptions focussing on how to control energy flexibility from buildings. The detailed descriptions can be found in the Annex 67 report: "Control strategies and algorithms for obtaining energy flexibility in buildings" (Santos et al., 2019)
- Chapters 31-35 are brief summaries of more detailed descriptions focussing on how to simulate energy flexibility from buildings. The detailed descriptions can be found in the Annex 67 technical report "Modelling of possible Energy Flexibility in Single Buildings and Building Clusters" (Li et al., 2019).

The 33 cases describe results from investigations applying different boundary conditions (weather, energy prices, etc.) and constraints (use of buildings, comfort range, etc.) so the results, and the metrics used to measure flexibility, differ between the examples or even contradict in some cases. This emphasises the potential complexity and emerging nature of the area of study.

7.3. Specific examples of energy flexible buildings

This section uses specific examples that aim to describe, in simple terms, the practical application of strategies that can achieve energy flexibility in buildings. They have been selected to represent the four main categories defined by the source of flexibility, and to provide any reader, regardless of their experience of the subject area, with a practical introduction to the subject. Examples for both domestic and non-domestic (commercial) buildings have been included as they can have very differents forms, functions, HVAC systems and operating patterns. More detailed explanantions of formulae, methods and building details can be found in the references provided in the following sections.

7.3.1. Passive thermal storage in constructions

Many of the studies included in Annex 67 have focused on domestic buildings. Although these buildings can be perceived as being relatively simple, the introduction of energy flexible strategies in these uncomplicated buildings does help to illustrate the complexity of this emerging field. This particular example demonstrates the role inherent structural thermal mass in the building constructions can play in energy flexibility, along with some of the intricacies, such as the impact of different building fabric constructions and the need to account for non-structural thermal mass.

The first example considered in this chapter is a numerical study that investigates and quantifies the impact of the main building parameters on the energy flexibility of space heating for single-family houses in Denmark (see (Johra et al., 2019) and (Jensen et al., 2019 – chapter 3)). Adjustments to the indoor heating set point over time are used to activate the inherent thermal storage capacity found in the building's thermal mass. The modulation of the indoor temperature set point for the heating system is based on the electricity spot price. This is a demand side management strategy that increases energy use when the electricity price is low by storing heat for later use. When the electricity price is high, the energy usage is delayed until the point at which heating is required to avoid occupant's thermal discomfort. The changes in price reflect the availability of renewable energy in the power grid. Particular attention has been paid to the influence of the building thermal inertia and the presence of additional thermal mass in the furnishings (including furniture, fittings and artefacts such as books for example) that are inside the building's thermal envelope.

Variations of a typical Danish single-family house (four occupants) with 126 m² of heated floor area were used in this case study. The geometry of the dwelling remains the same in all scenarios but the material types and thicknesses are changed to generate 144 different cases with two categories of building envelope performance (low-insulation house from the 80's and high-insulation passive house), three thermal mass classes (lightweight, medium-weight and heavy-weight structure) with three sub-variations in each of them, two types of heating system (convective radiators and under-floor heating system), and four additional indoor thermal mass configurations (empty rooms, furnishings, Phase Change Material - PCM - integrated in furniture elements, PCM wallboards placed on walls and ceilings) (Johra, 2018). The "furnishings" are defined as all items within the indoor environment that are not comprised in the construction elements of the building. Their representative thermo-physical properties and quantities inside the buildings are determined according to (Johra and Heiselberg, 2017). The additional thermal mass in furnishings is modelled as an equivalent fictitious planar element that aggregates all indoor items. The indoor thermal mass elements are 60 kg/m² of the room's floor area and have the thermal properties of an equivalent homogenous representative material (Johra et al., 2017). The PCM elements are 1.5 cm thick slabs and have the thermal properties of the well-known stable form PCM commercial product. Full details on the calculation of thermal mass can be found in (Johra et al., 2017).

Models were created using MATLAB-Simulink software. The rule-based control strategy uses the Danish electricity spot price to prompt the energy flexible operation of the building. For each hour, a low-price limit and a high price limit are calculated as the lowest and highest quartile of the electricity market spot price over the previous 14 days. When the electricity spot price falls below the low-price limit, the building temperature set point is increased to 24 °C in order to accumulate heat. When the electricity spot price rises above the high price limit, the building air temperature set point is decreased to 20 °C in order to save energy. When the electricity spot price is in between the low and high price limits, the building temperature set point is kept at 22 °C (see Figure 7.1). The indoor air temperature is, therefore, always maintained between 20 °C and 24 °C, which ensures good thermal comfort for the building occupants at all times (EN ISO 7730, 2005).

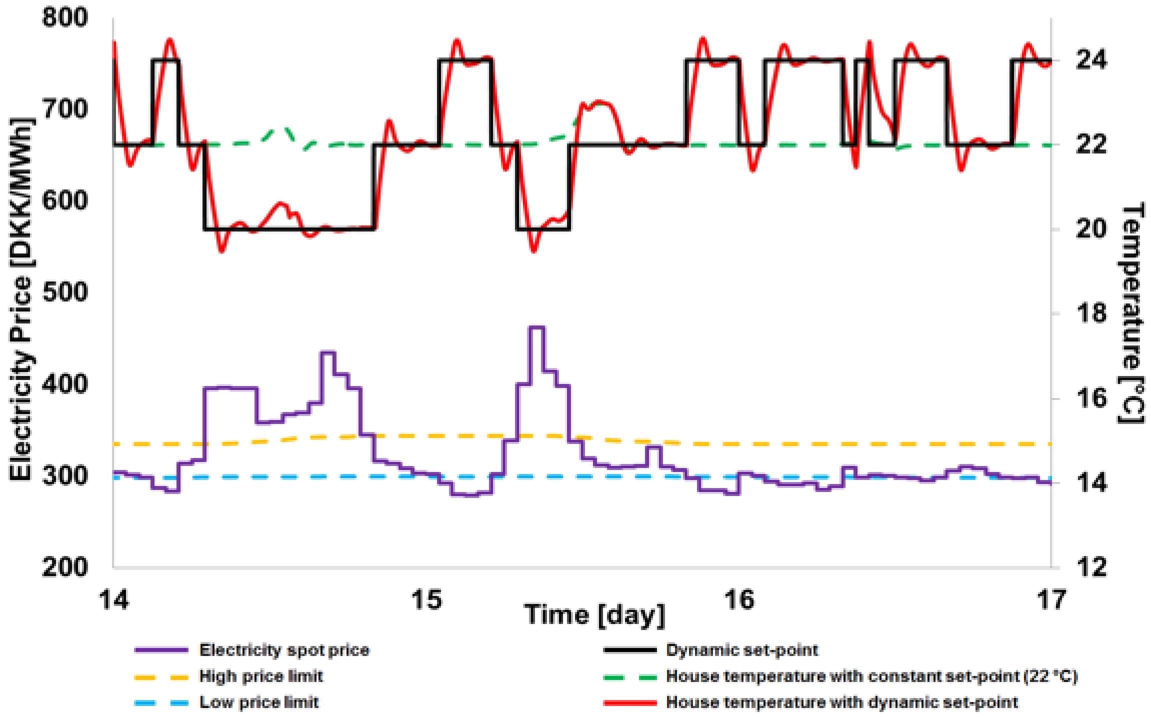


Figure 7.1 Example of control strategy for energy flexibility of buildings by means of indoor air temperature set point modulation with electricity price control signal.

In this study, the energy flexibility of buildings is defined as the ability to shift in time the heating use from high and medium energy price periods to low energy price periods. Consequently, a flexibility index is calculated as a function of the change in energy use during the “high”, “medium” and “low” price periods between the flexible case and the reference case. The flexible case actively tries to minimize energy usage during high price periods and maximize energy usage during low price periods. The reference case represents the baseline distribution of energy usage among the three price categories when the building operates without any energy flexibility strategy (constant indoor air temperature set point of 22°C). The energy flexibility index takes the value of zero if the energy use during flexible operation is the same as that under normal conditions. The index becomes negative if the share of high and medium price periods is larger than the reference values. If there is no remaining energy usage during the periods of high and medium price, the energy flexibility index takes the maximum value of 100 %. In that situation, the building presents a total energy flexibility (Johra et al., 2018).

The different building scenarios were simulated for an entire year under typical Danish weather conditions. Initial results demonstrated that thermal inertia contributes to an increase in the building heat storage capacity and consequently its energy flexibility index. However, above 80 Wh/(K m²), the energy flexibility of the building stagnates as seen in figure 7.2. It is not possible to shift more space heating load and, therefore, further increase of the building's thermal mass will have no impact on its flexibility past this point. This effect can be seen in Figure 7.2 which shows the energy flexibility index results for the 144 studied cases as a function of the total effective thermal inertia of the house.

