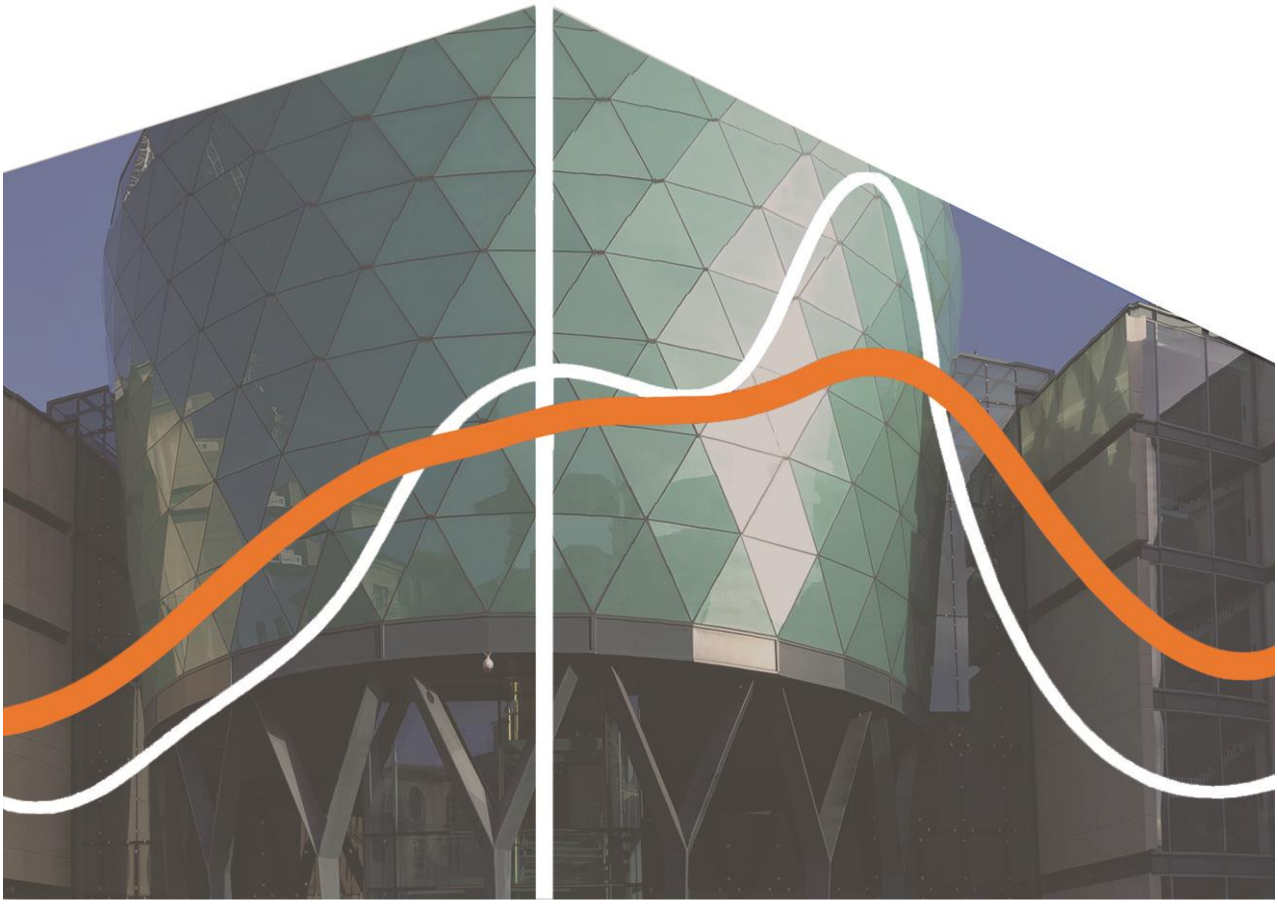
Energy in Buildings and
Communities Programme

International Energy Agency

Examples of Energy Flexibility in Buildings

Energy in Buildings and Communities Programme
Annex 67 Energy Flexible Buildings

September 2019



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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 ScaleAnnex 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

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

Increasing global energy demand over past decades, a foreseen reduction of available fossil fuels and increasing evidence of global warming have generated a great interest in renewable energy sources. However, energy sources such as wind and solar power have an intrinsic variability that can seriously affect the stability of the energy networks if they account for a high percentage of the total generation. Therefore, future high penetration of variable renewable energy sources forces a transition from generation on demand, to consumption on demand in order to match the instantaneous energy generation. In practice, this means that the energy consumption needs to become flexible to keep supply networks stable. Buildings are expected to play a central role in this transition, where consumers and “prosumers” (e.g. buildings with PV) become energy flexible in order to satisfy the generation and/or storage needs of the energy grids, either as single buildings or as clusters of buildings.

Energy Flexibility of buildings is typically obtained by using some type of storage in the building to shift the energy use from periods with a high price for the energy (e.g. when there is low input from renewable energy sources (RES) and therefore a high amount of CO_2 in the energy network) to periods with a low price (e.g. when there is high input from RES in the energy network).

The storage can be in the thermal mass of the building (walls, floors, ceilings, but also the building’s contents in some cases), where heat is stored and discharged by varying the indoor temperature of the rooms. This, however, may cause discomfort for the users, so heat can also be stored in containers not directly connected to the inhabited spaces. Such containers can be water tanks in the form of a domestic hot water tank or indoor swing pools, but may also be dedicated buffer tanks in combination with space heating or cooling systems. Electricity can be stored in its original form in batteries, for example, in connection with a PV system or in the battery of an electrical vehicle, which is docked at the building.

However, in order to harvest the Energy Flexibility of the storage, there is a need for an energy service system typically in the form of a heating system (e.g. a heat pump), a ventilation system, a cooling system or an electrical system, that are controlled in such a way that the storage can be charged and discharged at specific times, to provide flexibility services for the energy network, while also creating savings for the building owner.

Control strategies for obtaining Energy Flexibility range from very simple controls, like a heat pump being switched off every day during a predefined period, to more complex rule-based controls where several constrains are included (e.g. that the heat pump is switched off unless the indoor temperature is too low and only if the price of electricity is above a certain level), and further to model-based control, including forecasts of weather, occupancy behaviour (these two variables provide a forecast of the future demand) and energy prices.

The actual useful Energy Flexibility is, however, dependent on the need of the surrounding energy networks.

So, determination of the energy flexible service that buildings are able to provide to the energy networks is not a simple thing to define. Compared to energy efficiency of buildings, the subject of energy flexible buildings represents a relatively new area of research and development.

Energy flexibility of buildings and how to obtain and control this cannot easily be explained, especially as there are a wide range of stakeholders who could be involved, not all of whom will be experienced in the supply and demand of energy in buildings. However, good examples are often much easier to understand than definitions. For this reason, IEA EBC Annex 67 have in this report collected a number of examples on how to investigate, obtain and control energy flexibility from buildings.

Many types of buildings, storage, energy systems and control strategies have been investigated via simulations and/or measurements in the 33 examples included in this report. This will hopefully provide the reader with valuable insight into the different ways of obtaining Energy Flexibility from buildings and, thus, be a source of inspiration for future research and development in this area.

The report can either be read in full, or the reader may select specific examples of special interest.

Table of content

Teasers on how to control of energy flexibility in buildings

Abbreviations

Abbreviations	Meaning
ANN	Artificial neural network
AC	Alternating current
ACHP	Air Coupled Heat Pump
ADR	Automated Demand Response
ACST	Air Handling Unit Cooling Storage Tank
AEEF	Available Electric Energy Flexibility
AHU	Air Handling Unit
ASM	ASM Terni – a DSO in Terni, Italy
B2V	Building-to-vehicle
B4B	Battery for Buildings – 2nd life battery storage system
BAT	Battery
BEMS	Building Energy Management System
BESS	Battery Energy Storage Systems
BIPV	Building Integrated Photovoltaic
BMS	Building Management System
BR	Building Regulation
CCGT	Combined Cycle Gas Turbine
CCH	Compression chiller
CEC	Non-renewable cumulative energy consumption
CHP	Combined Heat and Power
CIBSE	Chartered Institute of Building Services Engineers
COP	Coefficient Of Performance e.g. of the heat pump
CWT	Chilled water temperature adjustment
D	Detached dwelling
DC	Direct current
DER	Distributed energy resources
DH	District Heating
DHW	Domestic Hot Water
DR	Demand Response
DT .	Définition Technologique – version of the 2nd life battery system
EGRID	egrid applications & consulting GmbH
ETP	Equivalent thermal parameter model
ELSA	Energy Local Storage Advanced system
EMS	Energy Management Systems
EMPC	Economic model predictive control
ENG	Engineering Ingegneria Informatica S.p.A
EPEX	European power exchange
DSO	Distribution System Operator
ε-NTU	Effectiveness – Number of Transfer Units
EV	Electric Vehicle

Abbreviations	Meaning
FI	Flexibility Index
FMU	Functional mock-up unit
FVM	Finite Volume Method
GCHP	Ground Coupled Heat Pump
GSA	Global setpoint adjustment
GSCabs	Absolute grid support coefficient
GSCrel	Relative grid support coefficient
HWST	Hot water storage tank -
HP	Heat Pump
HEX	Heat exchanger
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communications Technology
KPI	Key Performance Indicator
LCD	Liquid crystal display
LEC	Local Energy Communities
LED	Light emitting diode
Li-ion	Lithium Ion
LNEG	National Laboratory of Energy and Geology
ME	marginal emissions
MEF	Marginal emissions factor
MOGA	Multi-objective genetic algorithm
MPC	Model Predictive Controller
NO3	Norwegian bidding zone
nZEB	Nearly Zero-Energy Building(s)
OCGT	Open Cycle Gas Turbine
OCP	Optimal Control Problem
O&M	Operation and Maintenance
OPC	(Object Linking and Embedding) OLE for Process Control
OpenADR	Open Automated Demand Response
Org	Original construction state
OS	Operational Strategies
OTH	Operation Time for Heating
PCM	Phase Change Material
PER	Primary energy ratio
PLC	Programmable Logic Controller
PRBC	Predictive rule based controls
PV	Photovoltaic
Q_h	Heating demand
RC	Network consisting of resistors and capacities for emulating the heat flow in a building
RBC	Rule based controller
Ref	Refurbished construction state
RES	Renewable Energy Sources
RES	Residual load
R_{si}	Heat transmission resistance surface/room air

Abbreviations	Meaning
RWTH	Rheinisch-Westfälische Technische Hochschule Aachen
SASMI	Skills Academy for Sustainable Manufacturing and Innovation
4SC	Self-Consumption ratio
SCST	Space Cooling Storage Tank
SD	Semi-detached Dwelling
SFH	Single Family House
SH	Space heating
SOC	State of Charge
SPF	Seasonal Performance Factor
SS	Self-Sufficiency ratio
SSEC	Solar simulator/environmental chamber at Concordia University
T	Terraced dwelling
TABS	Thermally Activated Building System
TES	Thermal energy storage
TRL	Technology Readiness Level
TSO	Transmission System Operator
UFH	Under-floor heating
UTRC	United Technologies Research Centre Ireland Ltd.
V2B	Vehicle-to-building
VRF	Variable Refrigerant Flow
VSD	Variable speed drive

1. Introduction to IEA EBC 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 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, however, most buildings are not well-controlled. In the 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.

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, before now there was no overview or insight into how much energy flexibility different types of building and their usage may be able to offer to the future energy systems. This was the main, although not sole, reason why IEA EBC Annex 67 Energy Flexible Buildings was initiated.

1.1. IEA EBC Annex 67

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

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

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

1.1.1. Terminology for and characterization of Energy Flexibility in buildings

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

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

1.1.2. Determination of the available Energy Flexibility of devices, buildings and clusters of buildings

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

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

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

1.1.3. Demonstration of and stakeholders perspective on Energy Flexible Buildings

In order to be able to convince policy makers, energy utilities and grid operators, aggregators, the building industry and consumers about the benefits of buildings offering 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 reported 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 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 annex67.org/Publications/Deliverables.

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

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

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

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

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

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

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

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

2. Introduction to the report

Compared to energy efficiency of buildings, the area of energy flexibility of buildings is for most parties a rather new area of research and development. It is, however, an area that may become just as important as efficiency in facilitating the transition of energy systems from fossil fuels to renewable energy, as described in the former chapter.

Energy flexibility of buildings and how to obtain and control this cannot easily be explained, especially as there are a wide range of stakeholders who could be involved, not all of whom will be experienced in the supply and demand of energy in buildings. In addition to this, there was before Annex 67 no common framework on how to evaluate and assess the flexibility (see (Knotzer and Pernetti, 2019) for the developed Annex 67 methodology). However, good examples are often much easier to understand than definitions. For this reason this report contains a number of examples on how to investigate, obtain and control energy flexibility from buildings.

The many participants of Annex 67 have dealt with energy flexibility in different ways including the developed Annex 67 methodology (Knotzer and Pernetti, 2019). In order to enhance the benefit of reading the report, this chapter gives an introduction to energy flexibility in buildings, a guideline on how to read the report, and some statistics on the displayed examples.

2.1. Energy flexibility of buildings

Energy flexibility of buildings is typically obtained by decoupling energy demand and energy delivery using storage in the building to shift the energy use e.g. from periods with a high price for the energy (e.g. due to a low amount of energy from renewable energy sources and therefore a high amount of CO_2 in the energy network) to periods with a low price. Energy flexibility can also be obtained by peak shaving of 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, simplistic method is not dealt with in the examples presented in this report.

Figure 2.1 illustrates different ways of obtaining energy flexibility; Seen from the right:

Building mass: walls, floors, ceilings and furniture of buildings contain a certain amount of mass and thereby a certain thermal capacity, which can be utilized to store energy. During shortage of energy the heating or cooling system can, therefore, be switched off for a period without decreasing the comfort of the users. How long a period depends on the thermal mass and the heat loss of the buildings, but can be 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 storage outside of the occupied spaces. 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 also be indoor swimming pools. The storage can, instead of water, utilise PCM (phase change materials).

Fuel switch: if a building utilizes different fuels (e.g. a gas boiler and a heat pump) energy flexibility may be obtained by using the gas 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 stored. Batteries can either be the battery of an electrical vehicle or the battery of e.g. a PV system. The battery is charged during periods with surplus of electricity in the grid and thereby cheap, and discharged during periods when there is a shortage of electricity or otherwise beneficial for the grid. The battery can also be used for increasing self-consumption of electricity from a PV system for example.

Generation: many buildings are becoming prosumers – i.e. they no longer only consume energy, they also produce energy through PV, micro wind turbine or CHP (combined heat and power production) plant.

Networks: a building may be connected to one or more energy networks. Buildings are typically connected to a power grid (electricity) but may also be connected to a district heating or gas grid.

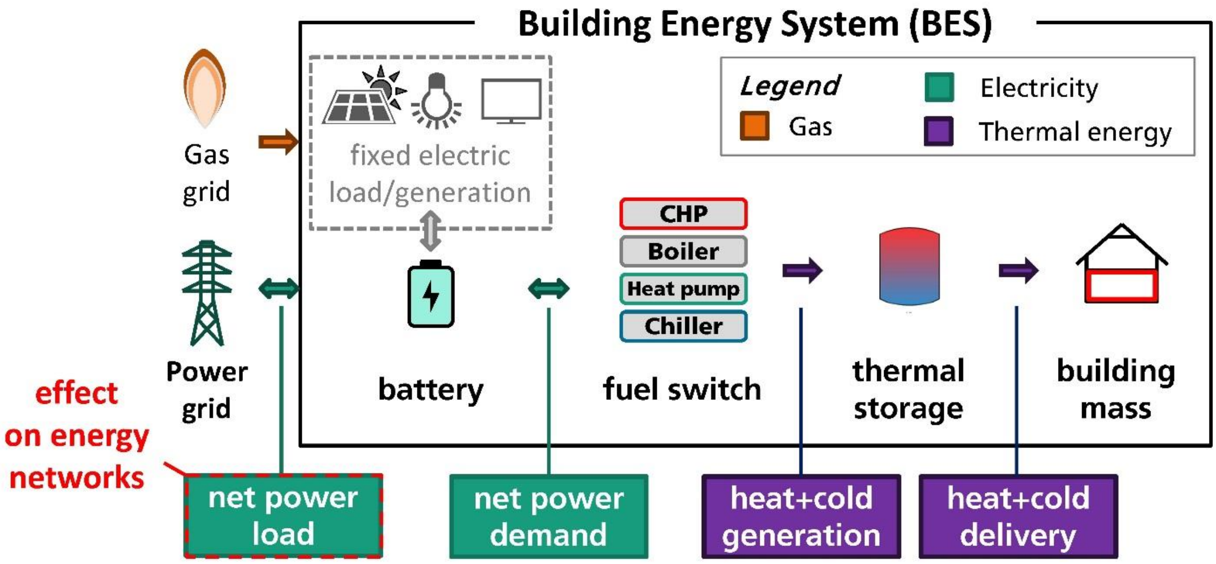


Figure 2.1 Sources for obtaining energy flexibility (Klein et al., 2017).

In order to utilize the aforementioned sources for energy flexibility there is a need for control. The following examples utilized/investigated different types of control, ranging from very simple control like a heat pump being switched off every day during a predefined period, to more complex rule-based control where several constrains are included (e.g. that the heat pump is switched off unless the indoor temperature is too low and only if the price of electricity is above a certain level), and further to model-based control including forecasts of weather, occupancy behaviour (these two provide a forecast of future demand) and energy prices.

2.2. Reading guide

The report can of course be read in full, however, if the reader is interested in some specific areas of energy flexibility and not in others, this section provides a guide to find the interesting examples.

The report is subdivided in the following way:

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

The main features of 33 examples/teasers are noted in Table 2.2 and 2.3 (with an 'X'). The features are grouped in five areas: Building typology, Energy system, Source of flexibility, Control system and what the Results based on (models or measurements). These five areas are further subdivided in to different technologies which are briefly explained in Table 2.1. It is the hope that Tables 2.2 and 2.3 will help the reader in finding the examples/features of most interest.

The examples/teasers 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 examples/teasers or even contradict in some cases.

The examples from Tables 2.2 and 2.3 are further shown on maps in figures 2.2-2.5 in order to provide an overview of the involved countries and the climate conditions of the different examples/teasers.

Table 2.1. The features of the different examples/teasers of Tables 2.2 and 2.3.

	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 building	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 located physically next to each other or not be physically connected but have the same aggregator controlling their energy flexibility – e.g. buildings with the same

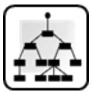
	Icon	Technology	Explanation
			type of heating system e.g. a heat pump, and are controlled as a group
Energy system		Heat pump	The utilized heat pumps are located in the buildings and may both be ground source or air source heat pumps
		District heating	Is considered in the sense, that the building(s) 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, ceilings 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 demand – e.g. a gas boiler and a heat pump
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 give 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 in real buildings 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

Table 2.2 Examples of how to obtain energy flexibility from buildings.

	Building typology				Energy system				Source of flexibility				Control system		Results based on	
Chapter	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
3	X								X				X		X	
4	X								X				X		X	
5		X				X			X				X		X	
6	X	X				X	X		X				X		X	
7		X			X			X	X	X			X		X	X
8	X				X					X				X	X	
9	X				X		X		X	X		X		X	X	
10	X			X	X				X	X				X	X	
11	X			X		X		X	X				X		X	
12			X				X		X				X			X
13			X								X			X		X
14			X				X	X			X		X			X
15			X					X	X	X	X		X		X	X
16			X		X		X		X	X	X	X			X	
17			X						X					X	X	
18			X	X		X								X	X	X

Table 2.3 Examples of how to obtain energy flexibility from buildings. Teasers for description in the Annex 67 report: Control strategies and algorithms for obtaining energy flexibility in buildings (chapters 18-30) and in the Annex 67 technical report: Modelling of possible Energy Flexibility in Single Buildings and Building Clusters (chapters 31-35).

	Building typology				Energy system				Source of flexibility				Control system		Results based on	
Chapter	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
19			X			X	X		X				X	X	X	X
20	X				X				X					X	X	
21	X				X	X	X	X		X	X		X	X	X	
22	X	X			X				X	X				X	X	
23	X				X			X			X		X		X	
24	X				X				X	X			X		X	
25	X						X		X	X			X		X	
26	X			X	X					X				X		X
27	X				X		X	X	X					X		X
28			X				X		X				X		X	
29	X						X		X				X			X
30			X				X	X	X		X		X		X	
31		X		X	X				X				X		X	
32			X		X		X	X			X				X	X
33	X						X	X	X		X				X	
34	X			X	X					X			X	X	X	X
35	X				X		X	X			X		X		X	

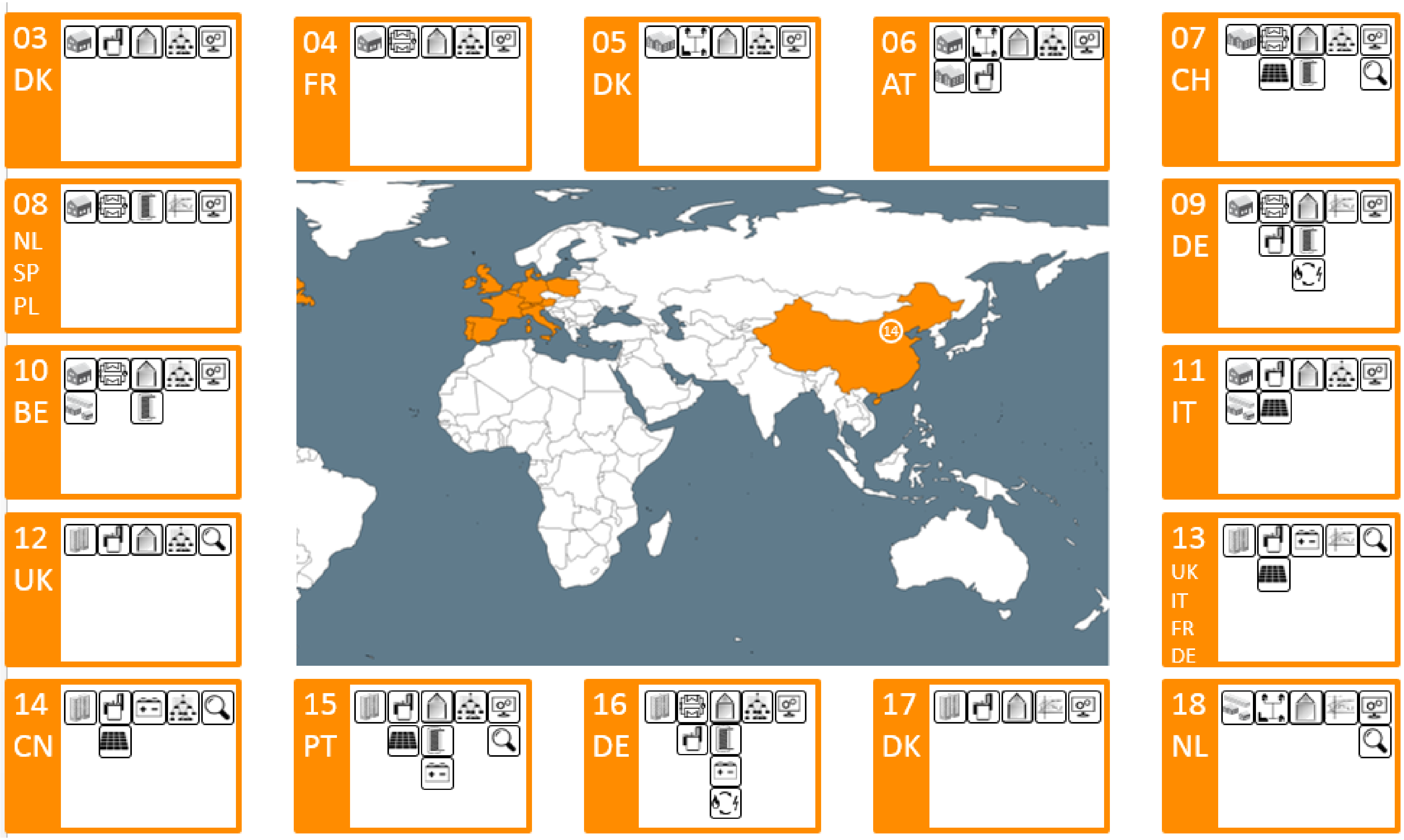


Figure 2.2 The examples from Table 2.2 shown on a map in order to give an impression of the climate conditions investigated in the different examples. The number in top left corner of the examples refer to chapter numbers in the report. The location of the European examples in shown in figure 2.3.

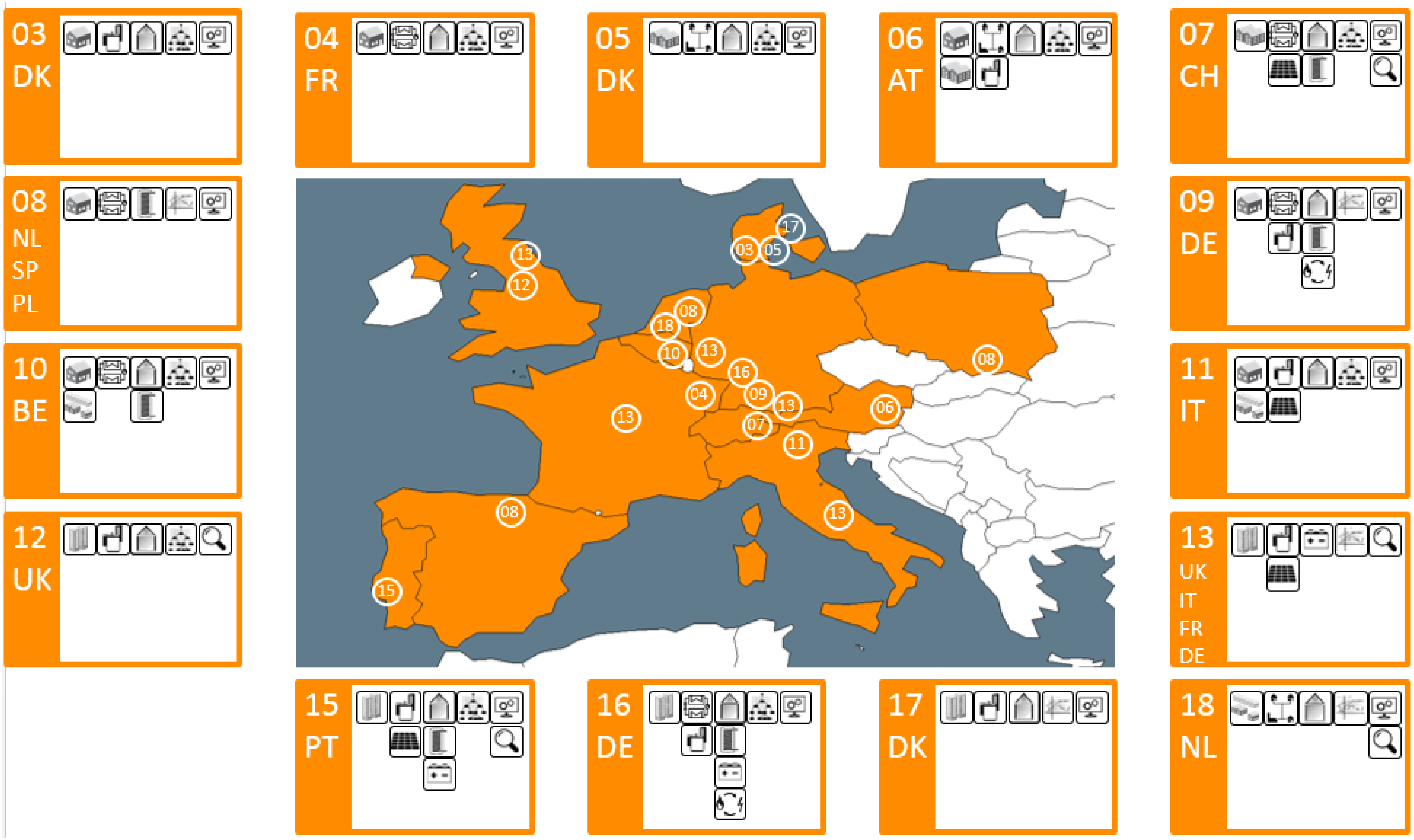


Figure 2.3 The examples of Figure 2.2 zoomed in on Europe where most examples originate.

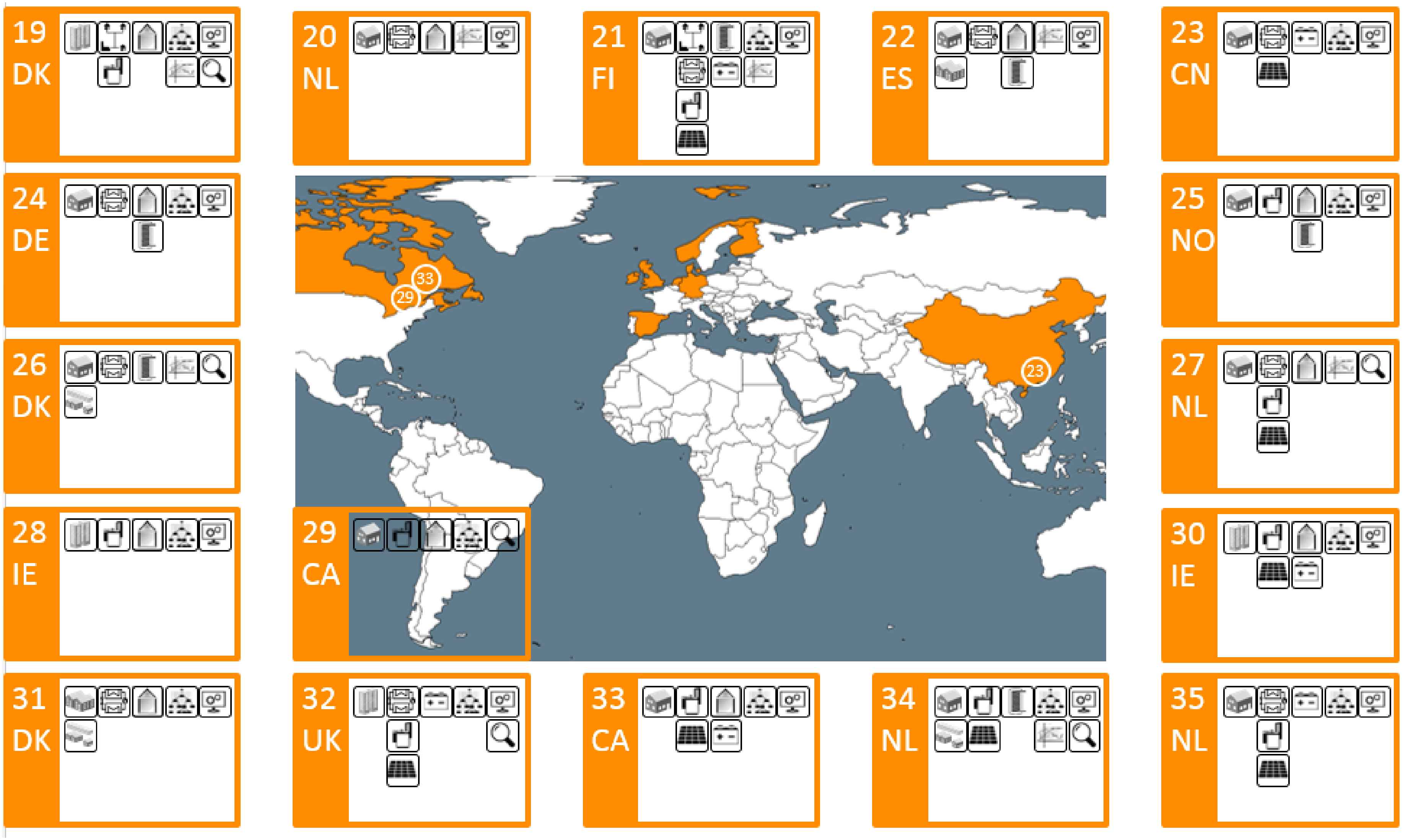


Figure 2.4 The teasers from Table 2.3 shown on a map in order to give an impression of the climate conditions investigated in the different teasers. The location of the European examples in shown in figure 2.5.

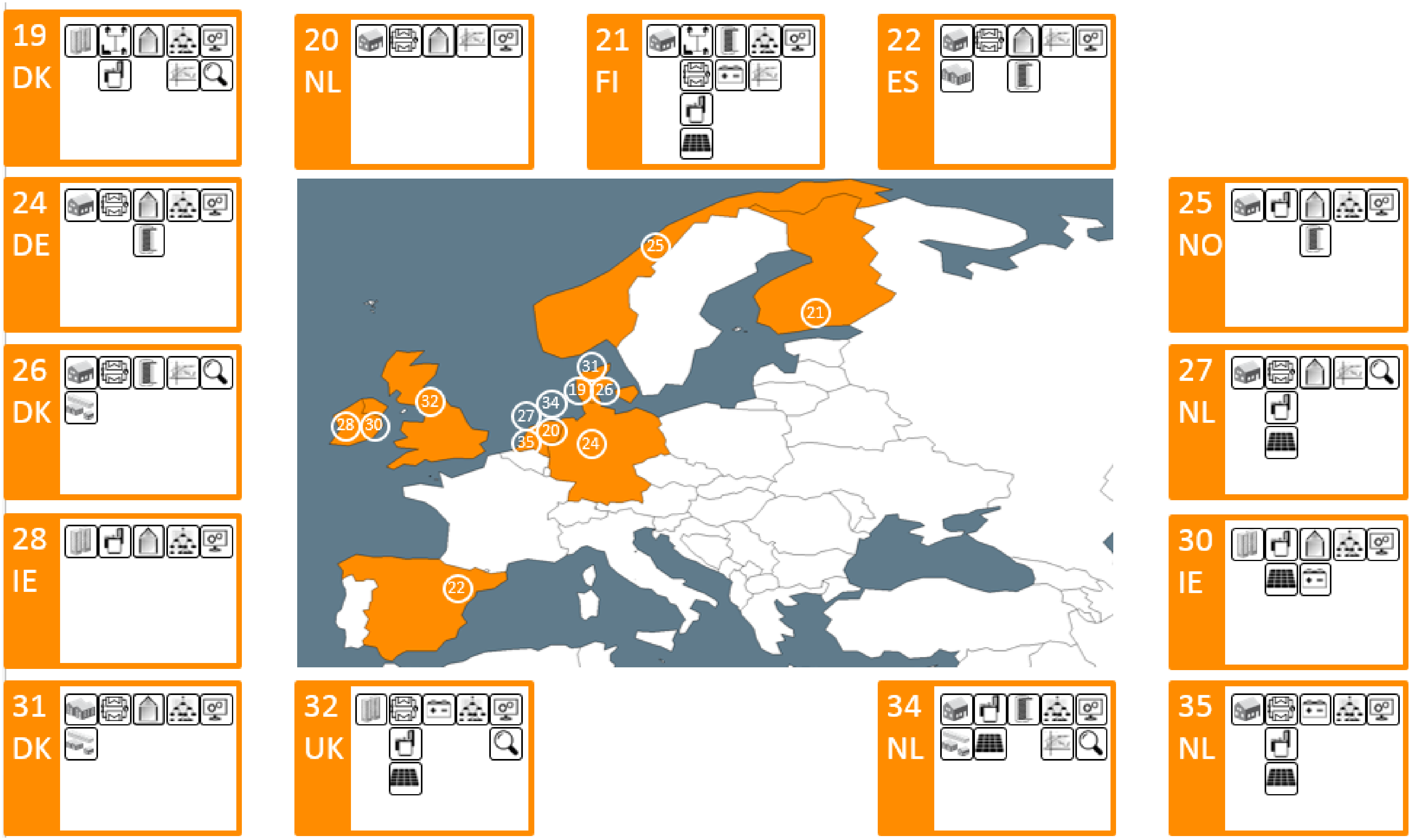


Figure 2.5 The examples of Figure 2.4 zoomed in on Europe where most teasers origin.

2.3. Statistics

Due to the many participating countries in Annex 67 (16 countries) - see Figures 2.2-2.5 - and the rather large numbers of examples/teasers in this report, it is possible to perform some statistical analysis on where the focus currently is with regard to buildings and technology. The following Tables 2.8-2.12 give some statistics on the flexibility features investigated in the examples/teasers, which provide an impression of where the focus currently is with regards to energy flexibility in buildings. The number of examples and teasers investigating the different features is in the following given as the percentage of the total number of examples and teasers = 33. **As several features are investigated in the examples/teasers, and as not all examples/teasers have an X in each of the five areas - see Tables 2.2 and 2.3, this means that the total percentage of Tables 2.4-2.8 does not add up to 100 %.** However, the values of the tables gives an idea of the focus of the examples/teasers.

2.3.1. Building typology

Table 2.4 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-residential buildings such as e.g. offices.

Non-residential buildings invariably have several different energy service systems: heating, ventilation and air-condition (HVAC) and often also a rather advanced Building Management System (BMS) by which more energy flexibility can be obtained compared to residential buildings. Non-domestic buildings have further also typically 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 with the energy networks is further necessary to incorporate in the investigation of clusters of buildings, especially if several of the buildings are prosumers.

Table 2.4 The focus within the area of Building typology.

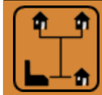
	Building typology	Number of examples [%]
	Single-family house	54
	Multi-family house	14
	Non-residential building	31
	Cluster of buildings	17

2.3.2. Energy system

In this section only HVAC and PV systems are considered.

Concerning heating: Table 2.5 shows that a majority of the examples/teasers focus on heat pumps (in the buildings). However, 27 % of the heating systems (17/(46+17)*100) 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 2.5 The focus within the area of Energy system.

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

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 are investigated in one third of the examples/teasers, illustrating the growing focus of buildings as prosumers. PV 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 to avoid causing severe problems for the power grid.

2.3.3. Source of flexibility

Four sources of energy flexibility, mainly in the form of energy storage, have been investigated in the examples/teasers: storage of heat in the thermal mass of the buildings, storage of heat in water storage, storage of electricity in batteries and a switch between different energy carriers.

Table 2.6 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 the thermal comfort.

Table 2.6 The focus within the area of Source of flexibility.

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

Thermal storage is considered by one third of the examples/teasers. The temperature of water storage can (except for swimming pools - dealt with in chapter 26) 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 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 e.g. university buildings. 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.

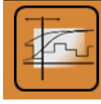
Fuel switch is only considered in two examples. Fuel switch demands the ability to switch between two energy carriers e.g. in a hybrid heat pump with an integrated gas boiler. The capital cost of a dual energy system is typically higher than a single energy system. However, in areas where there are currently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

2.3.4. Control system

Table 2.7 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 period of the energy service systems in the building, can be extended.

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

Table 2.7 The focus within the area of Control system.

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

2.3.5. *Results based on*

Table 2.8 shows that the main proportion of the results are based on simulation, which clearly indicates that the utilization of the energy flexibility in buildings is still in an early stage. However, it is expected that an increasing number of cases of utilization of energy flexibility from real buildings will be available in the near future.

Table 2.8 The focus within the area of Results based on.

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

2.4. Concluding remark

It is the intention that this 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.

When dealing with energy flexibility in buildings in future case studies, it should, however, seriously be considered to utilize the methodology developed in Annex 67 (Knotzer and Pernetti, 2019) on how to characterize energy flexibility in buildings. By doing this, the methodology may by time be developed into a common methodology making it easier to compare the results from different case studies and thereby enhance the mutual benefit of these studies.

Examples of energy flexibility in buildings

3. Influence of envelope, structural thermal mass and furnishings on space heating energy flexibility

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3.1. Abstract

Thermal energy storage in the indoor environment of buildings is an interesting and cost-effective solution to provide energy flexibility. However, buildings have complex thermodynamics and a deeper understanding of the latter is necessary to assess, control and optimize their thermal energy storage capacity and energy flexibility of space heating.

The numerical study presented in this chapter investigates and quantifies the impact of the main building parameters on the energy flexibility of space heating for single-family houses in Denmark. Indoor temperature set point modulation (and thereby activation of the thermal storage in the building) based on an electricity price signal has been used as a demand side management strategy. 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.

The results of this numerical investigation show that the level of insulation in the envelope is the building characteristic with the largest effect on the energy flexibility of space heating. To a lesser extent, the total thermal inertia also presents a significant influence. In addition, for the investigated dwelling cases with low structural thermal mass, the presence of furnishings within the thermal envelope can increase the energy flexibility by up to 21% for the investigated cases. It is therefore recommended that furnishings are accounted for when performing dynamic building simulations and energy flexibility assessments. Finally, it was also found that phase change materials integrated into wallboards or in furniture elements can substantially increase the energy flexibility of space heating in domestic buildings.

3.2. Background and objectives

Previous investigations have been conducted in different countries to study the ability of buildings to store thermal energy in their indoor environment for modulation of their heating demand profile over short periods of time.

The thermal performance of the building envelope determines how well the built environment can conserve accumulated thermal energy whilst maintaining the thermal comfort of occupants. The latter plays a major role in the temporal aspect of the energy flexibility of buildings. During winter periods, poorly insulated buildings can only sustain very short shifting of the space heating load while well insulated buildings can turn off their heating system for more than 24 hours (Le Dréau and Heiselberg, 2016).

The thermal inertia of a building's mass determines the maximum storage capacity of the indoor environment. The more thermal mass in the building's structure, the more heat energy can be accumulated during off-peak periods and partly recovered during peak periods (Reynders et al., 2015). Phase change materials (PCM) present a large energy storage density and can thus be employed to significantly increase the thermal inertia of buildings with lightweight structures. The integration of PCMs is therefore beneficial for improving the ability to shift the space heating load (Barzin et al., 2015).

The type of heat emitter also has an important influence on the activation of the building's thermal mass and its energy flexibility. Convective systems quickly activate the indoor air volume which has a low heat storage capacity. In addition, higher indoor air temperatures induce higher ventilation, infiltration and transmission heat losses. On the other hand, under-floor heating (UFH) or thermally activated building system (TABS) have a larger time constant but can store the thermal energy directly inside the heavy floor elements of a building, which improves the heating storage and energy flexibility (Le Dréau and Heiselberg, 2016).

The numerical study presented in this chapter aims at quantifying and ranking more precisely the influence of the different main building parameters on the energy flexibility of space heating in Danish dwellings. The implications of additional indoor thermal mass from PCM and furnishings are also studied (Johra et al., 2018).

3.3. Method

3.3.1. Study cases

The cases investigated for this numerical study are variations of a typical Danish single-family house (four occupants) with 126 m² of heated floor area. The geometry of the dwelling remains the same in all scenarios but the material types and thicknesses are varied 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 structural thermal inertia 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, furnishing, PCM integrated in furniture elements, PCM wallboards placed on walls and ceilings) (Johra, 2018). The "furnishings" are here defined as all items within the indoor environment that are not comprised in the construction elements of the building. Accordingly, furniture elements such as sofas, beds, tables, chairs, closets, finishing parts, accessories, books, plants, clothes and all appliances which are not emitting heat, are considered as "furnishings" (Johra and Heiselberg, 2017). The main information about the building cases is summarized in Table 3.1.

3.3.2. Numerical modelling of the building

Thermodynamic multi-zone models (10 thermal zones) of the building study cases have been created with the MATLAB-Simulink software. The heat transfer through the different planar construction elements is calculated with a one-dimensional finite volume method (FVM) formulation comprising a limited number of control volumes (Resistance-Capacitance thermal network).

Table 3.1 Characteristics of the building cases.

Building envelope category	House 1980's			Passive House		
Structural thermal mass category	Light	Medium	Heavy	Light	Medium	Heavy
Effective thermal mass (Wh/K.m² gross floor)	30 - 40 - 45	50 - 60 - 70	90 - 100 - 110	30 - 40 - 45	50 - 60 - 70	90 - 100 - 110
Building envelope heat losses (W/K.m² gross floor)	1.12	1.13	1.13	0.37	0.37	0.37
U-value windows (W/K.m²)	1.7			0.78		
g-value windows (-)	0.63			0.5		
Ratio windows / gross floor area (%)	16.7 %			26.9 %		
Windows area (m²)	25.1			40.4		
Air infiltration (ACH)	0.2			0.07		
Ventilation (ACH)	0.4			0.4		
Heat recovery (-)	0			0.8		
Air flow heat losses (W/K)	64			15.6		
Air flow heat losses (W/K.m² gross floor)	0.43			0.1		
Yearly radiator heating need with set-point at 22 °C (kWh/K.m² net floor.year)	164	160	155	14	13	12
Maximum radiator heating power (W/m² net floor)	75			25		
Under-floor heating type	Wood floor	Concrete screed	Concrete screed	Wood floor	Concrete screed	Concrete screed
Yearly under-floor heating need with set-point at 22 °C (kWh/K.m² net floor.year)	160	151	157	15	13.5	13
Nominal water flow per UFH loop (l/h)	170			125		
UFH maximum inlet water temperature (°C)	47	43	43	35	30	30

The UFH system is modelled by coupling a "plug flow" model with the ε-NTU (Effectiveness – Number of Transfer Units) method which accounts for the thermal interactions between the adjacent tubes of the hydronic circuits. The convective radiators are modelled with a first order transfer function.

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 Energain® (DuPont, 2012). The heat transfer inside the elements is calculated with a fully implicit one-dimensional FVM formulation. The melting/solidification phase transition process at constant temperature is simulated with an enthalpy formulation.

The simulation time step is set constant to 60 seconds which insures numerical stability. The entire building model and its sub-components have been validated against well-known commercial software (BSim and COMSOL Multiphysics), experimental data, and with a BESTEST procedure (Johra, 2018).

3.3.3. Control strategy for energy flexibility of the building

The principle of the control strategy for energy flexibility of buildings in this study is to accumulate thermal energy in the indoor space when there is an excess of renewable energy production, and reduce heating energy usage when energy production from renewable energy sources is insufficient. A large share of the electricity production in Denmark comes from wind turbines. The electricity spot price is, therefore, a good indicator of the availability of renewable energy production and the energy demand. Consequently, the Danish electricity spot price of 2009 is used as the control signal to drive the energy storage in the building (see Figure 3.1).

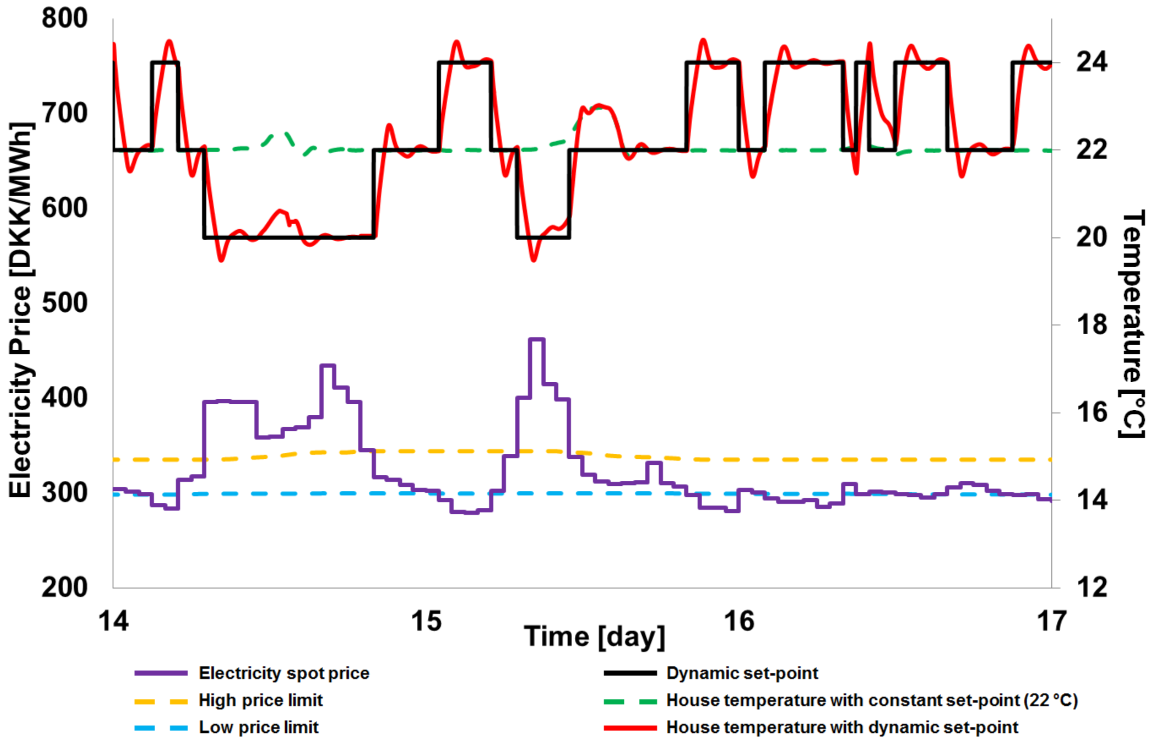


Figure 3.1 Example of control strategy for energy flexibility of buildings by means of indoor temperature set point modulation with electricity price control signal.

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. Accordingly, the indoor temperature set point modulation for thermal energy storage is as follows:

- 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 energy;
- when the electricity spot price rises above the high price limit, the building 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 3.1).

The indoor 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).

3.3.4. Energy flexibility index

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. To quantify this load shifting, the repartition of the annual heating use between the different price categories of the cases with set point modulation are compared to a reference case which does not have set point modulation (constant set point at 22 °C all the time). The energy flexibility index “F” is then calculated according to Equation (3.1) to assess the relative change of the distribution of energy use due to the set point modulation strategy.

$$\mathrm{F} = \left[\left(1 - \frac{\%\mathrm{High}}{\%\mathrm{High}_{\mathrm{ref}}}\right) + \left(1 - \frac{\%\mathrm{Medium}}{\%\mathrm{Medium}_{\mathrm{ref}}}\right)\right] \times \frac{100}{2} \tag{3.1}$$

Where $\%High$ and $\%Medium$ are the percentages of yearly heating energy (relative to the total yearly heating needs) used during high and medium price periods respectively, when the heat storage strategy is operational. Equivalently, $\%High_{ref}$.and $\%Medium_{ref}$ are the percentages of yearly heating energy for the reference scenario (no heat storage strategy). The energy flexibility index takes the value of zero if the repartition of the energy use is the same as in the reference case; when the building did not provide any energy flexibility. 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).

3.4. Results

The different building scenarios have been simulated for an entire year under typical Danish weather conditions. Figure 3.2 presents the results of the energy flexibility index calculations for the 144 studied cases with set point modulation, as a function of the total effective thermal inertia of the house. Results show that thermal inertia contributes to an increase in the building heat storage capacity and consequently its energy flexibility index. However, above 80 Wh/Km², the energy flexibility of the building stagnates. It is not possible to shift more space heating load and, therefore, further increase of the thermal inertia is mostly ineffective with regards to energy flexibility.

Results indicate that well insulated dwellings have a much higher ability for shifting of the space heating load than in 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, the latter represents an absolute amount of energy that is four times higher than that of well-insulated buildings. Nevertheless, this larger amount of energy can only be shifted over a short period.

It can be observed that houses equipped with under-floor heating systems generally present better energy flexibility than those equipped with convective radiators. Indeed, UFH hydronic circuits are often embedded in dense concrete screed floors, inducing a good thermal activation of heavy structural building elements with large heat capacity. In addition, radiant UFH systems can provide equivalent thermal comfort with a lower indoor air temperature, which reduces ventilation, infiltration and transmission losses and, therefore, improves the efficiency of the thermal storage and thereby enlarge the energy flexibility of the building.

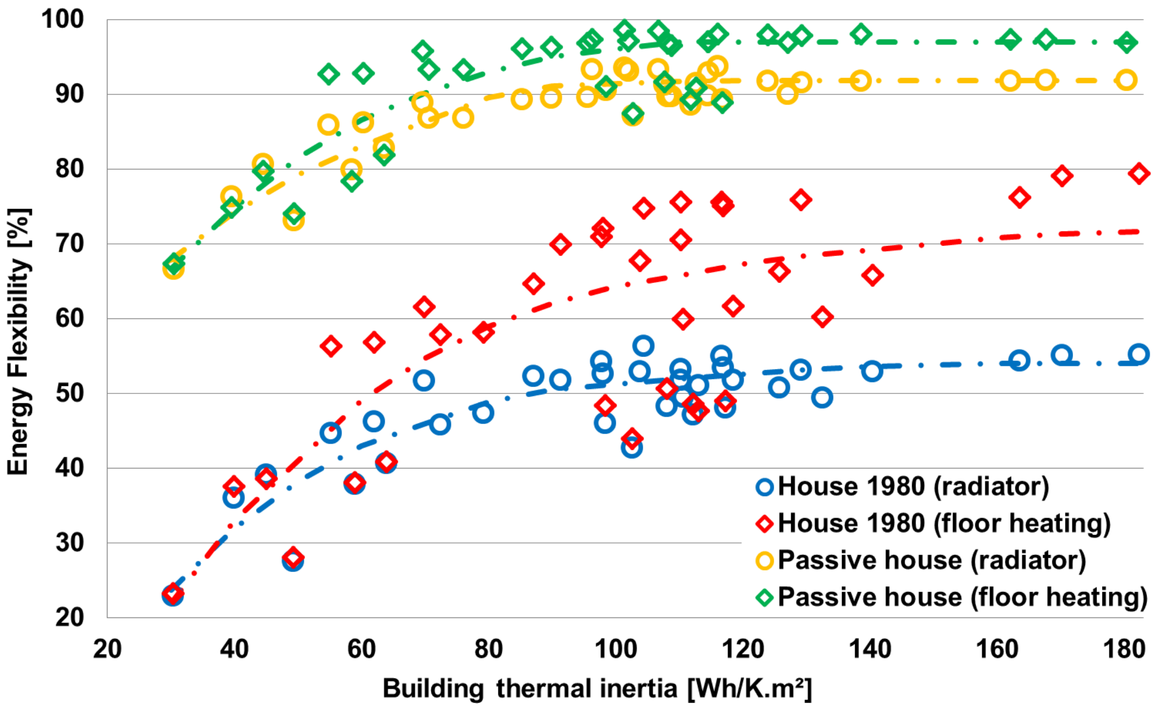
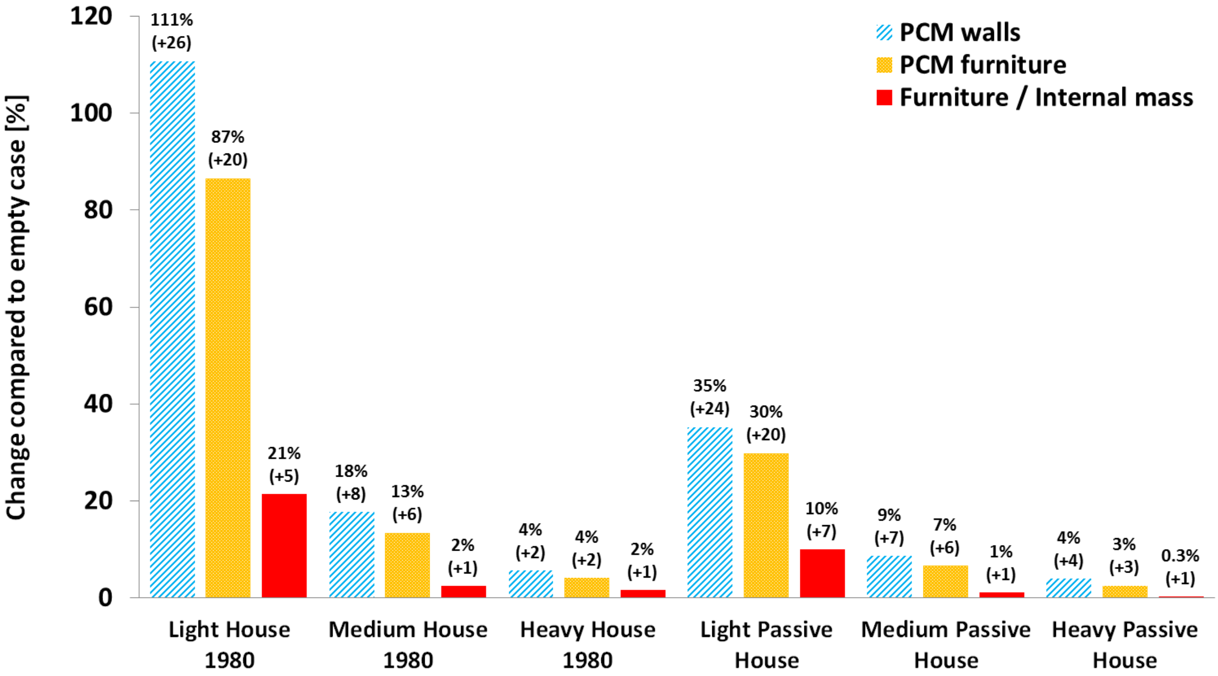


Figure 3.2 Evolution of the energy flexibility of buildings as function of the thermal inertia.

A particular focus has been on assessing the influence of additional indoor thermal mass elements on the energy flexibility of space heating in the houses. Figure 3.3 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). One can see that 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. Concerning furnishings, the increase of effective thermal inertia and energy flexibility of space heating are only significant for lightweight houses.



	Light House 1980	Medium House 1980	Heavy House 1980	Light Passive House	Medium Passive House	Heavy Passive House
Empty building energy flexibility [%]	**23**	**45**	**53**	**67**	**86**	**90**
Empty building thermal inertia [Wh/K.m²]	**30**	**50**	**100**	**30**	**50**	**100**

Figure 3.3 Change of energy flexibility of buildings with additional indoor thermal mass (radiator heating system).

A statistical analysis has been performed on the results of the 144 different aforementioned studied cases. The level of influence of the four main building parameters under study on the energy flexibility of space heating has been calculated. Table 3.2 presents the ranking of these parameters from the most significant one (highest *F-value*) to the least significant one (lowest *F-value*). Similar to the previous observations, this statistical analysis clearly shows that the level of insulation in the envelope of the house has the greatest impact on energy flexibility, followed by the building total thermal inertia, type of heat emitter and finally, the kind of additional indoor thermal mass.

For more information, please refer to (Johra, 2018).

Table 3.2 Significance ranking of the building parameters regarding energy flexibility of space heating.

Significance ranking	Building parameter	F-value
1	Level of insulation in the envelope	685.4
2	Thermal inertia	91.4
3	Heating system type	42.3
4	Additional indoor thermal mass type	14.6

3.5. Conclusion

The numerical study presented here investigates and quantifies the impact of the main building parameters on the energy flexibility of indoor space heating for single-family houses in Denmark. The demand side management strategy employed here is an indoor temperature set point modulation driven by an electricity spot price signal. Thermal energy is stored in the indoor environment when the electricity price is low, and part of it is retrieved when the electricity price is high.

The energy flexibility is defined here as the ability for the building to shift in time its space heating usage from high and medium energy price periods to low energy price periods without jeopardizing occupant thermal comfort. An energy flexibility index has been created to assess the change in heating load distribution when employing indoor temperature set point modulation, compared to a reference scenario with constant set point.

A statistical analysis is performed for 144 different building cases presenting variations of envelope thermal performance, structural thermal inertia, heating system type and additional indoor thermal mass. The results confirm that the level of insulation in the envelope is the building characteristic with the largest effect on the energy flexibility of 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.

To a lesser extent, the increase of the building thermal inertia improves its heat storage capacity and consequently its energy flexibility index. However, above 80 Wh/Km^2 of effective thermal inertia, further addition of thermal mass is mostly ineffective. In addition, 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 index.

For dwellings studied here with low structural thermal mass, the presence of furnishings within the thermal envelope can increase the energy flexibility by up to 21% for the investigated cases. It is therefore recommended to take furnishings into account when performing dynamic building simulations and energy flexibility assessments. Finally, it was also found that phase change materials integrated in wallboards or in furniture elements can substantially increase the energy flexibility of space heating in houses.

3.6. Acknowledgement

The work was financed by the ENOVHEAT project (http://www.enovheat.dk/) which is funded by Innovation Fund Denmark (contract no 12-132673) and was carried out partly within the framework of IEA EBC Annex 67 Energy Flexible Buildings.

4. Building stock characterisation of space heating flexibility from single-family houses

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4.1. Abstract

The control of residential space heating can play an important role in providing flexibility for future energy grids. In France, 25% of electrical heating systems are expected to be controlled dynamically by 2030. The objective of this study is to get a better understanding of the flexibility potential in residential buildings. In fact, the building stock is characterised by a large diversity, which makes it difficult to evaluate the flexibility potential. A systematic study of the building stock is performed, by simulating single-family houses with different energy classes, levels of thermal mass and various types of demand-response (DR) events. The main outcome of this study is to provide quantitative data on the flexibility potential. The evolution of this potential within the building stock can also be clearly observed, with large differences between old and new buildings.

4.2. Background and objectives

Space heating, which accounts for 61% of the energy use in residential buildings in France (ADEME, 2013), can play an important role in providing flexibility to the energy grid. Prospective studies on future electrical systems identifies the need for a large penetration of space heating flexibility in the residential sector to allow for the growth in the utilization of renewable energy. The French Transmission System Operator (TSO) estimates that up to 25% of electrical heating systems should be equipped with a dynamic controller by 2030 (RTE, 2017). The deployment is even projected to increase up to 75% by 2050 (ADEME, 2018).

Numerical studies were performed to estimate the energy flexibility potential from residential buildings in different European countries. It was observed that the potential varies greatly with the type of building (energy shifted ranging from 50 up to 140 Wh/m^2_{floor} during a 4-hour DR event) and with the type of modulation (activation of energy flexibility). Studies in Denmark were performed on two building energy classes (Le Dréau and Heiselberg, 2016) and for different levels of thermal mass (Johra et al., 2018). In Belgium (Reynders et al., 2017) showed large differences within the building stock. Similarly, some field tests carried out in France (e.g., the projects Modelec, 2011-2015 and Smart Electric Lyon, 2012-2017) estimated this potential from 1 up to 3 kW per household (ADEME, 2016). However, these studies focussed on a limited number of buildings to draw their conclusions, and no potential at the national level was given.

Therefore, there is a lack of comprehensive knowledge about how much energy flexibility different building types and their usage may be able to offer to the present or future energy systems. The objective of this study is to evaluate the energy flexibility potential of single-family houses with respect to their thermal characteristics, accounting for different types of DR events. Two types of modulations (DR events) are defined in this study:

- Upward modulation: heat is stored in the thermal mass by increasing the operative temperature set-point for a short period of time; this strategy can be used for valley filling.
- Downward modulation: heat is discharged from the thermal mass by decreasing the operative temperature set-point for a short period of time; this strategy can be used for peak shaving.

4.3. Method

4.3.1. Study cases

Five buildings were selected to perform modulations of the space heating and can be classified according to the year of construction and the building regulation: 50's (no building regulation), BR 1982 (first building regulation in France), BR 2005, BR 2012 and BR 2020 (extrapolated from the actual building regulation in France) – see Figure 4.1. These five buildings have internal wall insulation and a medium level of thermal mass. The thermal properties of these different buildings are listed in Table 4.1 and further information can be found in (Le Dréau and Meulemans, 2018). Due to these different characteristics, the space heating needs of the simulated buildings range from 21 kWh/m$^2_{floor}$.year up to 288 kWh/m$^2_{floor}$.year in Nancy (continental climate).

Table 4.1 Thermal properties of the simulated buildings.

	50's	BR 1982	BR 2005	BR 2012	BR 2020
Insulation walls	1 cm IWI *(U=2.75 W/m².K)*	4 cm IWI *(U=0.51 W/m².K)*	10 cm IWI *(U=0.30 W/m².K)*	18 cm IWI *(U=0.22 W/m².K)*	22 cm IWI *(U=0.19 W/m².K)*
Insulation roof	2 cm *(U=1.3 W/m².K)*	8 cm *(U=0.54 W/m².K)*	16 cm *(U=0.50 W/m².K)*	28 cm *(U=0.13 W/m².K)*	28 cm *(U=0.13 W/m².K)*
Insulation floor	2 cm *(U=1.96 W/m².K)*	8 cm *(U=0.81 W/m².K)*	10 cm *(U=0.24 W/m².K)*	16 cm *(U=0.20 W/m².K)*	15 cm *(U=0.20 W/m².K)*
Windows	Double glazing *(U_w=3.1 W/m².K & g=0.75*	Double glazing *(U_w=3.1 W/m².K & g=0.75*	Double glazing *(U_w=1.6 W/m².K & g=0.60)*	Double glazing *(U_w=1.5 W/m².K & g=0.63)*	Triple glazing *(U_w=0.8 W/m².K & g=0.54)*
Cm [Wh/K.m²floor]	55 (medium)	55 (medium)	55 (medium)	55 (medium)	55 (medium)
Ventilation	-	Mechanical ventilation by extraction (airflow 195 m³/h)		Mechanical ventilation by extraction (humidity controlled, mean 125 m³/h)	
Infiltration [ACH]	0.4	0.35	0.18	0.12	0.05
HLC [W/K]	602	330	193	125	97
G [W/m³$_{heated}$ .K]	1.91	0.94	0.59	0.42	0.33
τISO 13790 [h]	11	24	37	53	67
$Q_{heating\ needs}$ [kWh/m²floor.y]	288	141	66	41	21

Figure 4.1 Overview of the different single-family houses simulated.

In addition to the energy class of the building, variations of the thermal mass of the building components were performed. The thermal mass influences the dynamic behaviour, both in terms of thermal comfort and of quantity of energy that can be charged/discharged from the building components. It has to be noticed that internal floors and walls play an important role in this dynamic behaviour, as they constitute almost half of the surface in contact with the indoor air. Three levels of thermal mass (based on (EN ISO 13790, 2013)) were defined for each building class:

- Light thermal mass: 35 $Wh/K.m^2_{floor}$
- Medium thermal mass: 55 $Wh/K.m^2_{floor}$
- Heavy thermal mass: 75 $Wh/K.m^2_{floor}$

The heating system consists of radiators located in each room that emit heat through both radiation (30%) and convection (70%). The controller of the radiators is a “perfect” rule-based controller, which pre-calculates at each time-step the amount of heat to be injected in the thermal zone to reach the set-point (taking into consideration the limitations of the heating system).

4.3.2. Numerical modelling of the buildings

Each building was modelled by 11 thermal zones using a Building Energy Simulation software (EnergyPlus 8.8). The simulation time-step was set to 2 minutes. The control of the heating set-point is handled by an external interface named BCVTB. The controlled variable is the operative temperature.

4.3.3. Control strategy for energy flexibility of the building

This study focusses on the flexibility that can be gained by controlling the energy use for space heating. Upward and downward modulations (i.e. by increasing/decreasing the operative temperature set-point from 21°C to 23°C/19°C) were investigated for durations between 1 and 12 hours. These modulations do not jeopardise the thermal comfort of the occupants (as defined in the standard (EN 15251, 2007). The starting time of the modulations (noon) was chosen to match with the peak of production in an energy production system dominated by solar panels. These modulations are performed for each day of the heating season (i.e., between October 15th and April 15th in France) in order to observe the variation of the potential.

4.3.4. KPI for energy flexibility

In total, this study results in 195 different cases:

- 5 energy classes (50's, BR 1982, BR 2005, BR 2012 and BR 2020)
- 3 levels of thermal mass (light, medium and heavy)
- 2 types of modulation (upward and downward)
- 6 durations of modulation (1, 2, 4, 6, 8 and 12 h)

From the simulations, the heating power and operative temperature with and without modulation are compared. An example is given in Figure 4.2a, where an upward modulation for 2 hours (grey area) is performed in the building built according to BR 2012. During this DR event, the energy use increases compared to the reference case; this amount of energy is referred to as the energy charged in the thermal mass during the DR event. After the end of the DR event, the (heating) power profile adjusts itself in order to reach the set-point. For a downward modulation (see Figure 4.3), the energy use would decrease compared to the reference case and the amount of energy would be referred to as the energy discharged from the thermal mass.

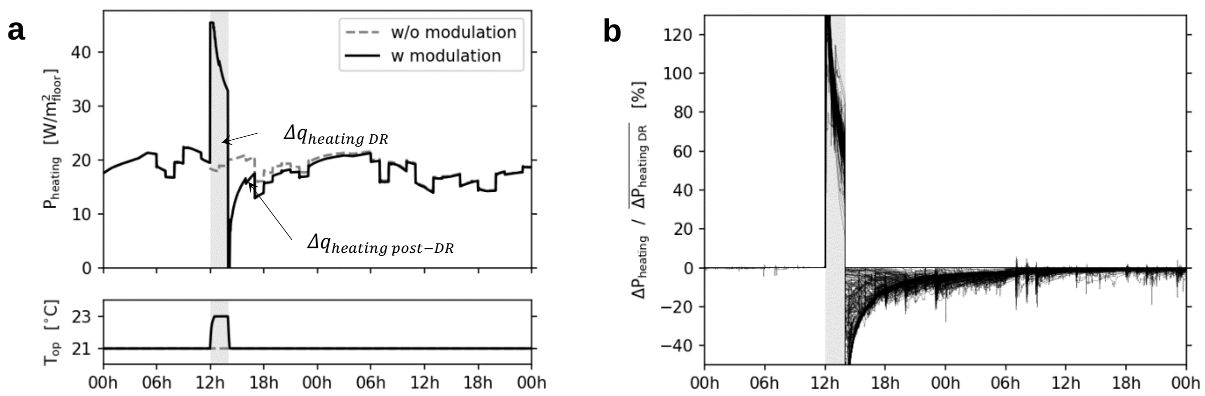

Figure 4.2 Heating power and operative temperature on the 26th of January (a) and dimensionless power profile during 200 days of the heating season (b) for the building BR 2012 (medium thermal mass, two-hour <u>upward modulation</u>).

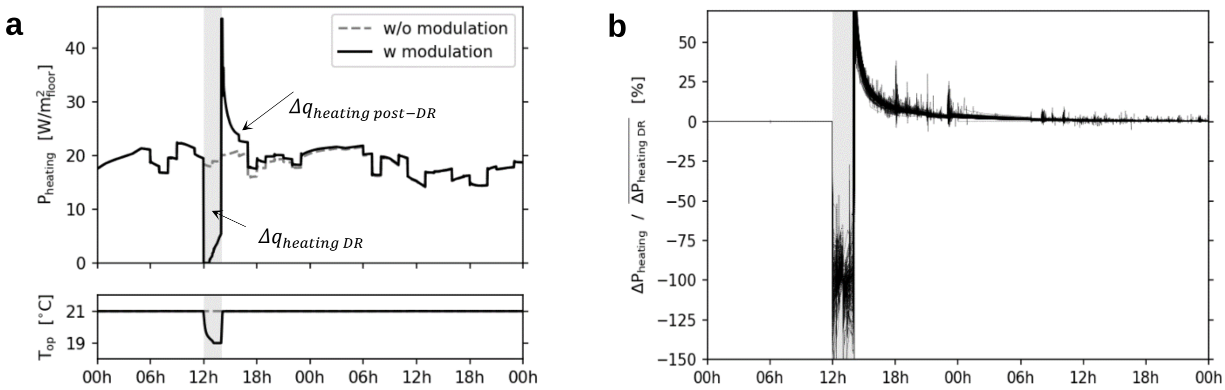

Figure 4.3 Heating power and operative temperature on the 26th of January (a) and dimensionless power profile during 200 days of the heating season (b) for the building BR 2012 (medium thermal mass, two-hour <u>downward modulation</u>).

From the simulations, the heating power difference between the case with and without modulation ($\Delta P_{heating}$ in W/m²$_{floor}$) is calculated. Three indicators are then derived to characterise the virtual storage capacity of each building: the energy charged in or discharged from the thermal mass during the modulation ($\Delta q_{heating\ DR}$, Equation 4.1), the energy change after the modulation ($\Delta q_{heating\ post-DR}$, Equation 4.2) and the efficiency (η in Equation 4.3) of the modulation. The efficiency is the ratio of the energy charged in (or discharged from) the thermal mass during the modulation to the energy change after the modulation. In case of an upward modulation, the efficiency is referred to as the storage efficiency and characterises the energy that has been lost in the charging/discharging process (Figure 4.2). In case of a downward modulation, the efficiency is referred to as the rebound rate and characterises the energy that has been saved in the discharging/recharging process (Figure 4.3).

$$\Delta q_{heating\ DR} = \int_{start\ DR}^{end\ DR} \Delta P_{heating}.dt\ \left[Wh/m^2{}_{floor}\right] \tag{4.1}$$

$$\Delta q_{heating\ post-DR} = \int_{end\ DR}^{\infty} \Delta P_{heating}.dt\ \left[Wh/m^2{}_{floor}\right] \tag{4.2}$$

$$\eta = \frac{-\Delta q_{heating\ post-DR}}{\Delta q_{heating\ DR}}\ \ [-] \tag{4.3}$$

The dimensionless power profiles (Equation 4.4) are also plotted for the different days of the heating season. For upward modulations (Figure 4.2b), a large variability can be observed and very long discharging time can be observed (over two days). For downward modulations (Figure 4.3b), the power profile after the DR event is similar for each day of the heating season and is therefore predictable for a specific type of building. However, it should be noted that the power decrease during the DR event depends much on the conditions and the time to fully recover the initial state is still long (over a day).

$$\overline{\Delta P_{heating\ DR}} = \frac{\int_{start\ DR}^{end\ DR} \Delta P_{heating}.dt}{\int_{start\ DR}^{end\ DR} dt}\ \left[W/m^2{}_{floor}\right] \tag{4.4}$$

4.4. Results

Only the results of downward modulations are presented in the following. The reader can refer to the references (Le Dréau, 2016) and (Le Dréau and Meulemans, 2018) for further information on upward modulations.

4.4.1. Influence of the duration

Single modulations were performed each day of the heating season (from mid-October until mid-April) starting at noon. For two hours modulation in the BR 2012 building, a large variability of the potential can be observed (Figure 4.4a). When the outdoor conditions are getting warmer, the heating power is lower and so is the discharged energy. In order to show the variability of the potential over the heating season for six durations of switching off the heating system, boxplots were used. The box shows the 25th, 50th and 75th percentiles, the whiskers extend up to 0.5 times the interquartile range and the dots represent outliers. In terms of energy, the longer the modulation, the larger the energy shifted, and the lower the rebound rate (Figure 4.4b).

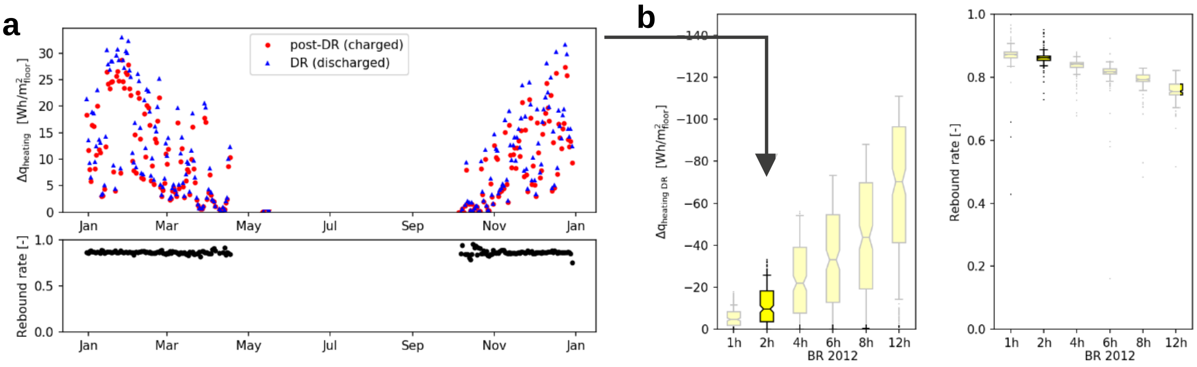

Figure 4.4 Energy discharged, energy recharged after the modulation and rebound rate for 2 hours modulations (a) and for the different modulations (b) for the BR 2012 building (medium thermal mass).