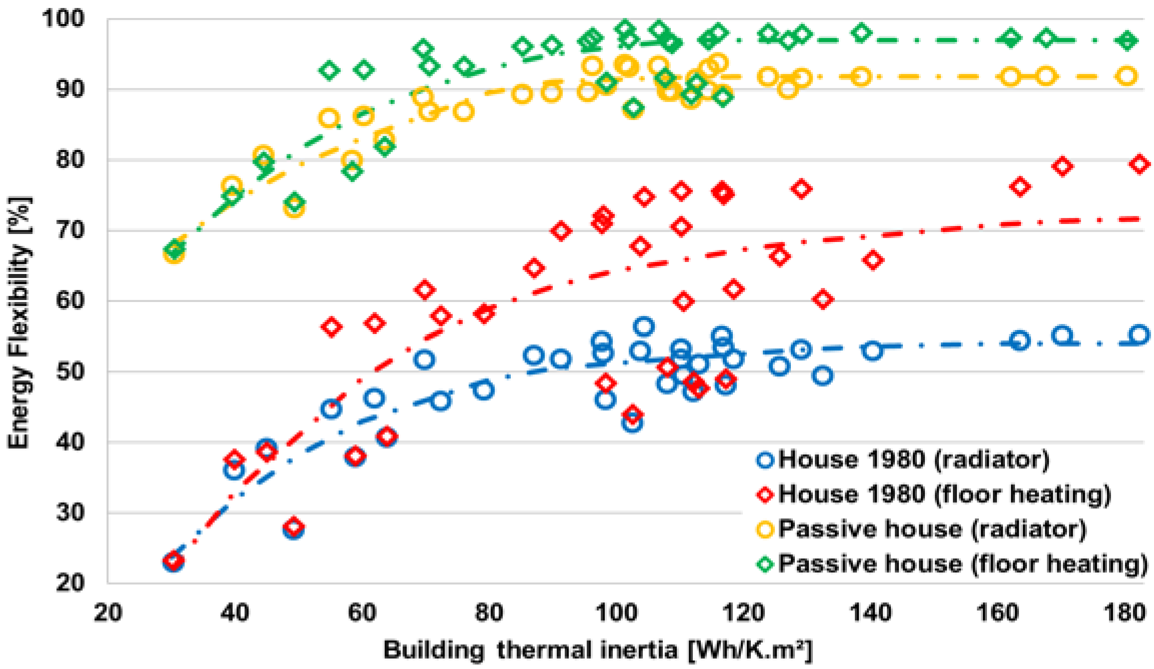
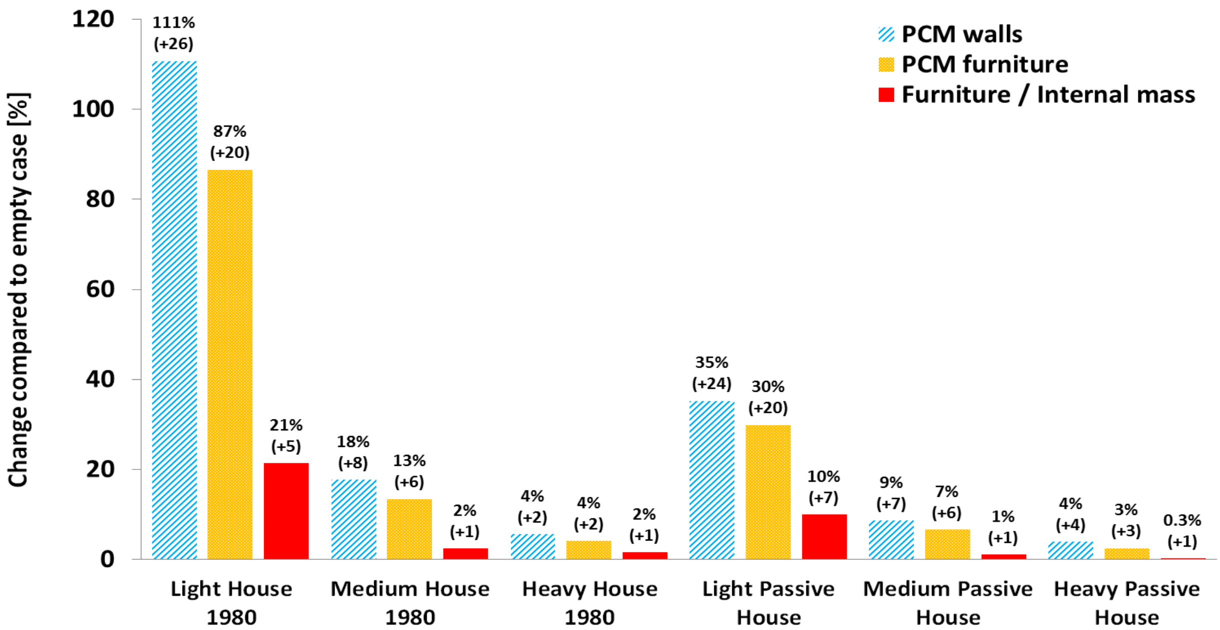


Figure 7.2 Evolution of the energy flexibility of buildings as function of the thermal inertia.

Results indicate that well insulated dwellings have a much higher ability for shifting of the space heating load than poorly insulated ones because thermally efficient envelopes allow a larger conservation and retrieval of the stored energy. However, it is important to note that, even if poorly insulated buildings can only shift a limited proportionate share of their heating load over a short period of time, the latter represents a larger absolute amount of energy compared to well-insulated buildings. This is illustrated in Figure 7.3. This was a common finding across many of the studies that were part of Annex 67, especially those evaluating domestic buildings.

In addition to understanding the role of inherent thermal mass included in the building's constructions, the study also aimed to evaluate the influence of additional indoor thermal mass elements on the energy flexibility of space heating in the houses. Figure 7.3 presents the increase of the energy flexibility index when introducing three kinds of additional thermal mass elements into the indoor environment, compared to the case with empty indoor space (no furnishings). The PCM wallboards and furniture with integrated PCM can appreciably increase the energy flexibility of houses with low structural thermal inertia. However, the improvement is very limited for medium-weight and heavy-weight houses.

This case study confirmed that the level of insulation in the building envelopes is the characteristic with the largest effect on the energy flexibility of domestic space heating. Well insulated dwellings are more efficient at thermal storage and heating load shifting. However, poorly insulated buildings can shift in time an absolute amount of energy that is around four times larger than well-insulated ones, but only during a very short period. It was also found that radiant under-floor heating systems can improve the heating energy efficiency of the building system and enhance the activation of the structural thermal mass, which contributes to a higher energy flexibility. In the models that included a low level of structural thermal mass, the presence of furnishings within the thermal envelope increased the energy flexibility by up to 21% for the investigated cases. Therefore, a particular recommendation of this case study was to take furnishings into account when performing dynamic building simulations and energy flexibility assessments of light-weight buildings.



Empty building energy flexibility [%]	**23**	**45**	**53**	**67**	**86**	**90**
Empty building thermal inertia [Wh/K.m²]	**30**	**50**	**100**	**30**	**50**	**100**

Figure 7.3 Change of energy flexibility of buildings with additional indoor thermal mass (radiator heating system).

7.3.2. Active thermal storage

To help illustrate the potential for thermal storage to provide energy flexibility, the second example included in this chapter aims to quantify the effect of major factors influencing the available energy flexibility from residential hot water systems. It helps to demonstrate the impact of stakeholders (in this case residents) on energy flexibility and also highlights the role that more advanced control strategies have on flexible operations.

The project considered for this example used data from a large-scale real-world pilot project in The Netherlands. The full example is included in (Jensen et al., 2109 - chapter 8). All the houses considered in the analysis featured identical hot water systems. Results demonstrate that ambient conditions, control algorithms and occupant behaviour, all influence the available energy flexibility of the hot water system, albeit in different ways. There are also some key differences in the way these factors influence the overall energy demand and the available flexibility. Available capacity and recovery periods can differ by as much as two to four times for identical storage, meaning that these differences have to be taken into account during operational planning with flexible loads. The recovery period is here understood as the time it takes before the storage is again able to deliver flexibility.

Although the case described here is based upon measured data, determining the energy flexibility of hot water systems requires a detailed dynamics model. Data-driven models were developed from measured data. A general-purpose framework, which could be applied to any hot water system, was then developed. The research project that this work formed a part of, REnnovates, involved hundreds of houses in the Netherlands (on which this chapter is based), as well as partners from Spain and Poland who aimed to investigate the replication potential in other climate conditions. Each of the refurbished houses was designed to be a net-zero energy building, with identical hot water systems that used an air source heat pump and a 200 litre storage tank. The heat pumps were responsible for both space heating and hot water production. The hot water system is visualized in Figure 7.4, along with the sensor setup used to monitor the performance.