4.4.2. Influence of the energy class

In order to evaluate the effect of the heat losses from the envelope, five types of energy classes were modelled. Figure 4.5 shows the energy discharged during the DR event and the rebound rate for the different buildings and the different downward modulation durations. The lower the level of insulation of the building, the higher the potential to shift energy. The amount of energy is around 4 times higher in a building built in the 50s than in the one's built nowadays. This can be explained by the larger heating power available in poorly insulated buildings. However, it has to be noticed that the larger potential comes at the cost of a lower thermal comfort (but still in the defined comfort band). More time is spent at slightly cool conditions, which can lead to a higher rejection rate from occupants. Variations of indoor environment are also faster in poorly insulated buildings. It should be noted that these simulations do not account for differences in space heating habits in poorly insulated buildings (e.g. unheated area, lower set-point). A correction is proposed below.

In terms of rebound rate, the lower the level of insulation, the lower the rebound rate. As the temperature drops quickly in poorly insulated buildings, energy savings can be achieved. This is not the case of better insulated buildings, where the time constant is higher and does not allow for major energy savings. This observation is in line with the different field studies performed in France (ADEME, 2016).

The average power decrease that is achieved during downward modulation can be calculated for each type of building and for different durations. The power decrease is then corrected to account for the heating habits of occupants according to (Allibe, 2012). In Figure 4.6, the median power decrease during the DR event is presented assuming a single-family house of 105 m². It can be observed that the building energy class highly influences the flexibility potential on heating. These results are similar to the one of (RTE, 2017) (black lines of Figure 4.6). However, the reader should keep in mind the large variability of this potential over the heating season, as shown in Figure 4.4.

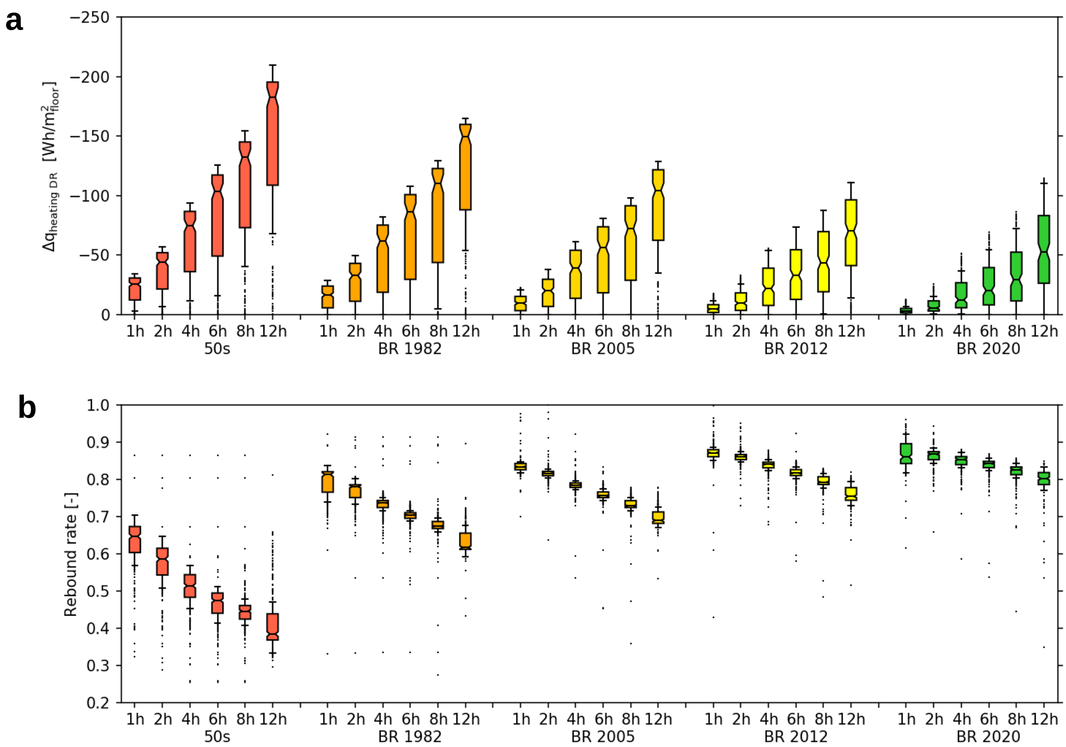

Figure 4.5 Heating energy discharged during the DR event (a) and rebound rate (b) for the medium thermal mass building.

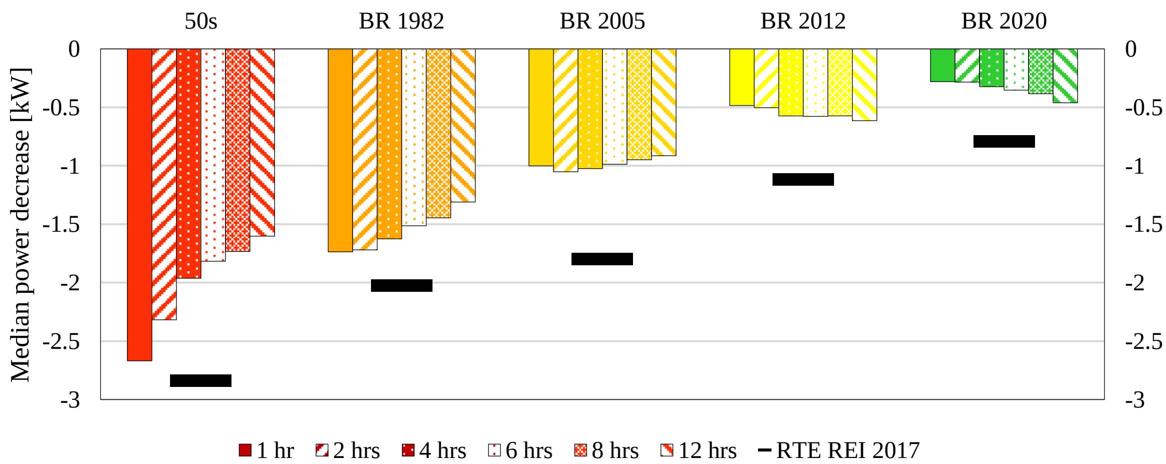

Figure 4.6 Median power decrease in a typical single-family house of 105 m² for different modulation durations (medium thermal mass).

4.4.3. Influence of the thermal mass

The different buildings are also modeled with three levels of thermal mass (light, medium, heavy) and the influence on the heating power and temperature profile is evaluated. From Figure 4.7, slight differences can be observed in the power and temperature profiles. Buildings with a heavy level of thermal mass can maintain comfort levels for a slightly longer time without any space heating, as the temperature decreased is slower in this type of building.

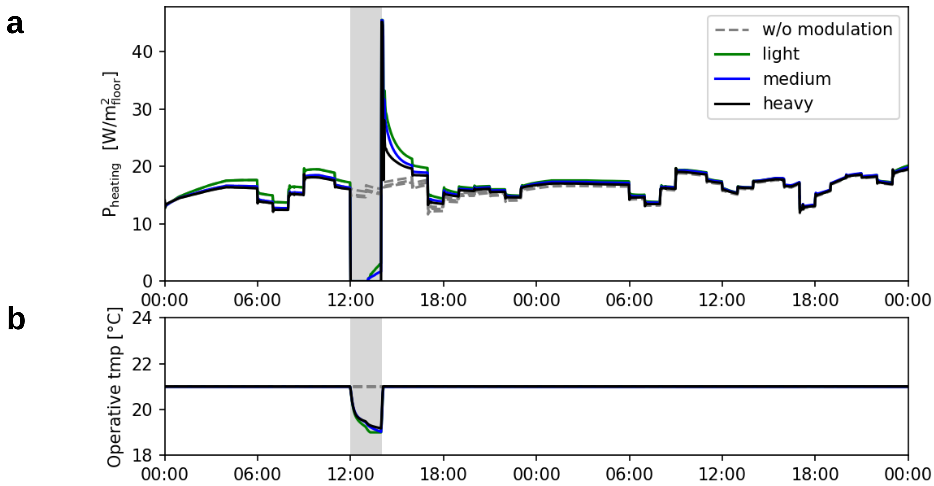

Figure 4.7 Heating power (a) and operative temperature (b) for three levels of thermal mass on the 26th of January for 2 hrs modulation (BR 2012 building).

In terms of energy shifted, the differences are small for downward modulations (Figure 4..8). Differences can only be noticed for very long modulations (longer than 6 hrs). For upward modulations, the differences are larger as a heavy building can store more heat. In fact, it takes more time to reach the higher band of thermal comfort.

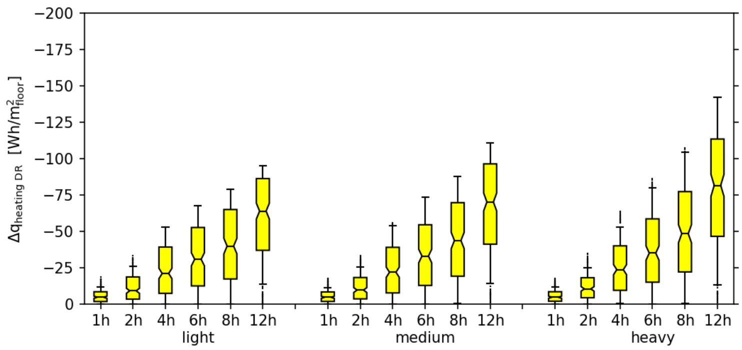

Figure 4.8 Heating energy discharged during the DR event for three levels of thermal mass and different durations (BR 2012 building).

4.4.4. Estimated potential for daily DR events

These different studies with single modulations performed at different times of the heating season were performed to get a better understanding of the flexibility potential and variability. It was observed that the energy class plays an important role, and the thermal mass also influences in the case of upward modulation.

In order to test a possible control strategy, the flexibility of buildings is activated once a day, starting at noon. The objectives of these simulations are both to validate the energy flexibility potential observed in the previous section and investigate the influence of the energy flexibility on the annual heating demand (energy flexibility vs. energy savings).

Figure 4.9 represents the annual space heating demand with a DR scenario (i.e., one downward modulation a day during six hours). For each building typology, the space heating energy use is reported for both the reference case (without modulation) and the DR scenario investigated. The relative change of energy use is indicated on top of each bar. In the top right-hand side of each graph, the energy discharged from the thermal mass (bars with dashed black lines), the efficiency of the DR event and the energy use change (white part of the bars) are reported.

From Figure 4.9, it can be observed that the energy need that can be shifted is relatively modest compared to the annual demand. It ranges from around 20 kWh/m$^2_{floor}$.year for a 50s building down to a few kWh/m$^2_{floor}$.year for a BR 2020 building. Moreover, the values of rebound rate are in accordance with section 4.4.2, leading to energy savings of 2-3%.

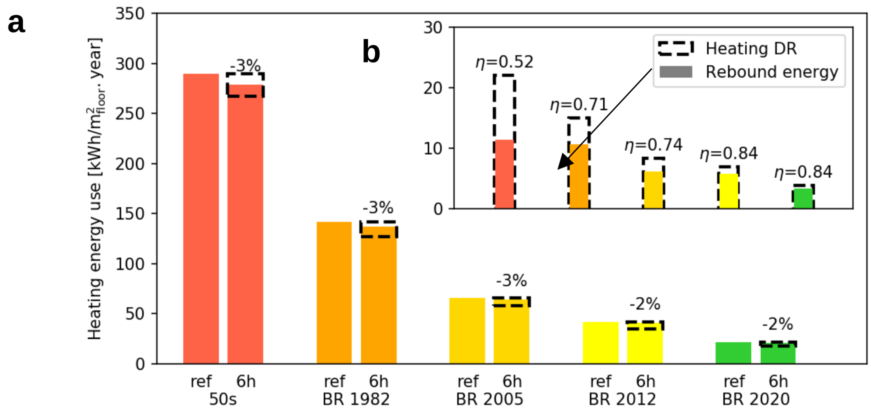

Figure 4.9 Annual heating need with a DR scenario (one downward modulation a day during 6 hours). The small graphs (b) details the energy shifted with the DR events.

4.5. Conclusion

This study describes a generic method and provides quantitative data to estimate the flexibility potential for demand response at the building level and to help designing future energy grids. Different sets of results are available to characterise the flexibility from space heating.

From these studies, it has been observed that activating the thermal mass results in long discharge or recharge time (several days). Upward modulations in poorly insulated buildings should be avoided, as it leads to large storage losses (around 50% in average). Downward modulations can be performed, but they will induce rapid changes in indoor climate, which can exceed the acceptable limit set by (ASHRAE, 2013) (1.1°C/15 min). For relatively well-insulated buildings (built after the BR 2005), the efficiency and the stored energy did not change much and a good potential for flexibility was demonstrated.

Estimations of the flexibility potential are also provided for a specific DR strategy (one modulation a day, during 6 hours). The energy shifted with the DR events is highlighted and is compared to the total energy use for heating. In this way, energy flexibility strategies can be put into perspective (better energy use vs. lower energy use) and the influence on the annual energy performance can be evaluated.

Further analysis is also available to quantify the influence of emitters (radiator vs. floor heating) on the energy flexibility potential (not reported here for the sake of brevity).

4.6. Acknowledgement

The work was carried out partly within the framework of IEA EBC Annex 67 Energy Flexible Buildings.

5. Evaluation of energy flexibility of low-energy residential buildings connected to district heating

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5.1. Abstract

Thermal energy infrastructure is a great asset for energy flexibility in systems with widely developed district heating networks. The aim of this example is to investigate the potential of residential buildings to be operated in an energy flexible way, according to the needs of a district heating system. A low-energy apartment block is studied, utilizing the storage capacity of thermal mass of the constructions as the storage medium. Two sets of data are utilized: heat load of Greater Copenhagen and dynamic marginal heat production cost which is used as a price signal for the scheduling of the heating use in the building. Scenarios with different control signals are determined in order to achieve load shifting. The findings show that pre-heating is highly effective for load shifting and peak load reduction. Heat load shifting is achieved in all scenarios between 40% and 87%. Although higher energy use may occur, it occurs mostly at times when the city heat load is lower and heat production is less expensive and less carbon-intensive.

5.2. Background and objectives

Initially, the focus of energy flexibility was on the electricity sector, though a multi-carrier energy system gradually developed. The need for the electricity grid to be seen as part of an integrated smart energy system is explained in (Lund et al., 2012) and the importance for the stability of the grid of including flexible Combined Heat and Power (CHP) production is emphasized. In (Münster et al., 2012) they concluded that a district heating (DH) system can cost-effectively contribute to the security of supply and to the sustainability of future energy systems. One very important element of DH networks is the potential for short-term heat storage, facilitating the optimization of the Combined Heat and Power generation (CHP) in relation to the electricity sector without compromising the heating sector (Cai et al., 2018) and (Nuytten et al., 2013). The thermal energy infrastructure, with its existing energy storage and the potential for extension, is thus considered a great asset for obtaining energy flexibility.

The building sector appears, because of the large thermal mass of the existing building stock, to have potential for short-term thermal energy storage. Compared to the electricity system, only a few studies have concerned buildings which are connected to a district heating grid. The available information and expertise on demand shifting for DH is limited. An important impediment to this is that the market structure for heat is not as developed and transparent as it is for electricity, so it is not yet sufficiently mature to manage demand response. Previous work on managing demand response in buildings connected to DH was focused on the load shape rather than heat pricing (Wernstedt et al., 2007), (Johansson et al., 2010), (Basciotti and Schmidt, 2013), (Kensby et al., 2015) and (Sweetnam et al., 2018). Only a few studies have reported demand response based on dynamic heat production costs. In (Van Deventer et al., 2011) they proposed and simulated an implementation of demand response, with a sensor network that exchanged information between the heat supplier and the building substation in a 5-day simulation model. In (Kärkkäinen et al., 2003) the results of three case study buildings in which demand response demonstrations were carried out are reported. It was recommended that DH tariff structures that encourage the use of demand response should be adopted, and that the tariffs in DH should reflect the suppliers' marginal heat production costs.

Denmark is one of the European countries with the most developed district heating networks, supplying 64% of Danish households (Danish Energy Agency, 2015). The heat generation for the Danish DH system already includes 52 % from renewable energy sources (Energistyrelsen, 2017) and the current Danish energy targets are that only renewable energy sources should be used by 2050. With the base load demand being gradually converted to CO_2-neutral energy by using biomass-fuelled plants, heat pumps and geothermal energy, the main goal to be achieved is to avoid the need for peak load boilers, which mainly use natural gas. In addition, 68.9 % of all heat is produced in cogeneration with electricity (CHP) (Danish Energy Agency, 2015), so the interaction between the sectors is profound. Extending the heat storage potential within the DH system is thus essential and it would further increase the importance of the role of DH in any future flexible energy system. The Danish district heating is considered a natural monopoly and it has, therefore, been regulated. The heat price paid by the customers is a flat rate across the year and fixed by individual contracts. However, the costs that can be included in the heating price paid by the consumer are defined by law, such that the heating price is influenced by many parameters, including investment, operation and maintainance (O&M) and efficiency of production facilities and DH network, fuel prices, taxes and VAT, subsidies, electricity price (relevant for plants that both use and produce electricity) (Danish Energy Agency, 2015). However, dynamic heat pricing is under research and it was the scope of the present work to propose a methodology for exploiting the flexibility potential of buildings connected to the district heating grid.

5.3. Method

The charging and discharging of the storage medium, i.e. structural thermal mass, is achieved by modulating the indoor air temperature set-point. When increasing the set-point, the heat load in a building is increased and the additional heat is stored in the thermal mass. When decreasing the set-point, the heat load in a building is reduced or interrupted completely, causing heat to be released from the thermal mass of the building to the internal zones. The reference operation of the building with thermostatic control with constant air temperature set-point at 22°C was defined, which is a typical desired indoor temperature in Danish households during the heating season (Larsen et al., 2012). Different signals then triggered an increase or decrease of the air temperature set-point in order to charge or discharge the thermal mass, respectively. At all times, the thermal comfort of occupants should not be compromised. The limits of comfortable conditions were chosen to be 20 – 24 °C, in accordance with the thermal comfort Category II of the standard (EN/DS 15251, 2007).

5.3.1. Data from district heating system

Two sets of data were used as an indication of the district heating requirement; the heat load of Greater Copenhagen and the respective marginal heat production cost calculated for a representative year. The marginal heat production cost is the cost to produce one additional unit of heat for DH. The marginal heat production cost was chosen to be used as signal, as it represents the variation of production costs and the effects of the market on the heat production are reflected adequately, as shown in (Li et al., 2015). The cost was used only as a signal, instead of using heat price on the demand side, to reflect the potential for cost reductions in a dynamic pricing scheme. The data sets were provided by the DH utility company of Copenhagen, HOFOR A/S (HOFOR A/S, 2018). Figure 5.1a illustrates a heat map graph of the heat load, having on the x-axis the months/days of the heating season and on the y-axis the time of the day. Marginal heat production cost data are shown in the same format in Figure 5.1b.

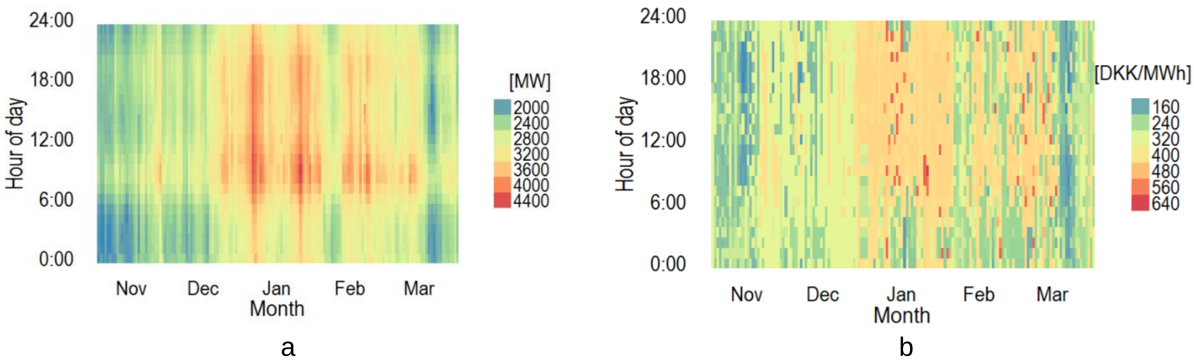

Figure 5.1 Heat map graph of heat load (a) and marginal heat production cost (b) in Greater Copenhagen during a heating season.

The graphs indicate a correlation between the heat production cost and the heat load, but only to a certain extent, since there are many parameters that affect the cost, as previously detailed. A clear diurnal pattern of heat load can be seen. A similar pattern may be seen for the marginal heat production cost, but it is not as clear as it is for heat load.

5.3.2. Implementation

Two indirect load control strategies were studied:

i) Assuming no communication platform between the building and the heat supplier, a constant strategy was implemented with fixed schedules for temperature set-points during the whole heating season (Figure 5.2), which were determined based on the average daily profiles of the heat load of the area and the marginal heat production cost.

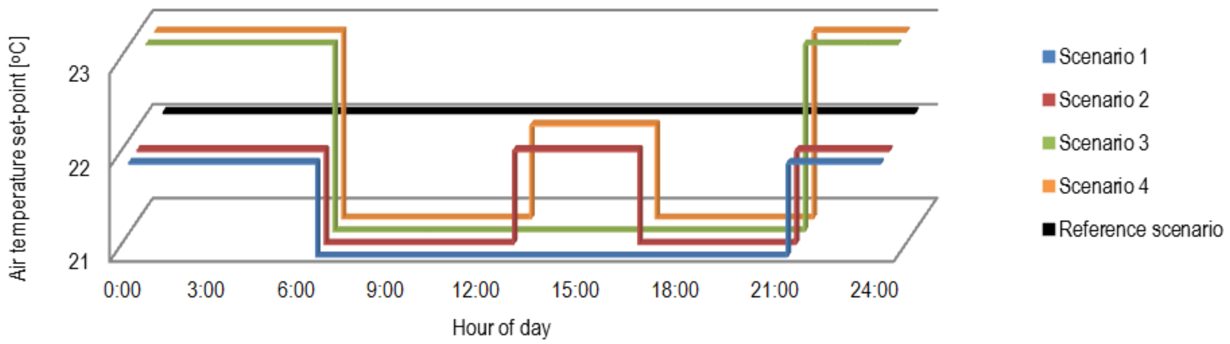

Figure 5.2 Scenarios for fixed schedules for the temperature set-points in the range 21-23 ºC.

ii) Assuming a communication platform between the building and the heat supplier, a signal can be sent to the building from the supplier to communicate the need for load adjustment and the home management system modulates the temperature set-points accordingly. In this study, the signal was the hourly marginal heat production cost. The aim of this strategy was to shift the energy use towards the hours when heat costs are low. Thresholds for the marginal heat production costs were set. When the signal was lower than the low cost threshold (C_{low}), the set-point was increased, in order to store heat in the thermal mass of the building. When the signal was higher than the high cost threshold (C_{high}), the set-point was decreased to discharge the stored heat. When the signal was between the two thresholds, an interpolation of the set-point was used according to Equation 5.1:

$$T_{setpoint,i} = \begin{cases} T_{setpoint,min}\ , & C_i > C_{high} \\ T_{setpoint,max}\ , & C_i < C_{low} \\ \dfrac{T_{setpoint,max} - T_{setpoint,min}}{C_{high} - C_{low}} \cdot \left(C_{high} - C_i\right) + T_{setpoint,min}\ , & C_{high} \geq C_i \geq C_{low} \end{cases} \quad (5.1)$$

The marginal heat production cost has large seasonal variations and considerable differences between the months of the heating season (Li et al., 2015). In this work, the percentile distribution of the marginal cost for each month was used and the thresholds referred to the respective percentiles for each month individually. The 25% or 50% percentiles of the monthly cost distribution were used as C_{low}, and the 50% or 75% percentile of the monthly cost distribution were used as C_{high}. Table 5.1 shows the scenarios examined with the minimum and maximum temperature set-point, and the low and high cost thresholds.

The building model used was a low-energy apartment block modelled in accordance with the Danish Building Regulation 2015 (BR15) (Danish Transport and Construction Agency, 2015). The apartment block has a net heated floor area of 6,272 m^2 and envelope area per volume 0.265 m^2/m^3. The building has 7 floors and an unheated basement, and each floor has 8 apartments with identical floor areas. Detailed information about the building structure, systems and internal gains can be found in (Foteinaki et al., 2018). The weather data from the year corresponding to the heat load and marginal heat production cost data were used.

Table 5.1 Scenarios for dynamic modulations for temperature set-points with the respective cost thresholds.

		$T_{setpoint, min}$	$T_{setpoint, max}$	C_{low}	C_{high}
Scenario 5	No pre-heating	21 ºC	22 ºC	-	50%
Scenario 6	No pre-heating	21 ºC	22 ºC	-	75%
Scenario 7	Pre-heating	21 ºC	23 ºC	25%	75%
Scenario 8	Pre-heating	21 ºC	23 ºC	50%	75%
Scenario 9	Pre-heating	21 ºC	23 ºC	25%	50%
Scenario 10	Pre-heating	21 ºC	23 ºC	50%	50%

5.3.3. Performance evaluation

For the scenarios examined, the following parameters were evaluated:

i) The total energy used for space heating of the building for the whole heating season.

ii) The total cost for production of the heat that was used in the building for space heating.

iii) The indoor operative temperature, as an indicator of thermal comfort (EN/DS 15251, 2007). For the sake of clarity, the operative temperature of the critical apartment is presented, which is a top-corner apartment and was chosen because of its higher exposure to ambient conditions.

iv) The energy used for space heating of the building between 6:00-9:00, namely the morning peak load hours for the DH system (Sandersen and Honoré, 2018).

v) The potential for flexible operation, based on two flexibility indicators, equivalent to the ones defined in (Le Dréau and Heiselberg, 2016):

a) Evaluation of total energy use during high load hours versus during low load hours according to the equation: $F_1 = \frac{E_{low\ load} - E_{high\ load}}{E_{low\ load} + E_{high\ load}}$, where: $E_{high\ load}$, the total space heating energy use during high load hours, between 6:00–21:00; $E_{low\ load}$, the total space heating energy used during low load hours, between 21:00-6:00 (next morning). The indicator ranges between -1 and 1, with the optimal operation being when $F_1 = 1$, namely energy was used only during low load hours.

b) Evaluation of total energy use during high production cost hours versus during low production cost hours, according to the equation: $F_2 = \frac{E_{low\ cost} - E_{high\ cost}}{E_{low\ cost} + E_{high\ cost}}$, where: $E_{high\ cost}$, the total space heating energy use during high production cost hours, when the cost was higher than the median value of costs of each month; $E_{low\ cost}$, the total space heating energy use during low production cost hours, when the cost was lower than the median value of costs of each month. The indicator ranges between -1 and 1, with the optimal operation being when $F_2 = 1$, namely energy is used only during low production cost hours.

5.4. Results

During the reference operation of the building, namely when the building was controlled with a constant temperature set-point of 22ºC, the energy use for space heating was 12 kWh/(year·m^2 net heated floor area) and the peak demand was 82 kW (13.1 W/m^2). Details of the energy performance, the thermal behaviour and the physically available energy flexibility of this building can be found in (Foteinaki et al., 2018).

Figure 5.3 presents the difference between the reference operation of the building and each scenario shown in Figure 5.2.

Using the 1ºC modulation schemes, in Scenarios 1 and 2, the cost and the total energy use were considerably lower compared to the reference operation, as the operative temperatures were lower. In Scenarios 3 and 4, which pre-heat the building during the night, the cost was decreased, while the total energy use was marginally increased. The mean operative (room) temperature in Scenarios 3 and 4 was almost the same as in the reference operation, but the room temperatures were fluctuating within a wider range. Using the 2 ºC modulation schemes, in Scenarios 1 and 2 both the cost and the energy use decrease were higher, but at the expense of lower operative temperatures, which dropped below 20 ºC. For the scenarios with pre-heating, there was higher cost and total energy use, which is attributed to the overall higher operative temperatures. In addition, the temperature fluctuations were strong. Therefore, those strategies with set-point modulations of ±2 ºC are not recommended for a control strategy with daily fixed schedules throughout the heating season in a low-energy building, but they can be possibly used for occasional events with other control strategies.

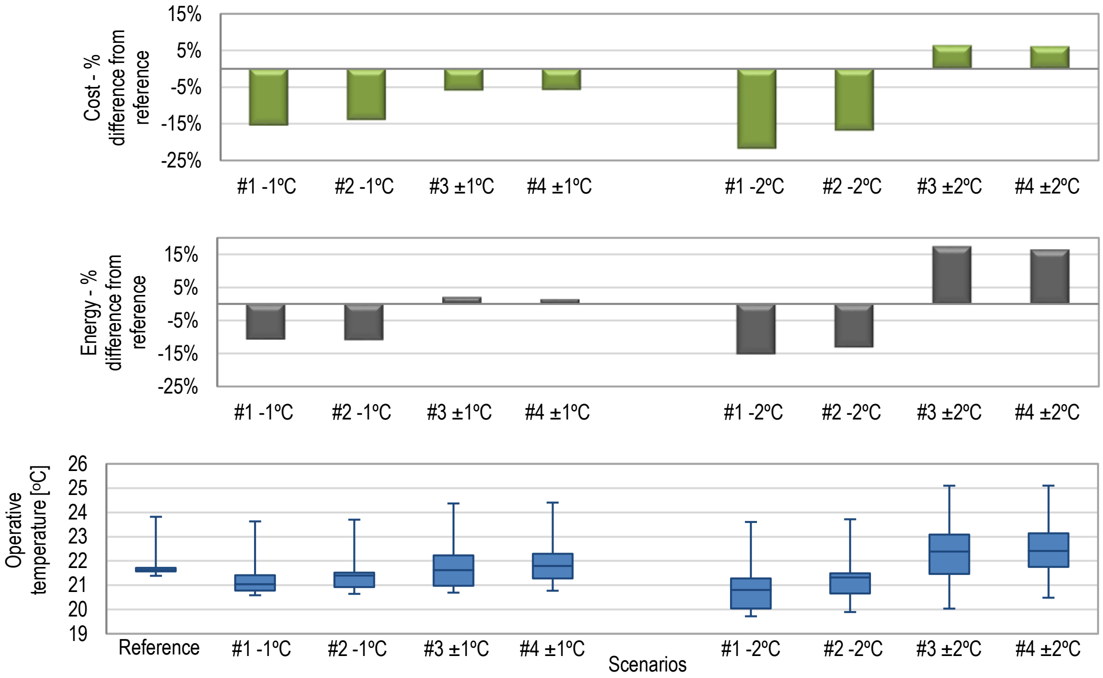

Figure 5.3 Effects of the schedules shown in Figure 5.2. Top: Percentage difference of cost between the reference operation and each scenario. Middle: Percentage difference of energy use between the reference operation and each scenario. Bottom: Box plots of operative temperature in the critical apartment during the heating season for the reference operation and each scenario.

Figure 5.4 presents the results for the scenarios that control the temperature according to the signal of marginal heat production cost. All scenarios implemented achieved cost reductions between 3% and 12%, while the effect on energy use and operative temperatures varied among the different scenarios. In Scenarios 5 and 6 cost and energy were reduced, and the median temperature was lower by 0.3ºC and 0.2ºC respectively. Scenarios 7 and 8 had overall higher temperatures leading to a higher total energy demand. In Scenario 9 there was a significant decrease of cost, while the energy use was almost the same as the reference operation. Scenario 10 led to a wide temperature range and slightly higher energy use. Nevertheless, the costs were still lower by 9%.

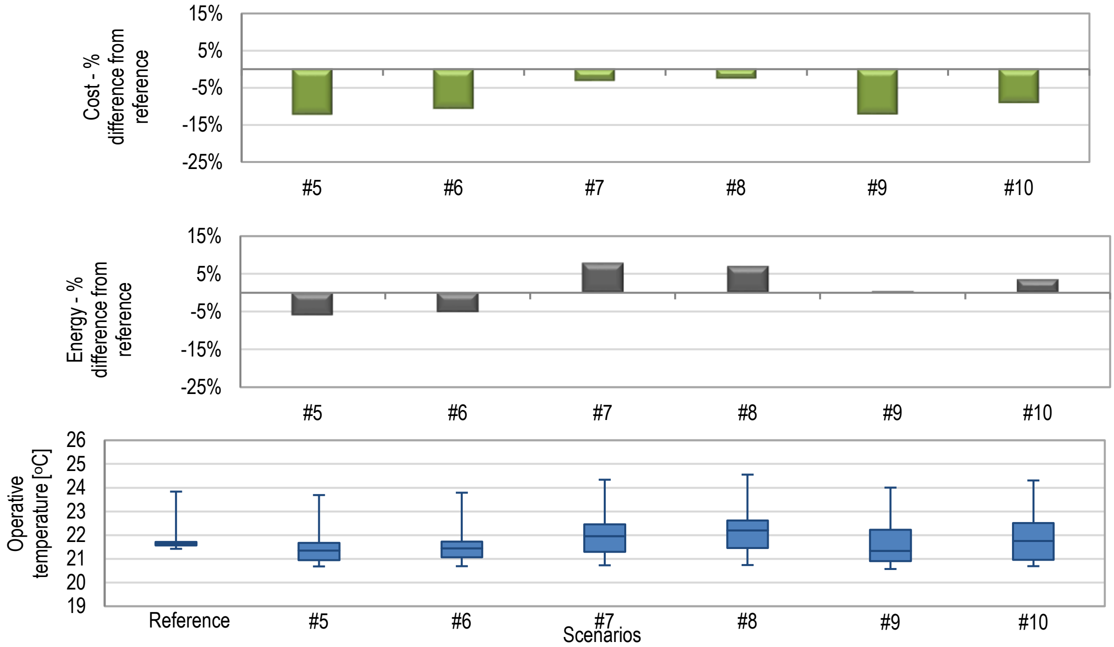

Figure 5.4 Effects of dynamic signal. Top: Percentage difference of cost between the reference operation and each scenario. Middle: Percentage difference of energy use between the reference operation and each scenario. Bottom: Box plots of operative temperature in the critical apartment during the heating season for the reference operation and each scenario.

- Scenario 1 yielded the highest cost decrease of 15.5%, and an energy decrease of 10.8%. However, this was at the expense of lower indoor temperatures, which were reduced by 0.6ºC compared to the mean temperature of the reference operation.
- Scenario 3 achieved the highest indicator of load shifting during night time, namely 0.79. Cost was decreased by 6%, but energy use was moderately increased by 2.1%. The mean indoor temperature was the same as that of the reference operation, but with more fluctuations during the day.
- Scenario 4 achieved the highest decrease in energy use during morning peak hours: 86.5%. Cost was decreased by 5.8%, with only small differences in the total energy use and mean indoor temperature.
- Scenario 9 achieved the highest indicator of load shifting during periods with lower heat production cost, namely 0.52. Cost was decreased by 12.2%, with almost the same energy use as the reference scenario. The mean indoor temperature was slightly lower than that of the reference operation and fluctuated within a wider temperature range.

Table 5.2 shows the average performance and flexibility potential across the heating season from the implementation of some selected scenarios, based on the previous evaluation.

Table 5.2 Average performance and flexibility potential in the different scenarios during the heating season.

Scenarios	Difference from reference operation				F1	F2
	Cost [%]	Energy use in morning [%]	Average temperature [ºC]	Total energy [%]		
Reference	–	–	–	–	-0.20	0.08
Scenario 1	-15.5%	-74.0%	-0.6	-10.8%	0.53	0.30
Scenario 2	-14.0%	-80.6%	-0.4	-11.0%	0.23	0.22
Scenario 3	-6.0%	-83.0%	0.0	2.1%	0.79	0.36
Scenario 4	-5.8%	-86.5%	0.1	1.4%	0.67	0.34
Scenario 5	-12.2%	-40.6%	-0.3	-6.0%	0.02	0.40
Scenario 6	-10.7%	-40.7%	-0.2	-5.1%	-0.01	0.36
Scenario 9	-12.2%	-42.7%	-0.3	0.3%	0.06	0.52

Figure 5.5 illustrates the average daily heat load patterns for the different scenarios together with that of Greater Copenhagen.

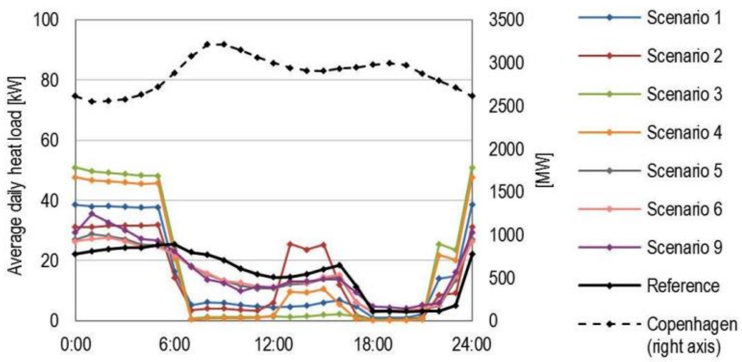

Figure 5.5 Left y-axis: Average daily heat load of the building in different scenarios and reference operation and right y-axis: average daily heat load in Greater Copenhagen.

For all scenarios, the maximum load was increased compared to the reference operation. The scenarios with pre-heating resulted in higher peak loads, while the scenarios which only decreased the set-point showed a behaviour closer to that of the reference. The occurrence of new building peak loads was a result that was anticipated, but it is arguable whether it undermines the implementation of those strategies. In terms of the building itself, the new peaks were within the installed capacity of the heating system, so no additional investment would be required. Regarding the DH system, the time when the new peaks occur can possibly be critical: the highest heating use occurred during the night period, i.e. 21:00 -6:00, namely at hours when the overall load of the system is low, and on average the marginal heat production cost is low. Whether or not the new peaks may pose challenges to the system, depends on the scale of the implementation. In all cases, load shifting from day to night was achieved, so the daily load pattern of the building contributed to smoothing the load of the Greater Copenhagen area. The morning peak in the heat load of Greater Copenhagen, which occurs between 6:00-9:00 could be mitigated by reducing the space heating demand in this type of building during this period.

Figure 5.6 shows the performance of the scenarios according to the two flexibility indicators described in Method section.