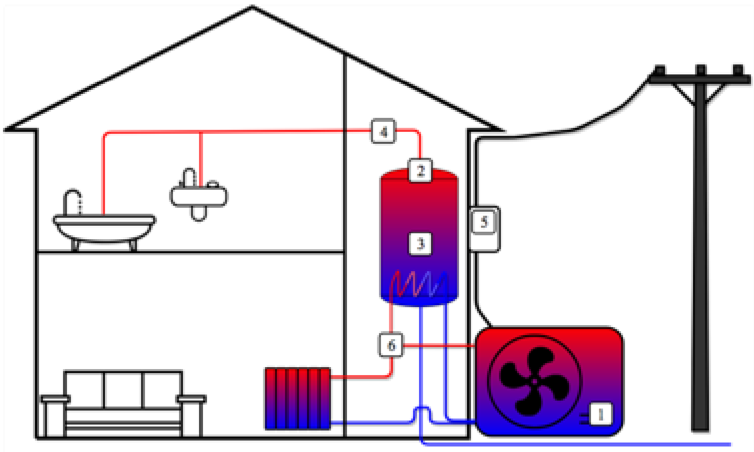


Figure 7.4 Sensor setup present in the houses.

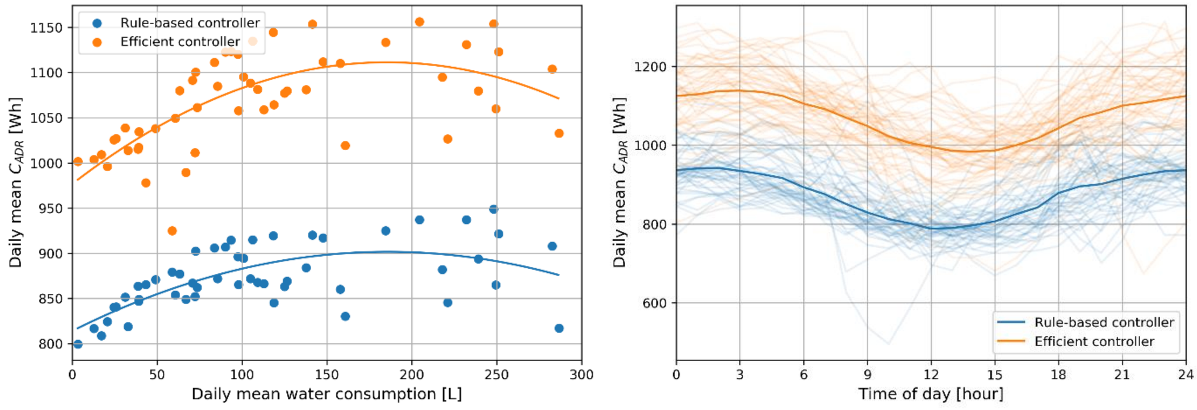
For the modelling of the hot water system under consideration, two models were trained with available data that amounted to approximately 20 data-years of device behavior. While not feasible with a single device, this data set was created by aggregating sensor data from different households using identical hot water systems. The first model (the storage model) learned to predict the temperature distribution in the storage as a function of its height, given some occupant and heating element behavior. This was then used to estimate the state of charge of the storage with respect to a reference temperature. Likewise, the heat pump model was trained in a way that it would predict the energy consumed by the heat pump to reheat the storage from any state of charge to a target state of charge, given some ambient conditions.

The inputs to both models were features extracted from the raw time series data (measured by the sensors). The raw time series corresponded to data from a temperature sensor installed midway in the storage as well as an ambient temperature sensor, a hot water flow meter and an energy meter measuring the heat pump's electrical consumption. Identifying key features reduced the range and number of inputs and considerably simplified the data-driven model. These features corresponded to (1) the initial state of the storage, (2) occupant behavior (i.e. hot water consumption since the last reheat cycle), (3) thermodynamic losses (i.e. the time elapsed since the last reheat cycle), and (4) ambient conditions (in this case, the unheated storage room within which the storage tank is located). Two control algorithms were employed in this analysis, which have been adapted from previous analysis conducted by (Kazmi, 2019). While both controllers can be simplified to a rule-based form to keep the analysis simple, one was designed to mimic default device behavior (referred to in the results as the 'rule-based controller') and the other was a just-in-time controller to improve device efficiency (referred to in the results as the 'efficient controller').

The metrics used to quantify energy flexibility in this example build upon definitions presented in (Reynders et al., 2015), and include capacity, efficiency, activation and recovery. The energy flexibility of the device is requested during an automatic demand response (ADR) event. This event can occur at any time of the day and year. Furthermore, the ADR event can call upon the system to either consume more or less power at any given time. However, as the hot water system is, more often than not, inactive, the focus of this example is on up-regulation - i.e. when the hot water system is instantaneously asked to consume more energy compared to a baseline. The baseline is in this case a situation with no water draw off, only heat loss from the storage tank. The ADR event, as implemented here, is seen as a request to consume more power. The individual systems, after receiving this request, reheat the storage to its maximum state of charge. In the following charts, the term (C_{ADR} [Wh]) refers to the amount of heat that can be added to the storage element in the time frame of an ADR event.

The capacity of an energy flexibility system is an indication of its ability to store or provide energy. This capacity is influenced by the features of a system and its use. For example, user behavior will have an influence on the available capacity at any given time. With increasing hot water demand, the storage's energy capacity increases up to a certain limit. The initial increase in capacity with consumption is caused by the discharge of energy, which leads to the possibility of the hot water storage consuming more energy. When there is very little consumption, the energy capacity of the storage is constrained by thermodynamic losses to the ambient environment. Therefore, the energy capacity of the storage increases from this baseline when building occupants consume more hot water over the course of a day (approaching or exceeding the storage capacity). The effect, while being significant, is not particularly large, i.e. a doubling of water consumption does not lead to a doubling of energy capacity. This is unlike the influence of consumption on energy demand where a much higher effect can be seen. In the investigation, it was found that the capacity fluctuations as a function of user behaviour are in the order of 10 %-15 % when compared with the baseline. These results are shown in Figure 7.5a.

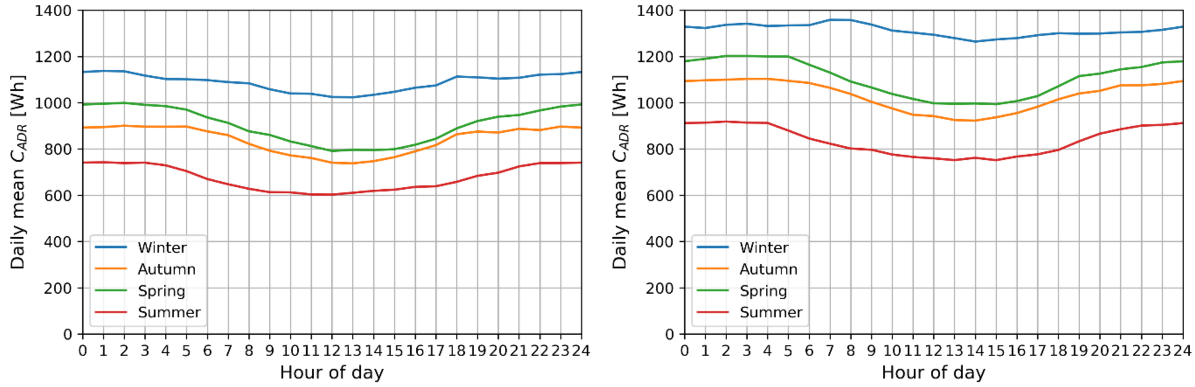
The choice of control algorithm also plays a major role in determining the flexibility of the storage under consideration. As explained earlier, only two controllers are considered to simplify matters. The efficient controller tries to postpone the reheat of the storage as much as possible, thereby minimizing thermodynamic losses and improving heat pump efficiency (by reducing the average temperature of the water at the inlet). However, it also influences the available capacity of the storage as is evident from Figures 7.5a and b and results in an increase of the available capacity by an average of 20 %, irrespective of user behaviour. As seen later, this has important repercussions for other aspects governing the energy flexibility of the device as well.



(a) (b)

Figure 7.5 (a) Effect of user behaviour on the available energy capacity [Wh] with different control strategies; individual dots refer to results obtained for different households.
(b) Effect of diurnal ambient condition variations and control algorithm on the available energy capacity [Wh]; transparent traces represent the behaviour of individual households while bold lines indicate the averaged behaviour.

There are a number of factors that influence the ambient conditions under which a hot water system operates. These include diurnal and seasonal temperature variations, which can influence the heat pump's coefficient of performance. Finally, the same device operating in different countries or regions (i.e. variations in geographical conditions) will also give rise to differences in the available energy flexibility (even when the hot water demand is kept constant across the households). In this case, seasonal variations had the largest effect on the available energy capacity of a storage system. The increase in available device capacity can be up to 50 % for the efficient controller from summer to winter, and almost 70 % for the rule-based controller. Keeping in mind the diurnal variations, the effect of ambient conditions can be considered even larger. These effects are visualized in Figures 7.6a and b.