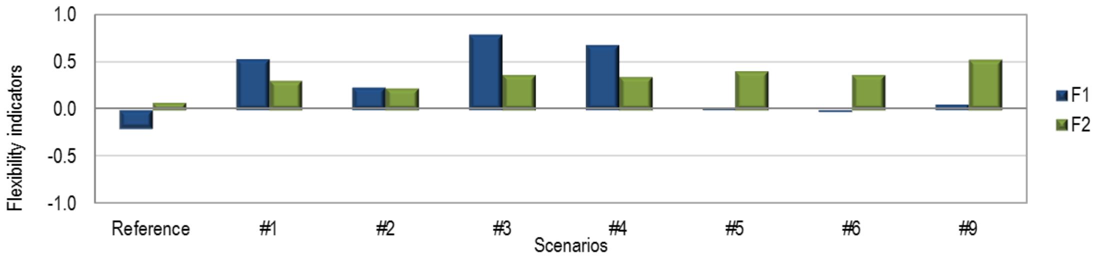

Figure 5.6 Flexibility indicators in the different scenarios and the reference operation.

For all scenarios both indicators improved compared to reference operation of the building. F_1 for the reference operation was -0.20, i.e. there was higher energy use during the high load hours than during low load hours. The scenarios with fixed schedules for set-points achieved higher values for F_1. The highest value of F_1 was achieved for Scenario 3 (0.79) followed by Scenario 4 (0.67), which were the scenarios with pre-heating during the night. Regarding F_2, during reference operation of the building it was almost 0, which means that there was equal energy use during high and low production cost period. The scenarios with dynamic response to the cost signal achieved higher values, with Scenario 9 being the highest with 0.52. For more information please refer to (Foteinaki et al., 2019)

Choosing which of the scenarios to implement is a multifactorial decision and it depends on the services that energy flexible buildings should provide to the energy system. It may be minimization of energy use during specific hours, reduction of cost, alleviation of local congestion problems, or smoothing the overall heat load. Such results may come at the expense of a wider indoor temperature range and/or more temperature fluctuations, so the level of acceptance of such changes may also affect the choice of the strategy.

5.5. Conclusion

This study examined the potential of low-energy residential buildings to be operated flexibly, using the thermal mass of the buildings for short-term energy storage, in order to be able to offer flexibility services to the district heating system. The requirements of the DH system were addressed by using rule based scheduling of the building's heating system based on the demand of the district heating system and cost-based scheduling corresponding to the marginal heat production cost. The different control signals triggered an increase or decrease of the air temperature set-point, in order to charge or discharge the thermal mass.

Highly effective heat load shifting was achieved (between 40% and 87%) to avoid the DH system peak load hours. Cost reductions of up to 15% were achieved. The total energy use either increased by up to 2% or decreased by up to 11%. Increased energy use may be considered acceptable as part of load shifting strategies, if it costs less to be produced and can be beneficial for the environment if it comes from renewable energy sources. With the implemented strategies, new peaks in the heating load of the building were created. However, they occurred during low load hours and were within the installed capacity of the building heating system. The thermal indoor environment was changed, as a wider temperature range and/or more frequent fluctuations in the indoor temperature occurred.

The choice of the best performing scenario is not straightforward, as it would depend on the services that the building is to offer to the district heating system. Some scenarios indicated higher potential for cost reduction, or achieved greater load shifting. The magnitude of the achieved benefits is associated with the acceptable changes in the energy use and in the thermal comfort set by the occupants of the building.

5.6. Acknowledgement

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6. Energy flexibility and shiftable heating power based on building type

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6.1. Abstract

Thermal load management has substantial theoretical potential for energy flexibility. To use the inherent flexibility in buildings, for example, district heating companies could temporarily control the heating system of buildings to switch-off or preheat dwellings in the morning to avoid using peak load gas boilers. The ‘thermal flexibility’ in this study indicates the tolerance of buildings towards the changes of its heating system operation according to an external signal. The focus of this investigation is to give an overview of the thermal flexibility of residential buildings in Austria, built between 1920 and 2020, with different envelope qualities, construction types and heating systems. Existing residential buildings in Austria usually have a high thermal mass within their massive brick or concrete primary structure, and therefore their indoor thermal conditions react slowly to operative changes in the supply of thermal energy. Depending on the building’s ability to retain or store heat inside the building envelope, space heating can be used to offer energy flexibility. Among other factors, especially the quality of the thermal envelope, the thermal capacity of the building, the sluggishness of the heat delivery system and passive solar gains are crucial for maintaining indoor thermal comfort. Dynamic building simulation in IDA ICE is used to evaluate the potential of selected building typologies to shift heating loads away from peak demand periods. Potentials of various building archetypes according to the EU-Tabula building database to time-shift the operation of the heating system are pointed out respecting occupants’ comfort.

6.2. Background and objectives

Domestic space heating is responsible for about 45% of the total household energy demand in Austria (Statistik Austria, 2016). In particular, dwellings built before the 1970s with a high domestic space heating demand have the highest share in the overall heating energy consumption. Still, due to their high heat storage capacity, if they have a certain thermal envelope quality, they can stay pleasantly warm for some time after the heating system has been switched off. Austrian buildings built before 1970 were often heated by single furnaces as heating systems, and the air-temperature control was dependent on how the air supply was adjusted and how the fuel was added to the furnace. Under these conditions, a large heat storage capacity of old buildings was highly desirable and helpful. It reduced the increase in air temperature when there was an excess of thermal heating energy and slowed down the drop in temperature when the furnace was turned off. The heat storage capacity has a ‘temperature-equalising’ or ‘temperature-stabilising’ effect especially useful for uneven or so-called transient-heat-delivery-systems like old furnaces. Under these heating conditions, the heat storage capacity was thus able to compensate for the poor controllability of the heating systems in a certain sense. The larger the storage mass, the better (Künzel, 1983).

Most of the old inefficient furnaces and heat delivery systems have been replaced in old buildings in the meantime, often by district heating grid connected heating supply systems or electric heat pumps. With today's low-temperature (compared to furnaces) heating systems and control options, the heat storage capacity has become less important for space heating. Mainly also because the charging of the storage masses by convective heat transfer is incomparably lower than by radiation. With convective heat transfer, the storage mass can at best be charged with the air temperature of the room and not, as in the past, absorb the radiant heat of the furnace. However, with the arising challenge of integrating high shares of renewable energy in energy supply grids, with particularly variable wind and solar, puts the idea of the heat storage capacity of a building into a new perspective. The concept of flexibility of buildings is to manage their loads based on the requirements of the surrounding grids. In the context of heating flexibility, this means to heat-up the building when there is excess solar, and wind energy available in electricity grids, or renewable heating grids can be operated ideally and reducing heating power at other times. Especially during cold winter periods, control systems in residential buildings can be used to reduce peak demands and take stress from electricity and heating grids (Cardinaels and Borremans, 2014). The energy flexibility of heating systems depends on the ability of a building to retain or store the heat inside the building envelope concerning comfort requirements. The amount of insulation, the thermal capacity and the passive solar gains of buildings are crucial for keeping indoor thermal comfort (Six et al., 2011) and (Le Dréau and Heiselberg, 2016).

The focus is here on a quantitative evaluation of the potentials of heating flexibility of residential buildings in Austria from 1920 – 2020 on the level of usable energy. The difference of envelope qualities, construction types and heating systems plays a crucial role in defining the possible heating flexibility of a certain building typology. Dynamic building simulation in IDA ICE is used to evaluate the potential of these building typologies to shift heating loads away from the peak demand periods. Potentials of various building archetypes to time-shift the operation of the heating system will be pointed out, with attention to occupant comfort. With the obtained data, it is possible to offer an estimation of the heating flexibility of prototypical residential buildings in Austria, assuming that they are equipped with a grid-connected heating system like electric heat pumps, district heating or direct electric heating. Also, the effect of the insulation level applied to the building envelope, as well as the effect of thermal mass on the heating flexibility, is analysed.

6.3. Evaluation Methodology

Heating energy flexibility also referred to as ‘thermal load shifting’ is here defined as the number of hours the energy system can be delayed or forced to operate considering the indoor comfort band as a constraint. For example, when space heating is switched off at the upper excepted limit of the indoor comfort temperature, the indoor temperature remains within the comfort zone for a certain period depending on the level of building insulation, ventilation and thermal mass. As the thermal energy inside the building envelope is vanishing, the indoor temperature drops. ΔT denotes the time after which the temperature has fallen from the upper comfort limit to the lower comfort limit, yielding a temperature difference of ΔT [°C]. Other essential definitions are explained in Figure 6.1.

6.4 Austrian dwellings - Simulation models

The calculation of thermal load management potentials for representative building typologies has been derived from the TABULA/EPISCOPE web database (Loga et al., 2016). For the simulation, the weather conditions of the test reference year of Graz, from the 2013 ASHRAE – Fundamentals (ASHRAE, Inc.: International Weather for Energy Calculations) – see Figure 6.2, has been applied. Four different detailed building models with different years of construction and controllable heating systems and defined user behaviour were modelled in IDA ICE. The ventilation and infiltration corresponds to 0.4 air change per hour in order to guarantee sufficient air renewal. All buildings are modelled as a single zone, with the exact physical characteristics derived from the TABULA/EPISCOPE database. Internal heat gains for multifamily buildings according to SIA 2024 (Schweizerischer Ingenieur- und Architektenverein, 2006) have been applied to the building models. The set-point for the indoor operative temperature is 22°C. The allowed temperature band is 22± 2°C, and the minimum allowed operative temperature 19°C matches to the PMV-PPD category II of the comfort standard EN 15251 (PPD < 15%, -0.7<PMV<0.7). The influence of different occupancy behaviour on the heat flexibility is not considered here.

6.5 Results

The resulting load shifting potentials for analysed building typologies defined in Table 6.1 are presented in the following.

6.5.1. Delayed operation – cooling down

The simulations were firstly carried out for a characteristic winter week, 16th – 23rd of January, using a simulation time step of 10-minutes. During the working days, the building is non-occupied from 8.00 am. to 17.00 pm. Each occupant emits 80 W due to the metabolism, and the assumed net floor are per person is 30 m^2. There are also internal gains from appliances during occupied hours resulting in internal heat gains of 13 W/m^2 as shown in Table 6.2. Figure 6.3 shows the cooling down of the operative temperature after the heating system is switched off. The period it takes for the operative temperature to reach the lower comfort level of 19°C is referred to as the potential ‘delayed operation’ of the heating system. The changes in of operative temperature after switch-off of the heating system on the 16th of January starting at 0:00 is shown in figure 1.3. When the heating is switched off, the operative room temperature drops rapidly at first and then more slowly. When the room air temperature drops during the first hour after the heat switch-off, the heat stored in the wall returns to the room, and the temperature drops more slowly. Throughout the day, the passive solar gains via the window surfaces lead to an increase in the temperature, which then drops again constantly during the evening and night-time. The positive effect of the passive solar gains during the daytime influences here only the newer better insulated cases (C and D) since the old buildings (A and B) cool down too fast in order to benefit from passive solar gains. If, however, the switch-off occurred during sunshine, building A and B would also benefit somewhat from the solar radiation.

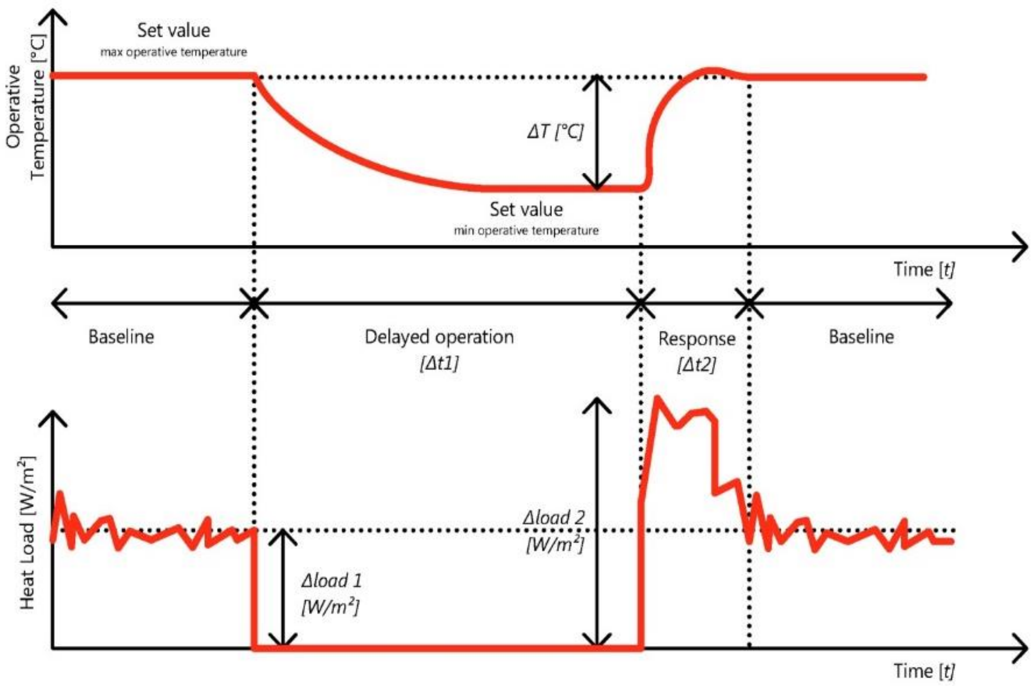


Figure 6.1 Demand-side control of set temperatures, representation of the cooling-down curve (delayed operation- Δt1) and heating-up time (response - Δt2) (graph based on (Palensky and Dietrich, 2011)).

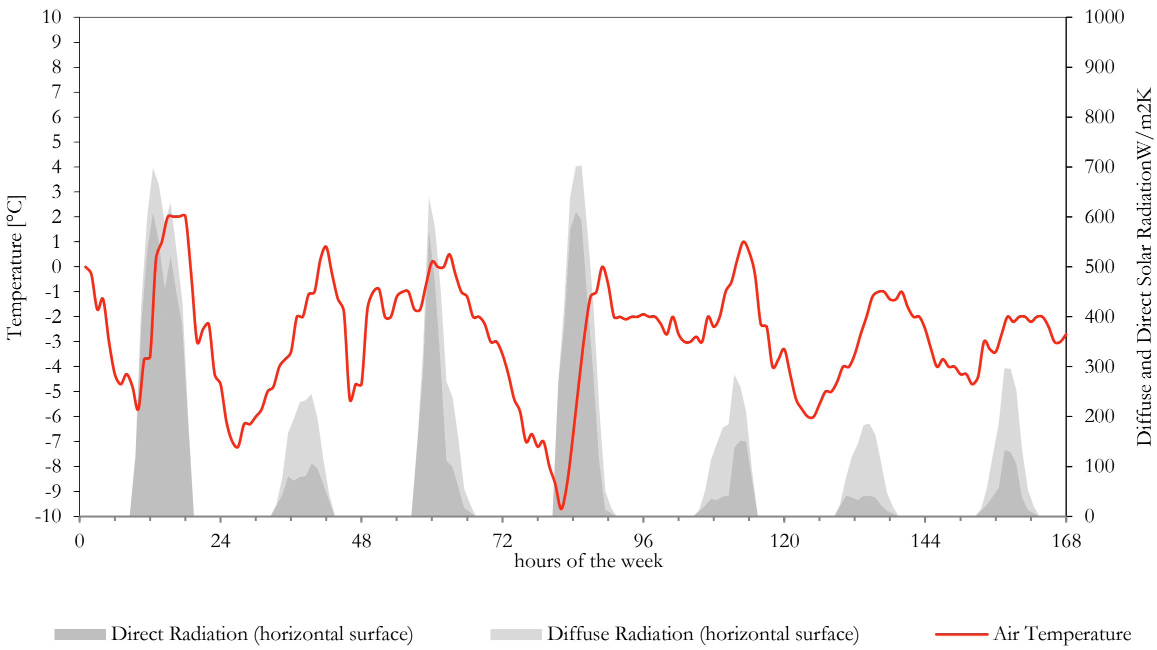


Figure 6. 2 Climate chart of the chosen reference week 16th January to 23rd January, Graz (ASHRAE, Inc.: International Weather for Energy Calculations).

Table 6.1 Representative building typologies based on TABULA/ EPISCOPE database (retrieved from http://episcope.eu (Loga, Stein and Diefenbach, 2016)).

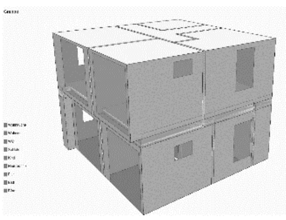
House type	Photo example	Building information	Values
[A]		Building Class: Tabula Code: Construction Period: Reference Floor Area: Net /Gross Energy need for heating U-Value exterior Wall U-Value Windows U-Value Roof	Single Family House ATN.SF.3.Gen 1945 – 1960 198m² 134 kWh/m²a 1,40W/m²K 2,30 W/m²K 0,50 W/m²K
[B]		Building Class: Tabula Code: Construction Period: Reference Floor Area: Net /Gross Energy need for heating U-Value exterior Wall U-Value Windows U-Value Roof	Multi-Family House ATN.MFH.5.Gen 1981 – 1990 590m² 90 kWh/m²a 0,60W/m²K 2,50 W/m²K 0,44 W/m²K
[C]		Building Class: Tabula Code: Construction Period: Reference Floor Area: Net /Gross Energy need for heating U-Value exterior Wall U-Value Windows U-Value Roof	Apartment Building ATN.AB.8.Gen 2010 - 906m² 47,8kWh/m²a 0,30W/m²K 1,40 W/m²K 0,40 W/m²K
[D]		Building Class: Tabula Code: Construction Period: Reference Floor Area: Net /Gross Energy need for heating U-Value exterior Wall U-Value Windows U-Value Roof	Single Family House no 2020 - 138m² 12,1 kWh/m²a 0,10W/m²K 0,60 W/m²K 0,10 W/m²K

Table 6.2 Building zone and occupancy assumptions according to SIA 2024.

Gains and load hours	Unit	Value	Area, activity level and room temperature	Unit	Value
Internal heat gains (People, equipment, lighting)	W/m²	13	Net floor area per person	m²	30
Internal heat gains per day (People, equipment, lighting)	Wh/m²	84	Activity level people	met	1,2
Full load hours per year	h	4090	Room air temperature without flexible operation (winter)	°C	22

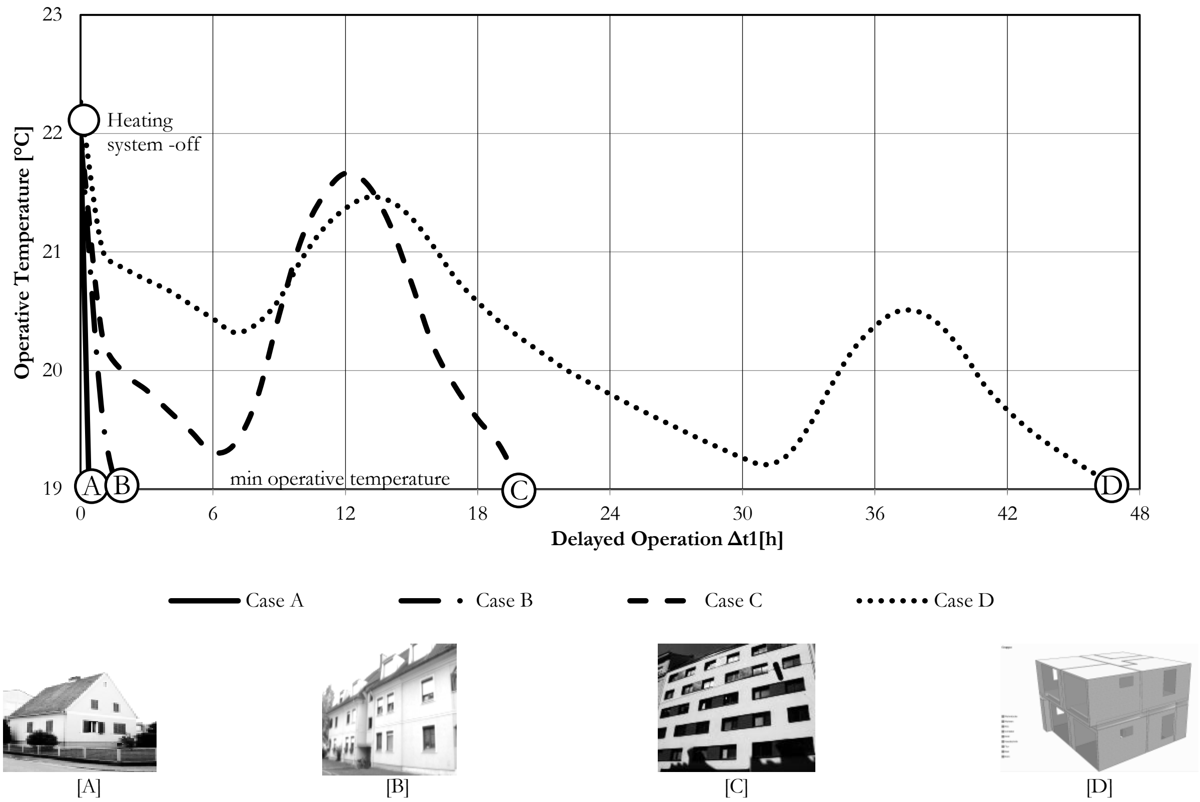


Figure 6.3 Cooling down time of 4 case studies - delayed operation (Δt1).

It should be noted that the shiftable heating loads are not constant over time as can be seen in Figure 6.4. Further, the average heating power needed to keep the buildings operative temperature at 22°C in this January week ranges from 55 W/m² in case A, 37 W/m² in case B, 18 W/m² in case C to less than 10 W/m² in case D. Buildings with lower heating loads, have longer delayed operation times. Passive solar gains have shown to increase the delayed operation time which is also noticeable in the reduced heating energy power during the daytime.

These reults lead us to the first conclusion: Old buildings, represented in simulation models (A and B), in contrast to new, and highly energy efficient buildings (C and D), have a higher specific performance due to the lower insulation standard. This leads on the one hand to a higher shiftable heating load, but shorter delayed operation periods as seen in Figures 6.3 and 6.4.

Figure 6.5 combines the simulation results of Figures 6.3 and 6.4. The resulting curve displays the delayed operation time (the time that it takes for the room to cool down from 22°C to 19°C) on the x-axis and the shiftable heating power (the average heating power that can be switched off during this period) on the y-axis. The curve shows how long the average specific heating power [W/m²] of the four different building typologies (A to D) can be switched-off while the operative temperature inside the building stays within the specified comfort band of 19°C-22°C operative temperature after the heating system has been switched off.

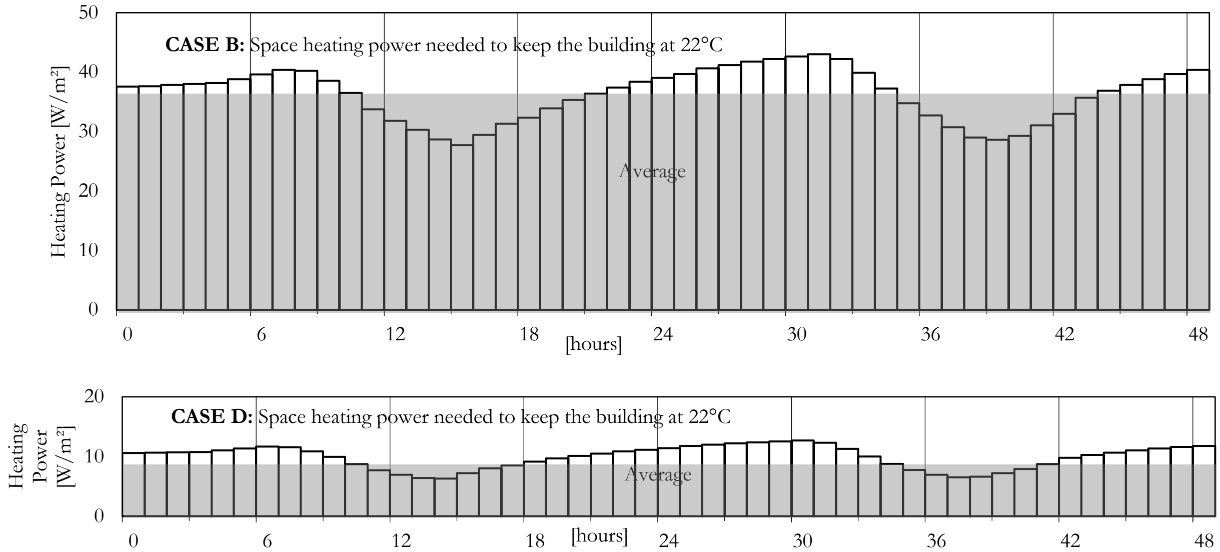


Figure 6.4 Heating power demand to keep the temperature of the building at a 22°C setpoint temperature (without load shifting) for case B and D.

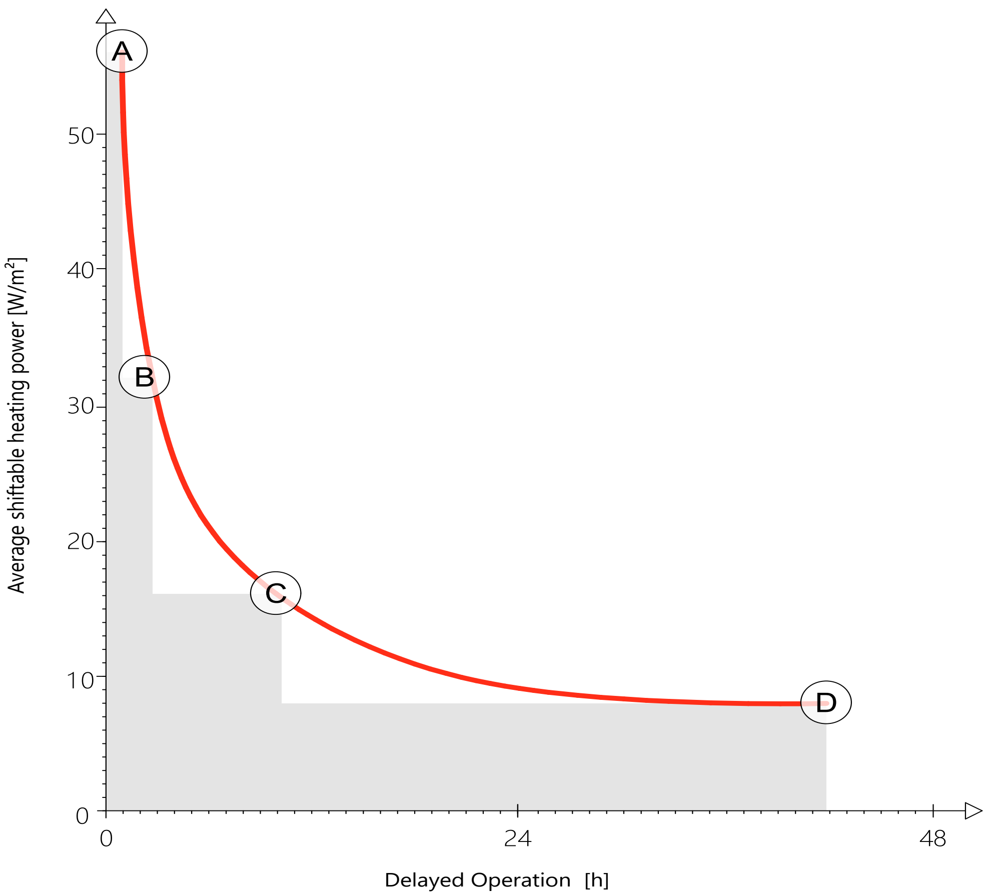


Figure 6.5 Load duration curves of case studies showing the potential of shiftable domestic heating load over time - delayed operation (Δt1)

6.5.2. Delayed operation – Optimisation

The effect of thermal inertia in relation to energy flexibility has been investigated in detail by (Reynders et al., 2015). Buildings with high thermal mass embedded in the construction, have a huge potential to store heat over long periods. The specific heat storage capacity of the analysed TABULA case studies accounts for approximately 120 Wh/m²K since the buildings all have brick walls and concrete ceilings. Follwing the primary structure of the case study buildings is changed to a concrete construction (specific heat capacity of construction = 200 Wh/m²K) in the simulation model. Figure 6.6 shows the effect of increasing the thermal inertia of the building when the heating system is switched off. The larger the storage mass, the slower the building cools down. A heavyweight constructed building in combination with a high insulation standard (case C and D) extends the timespan for thermal load shifting drastically as shown in Figure 6.6. The thermal mass of a concrete constructed building, in comparison to brick buildings, enables it to store more heat.

Results show that the delayed operation time of case study C can be extended from 20 hours up to 32 hours by adding more thermal inertia. This effect becomes even more drastic when adding thermal inertia to the most efficient building, case study D. Here the potential delayed operation time rises by a factor 2.3 from 46 hours up to 102 hours.

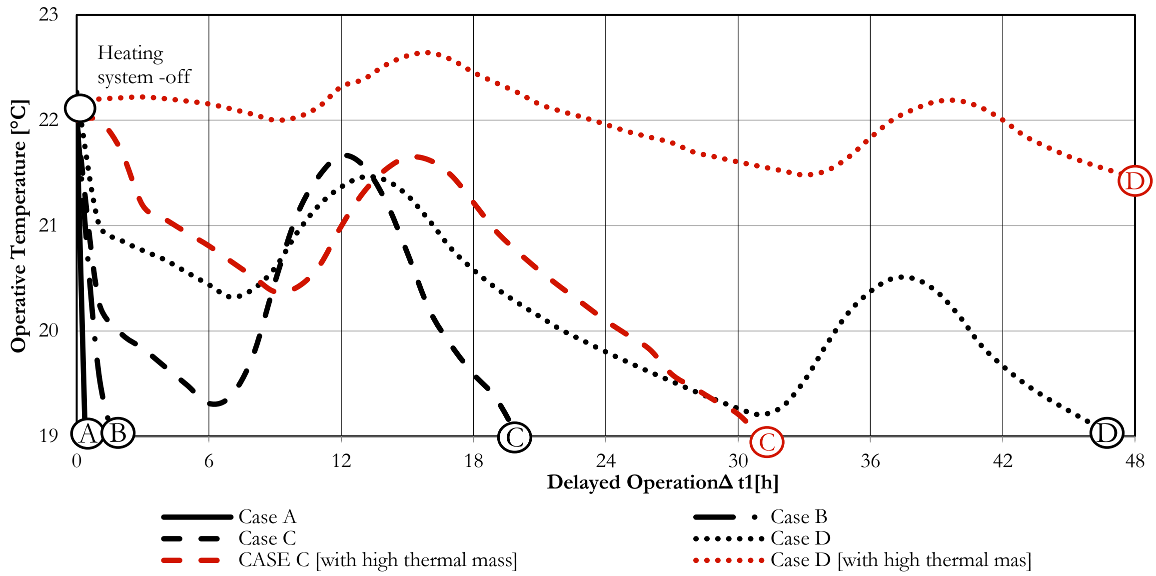


Figure 6.6 Cooling down time of thecase studies with increased thermal mass for case C and D.

Figure 6.7 allows us to explore the influence of shiftable domestic heating loads between heavy and medium-weight constructions, as well as different insulation levels based on the year of construction. The possible off time for case study B, C and C increased considerably, while there is no increase for case A. The latter due to the large losses through the poor thermal envelope.

Even though the load shift period was determined for a typical cold January week, this resulting curve can theoretically be used for any day/season of the year. If the heating power is known for a certain timespan, the ratio of the average shiftable heating power and the delayed operation time can be estimated depending on the thermal intertia.

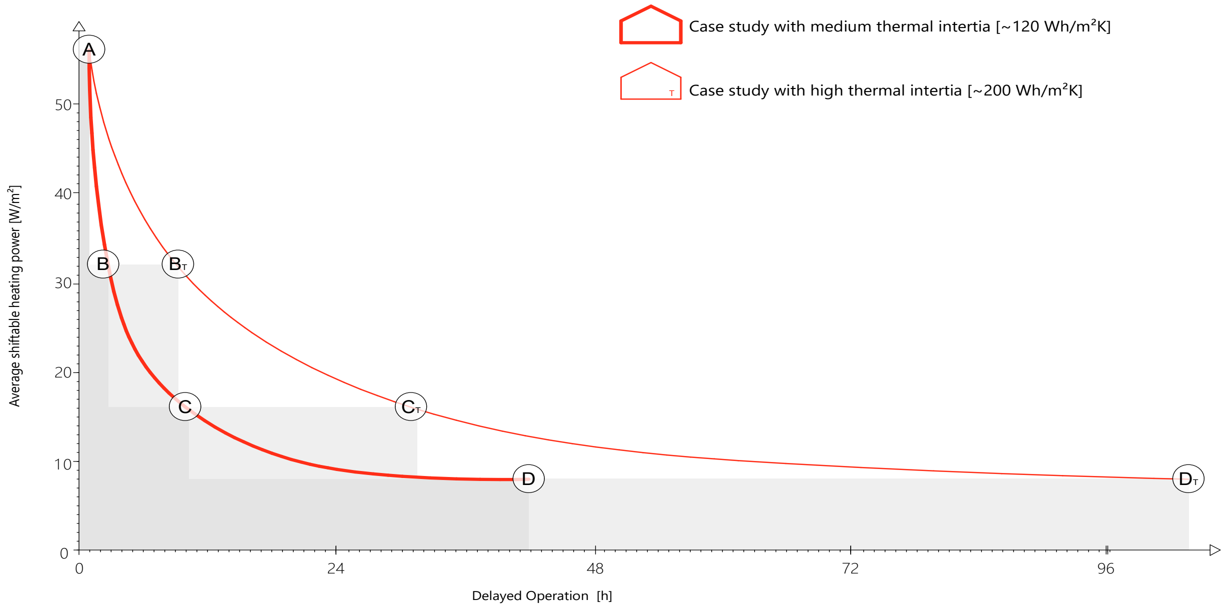


Figure 6.7 Load duration curves of optimised case studies showing the potential of shiftable domestic heating load over time - delayed operation (Δt1).

In comparison to the investigated load shifting options by modulating the heating system (on/off), state of the art thermal or electrical energy storage systems are a more common way of providing energy flexibility to heating systems. Based on the heating system a state-of-the-art thermal storage water tank of 0.15-0.6 kWh/m² can drastically extend the thermal load shifting potential/ thermal storage potential. These capacities represent a 20-80 kWh thermal storage tank (200-1000 litres) for a typical single-family home in Austria.

The curves in Figure 6.8 show how long a specific thermal power [W/m²] can be provided by different thermal storage system [kWh/m²] after the heat switch-off. It is seen that the load duration curves can be extended drastically by adding thermal storage systems.

Fgure 6.9 shows how long a specific electrical power [W/m²] can be provided by three different sized electrical batteries [kWh/m²floor area] after the active power supply has been switched off. It is important to note that this potential seems relatively small because it is assuming a direct electric heating system using each electrical kWh directly as thermal energy for heating the building. If the heating system was powered by, for example, a geothermal heat pump operating at COP 3.5, the load duration curves can be extended drastically. It is essential to note that batteries can be used all year round for electric energy demand of the building and not specifically only in winter for heating flexibility.

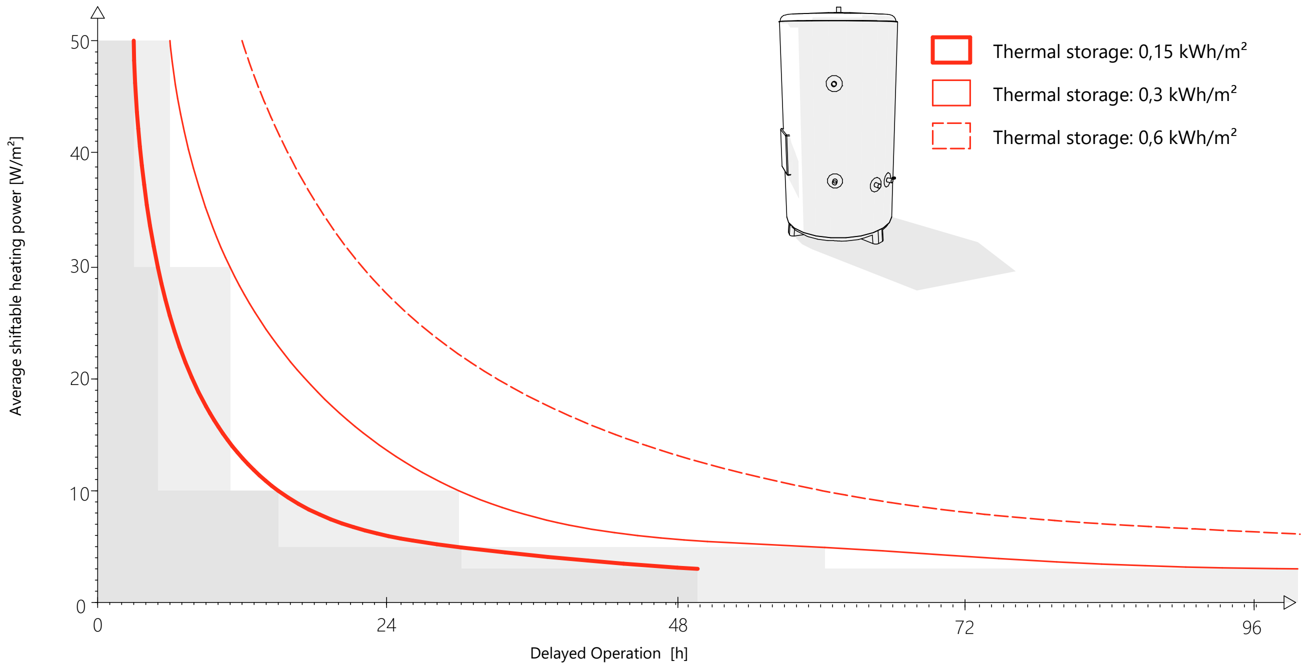


Figure 6.8 Load duration curves are showing the potential of storeable domestic heating load over time with three thermal storages - delayed operation (Δt1) without taking losses of the stoarge into account and without consideration of the different heat supply temperatures

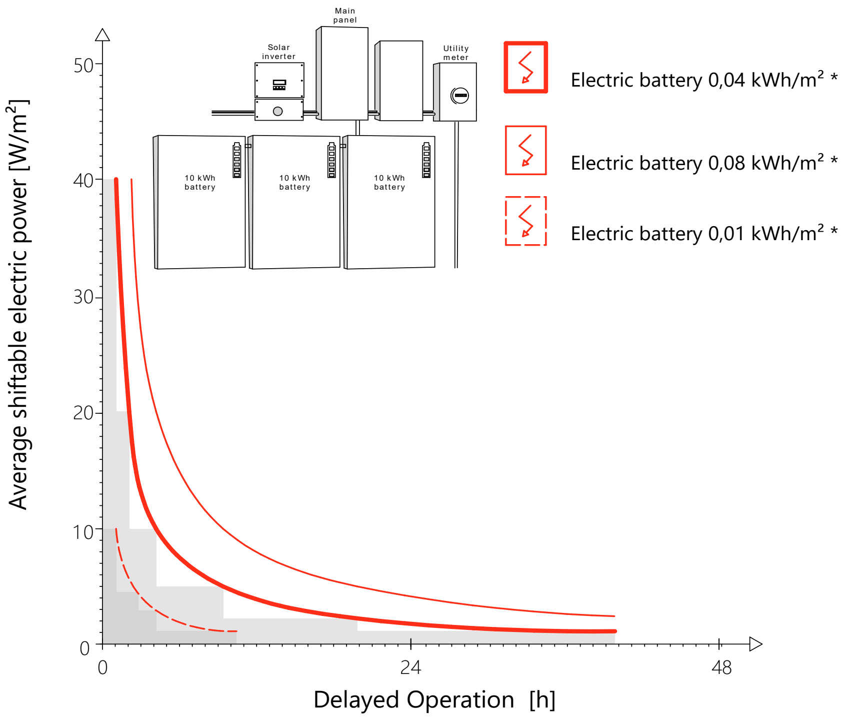


Figure 6.9 Load duration curves are showing the potential of battery storages to provide for electrical power after power switch-off - delayed operation (Δt1).