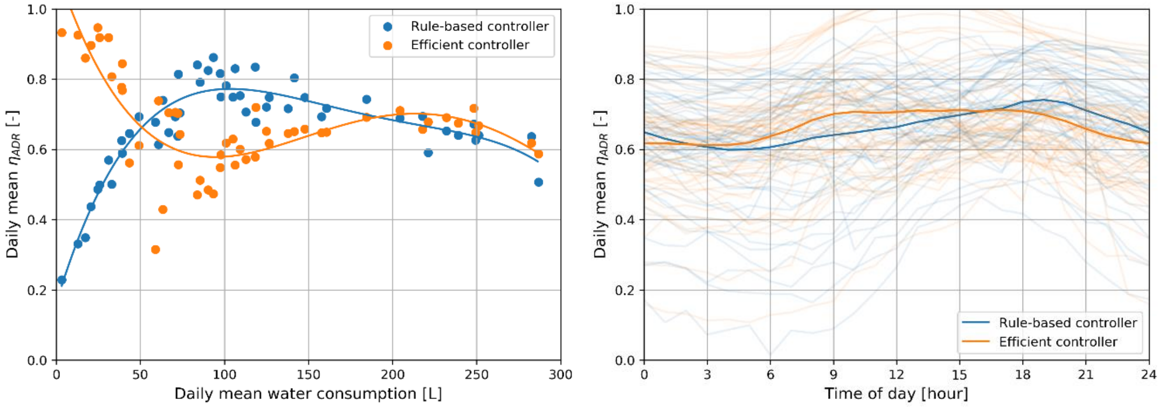


(a) (b)

Figure 7.6 Effect of seasonal ambient condition variations and control algorithm on the available energy capacity [kWh]: (a) rule-based control and (b) energy efficient controller.

While all the factors discussed above have a large effect on the available energy capacity of the storage, it is also interesting to consider their effect on the storage efficiency. Efficiency, in this context, is defined as the amount of usable heat arising from the ADR event compared to the heat put into the storage. The storage efficiency (η_{ADR}) is defined as the fraction of the heat that is stored during the ADR event that can be used subsequently to reduce the heating power needed to maintain thermal comfort. Here, unlike with available energy capacity, the effect is mostly dominated by user behaviour and the control algorithm, rather than the diurnal variations as shown in Figures 7.7a and b.

When considering efficiency, user behaviour and the control method can account for substantial variations of between 30 and 50 % in the achieved efficiency of the hot water system. It is important to stress here that this efficiency is not the device efficiency in general but the device efficiency in case of an ADR event. On average, this efficiency ranges between 60 % and 80 % in most cases, which means that a substantial portion of energy used in an ADR event is lost without doing any useful work.



(a) (b)

Figure 7.7 Effect of occupant behaviour, ambient condition variations and control algorithm on efficiency.

In this example, different determinants of energy flexibility of hot water systems have been investigated. While similar to the determinants of energy consumption for domestic hot water production in a building, there are nevertheless important differences. The most important of these is, rather surprisingly, in the way occupant behaviour influences the available energy flexibility but this, along with ambient conditions and control strategies all play a role:

Ambient conditions: In general, storage flexibility is highest during (cold) winter nights and lowest during (warm) summer afternoons due to the heat supplied from a heat pump. If the heat supply was a resistant heating element the ambient temperature would have no impact on the available energy capacity. However, the same system will have higher flexibility potential in Poland than in the Netherlands and Spain due to the generally colder conditions. The unifying theme for this space-time variation of the energy flexibility is of course the ambient temperature conditions.

Control algorithms: With a more energy efficient controller, it is possible to elicit higher capacity on average from the same hot water system. This is in keeping with many of the other studies included in Annex 67. However, this comes at the cost of a longer recovery period. This suggests at least one additional avenue for optimal control where controllers can be designed based on the grid supportive behaviour that is expected of them. If the hot water systems are only expected to provide large amounts of flexibility infrequently, an efficient controller will be more effective as it offers greater capacity at the cost of longer recovery times. On the other hand, if limited amounts of flexibility are required often and on a periodic basis, a less efficient controller is the more suitable choice. The loss of efficiency, leading to higher energy costs, however, has to be counteracted by other incentive mechanisms.

Occupant behaviour: The available energy flexibility is limited by constraints on occupant comfort (hot water when needed), which ensure that the system can only be operated within certain bounds. Furthermore, occupant behaviour works in tandem with thermodynamic losses to determine the capacity and recovery period of a device. This means that increasing hot water demand for users leads to only somewhat higher capacity, similar to the use of a more efficient controller. However, unlike with the controller, higher consumption also leads to a generally shorter recovery period, because the storage is more often emptied for heat at high consumptions.

The analysis of the energy flexibility of hot water systems has important repercussions for the use of hot water systems in grid supportive roles. In most Northern European countries, hot water systems have been considered as a means to reduce the peak injection of solar production during the summer months. However, the energy flexibility of such devices is generally at its lowest during this period. This information, and not the average flexibility of these devices, has to be taken into consideration during operational planning of modern grids. In a more general context, care must be taken to account for these differences in energy flexibility of the same type of system, which can vary by as much as three to four times depending on ambient conditions, occupant behaviour and choice of controller system.

7.3.3. Battery storage

This third example is primarily to illustrate the potential of battery storage as part of an energy flexible building. It is a case study on a Net Zero Energy office building and helps to illustrate the role non-domestic buildings can play in the provision of energy flexibility. It is important to note that this building, although used here as an example of battery storage, also included thermal storage capabilities as well. Many of the examples included in the "Examples of Energy Flexibility in Buildings" report included multiple sources of flexibility.

Solar Building XXI (see Figure 7.8), built in 2006 (Gonçalves and Cabrito, 2006) at the National Laboratory of Energy and Geology (LNEG) Campus in Lisbon, Portugal, is an example of a Net Zero Energy office building, with its high energy efficiency reached through passive systems (for heating and cooling) in combination with a Building Integrated Photovoltaics (BIPV) system (12 kWp) installed on the South façade and an additional photovoltaic roof system in a nearby car park facility (12 kWp) for electricity generation. As the achievement of the zero energy performance (net zero or positive) is often made with an increase of the amount of intermittent energy that flows to the grid, causing occasional periods of overproduction, it is worth investigating the possibilities of using the energy flexibility to increase load matching between electricity generation and consumption and improve grid interaction by the integration of Battery Energy Storage Systems (BESS). For further information see (Jensen et al., 2019 – chapter 15).

Solar XXI has a proven record of high performance with respect of the zero energy concept (Aelenei and Gonçalves, 2014). However, because the supply from renewable sources is governed by the availability of the respective primary energy source, there is often no correlation between production and consumption (Montuori et al., 2014). In addition, the Solar XXI building has power needs similar to a typical domestic building (with maximum demand peak of 9.6 kW), which limits considerably the options for improving the energy flexibility.

Figure 7.8 SOLAR XXI.

The BIPV system in the south façade includes 100 m^2 of multicrystalline silicon photovoltaic modules, resulting in a 12 kWp generation capacity, which equals the 205 m^2 PV modules capacity installed on the parking roof (a combination of amorphous silicon and thin-film modules). The PV generation of both systems is firstly consumed within the building, any generation surplus is supplied to the existing distribution grid of the campus. South oriented large windows, a solar thermal system and a gas boiler are used to provide space heating when required; the building has a very low heat demand, hence the gas boiler being included in a zero-energy building of this nature. In addition, the BIPV modules are mounted at a distance of 10 cm from the insulated masonry wall, allowing preheating of the airflow coming from outside. Detailed information regarding the thermal performance of the BIPV of Solar XXI is presented in (Aelenei and Pereira, 2013).

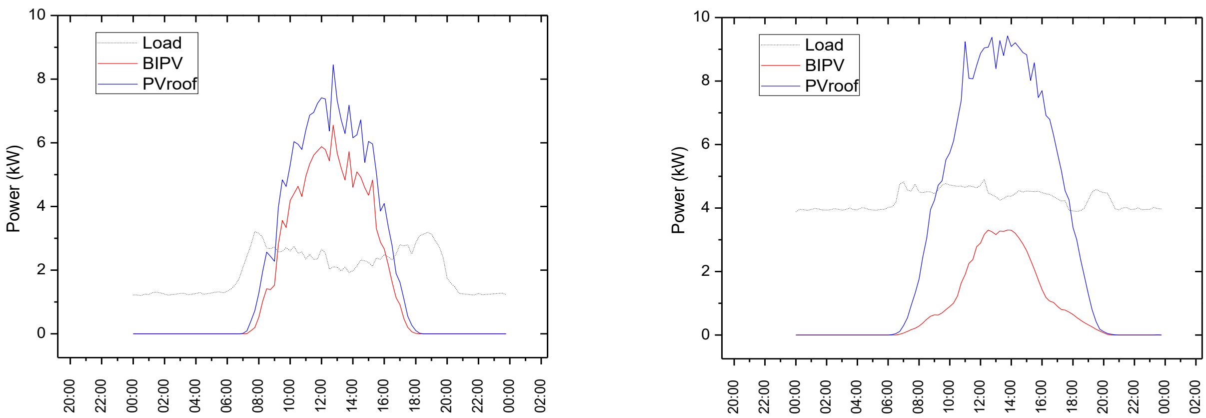


Figure 7.9 Average load and energy generation from BIPV and parking lot PV during typical winter (left) and summer (right) days.

In the storage approach, in order to improve the load matching and grid interaction performance of the building, different BESS based on Tesla's Powerwall (Tesla, 2018) are considered, with a total storage capacity of 13.5, 27, 40.5 and 54 kWh (as a result of the amount of batteries connected in parallel). In this case, the BESS acts as an additional load when generation surplus is registered and as a virtual generation unit during periods of excessive demand, reducing, therefore, the interaction with the distribution grid. The BESS charging is only allowed until the maximum storage capacity is reached, while the BESS discharging only occurs when there is a certain level of storage energy. The maximum charge and discharge power capacities for a single battery are set at 5 and -5 kW, respectively, whereas the roundtrip efficiency of Tesla's Powerwall is 90 % (Tesla, 2018). For a detailed description of this approach, which corresponds to numerical simulations, please refer to reference (Aelenei et al., 2018).

The improvement of the load matching performance refers to the process of increasing both the Self-Consumption (SC) and Self-Sufficiency (SS) ratios of a building, and the resulting grid interaction. SC essentially measures the amount of the building's on-site generation that is matched by the building's electricity demand and SS measures the amount of the building's electricity demand that is matched by the building's on-site generation; equations for how these ratios are calculated can be found in (Jensen et al., 2019).

Figure 7.10 shows the annual mean diurnal electricity demand profile of Solar XXI together with the modified one (including storage) and the annual mean diurnal generation profile. The electricity demand profile reflects the building's occupancy characterized by a reduced value during the night, followed by a morning peak between 7am and 8am due to cleaning operations. After this demand peak, the electricity demand of Solar XXI slowly increases until reaching the midday peak, remaining constant throughout the rest of the working day. When BESS is considered as a single battery, the demand modified profile is changed significantly with regard to the original profile. The daily average demand profile of Solar XXI increases during the morning because of battery charging. The demand increase introduced by the BESS diminishes until the battery reaches its maximum capacity. Then, the energy stored throughout the day is discharged later (around 5 pm), reducing the electricity demand.

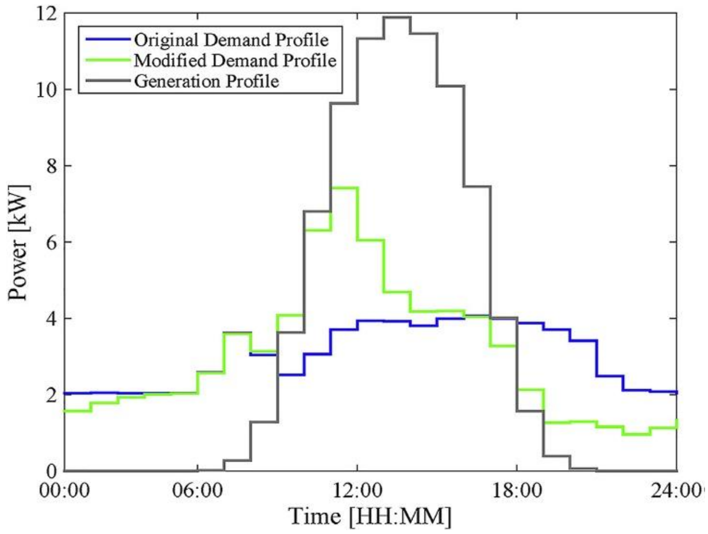


Figure 7.10. Original and modified (13.5 kWh BESS) daily average hourly demand profile of Solar XXI, together with its daily average hourly generation profile.

The results obtained following the integration of BESS, in terms of SC and SS ratios, for all considered battery capacities, are shown in Table 7.2. The collected results show that these ratios are significantly increased when the batteries are integrated into Solar XXI. The major improvement per additional battery is achieved when only one Tesla Powerwall is integrated, with improvements of 15.4 % and 17.1 % for the yearly SC and SS ratios, respectively. The SC ratio improvement results from increasing Solar XXI's demand when generation surplus is registered, while the SS ratio improvement is due to the Solar XXI demand decreasing when PV generation is lower than the electricity demand. Therefore, one battery is more cost effective than multiple batteries in this case, as shown in detail in (Aelenei et al., 2018).

Table 7.2. Summary of load matching related metrics.

Number of Tesla walls	Storage Capacity [kWh]	SC [%]	SS [%]
0	0.0	40.9	45.3
1	13.5	56.3	62.4
2	27.0	69.1	76.6
3	40.5	73.0	80.9
4	54.0	73.7	81.7

Despite the Solar XXI building only being occupied during daylight hours, when solar radiation is available, the load matching between the building generation and demand is far from being perfect as yearly SC and SS ratios are 40.9 % and 45.3 %, respectively. Improving the load matching with the objective to minimize the need to purchase power from the grid in passive solar buildings such as Solar XXI is difficult, due to an absence of electrical heating/cooling equipment, which could allow to deviate their normal consumption patterns in response to high renewable generation. Therefore, the mismatch between electricity production and consumption relies on the use of BESS with capacities between 13.5 kWh and 54 kWh to provide the required flexibility.

7.3.4. Fuel switching

The final example also has its focus on a non-domestic building, but the experiments described in this example are based upon a numerical study. This study actually considers all four main sources of flexibility but the elements of it reported here are primarily used to illustrate the potential of fuel switching. For further information see (Jensen et al., 2019 – chapter 16).

The ability of building energy systems to adapt their load and generation patterns to electricity demand is fundamental to support the efficient use of large amounts of intermittent renewable energy. Using a generic modern office building with concrete core conditioning and a heat pump as an example, the full version of this study evaluates and compares four different flexibility and storage options (batteries, fuel switching, water tanks, and building thermal mass) in terms of different sizing of the components, technical implementation and possible improvements in load scheduling and energy efficiency. The results of the detailed numerical simulation lead to the conclusion that current electricity prices do not offer sufficient variations to stimulate grid-supportive operation and a further monetary incentive is necessary.

The impact of a building on the power grid and electric energy system is determined by the trajectory of the net power load. Within the heating and cooling system of a building, different flexibility and storage options can be used to adapt the load trajectory based on some grid signal (for example, a notification of peak demand, an increase in price or an increase in grid carbon intensity). In this context, fuel switching involves a change in the sequencing of different heat and cold generators in paired systems, which make use of different end energy sources. For instance, selecting the heat pump instead of the gas boiler as the primary heat provider can effectively cause an energy storage process in the gas grid, which can be used later when a peak electricity demand situation is identified, and the gas boiler becomes the primary heat generator – see figure 7.11.

For the evaluation of grid flexibility, the (absolute) Grid Support Coefficient (GSC_{abs}) is introduced (Klein et al., 2016). It rates the grid impact of a building from the energy system perspective by evaluating whether electricity consumption occurs at times with electricity demands above or below average. Grid-supportive buildings have a GSC smaller than one while grid-adverse buildings have a GSC greater than one and a GSC close to one can be considered grid-neutral.

The considered building in this case is a generic 6-storey office building located in Mannheim, Germany, with a conditioned floor area of 2,433.6 m^2. The properties of the thermal envelope comply with the requirements of the German building code (EnEV, 2014) for non-residential buildings. The offices are partially occupied during workdays between 7am and 6pm with six full-occupancy hours per day. Details on the modelling of internal heat gains, illuminance, shading devices and the ventilation system can be found in (Klein et al., 2017).

The energy supply comprises a gas boiler with a peak capacity of 75 kW and a ground-coupled heat pump with a peak capacity of approximately 50 kW, which acts as a chiller plant in cooling mode. Both heating system can separately cover the heating load of the building. In the baseline operation, the heat pump is the primary heat generator, and the gas boiler is the secondary heat generator, which is activated in case of a fuel switch event or when the primary heat generator is not able to meet the heating load. This may happen when the load is increased temporarily in order to provide more flexibility. The hydraulic layout is illustrated in Figure 7.11: depending on the season, a stratified water tank is used for heat or cold storage, and concrete core conditioning is used for heat emission via separate hydraulic circuits for the northern and southern parts of the building.

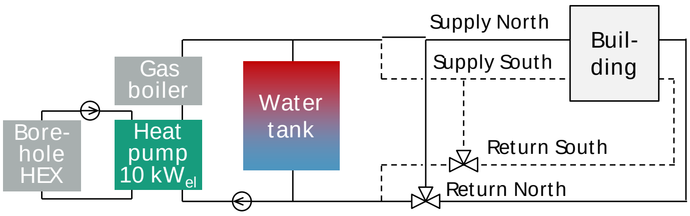


Figure 7.11 HVAC system and hydraulics.