6.5.3. Response – heating-up

Due to the low-temperature heating systems in cases C and D with lower maximum heating capacity, the heating up timespan from the lower temperature setpoint of 19°C up to 22°C usually takes much longer. Also, the sluggishness of low temperature heating systems and modern PI controllers slow down the heating-up timespan. This timespan to reach the original temperature setpoint of 22°C again is referred to as the "response time of the heating system" in Figure 6.10. It is heavily dependent on the capacity and the control strategy of the heating system and much more difficult to assume in general than the cooling-down period, which is more related to the physical properties of a building. Figure 6.10 combines the load duration curves of the case studies showing the potential of shiftable domestic heating load over time for the cooling-down timespan on the right side (delayed operation) with an average predicted heating-up timespan (response) after the thermal load shifting operation on the left side. Also, we can see in Figure 6.10 that from the end of the load shifting period till the heating system reaches the 22°C setpoint temperature again, there is an increase in heating demand since extra power is needed. Old, poorly insulated buildings with slightly oversized heating capacities, can react more quickly and reach the upper setpoint temperature relatively quickly.

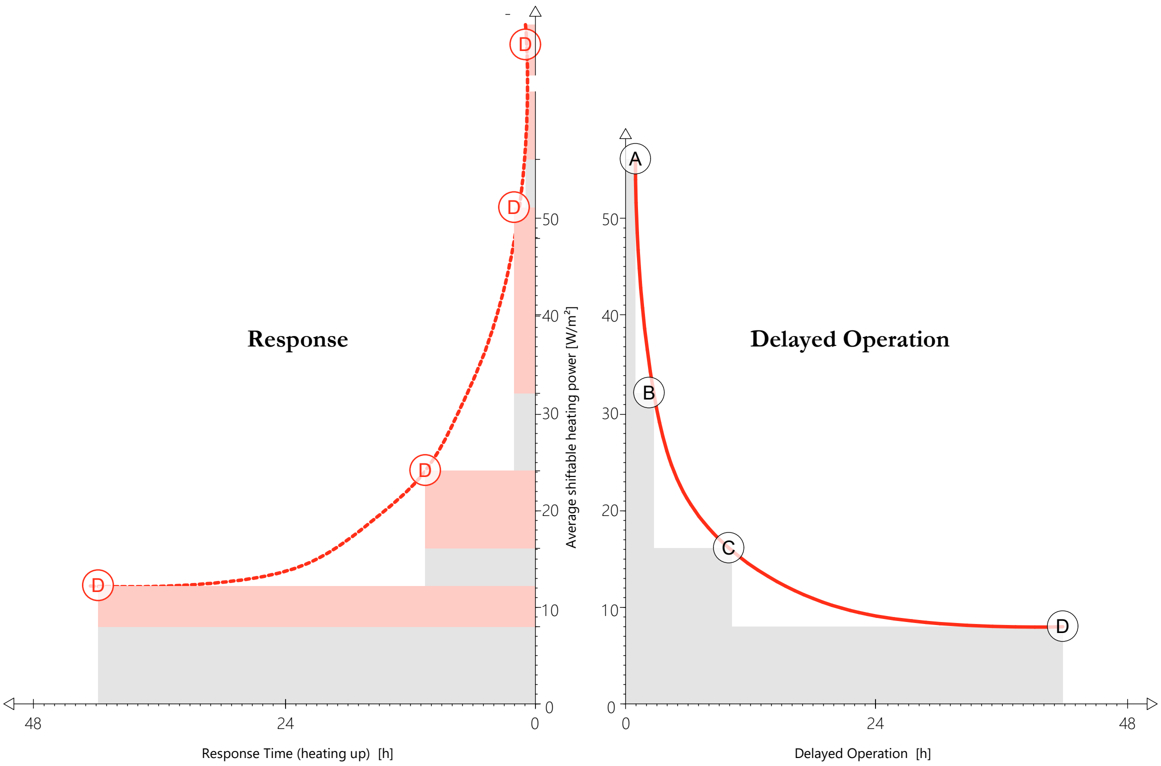


Figure 6.10 Rebound effect of shiftable domestic heating loads over time delayed operation (Δt1 – right) and response (Δt2 - left).

6.5.4. Seasonal effects

To determine the seasonal potential of the flexibility of thermal loads for the case studies the heating system was switched off on other days during the heating season. Again, a simple on-off control strategy is used to investigate the maximum heat flexibility potential. The heating system was switched off at 6:00 in the morning and counting the hours of the operating temperature drops from 22°C to 19°C. It can be observed in Figure 6.11 that with higher outdoor temperatures and more solar gains all buildings (case B, C and D) have relatively longer delayed operation times (Δt1) in the beginning (and also end) of the heating season (here shown for November). In these months the potential delayed operation time is generally longer than 24 hours for case C and D and around 10 hours for Case B. During high winter, in Figure 6.11 represented by January, the temperature drops much faster especially in case C where delayed operation range from only 4 to maximum 14 hours and a high deviation of the duration of the delayed operation is seen.

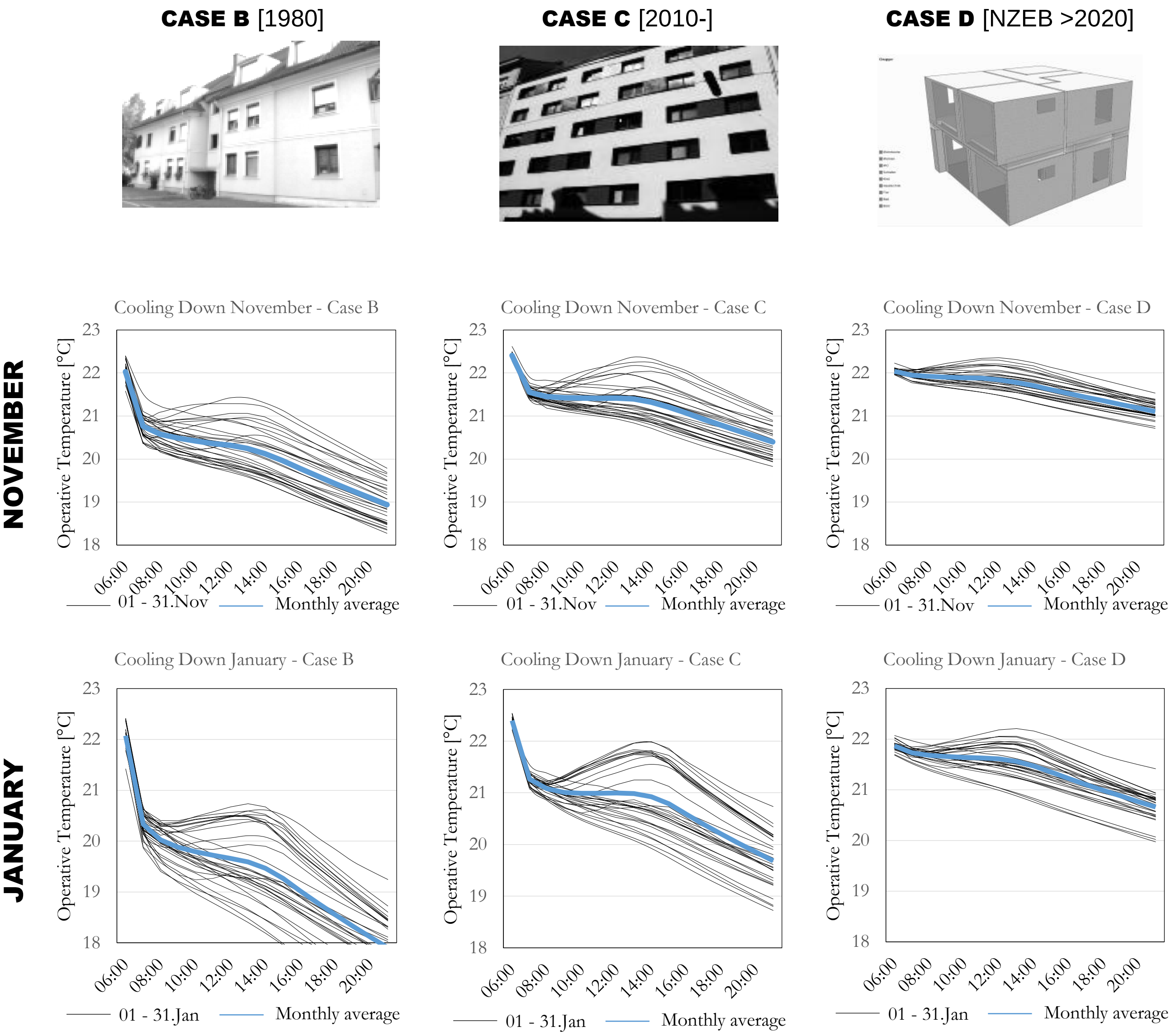


Figure 6.11 Daily heat flexibility - cooling down time during heating season - delayed operation (Δt1) with heating system switched off at 6:00 every day.

6.5. Conclusions

The potential for shifting domestic heat loads from the peak to low demand periods for Austrian building archetypes was investigated, and potentials for optimization were pointed out.

The findings are summarized as follows:

Old buildings (cases A and B) in contrast to the new (cases C and D) have higher specific loads due to the lower insulation standard. This leads to a higher switchable load, but also a shorter shutdown period. Heat flexibility, therefore, is mainly determined by the buildings' physical thermal properties. Also, energy efficient refurbishment of existing buildings can unlock a high load management potential since old buildings usually have high heating loads.

The total amount of heating energy that can be shifted is beside the thermal quality of the building envelope dependent on the heating set points and acceptable comfort range. Tolerating a larger deviation from the comfort band especially in unoccupied times can significantly extend the load shifting potential of domestic heat loads.

An increase of thermal mass/heat capacity leads to a damping effect on temperature changes, resulting on average in a 20-30% higher load shifting potential. At least 50% of the domestic heating peak loads can be shifted to off-peak periods during the day for buildings built after 1980 in Austria, even in January, and still reach the comfort band of EN 15251, category II.

The expansion of electric heating systems on the other side also poses the risk of worsening the seasonal gap of renewables in the grid, leading to higher specific emissions per kWh.

For all building types, large delayed operation times are possible on days with higher average outside temperatures and high solar irradiation. Also, it is concluded that for four prototypical buildings, it is possible to predict the heating flexibility based on weather conditions, namely outside temperature and solar irradiation. For the older dwellings, the outside temperature has a dominant impact on the heat flexibility, as cooling down times are so fast due to envelope heat losses that these buildings hardly benefit from passive solar gains from solar irradiance; especially when the switch-off starts few hour befor periods with solar radiation.

6.6. Acknowledgement

The above investigations are part of the Dissertation Project 'EFLEX-NZEB' [FFG 856025] with the support of the Austrian Ministry of Transport, Innovation and Technology by Tobias Weiß within the framework of Annex 67. Parts of this chapter have been published in an article the scope of this theses (Weiss, 2018).

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7. The impact of thermal mass on the energy flexibility of buildings

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7.1. Abstract

Usually buildings with photovoltaic systems feed a large amount of electricity into the public grid. The feed-in increases stress on the grid and is usually financially not attractive due to low feed-in tariffs. Shifting duty cycles of heat pumps during the daytime would, therefore, be a possible means to greatly increase the self-consumption and reduce the grid interaction. However, this is only possible when the building can offer this flexibility while thermal comfort is maintained. In this work, the energy flexibility is defined as the ability for the building to shift the operation time of the heat pump into daytime only without jeopardizing thermal comfort.

A real residential building with limited heat pump operation time during daytime only is investigated. Based on the real building transient thermal building simulations are done. The impact of thermal mass in the building structure, the insulation level and the available heat pump power on the possible reduction of heat pump operation times is investigated.

The results obtained for the real building show that limiting heat pump operation to daytime hours is possible. The simulation results show that a well-insulated building must have a middle or high thermal mass to be able to limit the operation time of the heat pump to daytime without incurring a non-negligible loss of thermal comfort. The operation time limitation proves not to be possible with a lightweight construction (low thermal mass).

Based on a wide range of simulations, a simplified method for the assessment of the necessary operating time of the heating is proposed. Thus, the operating time of the heating can be used as a parameter for flexibility. The shorter the necessary operating time of the electricity driven heating (e.g. heat pump) is, the higher the flexibility is of the building. The used on/off controller is simple, cheap and robust.

7.2. Background and objectives

The feed-in of solar energy based electricity into the grid can have detrimental effects due to an excessive supply during daytime. Ideally, buildings that consume electricity for space heating or cooling should align their demand with times of excessive supply. In the case of the aforementioned solar energy based electricity, this would be during the day in order to ensure a high self-consumption. Requiring only short windows of time for energy demand is advantageous, here.

A large number of publications can be found which address the use of thermal mass to describe the energy flexibility of buildings. Typically, the heating system is a heat pump which is controlled by electricity spot price signals (e.g Le Dréau and Heiselberg, 2016, Johra and Heiselberg, 2017*)*.

Different control strategies are also evaluated (Dar et al., 2014). Usually approaches are based on a smart controller and dynamic signals.

The approach described in this chapter is based on a simple, time-based on/off controller usually available within most heat pumps. The focus is to only operate the heat pump during daytime to increase the self-consumption of the building's on-site solar energy based electricity. Firstly, the findings of a real multi-family dwelling with a limited heat pump operation time are shown. Secondly, different thermal masses, insulation levels and installed powers of the heat pump are investigated by thermal building performance simulation.

7.3. Method

7.3.1. Case study

The basis of the investigation is an existing small multi-family building (Figure 7.1) which comprises three apartments (320 m^2 heated area, gross value) and is built to the Swiss MINERGIE-P Standard (MINERGIE-P, 2019), which means it has a very high level of thermal insulation (Table 7.1). The building can be viewed as a light/heavyweight construction. It features external walls in lightweight concrete and ceilings/floors as well as a flat roof in heavy weight reinforced concrete. Internal walls are in sand-lime brick and plasterboard. A ground-source heat pump (geothermal probe) heats the building with an installed capacity of 8.9 kW. The heat is distributed by underfloor heating. A mechanical ventilation system with heat recovery (80 % efficiency) is installed. A photovoltaic system with 20 kW peak capacity covers the roof facing south.

Figure 7.1 View of the small multi-family building studied (© Setz-Architektur, FHNW IEBau).

Table 7.1 Characteristics of the multi-family building ([a]= calculated according to SN EN ISO 13786:2007, [b] = SIA 2028:2010).

Property	Value
U-value, ext. walls	0.12 W/(m^2 K)
U-value roof	0.09 W/(m^2 K)
U-value windows	0.75 W/(m^2 K)
g-value, windows	0.5
Glazed part of wall (area weighted)	23 %
Solar control (blinds)	Not applicable
Shading (surrounding buildings)	yes
Thermal mass (with R_{si}) [a]	63 Wh/(m^2_{NFA} K)
Size of domestic hot water tank	800 l
Air exchange rate	0.39 1/h
Climate [b]	DRY Buchs-Aarau (CH)

7.3.2. Monitoring

Detailed monitoring was carried out for two years. The monitoring shows that the heat pump has the highest potential for load shifting. In order to increase the self-consumption, the operation time of the heat pump is limited to daytime hours (10:00–17:00) for heating and domestic hot water (DHW) as a proof of concept (Figure 7.2). Due to this limitation approx. 1,000 kWh (heat pump only) were shifted from night time to daytime. The self-consumption factor (Salom et al., 2014) increases from 21 % to 34 %. Additionally, the COP increases (heating 3.8 to 4.9, DHW 3.6 to 3.9) because the heat pump runs more continuously. The thermal comfort does not decrease. In particular, the heating of domestic hot water between 12–14 pm shaves the peak electricity export in this time interval. The building shows a high flexibility by using the thermal mass and the well insulated envelope. The advantage of this approach is that the control strategy is very simple. The standard timer function of the heat pump is sufficient, no special controller is needed (Hall et al., 2014).

7.3.3. Numerical modelling of the building

The thermal model of the multi-family dwelling consists of 15 zones. Furnishing is considered with a thermal mass of 36 kg/m^2 of the room's floor area (ÖNORM, 2012). This value correlates with a medium/high furnishing according to (Johra and Heiselberg, 2017). The furnishing is modelled explicitly with wood structures and planar shapes in each room. The thermal simulations are performed with ESP-r (ESRU, 2017). The simulations have a pre-simulation period of 60 days, to allow transient oscillation of the building model. The simulation time step is set constant to 6 min. The simulations are performed and evaluated for the period from 1st of January until 28th of February (coldest period). The simulation model is validated with the monitored data from the multi-family building in the former section. Afterwards, standard profiles according to Swiss guideline SIA 2024 (SIA 2024, 2015) are used for internal gains from occupants, devices and lighting. The heat supply temperature for the under floor heating is 35 °C with a set point temperature of 21.5 °C of the thermostat in each room (wall integrated).

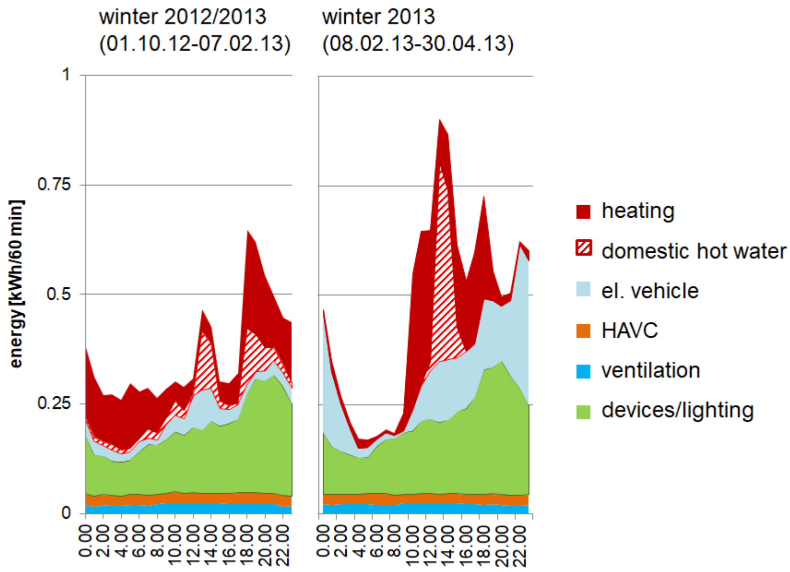

Figure 7.2 Hourly mean values of energy consumption for individual consumers, monitored data for the multi-family building based on 15 min values (heat pump: head driven - left, time scheduled - right) (Hall et al., 2014).

7.4. Results

In order to assess the flexibility of the necessary operation time of the heating, parameters such as thermal mass of the building construction, heating demand and capacity of the heating are varied. All thermal simulations are evaluated against the condition that the operative room temperature should never drop below θ_{op} = 20 °C (EN ISO 7730, 2005). Figure 7.3 shows the correlation between the operating time of the heating and the capacity of the thermal mass of the building. Five different insulation levels leading to different heating demands (represented by different colours) are analysed. The initial building as characterised in Table 7.1 has a heating demand of 18 kWh/(m^2 a), corresponding to the red lines. Two different installed powers of the heat generation system are symbolised by line styles (solid: 56 W/m^2, dashed: 22 W/m^2). The graph only takes the heating's operating time for space heating into account. Hot water generation requires approximately one additional hour operation time (which was included in the simulations by blocking the space heating between 12 am and 1 pm).

Figure 7.3 leads to following conclusions:

– reduction of the heating demand is paramount for a reduction of the necessary operation times of the heating

– increase of installed capacity of the heat pump also allows for a reduction of operation times

– a thermal capacity exceeding 60 Wh/(m^2 K) does not reduce the necessary operating time of the heating significantly. Thus, the simulations suggest that less thermal mass is actually usable within 24 h periods than the calculation according to SN EN ISO 13786:2007 indicates.

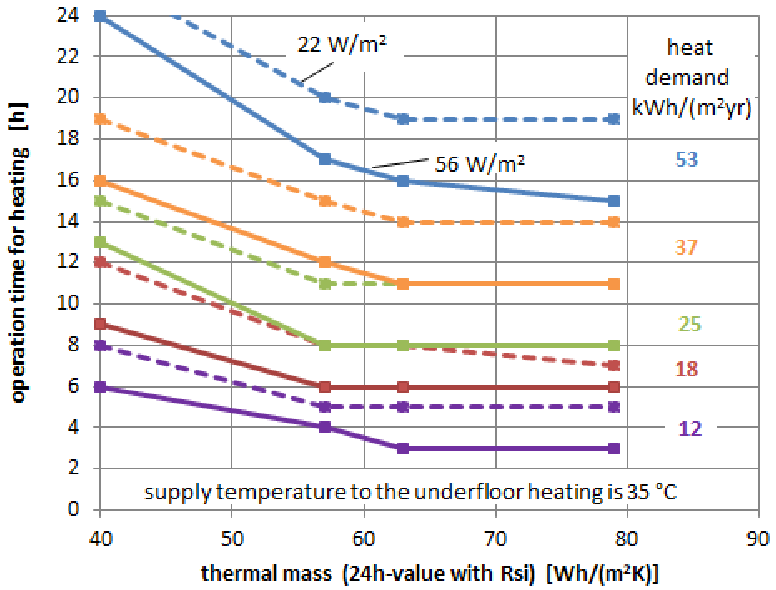

Figure 7.3 Operation time of the space heating vs. thermal mass. Heating demand (colour) and the heating's capacity (line style) are varied. Thermal mass of the building construction is calculated according to SN EN ISO 13786:2007 (calculated with a penetration duration of 24h and taking a heat transmission resistance Rsi into account).

Figure 7.4 gives simplified correlation equations for operation time of the heat pump vs. heating demand for two levels of the building's thermal mass. These simplified correlations can be used to assess design parameters for buildings with underfloor heating in a more comprehensible way. Preliminary tests with a highly glazed residential building (with a comparatively high average building envelope U-value) suggest that the graph in its current form might apply only to moderately glazed residential buildings. Figure 7.4 bases on a building with a window area of 23% of the façade area. In order to address a wider choice of buildings, further research is needed.

7.5. Discussion

The results obtained underline the results shown in (Johra and Heiselberg, 2017):

- The insulation level has the highest impact on the ability to shift the operation time of the heat pump.
- A well-insulated building can offer a high ability for shifting the operation time of the heating. In this study it is found that a heating demand of around 25 kWh/(m^2 a) or less is necessary to be able to operate the heating in daytime only without reducing thermal comfort.
- A high thermal mass contributes to an increase of the building's flexibility regarding shifting the operation time of the heating into daytime. But the flexibility stagnates above a certain amount: approx. 60 Wh/(m^2 K) in this evaluation, approx. 80 Wh/(m^2 K) stated in (Johra and Heiselberg, 2017). The first value includes only the thermal mass of the building construction, which is

readily available in an early planning stage. The simulations, however, additionally take the thermal mass of the furniture into account. The second value is the thermal mass of the building including the furniture.

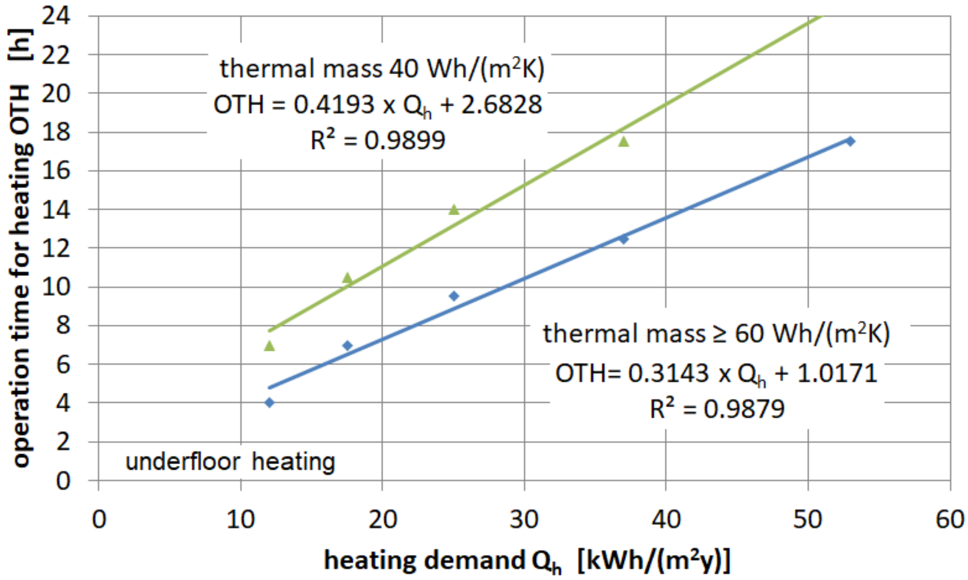

Figure 7.4 Operation time for heating (OTH) vs. heating demand Q_h for different powers of the thermal mass. Thermal mass (24h-value with R_{si}) is calculated according to SN EN ISO 13786:2007.

The combination of high thermal mass and high level of insulation leads to the highest ability for shifting the operation time of the heating. Operation times of less than 9 h are possible. This range corresponds with the possible daylight at the shortest winter days in Switzerland (Figure 7.5).

The shown ability for shifting the operation time of the heating can also be used to control the operation time with, for example, a dynamic electricity price signal. Today, constant daytime and night time prices are common. To reduce the costs, it is also possible to use the findings to operate the heat pump at night time in order to take advantage of the low night time prices. In this case, the simple on/off controller is sufficient, also.

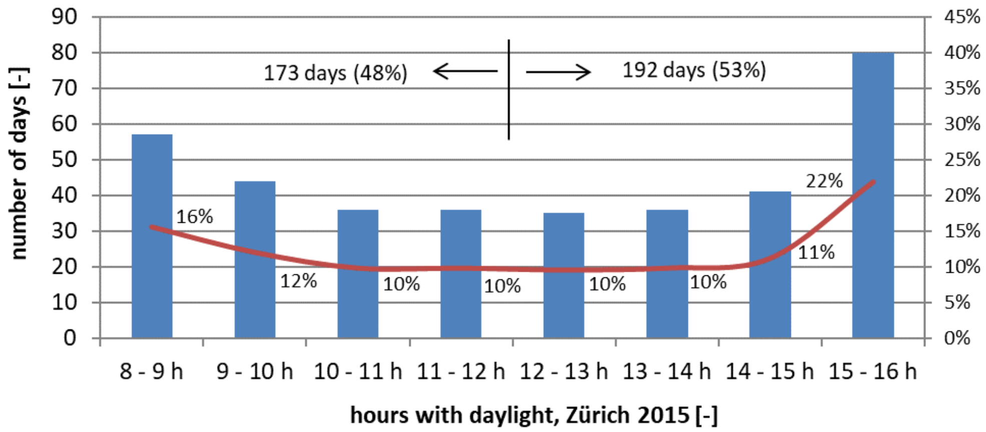

Figure 7.5 Hours with daylight in Zürich CH (Sunrise 2018).

So far, the discussed operation times of the heating were consecutive time blocks of different lengths during daytime. An obvious variation would be intermittent activation of the heating within 24 h periods. It is found, that such an intermittent activation of the heating allows to reduce the overall operation times according to Figure 7.3 by one to two hours. The probable reason for this is that with shorter time sequences between the on and off mode, the building cools down less than with the long shut down period (Hoffmann et al., 2018). The findings are valuable for energy suppliers. The typical ripple control switches all buildings independently, whether they can offer more flexibility or not. If the suppliers could control the heat pump operation individually for each building, they would be more flexible in how they can control the residual load in the grid.

The use of the simple on/off controller with the heat pump's timer is feasible when the goal is either to use the energy flexibility of the building to increase the self-consumption or to take advantage of a low price tariff at night time. The simple controller is not sufficient if the control strategy includes the use of dynamic signals, e.g. electricity price signals or the amount of renewable energy in the grid. Also, an active pre-heating – predictive control – is not possible. The advantage of the simple on/off controller is that

- it is very robust. This leads to less technical malfunctions and less costs, because no additional devices and maintenance are needed. The operation time can be set anytime and every heat pump features this timer function.
- the user/facility manager can easily manage this controller.
- the building operation does not depend on third party signals. No control signal from outside the building is necessary.

7.6. Conclusion

Due to the price development of electricity, the direct use of on-site generated electricity is becoming increasingly attractive. By having large consumption during daytime only, self-consumption can be increased quite naturally. For this purpose, heat pumps are well suited. The aim is to limit the operation time of the heat pump to the daytime hours. The shorter the necessary operation time, the greater the flexibility in terms of the choice of the operation time window. For this purpose, the active use of the thermal mass gets more and more important. All findings introduced here are based on a multi-family building with underfloor heating.

Monitoring of a real multi-family building shows that by limiting the operation time of the heat pump to 10:00–17:00, the self-consumption increases without jeopardizing thermal comfort.

The major findings of the simulations are:

- The heat demand has the highest impact on the necessary operation time of the heat pump
- Thermal mass of the building construction above 60 Wh/(m^2 a) doesn't increase the flexibility of the heat pump operation time
- Even significantly over-dimensioned heat pumps cannot heat up buildings with high heat demand and low thermal mass without running 24/7 during winter time.

The insulation level (expressed as the corresponding heating demand), thermal mass capacity and installed capacity of the heat generation system are combined graphically, thus presenting an easy to use tool for the first design stage to determine the potential of thermal flexibility. The graph is based on a residential building with a glazing ratio of the façade of 23 %. The correlation cannot be used for highly glazed buildings.

The results show that a simple timer with on/off control is sufficient to maintain the operation time of the heat pump to increase self-consumption. Such a controller is very robust, cheap and the building is independent of a third-party signal. Buildings with a low heat demand and large thermal mass offer the needed energy flexibility while thermal comfort is given.

7.7. Acknowledgement

The results presented in this chapter are based on research funded by the Swiss Federal Office of Energy SFOE under contract numbers BFE SI/500645 and SI/501240. The work was carried out partly within the framework of IEA EBC Annex 67 Energy Flexible Buildings.

8. Determinants of flexibility in residential hot water systems

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8.1. Abstract

The thermal storage inherent in residential hot water systems can provide a ubiquitous, low cost alternative to electrical storage for providing energy flexibility. This example quantifies the effect of major factors influencing available energy flexibility from residential hot water systems using data from a large-scale real world pilot project in The Netherlands. All the houses considered in the analysis feature identical hot water systems. It is shown that ambient conditions, control algorithm 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 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 again is able to deliver flexibility. The example also includes a discussion on the implications of variations in the energy flexibility, and the controllers that can be adopted to influence it in practice.

8.2. Background and objectives

Thermal storage of hot water in residential buildings is an important, ubiquitous source to provide energy flexibility to the modern grid that can be utilized for grid-supportive behaviour. Furthermore, they account for between 10%-25% of energy demand in residential buildings in many countries, and their relative importance will increase due to improvements in facade technologies reducing the energy consumed for space conditioning (Allouhi, 2015) and (Zhu, 2009). However, beyond improvements in the heating technology, the energy demand for hot water production has continued unabated. In the context of a recently concluded European Horizon 2020 project REnnovates (Rennovates, 2015) more than 70 recently refurbished households were analysed over the course of a year. All of these households were equipped with identical hot water and heating systems, where the heating technology used was an air source heat pump. Over the course of this research, it became obvious that, for most of these houses, the energy required for residential space heating was roughly the same as that for hot water production. Furthermore, the energy flexibility offered by the thermal mass of the building was found to be limited due to the low transmission and infiltration losses of the building. This energy flexibility was also not available during the summer months and only sporadically during the spring and autumn months. The energy flexibility offered by the hot water systems was, on the other hand, available year round (to varying degrees) and remained unaffected by the refurbishment. As such, the aim of this example is to quantify the effect of different influencing variables on the energy flexibility of hot water systems. Since there was practically no difference in the dynamics of the hot water system, the only variables that differed were differences in:

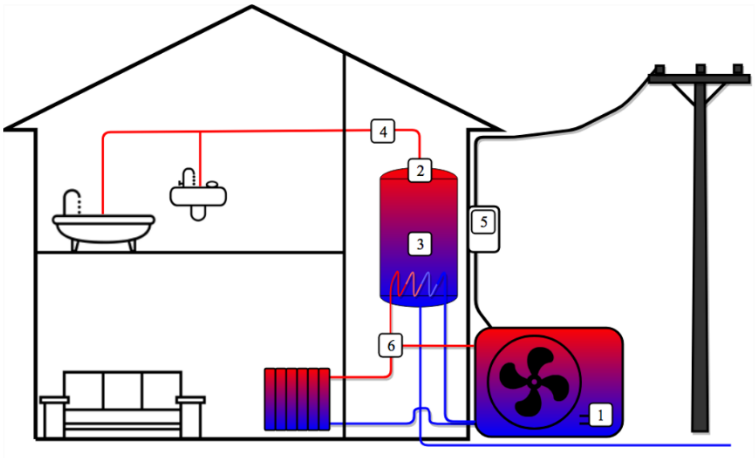
1. Occupant behaviour (manifested as demand for hot water)
2. Ambient conditions (manifested as outdoor temperature) as the hot water was heated by an air source heat pump
3. Choice of control algorithm

This example quantifies the effects of these variables on the energy flexibility of residential hot water systems and presents some suggestions on how this can be optimized. To date, the determinants of energy flexibility offered by thermal systems in general, and hot water systems in particular, remain poorly understood. Some recent work has addressed this to some extent. For instance, (Nuytten, 2013) have quantified the available energy flexibility of combined heat and power plant (CHP) systems with district storage while (Kazmi, 2016) have used a data-driven model to quantify available energy flexibility of heat pump heated hot water systems. However, these do not distinguish among the many variables influencing energy flexibility. More recently, (Fischer, 2017) and (Chen, 2017) have shown a clear link between ambient conditions and the energy flexibility of heat pump based systems and the building thermal mass respectively. However, other factors, especially those relating to occupant behaviour and the choice of control algorithm, remain largely unexplored in existing literature.

8.3. Method

Determining the energy flexibility of hot water systems requires a detailed dynamics model. This was learnt in a data-driven manner from observed data because of two reasons. The first was to develop a general purpose framework which could then be applied to any hot water system. The second was the large amount of hot water system data collected in REnnovates. This project entailed, among other things, the renovation and smart control of hundreds of social houses in The Netherlands. Data collection and smart control were enabled by the EEBUS (EEBUS, 2019) interface which allowed standardized communication between a central server (gathering and analyzing data) and the local gateways. Moreover, the project also had partners from Spain and Poland 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 200 litre storage tanks. The heat pump is responsible for both space heating and hot water production. This information is visualized in Figure 8.1, along with the sensor setup used to monitor performance.

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.



Legend:
1: Outdoor temperature
2: Outflow water temperature (optional)
3: Tank mid-point water temperature
4: Flow meter
5 Smart meter
6: Heat pump operation mode

Figure 8.1 Sensor setup present in the houses.

The inputs to both models were features extracted from the raw time series data (observed via the sensors). The raw time series corresponded to data from a temperature sensor installed mid-way in all 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. Feature extraction reduced the input dimensionality and considerably simplified the learning problem. 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 (i.e. outdoor temperature). The two neural networks took these features as inputs and solved a supervised learning problem to identify weights which could make the prediction with the least error. The model parametrization which minimized the error was then selected for subsequent analysis and to simulate the hot water system's behavior for determining its energy flexibility given the following three determinants:

1. **Occupant behavior** is defined as the hot water consumption over time by the household. The sampling interval of this time series is 15 minutes and the observation period is approximately a year for most houses considered in the analysis. As the sample set is fairly large and sampled randomly, it can be considered representative for Dutch households in general.
2. **Ambient conditions** refer to the temperature at the geographical location the hot water system is being operated. This can affect the operation of the hot water system in at least two ways: (1) the heat losses from the storage can increase or decrease based on the temperature in the conditioned space enclosing the storage, and (2) the coefficient of performance (COP) of the heat pump is strongly dependent on the ambient temperature. These ambient conditions vary over the course of a day (diurnal variations) and a season (seasonal variations). Furthermore, geographical variations also influence the ambient conditions, i.e. the summer day-time temperature in The Netherlands is different from both Poland and Spain. As the learned models incorporate the ambient conditions as their input features, it was possible to understand their effect on the energy flexibility.
3. Two **Control algorithms** were employed in this analysis, which have been adapted from previous analysis conducted by (Kazmi et al., 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 and the other was a just-in-time controller to improve device efficiency. These are shown in Figure 8.2.

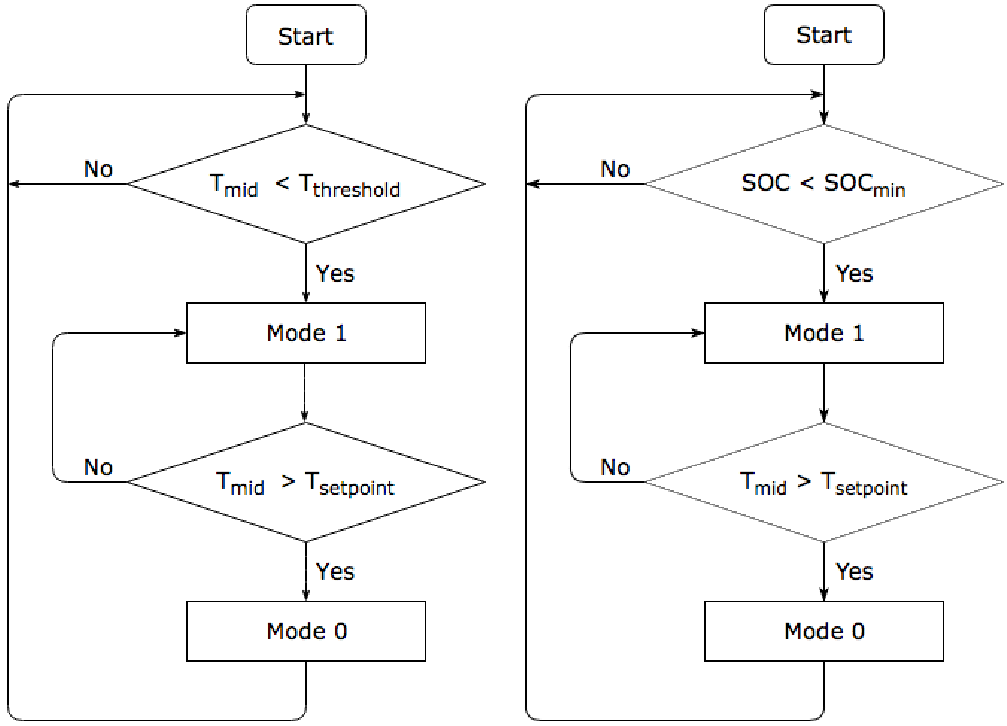


Figure 8.2: Control logic of rule based controller (left) and energy efficient controller (right) – the efficient controller makes use of the learnt models to determine the state of charge (SOC).

The metrics used to quantify energy flexibility build upon definitions presented in (Reynders, 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 a given time instant. However, as the hot water system is, at any given time, generally 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 SOC, in an uninterruptible manner. The power profile of the heat pump is determined internally, and cannot be controlled.

8.4. Results

8.4.1. Capacity

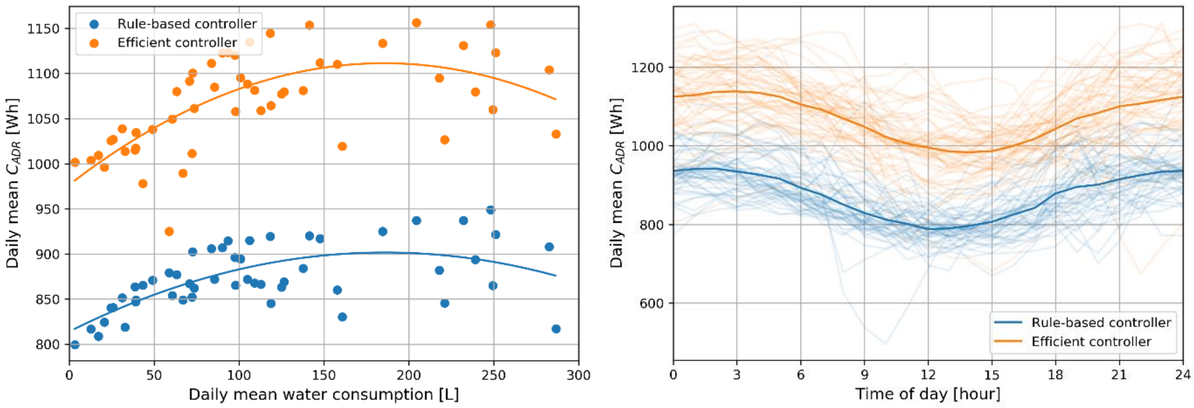
The capacity of an energy flexibility system is an indication of its ability to store or provide energy. More specifically, this metric defines the available structural storage capacity for active demand response (C_{ADR} [kWh]) as the amount of heat that can be added to the storage element in the time frame of an ADR event, without jeopardizing thermal comfort. The available storage capacity is given by the integral of the difference between the heating power during an ADR event (Q_{ADR} [W]) and the heating power in normal operation (Q_{REF} [W]):

$$C_{ADR} = \int_0^{l_{ADR}} (Q_{ADR} - Q_{REF}) dt \tag{8.1}$$

In the following, the influence of multiple factors on capacity is highlighted.

User behaviour

With increasing hot water demand, the vessel's energy capacity increases up to a certain limit and then asymptotes (or even slightly decreases). The initial increase in capacity with consumption is caused by the discharge of energy, which leads to the possibility of injecting more energy into the storage. When there is very little consumption, the energy capacity of the storage is constrained by thermodynamic losses to the ambient. 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 is 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 8.3a.



(a) (b)

Figure 8.3 (a) Effect of user behaviour on available energy capacity [kWh] with different control strategies; individual dots refer to results obtained for different households.
(b) Effect of diurnal ambient condition variations and control algorithm on available energy capacity [kWh]; transparent traces represent the behaviour of individual households while bold lines indicate the averaged behaviour.

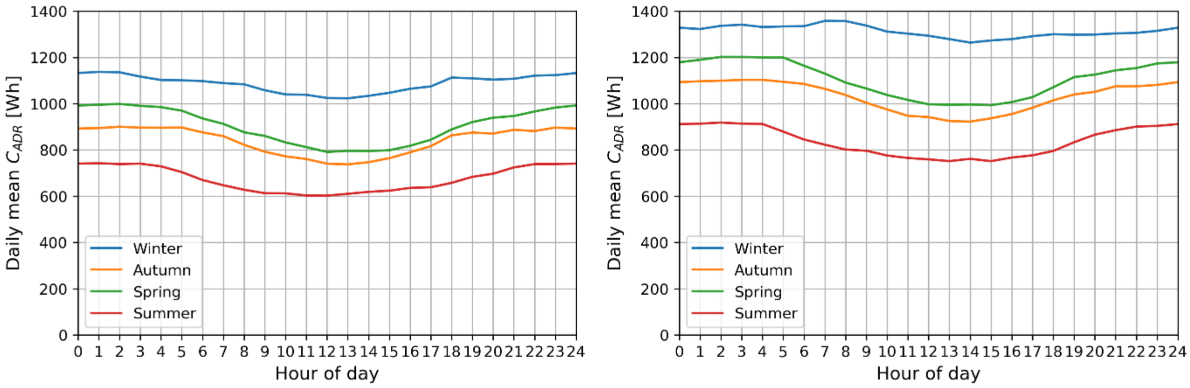
Choice of control algorithm

The choice of control algorithm also plays a major role in determining the flexibility of the device 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 vessel as is evident from Figure 8.3b and results in an increase of 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.

Ambient conditions

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 available energy flexibility (even when the hot water demand is kept constant across the households). These effects can be summarized as follows:

1. **Diurnal variations** can increase or decrease the available energy capacity of a hot water system by up to 15%. Generally, higher temperatures during the day mean that less flexibility is available during daytime hours even when accounting for occupant behaviour and controller. For countries in North-Western Europe where there is only a small difference in day and night temperatures in winter (such as The Netherlands), this effect is most pronounced in the non-winter months. These effects are highlighted in Figures 8.3 a and b.
2. **Seasonal variations** have arguably 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 8.4a and b.



(a) (b)

Figure 8.4 Effect of seasonal ambient condition variations and control algorithm on available energy capacity [kWh]: (a) rule-based control and (b) energy efficient controller.

3. **Geographical variations** have a largely similar effect to the diurnal and seasonal variations in the sense that different countries have very different climates. Here, simulations were run for different countries assuming similar hot water consumption profiles as those observed in The Netherlands. While this assumption is not necessarily true, it provides an indication of how the same hot water system would perform in a different geographical location. In Poland, the same devices have a much higher flexibility potential than in Spain where it is lower by almost 25% throughout the day, keeping all other variables constant. This is shown in Figure 8.5.

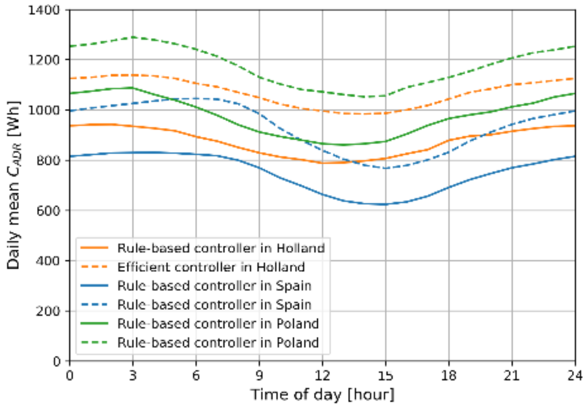


Figure 8.5 Effect of geographical ambient condition variations and control algorithm on available energy capacity [kWh].

These results are a timely reminder of the importance of planning and designing buildings and hot water systems based on local conditions to ensure availability of not just energy efficiency but also energy flexibility.

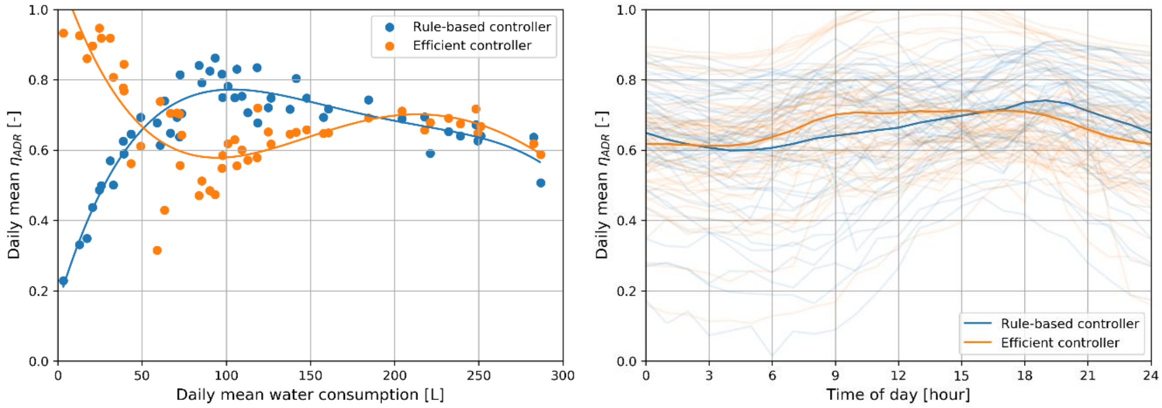
8.4.2. Efficiency

While all the factors identified and discussed so far 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. The efficiency is calculated using the same simulations that are used to quantify the storage capacity. Given these simulations, the efficiency is calculated as:

$$\eta_{ADR} = 1 - \frac{\int_0^{\infty}(Q_{ADR} - Q_{ref})dt}{\int_0^{l_{ADR}}(Q_{ADR} - Q_{ref})dt} \qquad (8.2)$$

The integral in the denominator is equal to the heat stored in the storage during the ADR event (i.e. the available storage capacity (C_{ADR})). A part of this heat can be used after the ADR event to reduce the heating power needed to maintain occupant comfort. The numerator represents this fraction of the heat stored during the ADR event that is not recovered over a long period.

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 8.6a and b. These 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%-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)

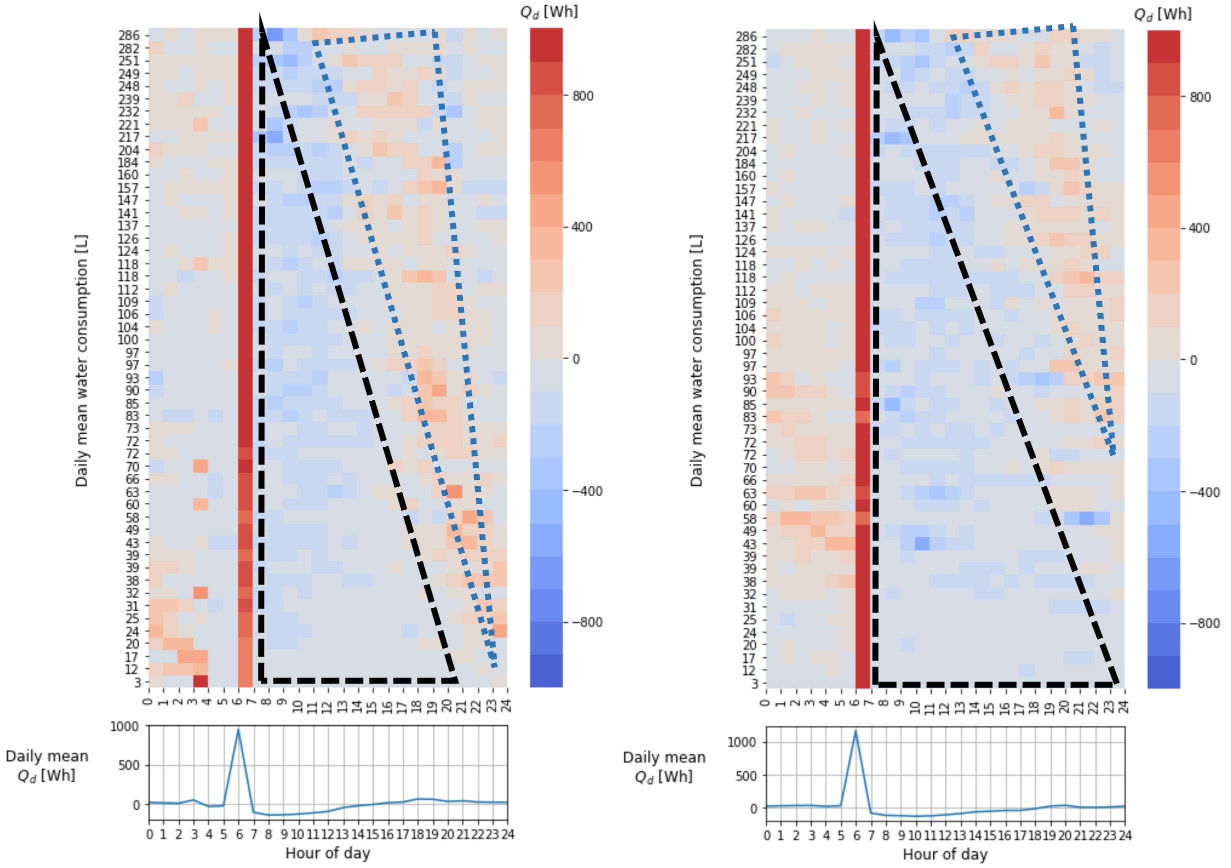
Figure 8.6 Effect of occupant behaviour, ambient condition variations and control algorithm on efficiency.

8.4.3. Power shifting potential

Device activation is, unlike capacity, a temporal measure of the power that can be provided to the grid or consumed from it at any given instant. As the heat pump can only consume electrical energy (and not generate it), the majority of flexibility offered by a heat pump is in the form of upwards regulation (i.e. request for using more energy), as mentioned previously. In general, the power shift (Q_d [W]) is defined as the difference between the heating power during the ADR event (Q_{ADR} [W]) and the reference heating power (Q_{REF} [W]) during normal operation. Starting from the storage in a current state, the thermal response of the storage is activated and the change in the heating power is estimated using the learned model.

This effect is visualized in Figure 8.7 with an ADR activation of an hour at 06:00. This time of activation is clearly visible as a red vertical line where all heat pumps are activated to consume power simultaneously to reheat the storage, i.e. the ADR activation increases the energy consumption significantly compared to the original behaviour. The line plots at the bottom of Figures 8.7a and b represent the shifted power averaged across all houses. This shows that, on average, an individual heat pump corresponds to 1 kW when activated. The exact amount of energy (i.e. capacity) available as flexibility is determined by the storage SOC. The exact power profile of the heat pump, on the other hand, is determined internally and cannot be controlled or modulated once the heat pump switches on. Furthermore, it is assumed that, once turned on, the heat pump reheats the storage to the maximum SOC in an uninterruptible manner. As the sampling period for the plots in Figure 8.7 is one hour and the heat pump is capable of reheating the storage in less than one hour, the temporal variations of the power profile are not visible. For applications which require a finer level of granularity, these effects will need to be taken into consideration.

Energy efficient control enables the hot water system to have an activation potential, which is typically 10%-20% higher than for the rule-based controller. This is because the efficient controller typically operates storage at a lower SOC, leading to a higher capacity and consequent power shifting potential. The available activation potential scales linearly with the number of heat pumps in the population only if a sufficiently large pool of devices is available to smooth out individual variations caused by occupant demand. This is because lower daily hot water demand can affect the amount of activation available over an hour by almost 50 %, as shown in the activation of different heat pumps at 06:00 in Figures 8.7a and b. Additionally, because of the ADR event in the morning, a rebound effect is present later in the day, where the Q_{ADR} turns negative for some time. This period is substantially longer in houses with low consumption, and gets shorter as daily water consumption increases, as anticipated, shown by the black dashed triangles in the two graphs of Figure 8.7. After the negative period, a second positive peak can be observed, as shown by the blue dotted triangles in the two graphs of Figure 8.7. This rebound effect is generally much lower than the peak at activation, and is an unintended but known consequence of ADR events, which must be taken into consideration during planning.



(a) (b)

Figure 2.7 The power shifting potential of the hot water system with varying occupant behaviour (consumption) for: (a) rule-based control, and (b) energy efficient controller. The line plots at the bottom are aggregations over all households, and show both the activation peak because of the ADR event and the subsequent rebound period.

8.4.4. Recovery

Once flexibility has been requested from a storage system, there is a subsequent recovery period during which time additional flexibility cannot be offered. While this can be either because of device or occupant comfort constraints, it is important to quantify the time period during which the device cannot be activated again. Once this time period has elapsed, the flexibility is available once more. Formally, the recovery period is defined as the time it takes for the storage tank to return to normal operation after an ADR event, thus $Q_{\delta} = 0$.

The different factors considered so far influence recovery in a highly inter-connected manner. The energy efficient **controller** lengthens the recovery period by two to three hours, or about 20%, on average compared to the rule-based controller, just as it increases the average time between reheat cycles. Compared to the rule-based controller, this generally longer recovery period can be observed in Figure 8.8.

The recovery period is also strongly influenced by the **occupant behaviour**, as higher hot water demand leads to a quicker recovery. This is because the available flexibility depends on the ability of the heating element to inject energy into the storage. The ability of this storage to hold charge is a function of both thermodynamic losses and mixing losses. While the thermodynamic losses are a function of the storage itself, the mixing losses increase with higher occupant consumption, leading to a quicker replenishment (or shorter recovery period) of available flexibility. As shown in Figure 8.8 a, in households with very low water consumption (lower than one quarter of the storage capacity on a daily basis) the recovery period can be even higher than 24 hours, which can reduce the amount of flexibility these devices offer considerably. It is straightforward to see that, at low consumption, the differences between controllers are not governed by user behaviour. However, with increasing occupant demand, the recovery period reduces drastically, by a factor of around two for the rule based controller (i.e. from 16 hours to 8 hours) and by almost three for the efficient controller (i.e. from 18 hours to only 6 hours).

Very low recovery periods caused by occupant behaviour can ensure that there is a constant supply of households available to provide flexibility to the grid. However, high demand substantially increases energy consumption. This represents one aspect of the many trade-offs between energy efficiency and flexibility. At the same time, the recovery period is relatively unaffected by ambient conditions such as seasonal or geographical variations. This is largely the case because the storage is located in a conditioned space, which reduces its exposure to the elements, and the consequent thermodynamic losses.

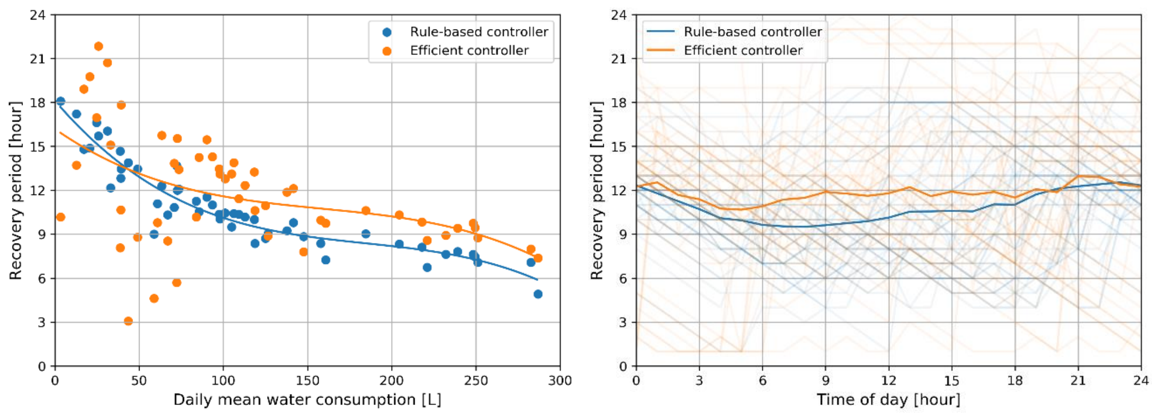


Figure 8.8 Effect of geographical ambient condition variations and control algorithm on available energy capacity [kWh].

8.5. Conclusion

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. In this section, key findings are summarized, which need to be considered when leveraging the energy flexibility offered by these devices.

Ambient conditions, including diurnal and seasonal variations in temperature, play a major role in determining the extent to which a heat pump hot water system can be operated flexibly to provide value added services. In general, device flexibility is highest during (cold) winter nights and lowest during (warm) summer afternoons. However, time of the day and year is not the only influencing factor here, and the geographical location in which the system is being operated substantially effects its available flexibility. The same system, with everything else held constant, has higher flexibility potential in Poland than in The Netherlands and Spain. The unifying theme for this space-time variation of the energy flexibility is of course the ambient temperature conditions.

The choice of **control algorithm** plays an important role in the available flexibility as well. With a more energy efficient controller, it is possible to elicit higher capacity on average from the same hot water system. 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.

Finally, **occupant behaviour** also influences the energy flexibility, albeit in a rather less direct manner, and much less than it effects energy consumption. There are numerous reasons for this. Primarily, 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.. This means that households with higher consumption can provide more flexibility to the grid, more often. In conjunction with smart controllers, this difference can be rather substantial with recovery periods varying by a factor of almost three.

While a heat pump hot water system is used in the analysis, the presented framework is generalizable with some important qualifications for the generalizability of the results. Foremost among these is the disproportionate effect of ambient conditions on energy flexibility of the device. In many instances, these can single-handedly alter a system's available capacity by a factor of more than two. This result is therefore only valid for a heat pump system in a strict sense because of its temperature dependent efficiency. In a system employing a different heating element, such as an electric resistance heater or gas boiler, this effect would persist but in a much diminished form.

As mentioned earlier in the paper, quantification of the energy flexibility of a device is an active area of research. The fact that different controllers and occupant behaviour influence energy flexibility significantly further complicates its quantification in a standard form by adding yet more degrees of freedom. This information must be utilized in future research on quantification of energy flexibility.

The analysis of the energy flexibility of hot water systems also has important repercussions for the use of hot water systems in grid supportive roles. More specifically, 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.

8.6. Acknowledgement

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9. Assessing the energy flexibility of a residential detached house

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9.1. Abstract

The increasing share of renewable energy resources in the electricity grid poses new challenges in terms of stability and management, due to the stochastic nature of their production. As well as traditional supply-side regulation, grid flexibility can also be provided by the demand side. Demand response is one such flexibility approach based on adapting user demand profiles to grid requirements. Nevertheless, defining the flexibility potential related to different buildings is not straightforward due to the fact that commonly accepted, standardized quantification methodologies and indicators have not yet been established. This chapter describes a new quantification methodology to assess the energy flexibility in residential buildings. A set of indicators, capturing three of the most common key elements of building energy flexibility for demand response, namely, capacity, change in power consumption and cost of the demand response action are identified. The proposed methodology is applied to a residential building, where the heating system is controlled by means of a model predictive control strategy. The building model is developed on the basis of the experimental data collected in the framework of a European Commission supported H2020 research project Sim4Blocks, which deals with the implementation of demand response in building clusters. The optimal control problem has been investigated by means of mixed-integer linear programming. Real-time prices from the grid are considered as external signals, which drive the demand response actions.

9.2. Background and objectives

With the increasing availability of smart-metering and smart-management systems, control strategies capable of unlocking the building energy flexibility potential to activate demand response (DR) programmes are becoming more common. However, one of the main challenges is the lack of a common and standardised assessment procedure capable of evaluating demand response programmes (Clauß et al., 2017). This is a critical issue in order to formalise targets and metrics that inform the selection of optimal DR measures. Moreover, the need to provide indicators which can be communicated and easily interpreted among different stakeholders, makes the development of this common framework even more challenging.

Different techniques can be used to implement assessment methodologies for demand response programs. However, lack of standards and the slow diffusion of building automation systems represents the first inhibitor. Secondly, the time-varying prices provided by utility companies for the electricity market do not necessary match customer consumption patterns, thereby methods for load shifting, i.e., energy storage, are required (Arteconi et al, 2013). Therefore, embedding building energy management systems with optimisation algorithms that have the potential to minimise consumption and the associated energy expenditure, whilst maintaining the thermal comfort and the service level expected by end users, is a vital task.

In this context, the research described here aims to analyse a set of indicators with the objective of capturing the three key elements of building energy flexibility for demand response: capacity, change in power consumption and cost of the demand response action. A residential detached building, part of the German pilot site within a H2020 research project Sim4Blocks, was used as a test case (Sim4Blocks, 2018). The building is equipped with a hybrid generator composed of an air-to-water geothermal heat pump and a gas boiler to cover the heating demand of the building.

Several demand response actions, based on switching between the two thermal energy generators depending on the evolution of the real-time electricity prices of the day-ahead market, are analysed and assessed. The impact of different DR measures was characterised by mapping the proposed indicators as a function of the duration and intensity associated with demand response actions.

9.3. Method

9.3.1. Case study

This work is based on an energy plus district located in the German community of Wüstenrot, Stuttgart, consisting on 17 highly efficient residential buildings. One of the residential detached houses was selected as a case study for the present work (Figure 9.1). The house, which has a living area of 310 m^2, is equipped with a hybrid thermal generator which integrates an air-to-water geothermal heat pump (HP) and a gas boiler to cover the heating demand of the building. A hot water tank is also included as thermal energy storage (TES), as shown in Figure 9.2. The main building characteristics are reported in Tables 9.1 to 9.3 (D’Ettorre et al., 2019).

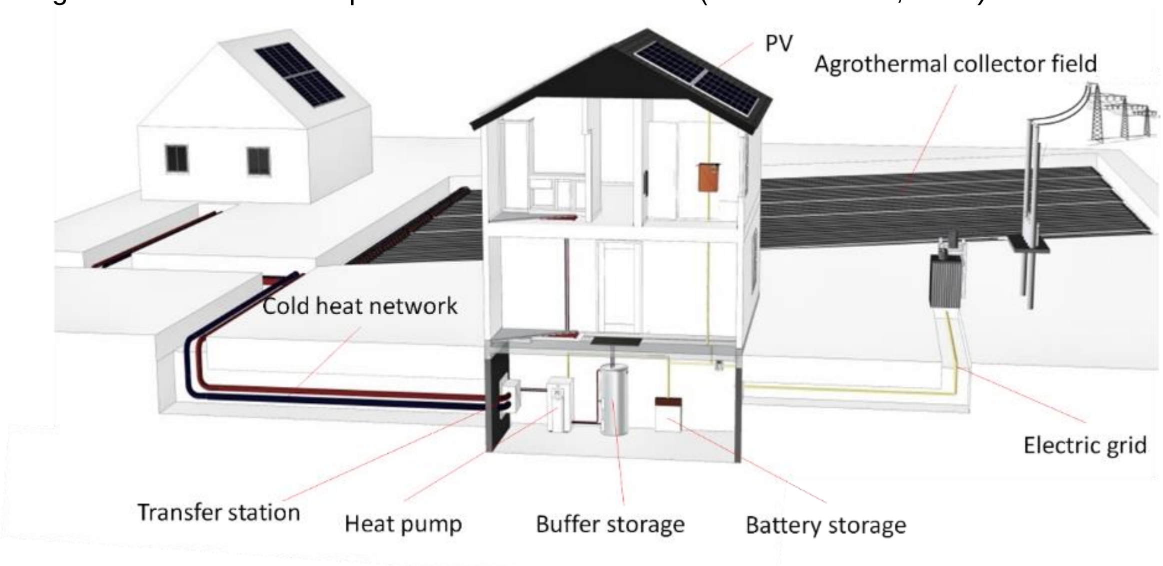

Figure 9.1 Schematic view of the residential detached house under analysis.

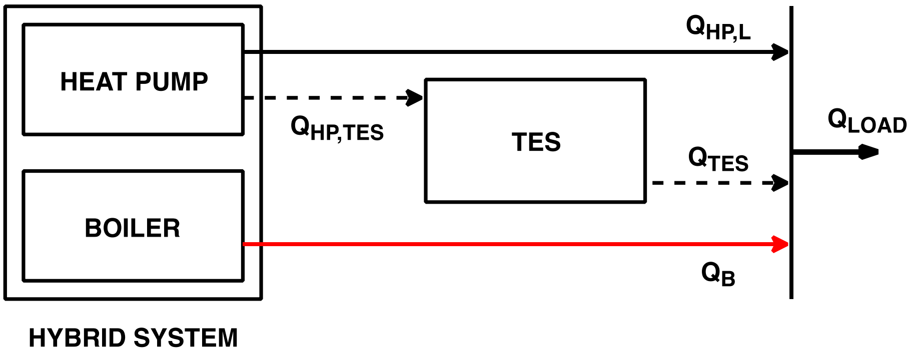

Figure 9.2 Hybrid system configuration (D'Ettorre et al., 2019).

The two generators are operated according to the control strategy resulting from the solution of an optimal control problem (OCP). The OCP is aimed at minimising user energy cost, while meeting thermal comfort constraints. The generators can be operated alternatively, implementing fuel switching strategies based on either cost or CO_2 emission minimisation, or simultaneously, according to the operational strategies (OS) reported in Table 9.3. The TES adds a degree of freedom to the control actions, since it can be charged by the HP ($\dot{Q}_{HP,TES}$) during low tariff hours in the night and then discharged during the day as an auxiliary source ($\dot{Q}_{TES}$) to meet the load demand (OS 4 and OS 5 in Table 9.3). The HP performance is modelled by using the second-law efficiency (η^{II}), as shown in Equation 9.1, where T_{sink} and T_{source} are the sink and source temperatures, considered equal to the external temperature (T_{ext}) and the HP supply temperature (T_{HP}^{sup}), respectively

$$COP = \eta^{II} \cdot \frac{T_{sink}}{T_{sink} - T_{source}} \tag{9.1}$$

The aim of the controller is to minimise the daily operational cost of the system (C_{op}^{Day}), while meeting several constraints, such as the comfort condition within the building, minimum/maximum heat pump power, temperature constraints for example. To this end, the objective function is defined as the sum of the hourly operational costs over the whole day (T = 24 h), as shown in Equation 9.2.

$$C_{op}^{Day} = \int_0^T \left[p_{el} \left(\delta_{HP,TES} \frac{\dot{Q}_{HP,TES}}{COP_{TES}} + \delta_{HP,L} \frac{\dot{Q}_{HP,L}}{COP_L} \right) + p_{gas} \frac{\dot{Q}B}{\eta B} \right] dt \qquad for\ all\ \ t \in [0, T] \tag{9.2}$$

The building dynamics are described by a linear state-space model validated by using experimental data collected in the framework of the Sim4Blocks project (Andrade-Cabrera et al., 2018).

Table 9.1 Characteristics of the building case.

Parameter		Value/Range
Latitude		49.6° North
Longitude		9.6° East
Elevation		495 m
Number of storeys		3
External walls	North	109.9 m^2
	South	147.3 m^2
	East	84.5 m^2
	West	85.0 m^2
	Basement	139.9 m^2
	Flat roof	25.0 m^2
	Tilted roof (South)	46.9 m^2
	Tilted roof (North)	78.9 m^2
Windows	North	36.5 m^2
	South	28.6 m^2
	East	5.20 m^2
	West	13.0 m^2
Solar heat gain coef.		0.583
Roof pitch		15°
Envelope leakages		0.3 l/h
Wall absorptance		0.2

Table 9.2 Characteristics of the building case study.

Part	U-Value [W/m^2K]	Thick. [cm]	Construction
Ext. walls	0.21	36.5	AAC/B (λ = 0.080 W/mK)
Basement plate	0.27	15 10	RC (λ = 0.08 W/mK) TI (λ = 0.02 W/mK)
Flat roof	0.27	20 12	RC (λ = 0.08 W/mK) TI (λ = 0.02 W/mK)
Tilted roof	0.14	20	TI - mineral wool (λ = 0.03 W/mK)
Ext. floor	0.23	20 15	RC (λ = 0.08 W/mK) TI (λ = 0.035 W/mK)
Inner walls	0.31	24	AAC/B (λ = 0.080 W/mK)
Windows	0.77	10/4/10/4	% Frame: 30 (U_f=1); Gas filling: Krypton (U_g=0.52); Transmissivity: g =0.6

AAC = Autoclaved Aerated Concrete; B = Brickwork; TI = Thermal Insulation; RC = Reinforced concrete.

Table 9.3 Characteristics of the building cases (D'Ettorre et al., 2019).

Operational strategy (OS)	Formulation	Mode
1	$\dot{Q}_{HP,L} = \dot{Q}_{Load}$	alternative
2	$\dot{Q}_{B} = \dot{Q}_{Load}$	alternative
3	$\dot{Q}_{HP,L} + \dot{Q}_{B} = \dot{Q}_{Load}$	hybrid
4	$\dot{Q}_{TES} + \dot{Q}_{B} = \dot{Q}_{Load}$	alternative
5	$\dot{Q}_{TES} = \dot{Q}_{Load}$	-

9.3.2. Flexibility metrics

In the present work, the DR action is activated when the electricity price lies outside the lower or upper threshold values, evaluated each day as a function of the average price and its standard deviation, as shown in Figure 9.3. In order to assess the performances of the flexibility provided by these DR programs from an economic, technical and environmental point of view, three different metrics were introduced. First, the cost associated with a DR measure (ΔC_{Flex}), is defined as the difference between the operational costs resulting with and without the DR strategy, $C_{op\_DR}^{Day}$ and $C_{op\_ref}^{Day}$, respectively, as shown in Equation 9.3. Generally, when cost-optimal control algorithms are used, the activation of DR action leads to higher operational cost due to the deviation from the optimal control profile (D'Ettorre et al., 2018).

$$\Delta C_{Flex} = C_{op\_DR}^{Day} - C_{op\_ref}^{Day} \tag{9.3}$$

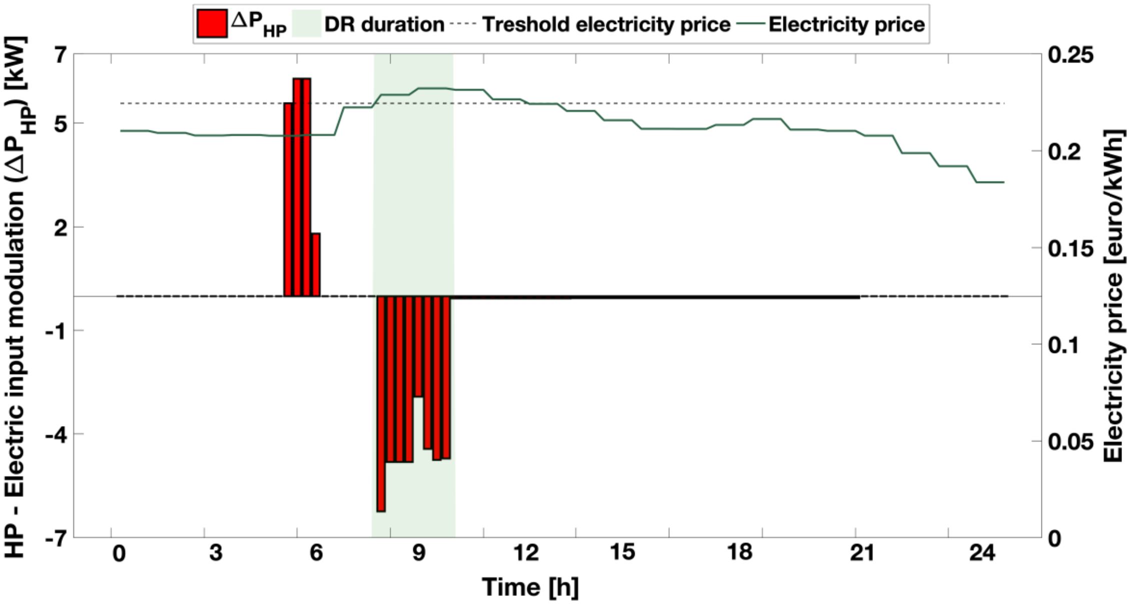

Figure 9.3 Example of a DR event for the HP power consumption.

The storage capacity has been defined as the available electric energy flexibility (AEEF) resulting from the implementation of the DR measure, as reported in (Kathirgamanathan et al., 2018). This index measures the variation of the building electrical energy consumption over the period during which the DR action is applicable, as shown in Equation 9.4.

$$AEEF = \int_{\tau}^{\tau+\Delta t_{DR}} \left[P_{HP_{ref}} - P_{HP}\right] \cdot dt = \int_{\tau}^{\tau+\Delta t_{DR}} (1-\pi) \cdot P_{HP_{ref}} \cdot dt \tag{9.4}$$

Finally, a primary energy efficiency index, defined as the ratio between the primary energy consumptions in the base case scenario (PE_{BC}) and the one with the activation of the DR measure (PE_{DR}), is considered.

$$\eta_{PE} = \frac{PE_{BC}}{PE_{DR}} \tag{9.5}$$

9.4. Results

Figure 9.4 presents the daily operation of the hybrid generator and the evolution of the room and TES temperatures over the first week of January when no DR programs are implemented (reference optimised scenario). The control strategy prioritises the direct operation of the heat pump, by limiting the use of the gas boiler and TES, only to periods with higher load demands than the heat pump capacity. Peak demand shaving is typically carried out by the TES during the early hours of the morning, while the heat pump charges the TES during the night, when less expensive electricity prices apply. It can be also noted that during the heating hours, the controller is always capable of keeping the indoor temperature at its set point value, i.e. 20°C.