The approach of fuel switching refers to a variation of the sequencing of heat generators. The decision when to switch between the different heat generators depends on the grid signal – the residual load in this study. For a definition of the residual load please see section 2.2. The reasoning is that a high residual load signal is an indicator of a peak electricity demand situation and the heat pump operation should consequently be avoided. Thus, when the grid signal exceeds a pre-defined upper threshold (switching signal), the gas boiler starts operating as primary heat generator. When the residual load falls again below the switching signal, the sequencing is reversed, and the heat pump becomes again the primary heat generator. In this study, the switching signal is given as a percentile of the residual load, e.g., the 95th percentile, which can be pre-computed based on the given full residual load profile for the simulation period.

In the reference operation, the building consumes 21 kWh/(m^2 a) of final energy and 26 kWh/(m^2 a) of primary energy. The comfort temperature range is between 20 and 24 °C (heating season) and between 23 and 26 °C (cooling season). Exceedances during occupancy are more frequent in the south-facing zone, especially towards the end of the heating season and during the cooling season. The results of the simulated load shifting algorithms are compared in terms of grid support and efficiency, determined by the final energy demand. The latter is given as the sum of additional gas demand and additional electricity demand. A more in-depth interpretation of results for all sources of flexibility is provided in (Klein, 2017).

Figure 7.12 illustrates the grid support coefficient and energy demand for different switching signals – here given as percentiles of the residual load as explained above. Smaller switching signals indicate an earlier signal to switch from the heat pump to the gas boiler as primary heat generator. Consequently, gas demand increases while electricity demand is reduced, which also improves grid support. However, this happens at the expense of an increase in final energy demand because the more frequent operation of the gas boiler requires more final energy per generated heat unit than the heat pump. The changes in GSC_{abs} and final energy demand are almost directly proportional to the defined switching signals.

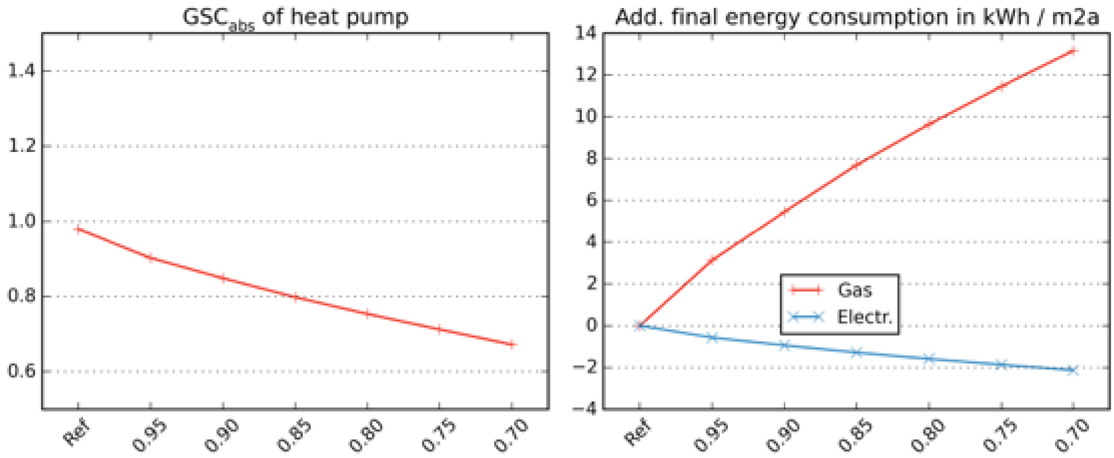


Figure 7.12 Fuel switching: grid support (left graph) and energy efficiency (right graph) for different switching signals. Switching signals designated as "0.95" refer to the 95th percentile of the grid signal residual load. The abbreviation 'Ref' denotes the reference load, which is the baseline scenario.

The benefit of the load shifting for all flexibility sources is illustrated through a comparison between grid support and efficiency (Figure 7.13). Improved grid support is indicated by a lower value of the proposed metric GSC_{abs}. Energy efficiency is determined in form of lower mean final energy consumption (Figure 7.13a) and lower mean Cumulative Energy Demand (CEC, on the x-axis in Figure 7.13b) per consumed electricity unit.

Out of the considered flexibility options for heat pump systems, batteries achieve the lowest GSC_{abs} values with the least additional final energy demand. Considering the CEC, batteries are even more attractive in comparison to the other flexibility and storage options, as they reduce the CEC of the building by up to 10 %. Using the building's thermal mass for storage leads to CEC savings of up to 4 %. However, in combination with an oversized heat pump, building mass is an attractive option. Using water tanks for thermal storage of heat pump energy suffers from the trade-off between improved grid support and higher additional final energy demand. However, due to the resulting favourable timing of the heat pump, the increase in CEC is much smaller.

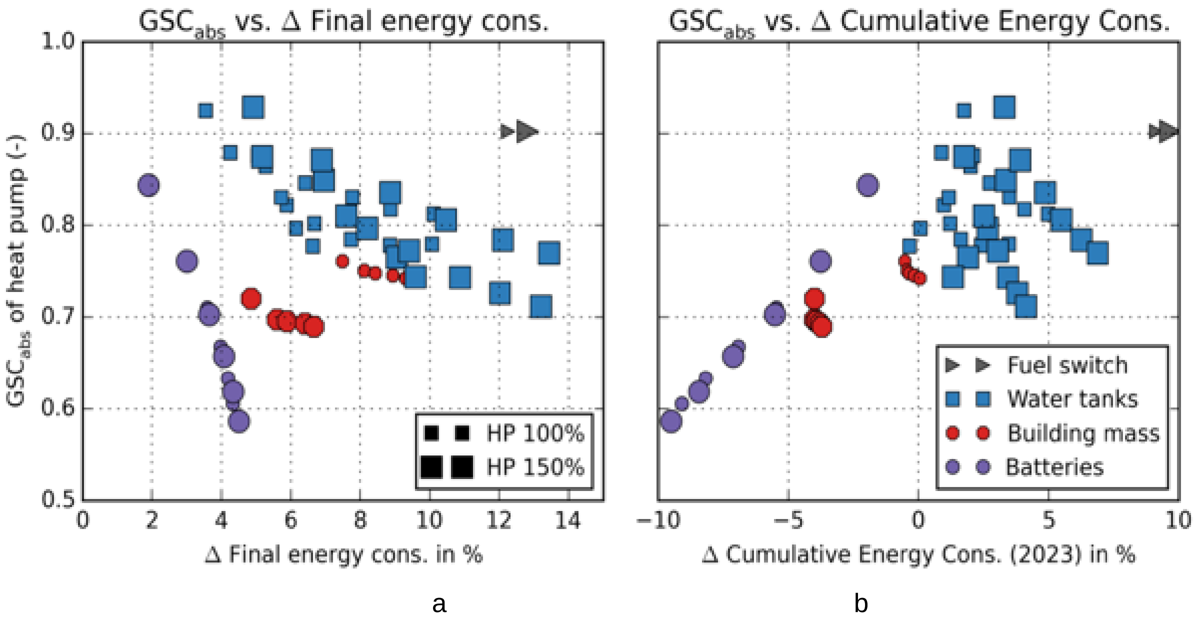


Figure 7.13 Comparison of flexibility and storage options. Each option is considered for standard and over-sized heat generators (illustrated by small and large points) and varying sizing and parameters as presented in the previous section.

Fuel switching improves grid support only marginally at the expense of a very large additional final energy demand and CEC, which is why only the first data point appears in the value range of the diagram. The main reason is the short duration of peak demand periods, during which heat pump operation should be avoided and which can be well managed by thermal storage. Boiler operation is strongly penalized in terms of final energy demand because it is several times less energy-efficient than the heat pump. This discrepancy is much smaller when considering the CEC, which weights electricity and gas differently. In building energy systems that are more complex than the example considered here, e.g. in tri-generation (combined heat power and cooling) systems, fuel switch may provide a more effective and capable option.

The aim of this study is to investigate the technical load shifting potential of non-residential building with a heating and cooling system based on a paired system consisting of a heat pump and a gas boiler. It is demonstrated that batteries are the most effective and efficient of the considered options. Based upon results presented here, fuel switch is not feasible for grid flexibility due to the properties of the considered grid signal and the large difference in final energy efficiency between the heat pump and the gas boiler, which acts as the back-up heat generator.

There were only two practical examples of fuel switching that were included in the main “Examples of Energy Flexibility in Buildings” report; the conclusions drawn here around fuel switching do, however, agree with the other study that considers this source of flexibility. It should however be noted that both studies considered hybrid heat pump and gas boiler systems, further work is required to explore the potential for fuel switching using alternative fuels and more diverse systems.

7.4. Statistical overview of energy flexible buildings examples

The following Tables 7.3-7.7 give some statistics on the flexibility features investigated in all of the 33 examples included in Annex 67, which provides an impression of where the current focus is in work exploring energy flexibility in buildings. Numerous examples included in the “Examples of Energy Flexibility in Buildings” report evaluated more than one source of flexibility. The number of examples investigating the different features is in the following given as the percentage. **As several features are investigated in the examples, and as not all examples cover all of the five areas in Table 7.1, the total percentage of Tables 7.3-7.7 does not add up to 100 %.** However, the values in the tables provide an overview of the focus of the examples as a whole.