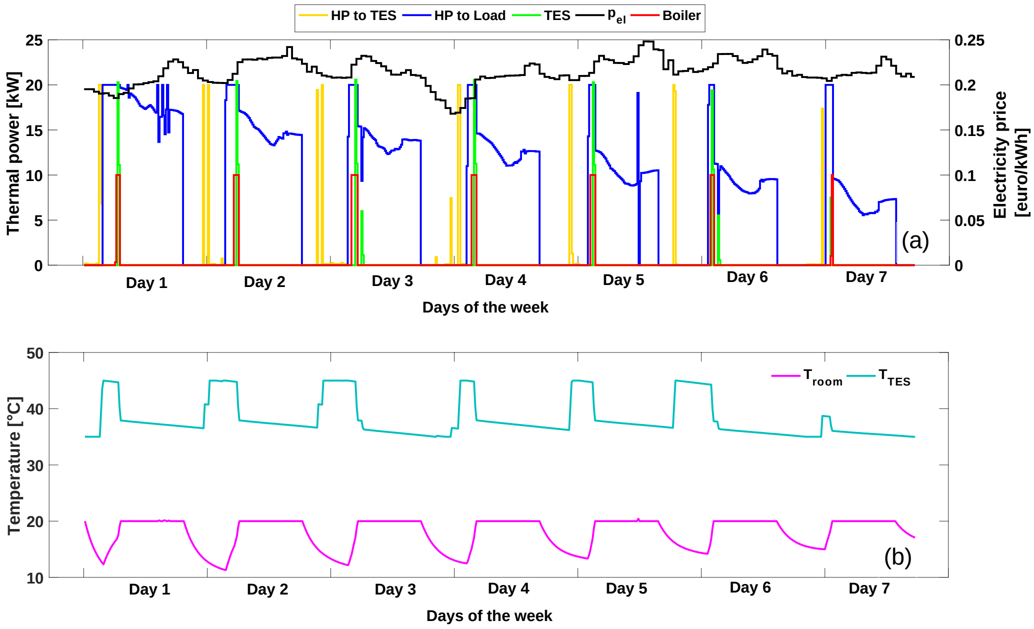

Figure 9.4 Reference scenario (top): Hybrid generator and TES operation profile. Zone and TES temperature profiles (bottom).

In order to highlight how different operative conditions affect the performance of the hybrid system generators, Figure 9.5 shows the daily profile of the heat pump COP during the two different services provided: to meet the load demand (COP_L) and to charge the storage tank (COP_{TES}). The equivalent COP_{eq}, which is defined as the COP at which operating the HP is economically equivalent to operating the gas boiler, is also reported. The profiles presented reflects the implemented optimised control strategy.

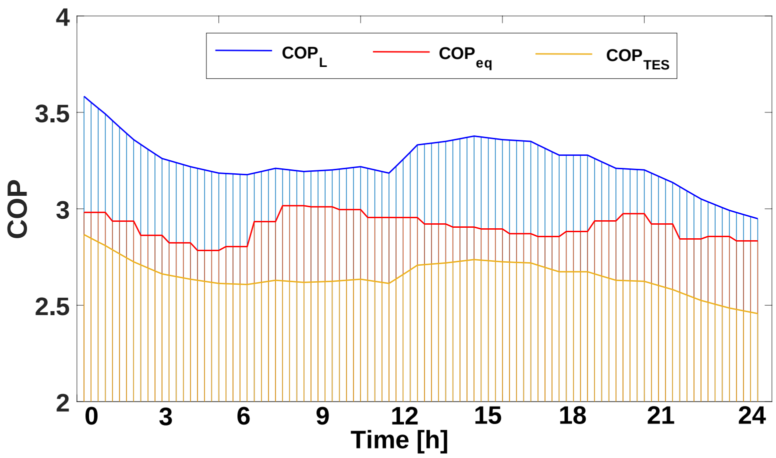

Figure 9.5 Example of heat pump performance (Day 3).

Figure 9.6 shows the impact of a DR event on the daily profiles reported in Figure 9.4. In this case, a DR measure consisting of forcing the controller to turn off the HP for a duration of 2 hours is considered. As it can be seen in Figure 9.6, an internal temperature at its set point value (i.e., 20 °C) is maintained by the controller, by operating the gas boiler and the TES, in order to meet the thermal comfort requirements. As a consequence, no rebound effect can be observed in the daily variation of the HP power consumption between the two analysed scenarios (i.e., with and without DR).

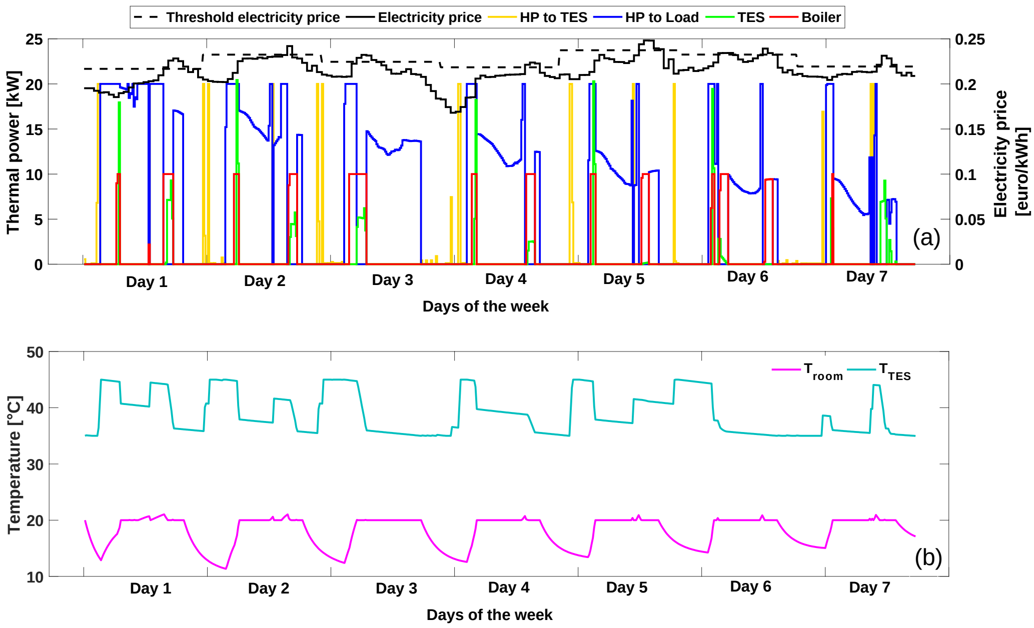

Figure 9.6 DR scenario: Hybrid generator and TES operation profile (top). Zone and TES temperature (bottom).

Once the optimal control strategy is defined, the impact of each DR measure, identified by its intensity (π - normalised between 0 and 1) and duration (δ - in 15 mins step), can be assessed using the three performance indicators described in the former section. Figure 9.7 shows the performance maps derived by applying the proposed methodology for Day 3 for the week under consideration.

The results show that the deviation of the operational costs increases as the intensity of the DR action increases. For instance, Figure 9.7a shows that a DR event characterised by δ = 3 and π = 0.4 leads to a cost deviation of around 0.8%. Increasing by one hour the duration of the DR event (δ rise from 3 to 7, since the time step considered is 15 minutes) and applying a further 30% reduction in the HP power consumption (π is reduced from 0.4 to 0.1), the cost increases up to 1.9% (Figure 9.7a). Therefore, the modification of the HP power consumption from the reference profile (i.e., without DR) leads to a deviation from the optimal control strategy and, consequently, to higher costs. Moreover, the first DR measure (δ = 3, π = 0.4) provides about 1.7 kWh of electrical energy flexibility (Figure 9.7b), with a primary energy efficiency of 0.98 (Figure 9.7c). On the other hand, a more intensive DR measure can provide a higher electrical energy flexibility, but results in lower primary energy efficiency. Generally, the AEEF increases with the increase of both intensity and duration of the DR action. Its value is equal to the avoided energy consumption due to the DR event, which in turn is proportional to the percentage reduction (1-π) of the baseline HP power and the time-span during which the DR request is active (δ). Finally, the impact of intensity and duration of the DR action on the primary energy efficiency shows that lower performances are generally obtained for low values of π (high DR intensity) and high δ (long DR duration). Generally, longer DR duration leads to higher percentage of load demand covered by the less effective gas boiler or TES. As it is shown in Figure 9.7, during the charging phases of the TES, the HP is operated with lower COP compared to when the HP directly meet the load, thus leading to a higher primary energy consumption.

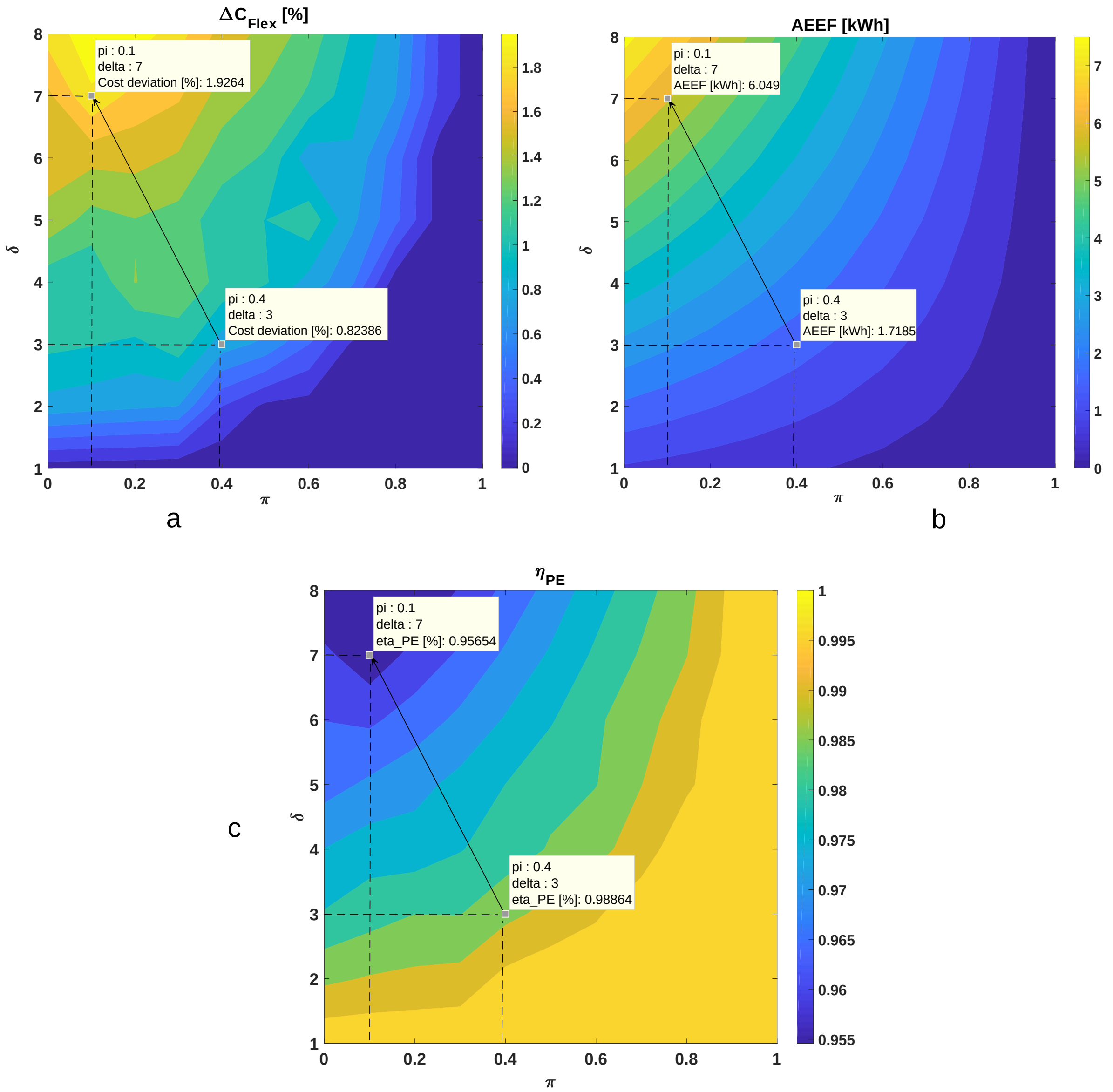

Figure 9.7 Key perfomance indicators of the DR actions. Variation of the operative costs (top left). Available electric energy flexibility (top right). Primary energy efficiency index (bottom).

These results also highlight the capability of the proposed metrics to provide information that is useful for different stakeholders. The three metrics reflect the three DR dimensions assessed: economic (costs), technical (availability) and environmental (PES) and they are aimed at providing information about the performance of a DR program based on intensity (delta) and duration (pi). It is important to highlight that these metrics has to be used together for a correct assessment in a decision-making process. Thanks to this methodology, the user can assess and optimise the DR programs, while an aggregator can evaluate all the possible combination of DR measures that can be implemented, together with the associated costs and environmental impact, and eventually evaluate its best bidding strategy.

9.5. Conclusion

The presented research describes a methodology for the assessment of the energy flexibility offered by a residential building for various DR strategies. A set of simplified indicators were derived in order to cover the three main aspects of the energy flexibility (i.e., technical, economic and environmental). A case study consisting of a residential building located in Germany and part of the H2020 Sim4Blocks project was used to test different DR programs. The building is equipped with a hybrid generator that is composed of a heat pump coupled with a gas boiler and an energy storage tank. Different DR measures were applied by reducing/increasing the HP power consumption during a DR event. The DR activation request was defined according to the evolution of the electricity prices on the day-ahead electricity market. The impact of different DR measures was characterised by mapping the proposed indicators over the allowable range for the intensity (π) and duration (δ) of the demand response action. This information, presented in the form of daily performance maps, can then be used by a grid operator for the assessment of the overall flexibility that can be provided to the grid. This makes it possible to analyse all possible combinations of DR actions that can be implemented among end-users, along with knowledge of associated costs and environmental impact. This set of indicators can be used for identifying the most profitable control and bidding strategy. In such a scenario, it would be possible to evaluate and compare the suitability of several DR programs from an aggregation point of view.

9.6. Acknowledgement

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10. Potential of energy flexibility when integrating heat pumps in an energy system with a high penetration of renewable energy

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10.1. Abstract

This study quantifies the impact of large-scale integration of residential heat pumps on the Belgian electricity system and the potential of including energy flexibility using building thermal mass and domestic hot water storage. More specific, a case study is used to quantify how energy flexibility from thermal storage can support a widespread integration of renewable electricity production and heat pumps in the Belgian residential sector. Thereby the goal is to demonstrate the impact of energy flexibility by active demand response on the CO_2 emissions and operational savings of the central electricity production in the case of a large-scale introduction of residential heat pumps.

To evaluate the flexibility potential of the Belgian building stock, an integrated operational model has been developed at KU Leuven (Bruninx et al., 2013) The model combines detailed operational aspects of both the electricity generation system as well as single-family residential buildings with heat pumps. This simultaneous optimization and the level of detail in the bottom-up models for both supply and demand sides are considered as the main contribution of this model compared to other models available in literatures, as shown by (Patteeuw et al., 2015b)

The results presented below are based on (Patteeuw et al., 2015b). The goal of the work was mainly to quantify the CO_2-abatement cost, taking into account both the operational aspects of the production side and the physical properties of the demand side. The CO_2-abatement cost is defined as the sum of the difference in annual operational costs of the system and the annuity, of the additional investment, divided by the annual CO_2-emission savings In the discussion of the results presented in this section, the focus will be on the impact of Active Demand Response (ADR) using the structural thermal energy storage on: the need for peak production capacity (section 10.4.1) and the CO_2-emission reductions (section 10.4.2). More details on the impact of energy flexibility on the CO_2-abatement cost and the operational savings is given in (Patteeuw et al., 2015b). Compared to the results presented in section 10.4 the discussion below puts more emphasis on the comparison of the impact of the building type and renovation level on the potential of ADR.

10.2. Background and objectives

The emission savings are determined by applying an integrated system modelling approach that combines detailed operational aspects of both the electricity-generation system and single-family residential buildings with heat pumps. According to (Arteconi et al., 2013) buildings equipped with heat pumps can play a role in coping with the variability and limited predictability of renewable energy sources. Different studies illustrate how introducing heat pumps, possibly combined with ADR, may be used to increase the penetration of Renewable Energy Sources (RES) and avoid curtailment losses (Lund and Mathiesen, 2009; Pensini et al., 2014; Waite and Modi, 2014). Hedegaard et al.(Hedegaard et al., 2012; Hedegaard and Münster, 2013) evaluated the added value of using heat pumps with ADR in energy systems with 50% wind power penetration. However, in all of the above mentioned studies, the building types which are better suited for installing heat pumps were not evaluated. Thereby, the main challenge lays in the wide variation of building types, all with their own characteristics. The building parameters may affect many important factors, such as the overall heat demand, the heat pump cost and heat pump efficiency as well as the load shifting potential and peak electric power demand.

In order to compare the suitability of different building types for installing heat pumps with ADR, the CO_2-abatement cost is calculated, which is a measure for the cost of reducing CO_2 emissions. Although CO_2-abatement costs are known to be sensitive to assumptions on economic parameters such as fuel prices (Delarue et al., 2010) or discount rates (Nordhaus, 1991), the CO_2-abatement cost is used in this study for relative comparison between building and heating system types. As such, the numerical results obtained from this study on CO_2-abatement costs can only be compared to other technologies if identical assumptions on technical and economic parameters are made. A few studies report a CO_2-abatement cost for installing a heat pump instead of another heating system, but with not-fully adequate results due to simplifying modelling assumptions. (Joelsson, 2008) reports an abatement cost of 100 EUR/ton CO_2 for a heat pump compared to a condensing gas boiler, 120 EUR/ton CO_2 compared to an oil-fired boiler and 190 EUR/ton CO_2 compared to direct electric heating. These values are obtained by considering yearly average values for energy use, heat pump performance and efficiency of the electricity-generation system. No attention is paid to the impact the heat pumps may have on the electricity generation. (Kesicki, 2010) employs a long-term energy planning model, UK MARKAL, which considers system-wide interactions, and finds that heat pumps would become widely implemented in the UK if the CO_2 price exceeds 137 £/ton CO_2. However, Kesicki reports that his study lacks the inclusion of more than two building types, heat pump peak demand, demand side management and occupants behaviour.

The current study goes beyond this work by thoroughly taking into account all important factors for determining the CO_2-abatement cost, specifically: the operational cost and CO_2 savings, the investment in heat pumps and the investment in extra peak electric power capacity needed to cover the additional peak electricity demand. This is done by applying the integrated modelling approach as presented by (Patteeuw et al., 2014), which includes models of both the electricity-generation system and residential buildings equipped with heat pumps. The analysis in this chapter is carried out for an energy system inspired by the Belgian power system. A high RES future energy system is assumed with wind and PV providing respectively 30% and 10% of the electric energy on an annual basis.

10.3. Method

The general framework of the integrated operational model is formulated as an optimization problem that optimizes the operational cost for electricity production on the national level taking into account both the operational aspects of the electricity production system and the physical behaviour of the demand-side. As such, the main added value of this integrated operational model lies in the combined optimization of both demand and supply side. The model structure is illustrated in Figure 10.1 and consists of three main parts: (i) the building stock model, (ii) the heating system models and (iii) the electricity production system. The following paragraphs summarize these three components. A more detailed description of the building stock model and its implementation is given in (Reynders, 2015). A more detailed description of the operational model and the heating system implementation can be found in (Patteeuw et al., 2015b).

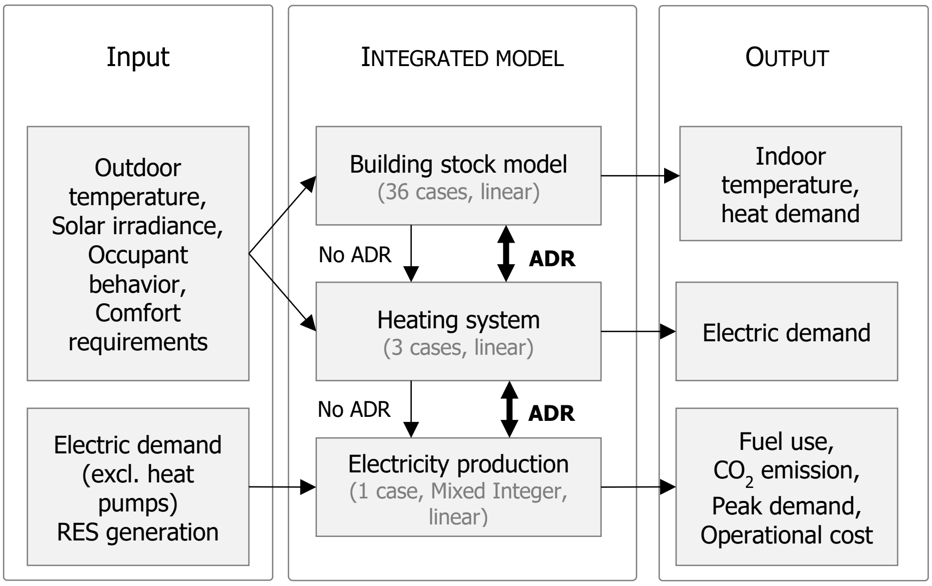

Figure 10.1 Architecture of integrated operational model.

10.3.1. Building stock model

In this study, only single-family residential buildings are considered. The building descriptions for the dynamic models originate from a bottom-up stock model based on the TABULA (Cyx et al., 2011) building stock, as presented by (Protopapadaki et al., 2014), to which additions for new and renovated buildings are made. As illustrated in Figure 10.2, a total of 36 different building types is considered, representing the Belgian residential building stock. The latter is divided in three typologies, six age classes and two renovation levels. The three different building typologies are typical for single-family buildings (i.e., detached, semi-detached and terraced houses).

Each of these typologies is subdivided in six age classes (i.e., before 1945, 1945–1970, 1971–1990, 1991–2005, 2006–2012, after 2012), of which the most recent class is represented by low-energy houses with an overall heat loss coefficient of 30 W/K, corresponding to the economic optimum for Belgium found by (Verbeeck, 2007). Only in buildings constructed after 2005 is a ventilation system installed, for which there are two cases, with and without heat recovery. These are considered according to the TABULA description. A thermal efficiency of 84 % is assumed for the heat recovery unit.

For each age class before 2005, two renovation scenarios are considered. First, a ‘‘mild’’ renovation scenario includes roof insulation, replacement of the windows and an improvement of the air tightness. In the second, ‘‘thorough’’ renovation scenario, the outer walls and floor are also insulated (Protopapadaki et al., 2014). The original buildings without renovation are not considered in this chapter since the supply water temperature for these buildings is too high to be supplied by a heat pump. Additionally, all poorly insulated Belgian buildings are assumed to have undergone at least a light renovation by 2030, in accordance with the proposed evolution of the Belgian building stock by (Gendebien et al., 2015). The thermal behavior and heat demand of the dwellings are modeled using a two-zone reduced-order building model consisting of a 9 states lumped capacity model (Reynders et al., 2014). This thermal network model is translated to a linear state space model. The assessment of the accuracy of this representation is described by (Reynders et al., 2014).

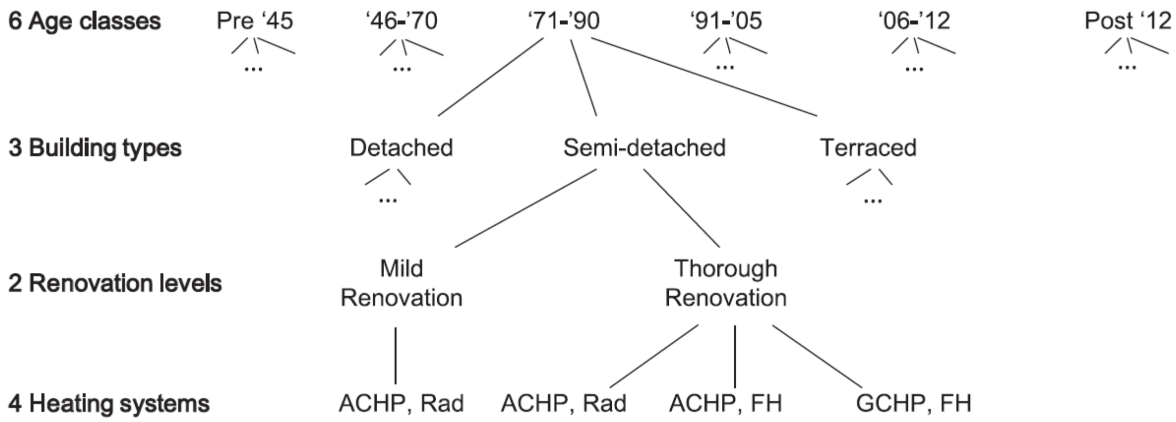

Figure 10.2 Overview of the different building types based on the Belgian residential building stock. Given the 6 age classes, 3 building types, 2 renovation levels, there are in total 36 building cases.

10.3.2. Electricity generation

The electricity generation system is modelled by a merit order, which considers efficiencies, minimal and maximal power output of power plants and neglects all other technical constraints. As shown by (Patteeuw et al., 2015a), this approach can approximate the cost savings determined via a state-of-the-art unit commitment and economic dispatch model.

For the electricity generation side, data related to the fixed electricity demand and electricity generation from RES is taken from the Belgian transmission system operator Elia for the year 2013. A high renewable energy sources (RES) scenario is implemented with 30 % and 10 % of the electricity use covered by wind and photo-voltaic (PV) systems respectively.

The residual demand - defined as the electricity demand of the heat pumps that is not covered by RES - is assumed to be fully covered by combined cycle gas turbines (CCGT) and open cycle gas turbines (OCGT).

For RES based electricity generation, it is assumed that the marginal cost is zero. Curtailment costs are zero since these are assumed to be internal transfers within the model. Note that this is an optimistic scenario for ADR, since excessive use of the storage capacity to buffer renewable production, is not penalized.

10.3.3. Heating systems

For the application of heat pumps, three main cases are considered: (i) an air coupled heat pump (ACHP) with radiators, (ii) an ACHP combined with floor heating and (iii) a ground coupled heat pump (GCHP) with floor heating. The radiators in the thoroughly renovated buildings are assumed to have a nominal supply water temperature of 45 °C. For the lightly renovated buildings, the water temperature is adjusted to allow a recuperation of the existing emission systems, since replacing the heat emission system in a light renovation scenario was found to be not cost-effective in (Heylen et al., 2014). GCHPs are in general not combined with this kind of radiator system. In each case, the heat pump also supplies the domestic hot water demand (DHW). For the lightly renovated building, depending on the age category, the nominal supply water temperature for zone heating can be higher than 60 °C. This is too high to be supplied by a standard heat pump, in which case a double-compression, high-temperature air coupled heat pump is considered (Heylen et al., 2014). The heat pump's efficiency is typically expressed by the coefficient of performance (COP). In this study, the COP is determined according to (Bettgenhäuser et al., 2013), which results in a seasonal performance factor (SPF) as shown in Table 10.1, assuming that the COP is constant during each week and not effected by ADR.

In addition to space heating, the central heating system also produces domestic hot water. For the latter a water storage tank of 200 l is included. The water temperature inside this tank can also be modified for demand response as described in (Patteeuw et al., 2015b).

Table 10.1 Range of heat pump SPF for the different building cases. The seasonal performance factor (SPF) is defined as the ratio of the heat delivered throughout the year to the yearly electricity use of the heat pump.

Renovation level	Mild	Thorough	Thorough	Thorough
Heat pump source	Air	Air	Air	Ground
Heat emission	Radiator	Radiator	Floor	Floor
Min SPF	1.8	2.3	2.5	3.3
Mas SPF	2.1	2.6	3.0	4.0

10.4. Results

The central goal of this study was to quantify the impact of energy flexibility, by Active Demand Response (ADR) on the energy system cost for a large-scale integration of heat pumps. Thereby an underlying hypothesis was that both the impact of heat pump integration and the potential for energy flexibility vary among the type of house (through its thermal properties) and the type of heating system (through the HP type and heat emitting system). In order to evaluate this later hypothesis, the 250,000 installed HP have been theoretically supposed to be installed in only 1 building type at a time and to consist of only type of system (HP source & emission system). For all resulting cases, three scenarios are computed as shown in Figure 10.3.

Based on the results of these 3 scenarios, analysis has been carried out to quantify the impact of ADR on the CO_2-abatement cost by analyzing the resulting CO_2 emissions and system cost. Moreover detailed analysis was carried out to explain the driving factors in cost increases or decreases, such as peak capacity requirements, renewable energy curtailment, and to quantify the impact on thermal comfort and building level energy use. In this report only the impact on peak capacity and CO_2 emissions are presented. More results are presented in (Patteeuw et al., 2015b; Reynders et al., 2015).

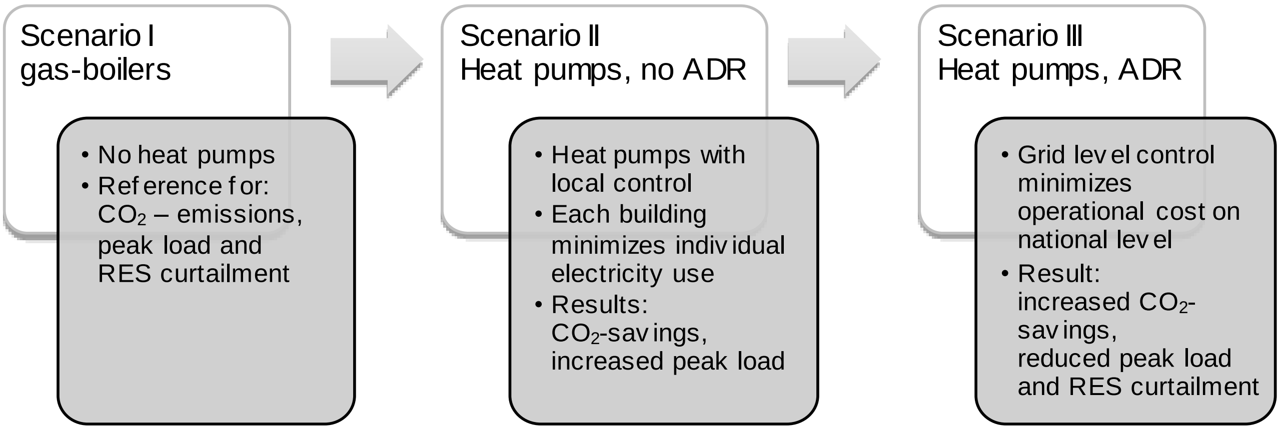

Figure 10.3 Overview of scenarios calculated to compute energy flexibility, or active demand response (ADR), potential.

10.4.1. Peak capacity

A transition from gas-boilers to heat pumps will evidently result in an increase of the electricity use that has to be covered – given the production system assumed in this work – by either the renewable energy sources or an increased production of the OCGT and CCGT plants. When the electricity demand of the heat pumps coincides with the electricity demand that already exists in the network, this may significantly increase the total peak demand in the network and thus additional peak production units need to be installed. At an investment cost of 750 EUR/kW (IEA and NEA, 2010) this additional capacity can be an important term in the CO_2-abatement cost, which is typically not included in heat pump CO_2-abatement cost in the literature. Therefore in this section, the potential of ADR to reduce the peak demand is evaluated as a first performance indicator.

The required peak production capacity is for each building scenario determined through an a-priori optimization of a critical week, i.e. the week with the highest residual electricity demand. The residual electricity demand is defined as the electricity demand from which the generation from renewable energy sources is subtracted. Hence, this is the demand which the traditional power plants need to deliver. When ADR is applied, the demand of the heat pumps during this week is optimized using the flexibility of both the structural and non-structural storage capacity to minimize the required capacity of the power plants. Note that this installed capacity is then applied as an upper bound for the production capacity throughout the considered year.

Figure 10.4 shows the contribution of each building to the increase of the peak electricity demand [kW/build] by introducing heat pumps with (solid line) and without (dashed line) ADR as a function of the electric nominal power of the heat pump. The color-scale indicates the type of building (D: detached, SD: semi-detached, T: terraced). The markers indicated the state of the building (Ref. 1: mild renovation, Ref. 2 thorough renovation). When no ADR is applied, Figure 10.4 shows that the additional peak demand per building is strongly correlated with the nominal power of the heat pump. The lowest increase is thus obtained for the thoroughly renovated terraced buildings. Regarding buildings with the same heat demand, a ground-coupled heat pump performs best because this system has the highest COP and therefore the lowest peak electricity demand.

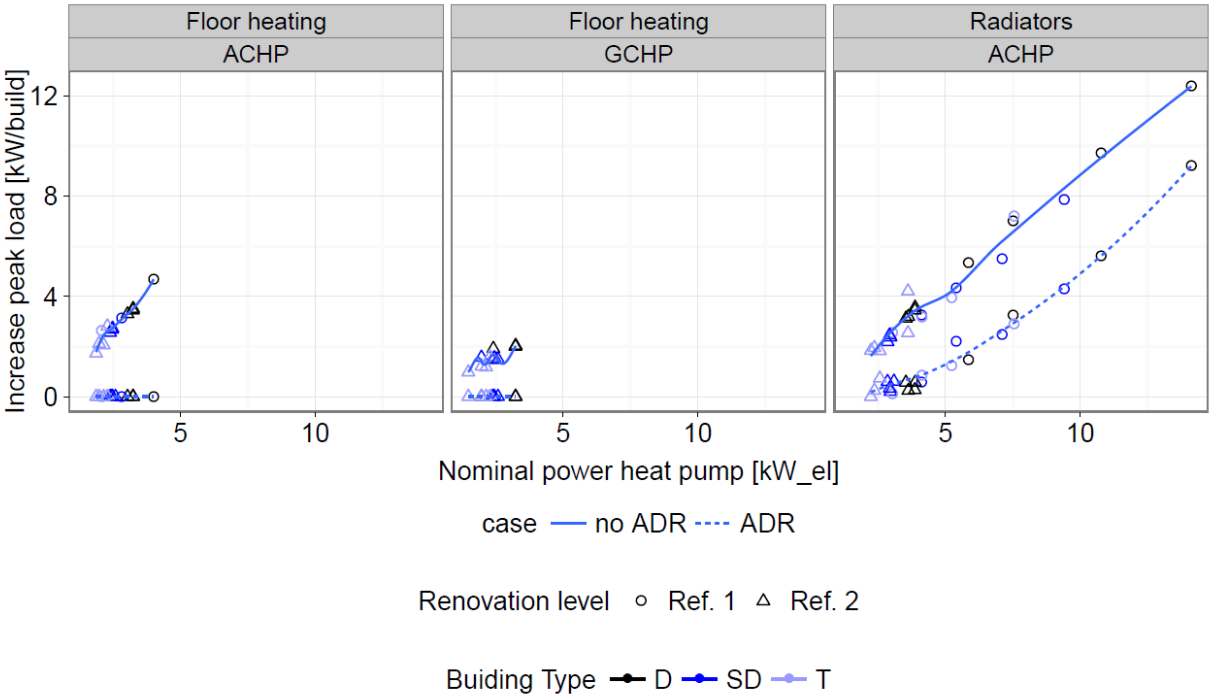

Figure 10.4 Contribution of each building to the increase of the peak demand by introducing heat pumps with (full line) and without (dashed line) ADR as a function of the electric nominal power of the heat pump. The colour-scale indicates the type of building (D: detached, SD: semi-detached, T: terraced). The markers indicated the state of the building (Ref. 1: mild renovation, Ref. 2 thorough renovation).

ADR is found to significantly reduce the need for additional peak power plants, as indicated by the dashed trend line (Figure 10.4). For the floor heating cases and the thoroughly renovated dwellings, the use of the structural and non-structural thermal energy storage allows to shift almost all demand away from the period with the highest electricity use. The buildings with floor heating generally perform better than the same building with radiators. This is in line with the findings of (Reynders et al., 2013), demonstrating that the available storage capacity is lower for the radiator heated buildings. Hence, the heat stored within the thermal mass is found to be inadequate to cover the peak demand period, especially for the less insulated dwellings (Ref. 1 in Figure 10.4).

Consequently, active demand response using the structural thermal mass is found to be an effective measure to avoid the need for additional production units when applied in thoroughly renovated buildings. When heat pumps are to become common practice in less insulated buildings (Ref. 1), ADR cannot avoid the need for additional production capacity. However it is able to reduce the required capacity on average by 30 %, by shifting the heat pump operation away from periods where a peak demand is already present.

10.4.2. CO_2-emissions

Due to the reduction of the use of fossil fuel and the increased penetration of renewable energy sources, the introduction of heat pumps significantly affects the CO_2-emissions, especially when ADR is considered. Figure 10.5 shows the relative change in CO_2-emissions associated with replacing the condensing gas boilers with heat pumps. The relative CO_2-emission savings are highly dependent on the SPF of the heat pump, for which four groups can be distinguished based on Table 10.1. The first group consists of the mildly renovated buildings which are all equipped with a high temperature ACHP and radiator heating (SPF 1.8 to 2.1) and shows that the CO_2-emissions are reduced by 15 % to 25 % compared to the CO_2-emissions for the scenario without ADR (no ADR), depending on the building type as indicated by the circular markers in the middle pane of Figure 10.5. For the second group, consisting of the thoroughly renovated buildings (indicated by the triangular markers) with an ACHP and radiators (SPF 2.3 to 2.6), the CO_2-emission reduction compared to the no ADR scenario varies between 25 % to 35 %. The third and fourth groups represent the buildings with floor heating combined with an ACHP (SPF 2.5 to 3) or a GCHP (SPF 3.3 to 4) respectively. For these groups the reductions in CO_2-emissions compared to the no ADR scenario are respectively 30 % to 40 % and 40 % to 55 %.