7.4.1. Building typology

Table 7.3 shows that the main focus is on residential buildings, and particularly on single-family homes. The reason for this is that energy flexible buildings are a relatively new area of research and residential buildings, and especially single-family homes, are far less complex compared to non-domestic buildings. Offices are the most common type of non-domestic building considered within Annex 67.

Table 7.3 The focus within the area of Building typology.

Building typology	Single-family house	Multi-family house	Non-residential building	Cluster of buildings
Percentage of examples [%]	54	14	31	17

Non-domestic buildings often include several different energy service systems: heating, ventilation and air-condition (HVAC) and often also more advanced Building Management Systems (BMS); this increased level of control allows for more flexible energy use when compared to most residential buildings. Office and multi-use buildings (e.g. universities) also typically have a larger energy demand than residential buildings making them more interesting for those who operate the energy networks. Clusters of buildings add to the complexity, as the single buildings can no longer be considered as single units. Due to the larger number, the aggregated pattern of the energy demand is smoother and less stochastic than the energy demand of the individual buildings. The interaction of clusters of buildings with the energy networks is a topic which requires further investigation, especially if several of the buildings are prosumers.

7.4.2. Energy system

In this section, only HVAC and PV systems are considered. Concerning heating: Table 7.4 shows that a majority of the case studies focus on heat pumps (in the buildings). However, 27 % (17/(46+17)*100) of the heating systems considered, are based on district heating. This shows that the focus isn't only on power grids. District heating systems also have major flexibility issues, especially concerning shaving of peak loads.

Table 7.4 The focus within the area of Energy system.

Energy system	Heat pump	District heating	Other HVAC system	PV
Percentage of examples [%]	46	17	43	32

The investigation of energy flexibility from 'Other HVAC system' – ventilation and air-conditioning – is equally distributed between residential and non-residential buildings, illustrating the diversity of the investigated climates. In the northern countries, air-conditioning is not common in residential buildings but is often used in offices. In the southern, warmer climates, air-conditioning is utilized in both building typologies.

PV systems are investigated in one third of the case studies, illustrating the growing focus of buildings as prosumers. A PV system makes a building more self-sufficient, but puts more stress on the power grid, especially if the building is heated by a heat pump and powers electrical vehicles. During a cold winter night such a building requires much electricity, while the same building exports much electricity during a sunny summer day and in office buildings during weekends. This type of building needs, therefore, advanced control in order not to be a severe problem for the grid.

7.4.3. Source of flexibility

Four sources of energy flexibility, mainly in the form of storing of energy, have been investigated in the case studies: storage of heat in the thermal mass of the buildings, storage of heat in water storages, storage of electricity in batteries and switching between different energy carriers.

Table 7.5 shows that the main focus has been on storage of heat (or cold) in the thermal mass of the buildings. This is no surprise, as this storage is normally considered to be cost-free as it is already included in the building. However, in order to utilize this storage, there is a need for a controller that can control the energy service system and the indoor temperature in such a way that the thermal mass can be charged and discharged without jeopardizing thermal comfort.

Table 7.5 The focus within the area of Source of flexibility.

Source of flexibility	Constructions	Thermal storage	Battery	Fuel switch
Percentage of examples [%]	66	34	29	6

Thermal storage in water tanks is considered by one third of the case studies. The temperature of water storage can, except for swimming pools, normally be oscillated within a larger temperature range than the thermal mass of the building. However, a large tank is often necessary in order to obtain the same amount of energy flexibility as with the thermal mass of the building.

Batteries are considered in 29 % of the examples, mainly in the form of static batteries in the building. 40 % of these are in single-family houses and 60 % are in office or multi-use buildings (e.g. universities). The rather large share of single-family houses can mainly be explained by a wish for a higher self-consumption of PV electricity due to, for example, a low feed-in tariff for the exported electricity.

Fuel switching is only considered in two examples. Fuel switching demands the ability to switch between two energy carriers e.g. in a hybrid heat pump with an integrated gas boiler. The capital cost of a dual energy system is typically higher than a single energy system. However, in areas where there currently are gas boilers, when heat pumps are introduced a dual energy system can be utilized for a period of time in order to provide energy flexibility during the transition to an electricity only energy system, for example.

7.4.4. Control system

Table 7.6 shows that the main type of controller applied is rule based, which is the traditional way of controlling energy service systems. However, in 37 % of the cases, model based controllers have been investigated. Model based controllers have the advantage that they can include forecasts and the future energy demand can be estimated using the controller. With forecasts, it is possible to utilise excess energy in the network (e.g. fill up storage) before a period with a shortage in the energy network. In this way, the duration of the following switch off of the energy service systems in the building can be extended.

Model based control is currently not often applied in the control of buildings, however, is foreseen to be much more utilized in the future.

Table 7.6 The focus within the area of Control system.

Control system	Rule based	Model based
Percentage of examples [%]	57	37

7.4.5. Results based on

Table 7.7 shows that the majority of the results are based on simulations, which indicates that the utilization of the energy flexibility in buildings is still in an early stage. However, it may be foreseen that an increasing number of cases of utilization of energy flexibility from real buildings will be available in the near future. But in-situ measurements in real buildings are expensive so it may be expected that only few buildings will be monitored to the extent that make them suitable for detailed research.

Table 7.7 The focus within the area of Results based on.

Results based on	Simulations	Measurements
Percentage of examples [%]	77	34

7.4.6. Conclusion

The 33 case studies documented by Annex 67 covers a broad variety of the building typologies, energy systems, sources of flexibility and control strategies highlighted in Table 7.1. The technologies of the four categories in Table 7.1 are mixed in many different ways in the 33 case studies, which is hoped to make this collection of case studies of energy flexibility in buildings a unique source for inspiration.

It is further hoped that these case studies may help the reader to understand how energy flexibility from buildings may be obtained, controlled and utilized.

8. Conclusions and reach out

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For the last decade, the Energy Flexible Building concept has gained wide international attention. It is seen as one possible solution that can help to overcome the new challenges imposed on the energy system, such as the variability and limited control of energy supply from renewables or the increasing load variations over the day. The concept of energy flexibility of buildings originates from the demand side management regime, though for most individuals it is a new subject, and, therefore, there is a need for an increased, shared understanding of how to obtain, characterize and control energy flexibility from buildings.

The objective of this report is to provide a summary of the wide range and depth of work conducted as part of the IEA EBC Annex 67 Energy Flexible Buildings, and to create a quick, but at the same time comprehensive, guide through the main aspects of this building concept. All material created by Annex 67 may be found on annex67.org/Publications, which also include links to articles and papers written by participants of Annex 67.

8.1. Main findings

The scope for energy flexibility depends on the type of building, the types of energy service systems in the building, the control possibilities, the climate, the time of day and year, the acceptance of the users and owners of the building, the state of the storage, etc. The actual useful energy flexibility is further determined by the needs of the surrounding energy networks to which the building may provide flexibility services.

The amount of available energy flexibility can, thus, not be expressed by a single number, as for example when dealing with energy consumption. Therefore, Annex 67 has developed a methodology including key parameters for the characterization of energy flexibility based on the response of buildings when receiving some sort of control signal – referred to here as a 'Penalty signal.'

The Penalty signal can be chosen according to specific conditions: often the Penalty signal is a price signal, but can also be a signal based on the actual CO_2 intensity of the power supply or the level of energy from renewable energy sources (RES) in an energy network. For these signals the controller should minimize the price or CO_2 emissions or maximize the utilization of RES.

The Penalty signal can either be a step response (e.g. a sudden change of the price of energy) as in Figure 3.1 in order to test different aspects of the available energy flexibility in a building or clusters of buildings, or it can be a temporal signal varying over the day and year according to the requirements of the energy networks as seen in Figure 3.2. A step response test may be utilized in simulations to test the capacity of a thermal storage system for example. Temporal signals will typically be used when utilizing the energy flexibility in an area of an energy network and will concurrently feedback knowledge on the available energy flexibility in this area.

Based on the response to a Penalty signal it is possible to obtain a Flexibility Function, which describes the response and thereby the energy flexibility of a building due to the chosen Penalty signal. By using the Flexibility Function in connection with the needs of an energy network it is possible to calculate the Energy Flexibility Saving Index (EFSI) and the Flexibility Index (FI), which state how much (cost or CO_2) the building can save (EFSI) when delivering energy flexibility and how much the building can help the energy network (FI). In this way it is possible to quantify the benefit of providing energy flexibility to the surrounding energy networks. The tested cases show that some buildings are better suited for supporting some types of energy networks while other buildings are more valuable for other networks depending on the mix of RES and problems in the networks.

EFSI and FI may possibly form the basis for a labelling scheme of buildings in order for energy network operators and aggregators to evaluate if a certain building is suited to deliver flexibility services to the surrounding energy networks.

Suitable control of the energy systems of a building is necessary for making energy flexibility available. However, today buildings are controlled in order to obtain indoor comfort for the users of the buildings in an energy efficient way. But, for providing energy flexibility to the surrounding energy networks it is necessary to consider other relevant factors such as occupant behaviour patterns, weather conditions, thermal properties and their complex interactions, without compromising the occupants' comfort. Buildings – and particularly building HVAC systems – need to be redesigned so that the potential energy flexibility of both commercial and residential buildings can be unlocked to support future smart energy networks.

Since buildings are in many cases unpredictable consumers of energy, optimal control strategies are a key technology in next-generation energy efficient buildings. However, twelve case studies carried out in Annex 67 show that traditional, rules based, control strategies are still being used in most of building subsystems even with the recent development of better alternatives. In addition, many studies have focused on independent components of the building rather than building-wide optimization, neglecting the potential efficiency improvements to be exploited for the entire system in order to achieve significant energy flexibility. There is a need to identify new methods and technologies that provide fast and optimized management and control. Appropriate methods must be efficient, robust, reliable and secure.

Stakeholder acceptance and behaviour are crucial to the success of strategies for energy flexibility in buildings. Without careful design and implementation, introducing energy flexibility has the potential to disrupt occupant lifestyles, building systems for thermal comfort and health, as well as potentially increasing cost or energy consumption. Stakeholder acceptance and behaviour may also be a barrier, but this can be reduced, or overcome entirely, if the related stakeholders are informed about flexibility measures and support the measures that are introduced. Stakeholder acceptance and behaviour is, therefore, an important source of knowledge from Annex 67 as some solutions, although technically sound, may not be feasible as the consequences for the involved stakeholders may not be acceptable to them.

There are a wide range of different stakeholders (related to both power grids and district heating/cooling networks) who may be affected by energy flexibility measures: end-users (occupants of buildings), building owners, facility managers, Energy Service Companies (ESCOs), developers, architects, contractors, and product/system suppliers. The energy flexibility is ultimately useful for aggregators, DSOs (District System Operators for both the power system and district heating systems) and TSOs (Transmission System Operators). It is important to establish a comprehensive understanding of acceptance, behaviour, and motivation at different levels of involvement for the relevant stakeholders.

Annex 67 has investigated the roles, motivations, and barriers for different stakeholders in energy flexible buildings through sixteen case studies. By systematically studying the motivations and barriers revealed in these case studies, suggestions for how to strengthen the motivations and how to eliminate or reduce the barriers have been identified. It is shown that, although 'consumer driven/centred' approaches have been emphasized in recent years, policy makers are still the lead stakeholders for strengthening opportunities and eliminating barriers in the energy system. To establish and realize the markets for energy flexible buildings, decentralization of the power hierarchy is necessary, especially for international collaboration and trading and flexibility. The aggregation market is for example in many countries still immature, and the regulations and policies of aggregation markets vary across countries. For instance, in Europe, the countries Belgium, France, Ireland, and the UK have created the regulative framework to enable both DR and independent aggregators, whereas other European countries have not yet engaged with DR reforms, for example Portugal and Spain.

Test and demonstration in real buildings is preferable when evaluating new concepts like energy flexibility in buildings, however, there are many non-controllable variables in a real building, which makes it difficult to draw reliable, significant conclusions - unless the concept is demonstrated in several buildings. Moreover, test and demonstration in real buildings is time consuming and can often be expensive. Simulation is on the other hand relatively cheap and fast, so that parametric studies can easily be performed. However, since all inputs and the environment are often specified in a very simple way, this may lead to conclusions that are not viable in real life.

Hardware-in-the-loop test facilities, where parts of a system are physical components while others are virtual, has, therefore, been investigated in Annex 67 in order to establish a bridge between simulations and tests in real buildings. Compared to field testing, dynamic tests in a controlled laboratory environment with a semi-virtual approach offer the flexibility of imposing well-controlled and repeatable boundary conditions on real physical equipment, without waiting for given conditions to occur in the real world. The same system can be tested in different environments (e.g. connected to different building types exposed to different climatic conditions) quickly by re-configuring the simulation of the virtual parts. Unwanted interferences (e.g. from users) can be avoided and the accuracy of measured data is generally better in a controlled laboratory than in a field study. Of course, field tests are still necessary for a complete performance assessment, but semi-virtual testing allows going further than conventional laboratory tests at a fraction of the cost of a pilot project. Nine hardware-in-the-loop test facilities have been described in Annex 67, of which special purpose tests have been carried out and described for six of the nine test facilities in order to show the strength of the concept. Based on the performed tests, advice on how to carry out future tests in hardware-in-the-loop have been given.

To support the investigation of different possibilities to obtain and control energy flexibility from buildings, the participants of Annex 67 have studied several specific cases either by modelling or by measuring in real buildings or systems. As energy flexibility from buildings for most is a new area, well documented examples will often be easier to comprehend than theoretical descriptions of this very complex area. Annex 67 has, therefore, documented 33 case studies.

The 33 case studies cover a broad variety of building typologies, energy systems, sources of flexibility and control strategies. The technologies are mixed in many different ways in the 33 case studies, which it is hope to make this collection of case studies of energy flexibility in buildings a unique source for inspiration.

8.2. Reach out

The developed methodology for characterization of energy flexibility from buildings is considered as a major breakthrough with the potential of becoming a common basis for future research and development with regards to describing and quantifying available energy flexibility from buildings. However, further tests of the methodology are required.

Primarily, the work of Annex 67 has focused on understanding how a building may be controlled in order to deliver energy flexibility to the energy networks. However, the single unit "seen" from the grid side is typically not an individual building but rather a feeder (electricity) or a branch of a district heating/cooling system. This feeder or branch serves a cluster of buildings, and the grid "sees" the aggregated energy demand of these clusters, rather than single buildings. Unless a building has a very high energy demand, the possible energy flexibility from a building is typically too small to be bid into a flexibility market. An aggregation of the energy flexibility from several/many buildings is thus mandatory in order to make an impact. Annex 67 have investigated energy flexibility from clusters of buildings, but more work is needed in order to fully understand the aggregated energy flexibility from clusters of buildings and how to control this.

The transition to renewable energy systems will in many areas lead to an increased use of electricity - e.g. by heat pumps or resistance heaters – even if the foreseen reduction in the space heating demand via energy renovation is realized. The expected penetration of electrical vehicles will further increase the loads in the distributed grids but may also be used for peak shaving using their batteries. This will in many distribution grids call for major reinforcement of the existing grids or a more intelligent way of consuming electricity. However, during the transition many buildings will still be supplied by the original energy carriers like gas and oil. Other buildings are already now connected to district heating/cooling or will in the future be connected. There is, therefore, a need for a deeper understanding on how the existing multi-carrier energy systems (power, district heating/cooling, gas and oil) can support the transition to energy systems based entirely on RES when phasing out fossil fuels. How can buildings, by switching between new and old energy carriers, help stabilize the energy systems so that these become resilient and thus be able to withstand the coming challenges?

Annex 67 has explored what drives stakeholder acceptance and their motivations for implementing energy flexibility in buildings. However, more knowledge is needed in order to fully understand the stockholders so that they can be motivated to play a more active role in the implementation of buildings as an active asset in the future energy systems.

Annex 67 has revealed that one of the main motivators for utilization of the energy flexibility from buildings is financial. It is, therefore, important to investigate and develop business models where all the stakeholders obtain proper remuneration for providing or utilizing energy flexibility. In order to facilitate an economically efficient result, it will be necessary to engage with policy makers establishing the proper legal and regulatory frameworks.

The above is important knowledge when designing the energy systems of the future. The knowledge is important for all stakeholders but especially for energy system operators and developers, aggregators and legal entities. Annex 67 has, therefore, proposed a follow-up annex to Annex 67 in order to carry out the above described investigations. The proposed new annex is named IEA EBC Annex 82 Energy flexible buildings towards resilient low carbon energy systems (https://www.iea-ebc.org/projects/project?AnnexID=82).

9. Acknowledgements

The work described in this report has been done in the frame of IEA EBC Annex 67 Energy Flexible Buildings as an expert cooperation among 16 countries. National governmental and different project based funding sources made this cooperation possible.

The participants of Annex 67 are thanked for their hard and dedicated work, which has made Annex 67 an success.

A special thank to Achim Geissler, University of Applied Sciences Northwestern Switzerland, Switzerland, who have carried out the internal review of the report.

A major thank you to:

Per Heiselberg, Aalborg University, Denmark
Dietrich Schmidt, Fraunhofer Institute for Energy Economics and Energy System Technology IEE, Germany
Josef Ayoub, Natural Resources Canada, Canada

who performed an external review of the report.

For the Excecutive Commitee of IEA EBC the report was reviewed by:

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