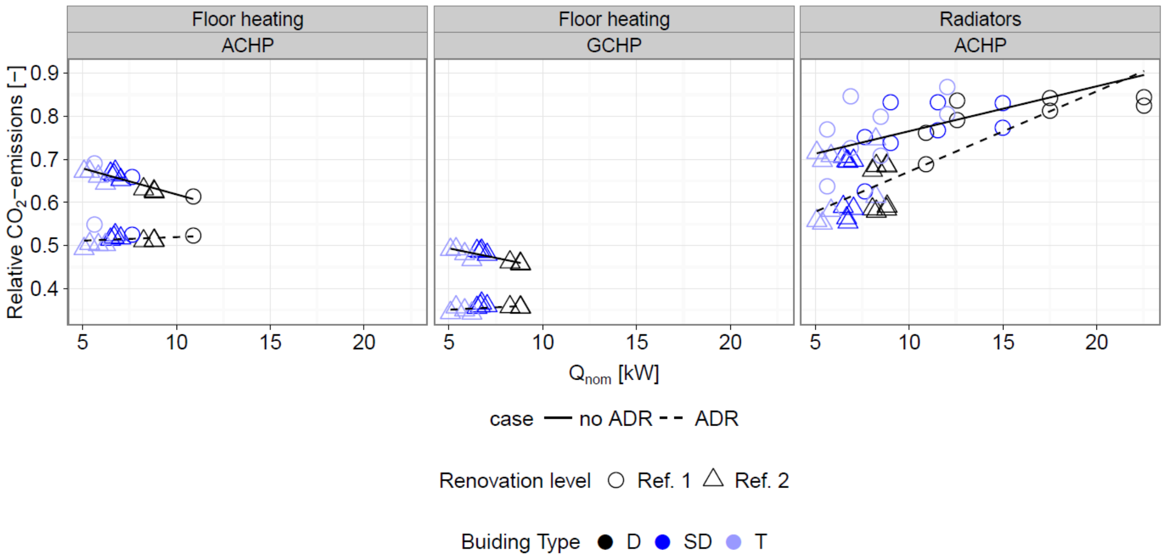

Figure 10.5 Relative CO_2 -emission compared to the reference scenario without heat pumps, for the heat pump scenarios with ADR (dashed trendline) and without ADR (full trendline). The results are function of the nominal thermal power of the heat pump. The markers indicate the renovation level, while the colour of the markers shows the building type.

Including ADR leads to an average additional reduction in emission of approximately 15 %. However the relative reduction in CO_2-emissions by ADR depends significantly on nominal power of the heating system and hence on the insulation level of the building. Thereby a reduction of the relative CO_2-emissions due to ADR by up to 25% is found for the thoroughly renovated terraced buildings, indicated by the light-blue triangular markers. In contrast, for the mildly renovated detached dwelling equipped with radiators, no significant reduction of the CO_2-emissions is found. The latter is in line with the findings of Figure 10.4, where it was shown that for the mildly renovated dwellings equipped with radiator heating, ADR has no significant impact on the heat demand that is covered by renewable production. Note that these are all relative reductions in

CO_2-emissions. As buildings get better insulated and the annual heat demand lowers, the absolute CO_2-emissions for the heat pump cases will converge. To illustrate this, Figure 10.6 highlights the CO_2-savings that are obtained by ADR. The figure shows the absolute CO_2-emission savings for the different heating systems as a function of the nominal power of the heating system – which is strongly correlated to the heat loss coefficient. Thereby, two important trends are shown, depending on the heat emission system.

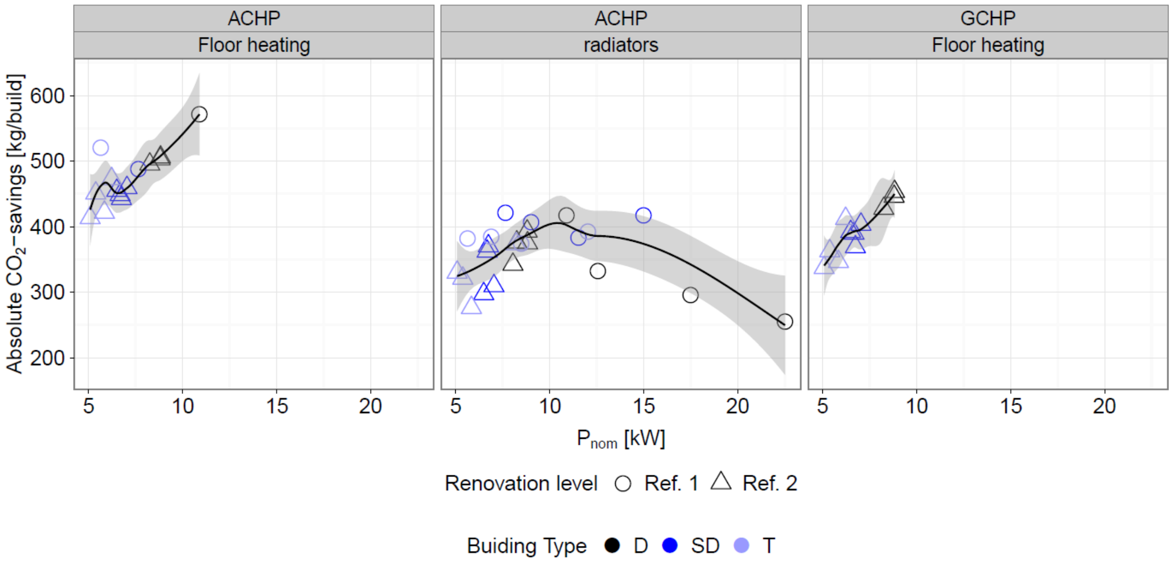

Figure 10.6 Absolute additional CO_2-savings due to ADR as a function of the nominal power of the heat pump for the floor heating and the radiator cases and for the air coupled heat pump (ACHP) and ground coupled heat pump (GCHP). The marker types and colours show respectively the different building types (D: detached, SD: semi-detached, T: terraced) and renovation levels.

For the buildings equipped with floor heating the additional CO_2-savings for the ADR scenario compared to the no ADR scenario increase with increasing nominal heating power. This confirms the findings of the former section, where for increasing heating power a higher available storage capacity was found. In contrast, for the buildings heated by radiators, a parabolic trend is shown. This indicates that for a high nominal power – which corresponds to the mildly renovated buildings built before 1990 – the low storage efficiency jeopardizes additional CO_2-savings. This effect is amplified here since the driving force for ADR, i.e. the remaining curtailed RES production after installing the heat pumps without ADR, is already lower for the uninsulated dwellings.

10.5. Conclusion

In this study, an integrated model coupling demand and supply side system models is developed for the Belgian electricity system. This model allows a thorough assessment of the peak-capacity investment, fuel and renewable energy usage, CO_2-emissions. The results show that as a consequence of the electrification of the energy demand for heating, a significant increase in the required peak production capacity is found when introducing heat pumps without ADR. Thereby the required peak production capacity increases linearly with the installed power of the heat pump.

For the floor heating cases and the thoroughly renovated radiator heated buildings, the need for investments in the peak production capacity can almost entirely be avoided when ADR is taken into account. For the mildly renovated buildings with radiator heating, the available storage capacity is found to be inadequate to shift the entire peak load to off-peak periods. Nevertheless, even for these cases, the required production capacity is reduced by 30 % compared to the scenario without ADR. In addition to the reduction in peak demand, ADR is able to increase the fraction of the electricity use of the heat pumps that is covered by RES from 2.4-3.5 % to 6-24 %. As a down-side of this increased RES penetration, the total electricity use of the heat pumps increases by 1.5-7.5 %. Based on both results the efficiency of the storage was estimated at 70 % for the floor heating buildings in cases where an air coupled heat pump is used. For the radiator heated buildings, the efficiency strongly depended on the building typology and renovation level. Thereby, efficiencies up to 55 % are obtained for the terraced buildings, while efficiencies below 30 % were found for the mild renovation case. As a result of the increased penetration of renewable energy sources, a reduction in CO_2 emission is obtained. This reduction is dominated by the seasonal performance factor of the heat pump and the application of ADR. This ADR allows a higher uptake of RES-based electricity generation that would have otherwise been curtailed, reducing the CO_2 emission on average by 15 %.

11. Effect of the building thermal mass on energy and flexibility performance of building clusters

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11.1. Abstract

This study investigates the impact of the level of thermal mass on the energy flexible performance of building clusters during the heating period, considering as a forcing factor (often also called a penalty signal, especially when economy is involved) the production from a PV plant. The focus on a cluster domain enables the exploitation of the synergies among buildings, renewables and energy infrastructure, while keeping the envelope and HVAC system technological details.

First, building cluster models are set up in Modelica language. Then, different scenarios are evaluated, performing a variation of the building thermal mass, and a Flexibility Index (FI) is designed to quantify the energy matching improvement from reference to smart operation.

11.2. Background and objectives

The concept of using thermal mass in buildings for thermal energy storage facilitating the load shifting has been recently investigated (Reynders et al. 2013, Le Dréau and Heiselberg 2016, Foteinaki et al. 2018 and Wieß et al. 2018). The novelty of the work presented in this chapter is the investigation of the impact of the thermal mass characteristics on energy and flexibility performance at the cluster scale (and no longer at the component/single building scale).

The necessity to shift the focus from single buildings toward a cluster domain is put forward by the European Commission in the “Clean Energy for all Europeans” legislative proposals (EC, 2016a), emphasizing the role of Local Energy Communities (LEC) (EC, 2016b). These LECs are conceived as new market players that are able to generate, consume, store and sell renewable energy. Some prominent clusters in the European context – the BedZED eco-community in London, the Vauban sustainable neighbourhood in Freiburg and Hammarby in Stockholm (Williams, 2016) – demonstrate that the management of a shared distribution network powered by renewables can lead to greater benefits in terms of efficiency, storage and load complementarity due to building usage differences (Metz et al., 2007). Therefore, the cluster represents an intermediate level between single building and the whole city and offers the possibility to describe the synergy between buildings and energy grid (unlike the single building) while keeping track of the detailed technological building related aspects (unlike the city scale). From an energy system perspective, the building cluster is defined as “a group of buildings interconnected to the same energy infrastructure, such that the energy behaviour of each building affects the energy performance” (Vigna et al., 2018a). This definition does not assign fixed dimensions or boundaries to the building cluster scale, but is based on building interconnection that could be physical and/or market related. The physical connection to the same grid allows the exchange of energy between buildings or from a central source towards the buildings. The market aggregation (Eurelectric, 2014) enables the management of the building cluster by a common agent or company who can potentially exploit the energy flexibility of the whole cluster (Langham et al., 2013). In the present work, we refer to the physical connection of the buildings forming the cluster.

11.3. Method

To simulate the interaction between buildings and the energy grid, a simplified thermodynamic model of the cluster, shown in Figure 11.1, is defined in the Modelica language using the components of the IDEAS Modelica library (Jorissen et al., 2018) in the Dymola environment (Dassault Systèmes).

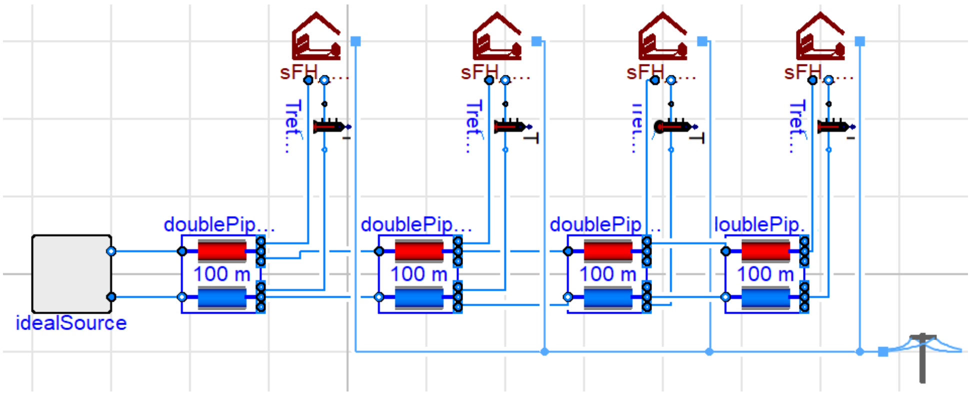


Figure 11.1 Model of the building cluster integrated with thermal and electric grid in a Dymola environment.

Based on the archetypes of the Italian building stock presented in the TABULA database (webtool.building-typology.eu), the geometrical and thermal properties of the selected buildings are translated into reduced-order Modelica models using the Python package TEASER developed by RWTH Aachen (Remmen et al., 2017).

The simulation of different cluster configurations is performed to obtain different energy demand profiles at cluster scale and then evaluate the impact of the level of the thermal mass in buildings on the energy demand and the energy flexibility of the cluster.

11.3.1. Building cluster configurations

The buildings adopted for this study are obtained from the archetypes presented in the IEE-Project TABULA database for the Italian building stock typology of the detached Single Family House (SFH) (Corrado et al., 2011) construction after 2006. The post 2006 construction period is selected with the aim to investigate the flexibility performance of new buildings (nZEB) with local integrated renewable energy sources.

The geometrical properties of the building typology used in simulations are summarised in Table 11.1.

Table 11.1 Geometrical properties of the building typology used in simulations.

Single Family House SFH	
Volume	607 m^3
Gross heated area	174 m^2
Number of floors	2
Component area	
Exterior walls	225.3 m^2
Ground slab	96.4 m^2
Roof	96.4 m^2
Window area	21.7 m^2
Internal walls	225.3 m^2
Internal floor	96.4 m^2

The internal walls and floor are assumed to have the same surface area as respectively the outer walls and the ground floor. The thermal transmittance values of the building envelope components are set accordingly to NZEB Italian requirements defined in D.M. 26.06.2015 (Decreto del Ministero dello Sviluppo Economico, 2015): U-value of 0.22 W/m²K for the opaque elements (exterior walls, ground slab, roof) and U-value of 1.1 W/m²K for the transparent elements.

A variation of the thermal mass of the building components is carried out to investigate its impact on the energy and the energy flexible performance of the cluster. For the exterior walls, roof, internal walls and internal floor, two different levels of thermal mass - heavy (H) and light (L), respectively referred to two different structural cores (concrete and laminated timber) are considered. The main thermal properties are reported in Table 11.2.

Table 11.2 Thermal properties of building components for different cluster configurations.

	Heavy configuration (H)	Light configuration (L)
Structural core	Concrete	Laminated timber
Thermal transmittance U-value [W/m²K]	0.22	0.22
Heat capacity [MJ/K]	68	25

In each configuration, the cluster is composed of four residential detached buildings with four different stochastic occupant behaviours, connected to a district heating system that allows energy exchange between buildings.

11.3.2. Definition of renewable energy production profile of the local installed cluster PV system

A reference PV system capacity and solar collectors' position for the cluster are defined according to an energy optimization, as described in (Vigna et al., 2018b) and (Lovati et al., 2018). The resulting renewable energy production profile serves as a forcing factor (i.e. an external signal to which the building cluster is supposed to react) for the energy flexibility assessment of the cluster, as explained below. The monthly values of the production from the PV plant are reported in Figure 11.2. The PV capacity installed in the cluster is 14.33 kWp. The module's dimensions are 1.989 x 1.63 m, the static performance ratio coefficient is 0.8 and the efficiency is assumed to be 17%.

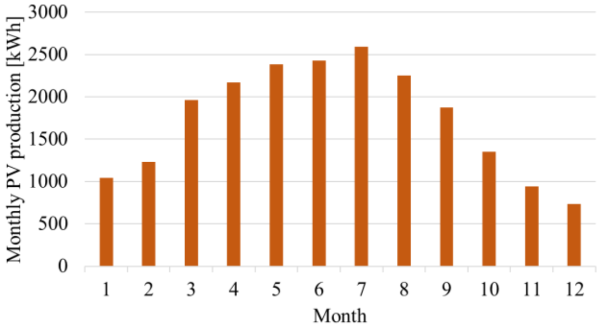


Figure 11.2 Monthly renewable energy production from the cluster PV plant.

11.3.3. Flexibility assessment

In this chapter, energy flexibility is calculated as the measure of the reaction of the cluster to external forcing factors, i.e. as the difference in terms of net energy use, between the cluster managed by a control system that is not aware of the forcing factor (reference operation), and the control sharpened according to the forcing factor (smart operation). The availability of local RES production from a PV system is settled as the forcing factor and for the heating period (January-April and October-December), two different temperature set-point controllers of the heating systems are defined (an example is illustrated in Figure 11.5a-b and Figure 11.6a-b):

- for the reference operation (R) of the heavy weight (H) and of the light weight (L) clusters, a set-point of 20 ˚C is used during the day (7am-11pm) according to the standard EN15251 (CEN, 2007), while a set-point of 16 ˚C is fixed for the night hours (11pm-7am).
- for the smart operation (S) of the heavy weight (H) and of the light weight (L) clusters, a forcing factor-aware controller is designed based on the available RES produced by the PV system. First, a forcing factor signal is defined: for each month of the heating period, the minimum and maximum values of the renewable energy produced are sorted; these two values are respectively associated to the upper limit of the forcing factor signal of +2 ˚C (intervals with high renewable production) and to the lower limit of the signal of -2 ˚C (intervals with low renewable production). The limits of comfortable conditions of 20 ˚C ±2 ˚C are chosen. Then, in order to define a proper signal for controlling the building set-point temperature according to the PV production, the range between the minimum and maximum production is subdivided in to nine intermediate intervals. Each interval indicates a variation of the set-point of ±0.5°C respect to the adjacent intervals as seen in Table 11.3.

Table 11.3 Definition of the forcing factor signal according to the available PV production.

PV production	Min production	⟵						⟶	Max production
Set-point variation [˚C]	18	18.5	19	19.5	20	20.5	21	21.5	22

For the periods of zero renewable production, no signals are applied and the temperature set-points are kept the same as the reference operation building. Finally, the temperature set-points of the smart buildings are modulated according to the forcing factor signals.

In this study, the energy flexibility is defined as the ability of the building to minimize the heating energy use during the absence of RES production and maximize it during periods of available renewable production. Therefore, the final objective of the energy flexible cluster is to maximize the use of renewable energy sources (RES) and reduce the use of non-renewable energy. The flexibility of each cluster configuration is quantified considering the Flexibility Index (FI), expressed as the difference between the residual demand of the reference cluster q_{match}^{REF} and the residual demand of the smart cluster q_{match}^{SMART} divided by the reference heating demand $q_{consumed}^{REF}$ as reported in Equation (11.1). All the terms under the integrals are expressed as power (i.e. in kW).

$$FI= \int \left(q_{match}^{REF} - q_{match}^{SMART}\right) dt \ \Big/ Q_{consumed}^{REF} \tag{11.1}$$

For the heating period, the residual demand of the clusters Q_{match}^{REF} and Q_{match}^{SMART} are respectively calculated as the maximum value between 0 and the difference between the energy demand of the cluster and the renewable energy produced:

$$Q_{match}^{REF}= \int \max\left(0,\ q_{consumed}^{REF} - q_{produced}^{REF}\right) dt \tag{11.2}$$

$$Q_{match}^{SMART}= \int \max\left(0,\ q_{consumed}^{SMART} - q_{produced}^{SMART}\right) dt \tag{11.3}$$

Thus, the residual demand refers to the energy demand not covered by RES and must, therefore, be satisfied with non-renewable energy sources.

11.4. Results

11.4.1. Energy performance

In Figure 11.3, the monthly heating demand values of the heavy H (top) and light L (bottom) cluster configurations are reported.

- the grey bars show the total heating demand of the cluster during the reference operation (R), i.e. the energy performance of the cluster before considering the contribution of the PV production and without the smart control;
- the grey dashed bars show the residual demand of the cluster during the reference operation (R), i.e. the energy savings of the cluster considering only the contribution of the PV production (without smart control);
- the black bars show the total heating demand of the cluster during smart operation (S), i.e. the energy performance of the cluster considering only the contribution of the smart control;
- the green bars (for the heavy H cluster configuration) and the blue bars (for the light L cluster configuration) show the residual demand of the cluster during smart operation (S), i.e. the energy savings of the cluster considering both the contributions of the PV production and the smart control affecting the timing operation of the heat pump.

The values of the residual demand of the simulated configurations (Q_{match}^{REF} and Q_{match}^{SMART}) are calculated as shown in Equation (11.2) and Equation (11.3). For the whole heating period, it is visible that both the PV system and the smart control contributions result in significant energy savings.

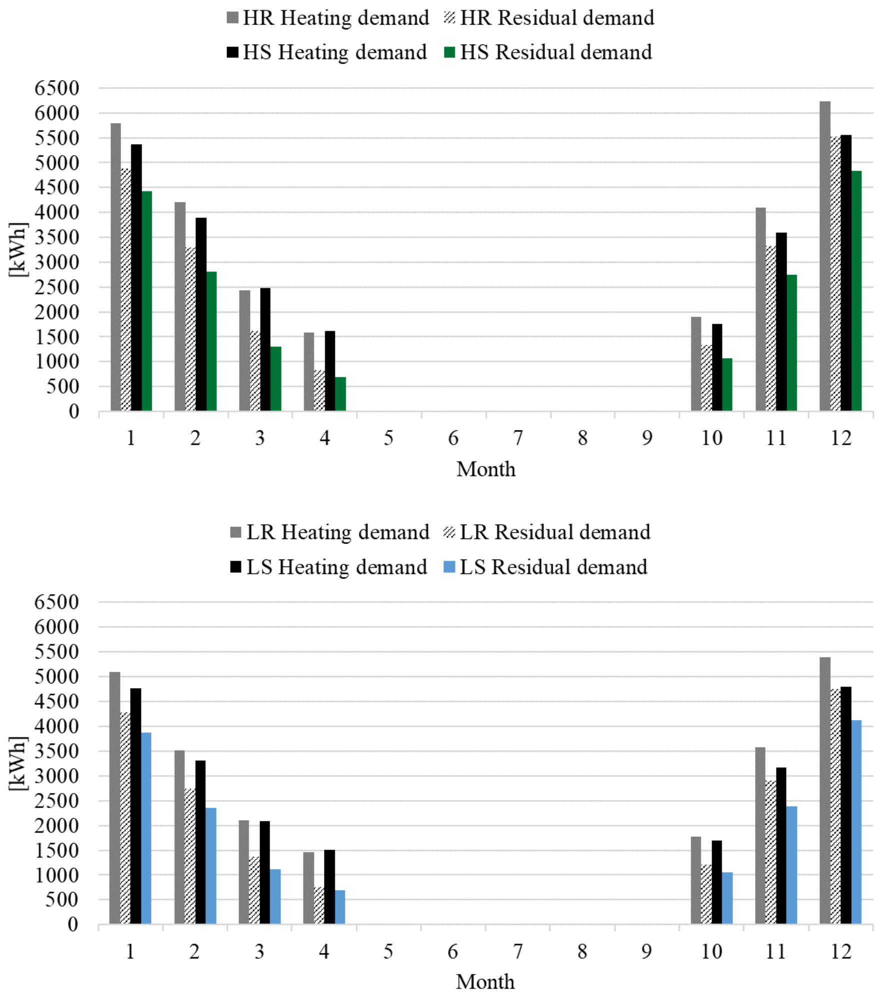


Figure 11.3 Monthly heating demand of the heavy weight (H) (top) and light weight (L) (bottom) simulated cluster configurations. Reference case (R) versus smart case (S).

Considering the annual energy demand shown in Figure 11.4 and Table 11.4, for both the heavy weight (H) and the light weight (L) configurations the smart operation (S) improves the energy usage during periods of available renewable production, resulting in a reduction of 14 % of the residual demand (i.e. the energy demand not covered by renewables) compared to the reference (R) operation.

The daily trends for two representative days of January and March are respectively presented in Figure 11.5 and Figure 11.6. Figure 11.5a and Figure 11.6a show the variation of the smart set-points (red lines) compared to the reference set-points (black dashed). Figure 11.5b and Figure 11.6b show in grey bars the forcing factor signal (˚C) based on available renewable energy produced by the PV system. Figure 11.5c-d and Figure 11.6c-d present the heating demand of the reference (black dashed line) and smart configuration (green line for the heavy cluster and blue line for the light cluster) and the trend of the PV production (grey dotted line).

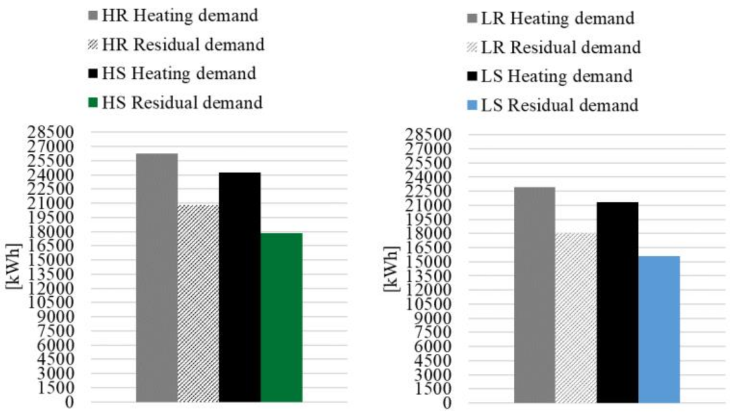


Figure 11.4 Annual heating demand of the heavy weight (H) (left) and light weight (L) (right) simulated cluster configurations. Reference case (R) versus smart case (S).

Table 11.4 Annual heating demand values for different cluster configurations.

	Heavy configuration (H)		Light configuration (L)	
	Reference (R)	Smart (S)	Reference (R)	Smart (S)
Heating demand [kWh]	26,262	24,263	22,900	21,338
Residual demand [kWh]	20,804	17,865	18,023	15,600

What the smart control tries to do is to decrease the heating demand during periods of null PV production and shift/increase it during periods of available renewable energy. The aim is to store the energy while it is available from the PV production, and reduce the use while it is not available, while keeping the comfort ranges in the building.

During representative days of January, it is not possible to completely shift the smart heating demand curve in correspondence to the PV production curve, because the PV starts to produce at around 9am but the heating system has to be turned on at 7am to ensure comfort conditions, both in reference and smart operation. The smart control contributes to decrease the energy demand during periods of absence of renewable energy production and increase it during periods of available renewable production, for both the heavy and the light configurations.

During representative days of March, the PV system starts in advance to produce renewable energy (7am) and thus has a better correspondence with the trend of the heating demand. Here again, the smart control lowers the demand during periods without renewable energy production and tries to shift it during periods of available renewable energy for both the heavy and light configurations.

11.4.2. Flexibility performance

The values of the Flexibility Index FI of the two configurations, calculated using Equation 11.1, are shown in Figure 11.7 and Figure 11.8. From the monthly results, it is visible that in the cold months of January, November and December, the light cluster is more flexible than the heavy cluster. On the contrary, during the warmer months of April and October the FI for the heavy cluster is much higher than for the light cluster; however, the residual demand is quite low in these months, so the energy saving is limited.

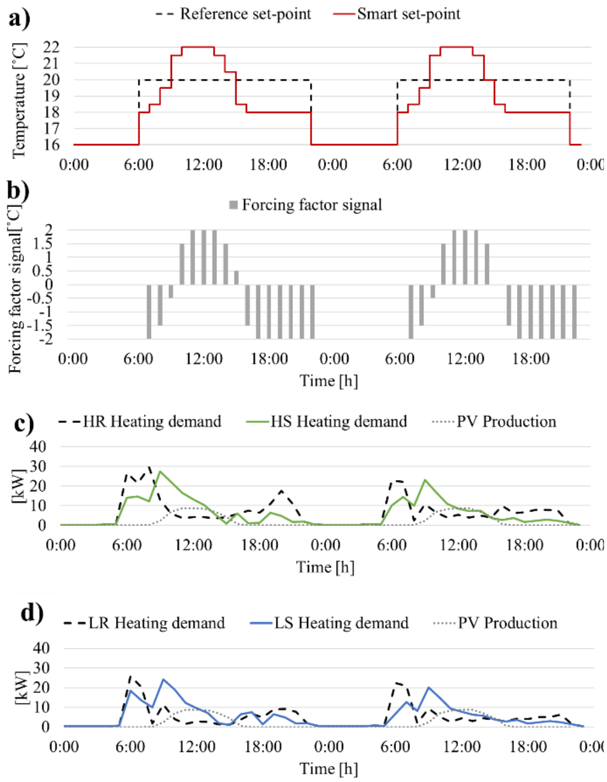


Figure 11.5 Daily trends for two representative days in January. a) Temperature set-point of reference and smart operation; b) Forcing factor signal; c) Heating demand of the simulated heavy weight (H) configurations (reference case (R) versus smart case (S)) and PV production profile; d) Heating demand of the simulated light weight (L) configurations (reference case (R) versus smart case (S) and PV production profile.

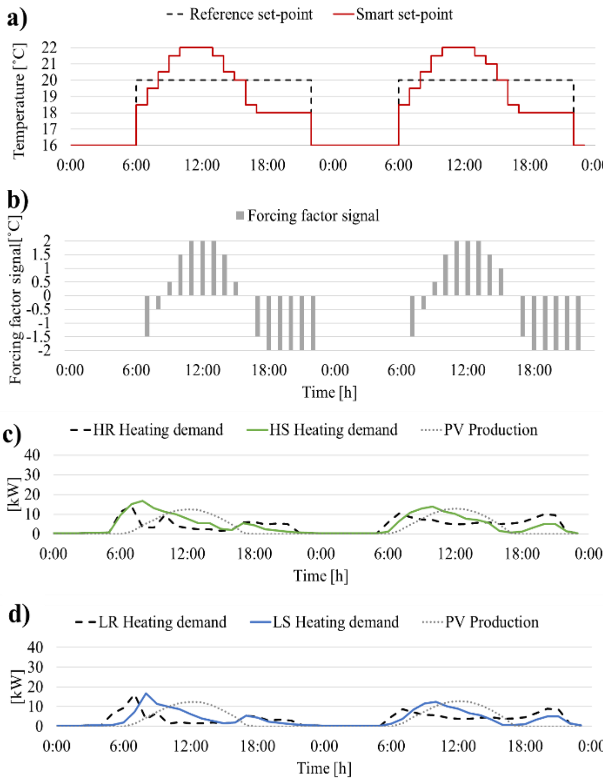


Figure 11.6 Daily trends for two representative days in March. a) Temperature set-point during reference and smart operation; b) Forcing factor signal; c) Heating demand of the simulated heavy weight (H) configurations (reference case (R) versus smart case (S) and PV production profile; d) Heating demand of the simulated light weight (L) configurations (reference case (R) versus smart case (S) and PV production profile.

Therefore, on an annual basis, the FI value obtained by both clusters is the same (0.11). This means that in this case, the heavy cluster does not increase the flexibility index with respect to the light cluster, because the solar and internal gains during the day are insufficient to effectively charge the high thermal mass and consequently much energy is taken from the storage and more energy needs to be supplied in order to restore the thermal balance of the buildings.

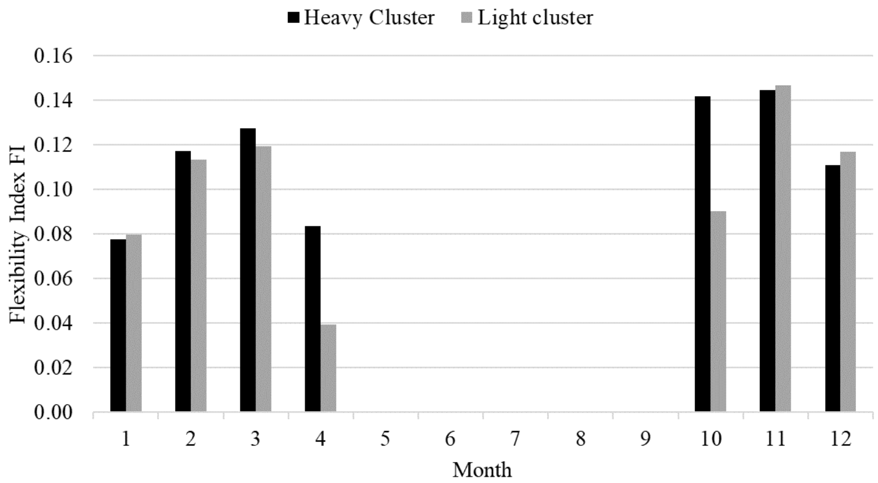


Figure 11.7 Monthly values of the Flexibility Index FI for the simulated cluster configurations.

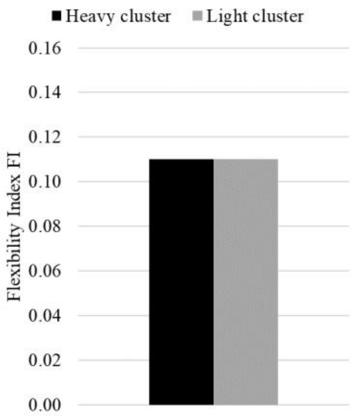


Figure 11.8 Yearly values of the Flexibility Index FI for the simulated cluster configurations.

11.5. Conclusion

This study presents a methodology to define building cluster models connected to a thermal network in Modelica language. Two building cluster configurations are modelled using the IDEAS library and a variation of the thermal mass level (Heavy and Light) of the opaque building components is performed. The energy and flexibility performance are evaluated for the heating period. The availability of local renewable production from a PV system is defined as a forcing factor and the flexibility performance is quantified as the reduction of the heating energy demand not covered by renewables, i.e. the improvement of energy usage during periods of available renewable production.

Based on the methodology defined in IEA EBC Annex 67 (Grønborg Junker et al., 2018), the energy flexibility potential of the different scenarios is assessed.

A scenario for reference operation of the buildings with a constant heating temperature set-point at 20 ˚C during the day (7am-11pm) and 16 ˚C during the night (11pm-7am) is initially simulated. According to the availability of local renewable energy, a smart set-point is provided based on a forcing factor signal (temperature modulation of 20 ˚C ± 2 ˚C with steps of ± 0.5 ˚C), with the aim of decreasing the heating demand during periods of zero PV production and shift it to periods with available renewable energy.

For the whole heating period, the smart operation of both the heavy and the light smart cluster configurations enables an improvement of RES usage, with a consequent reduction of the residual demand (i.e. non-renewable energy demand) of 14 % compared to the reference residual demand.

For both cluster configurations, the flexibility performance is evaluated by defining a Flexibility Index (FI) to quantify the amount of energy that can be shifted towards RES-availability through the smart control operation in comparison to the reference case. In this first attempt, the FI obtained for both configurations is the same, so in this case the higher thermal mass of the building does not increase the flexibility index, because the solar and internal gains during the day are insufficient to effectively charge the high thermal mass and consequently much energy is taken from the storage and more energy needs to be supplied in order to restore the thermal balance of the buildings.

To conclude, this work introduces a preliminary approach for modelling a building cluster in the Modelica language and for assessing the influence of thermal mass both on energy demand and on the energy flexible performance. In future developments, the methodology for the flexibility assessment will be applied considering further variations in the cluster features (e.g. insulation level, building use, building typology) and different forcing factors/penalty signals (e.g. energy price or CO_2 intensity of the energy used). Moreover, the control strategies will be improved to enhance the energy flexible behaviour of the whole building clusters, for example by increasing the upper value of the forcing factor signal affecting the internal set-point temperature, according to detailed comfort evaluations to better take advantage of the energy storage in the heavy thermal mass.

12. Impact of flexible operation on thermal comfort in a large non-domestic building

James Parker, Leeds Beckett University, UK

12.1. Abstract

Maintaining the thermal comfort of building occupants places limits on the scope for energy flexibility in the operation of Heating, Ventilation and Air Conditioning (HVAC) systems. The work presented here describes results from simple field trials that were intended to shed loads and reduce power demand during periods when the price of electricity increased. Unsophisticated binary controls were used to reduce loads and these controls were not linked to internal environmental conditions; it was therefore important to evaluate the impact of the control strategy on comfort conditions in specific rooms within the case study building. The field trials were carried out in an operational, large mixed-use building that is part of the Leeds Beckett University estate. Although a manual control strategy was used in these trials, in the context of IEA EBC Annex 67, the controls mimicked that of an active demand response (ADR) event. In a practical context, the aim of these trials was to reduce power demand during times of peak electricity price, therefore reducing costs and saving energy. Due to the distribution of temperature sensors throughout many occupied spaces within the building, these trials offered an opportunity to evaluate the potential impact on thermal comfort during these demand response periods. Data taken from a sample week during the trial period have been used to quantify the impact of the flexible operation on power demand and room air temperature.

12.2. Background, aim and objectives

The focus of this case study is the Rose Bowl building, a large mixed use facility that is part of the Leeds Beckett University City Campus. The building has approximately 10,000 m^2 of floor space and incorporates a range of offices, classrooms and lecture theatres, as well as a large lobby and café area and various ancillary spaces. It is served by a shared gas-fired combined heat and power (CHP) unit (housed in a neighbouring building) and traditional gas-fired boilers. The entire building is mechanically ventilated and air conditioning is used to provide comfort cooling as required. In most of the office and teaching spaces, a chilled/heated beam system is used. This system provides tempered air in the occupied spaces by passing incoming air over these beams. Larger lecture theatres are kept comfortable using distributed variable-air volume systems and the circulation spaces are heated using traditional radiators as required. The Rose Bowl was constructed in 2009 and, in keeping with UK Building Regulations from this time, the fabric of the building is relatively thermally efficient. It is, however, a lightweight construction and does not incorporate a significant amount of exposed thermal mass. There is some thermal mass in the concrete floors, but this is decoupled from the conditioned space in most areas, by either floor coverings or suspended ceilings. Sample images of the external and internal areas of the building are presented in Figure 12.1.

Figure 12.1 External and internal images of the Rose Bowl building in Leeds City Centre.

This work uses data captured during a field trial period, which, primarily, aimed to reduce power demand during times of peak electricity price. The air-handling units (AHUs) in the building represent the greatest proportion of power demand during occupied periods; the building is actively conditioned between 06:00 and 10:00. The first objective of the trials was therefore to shut down these systems during the periods of peak cost. In the UK, the national grid calculate peak periods of demand, known as Triads (National Grid, 2015). The term 'Triads' is used as it refers to a grouping of three half-hour periods which represent the time at which demand is at its highest. During these Triads, electricity prices for consumers billed using half-hourly meters are significantly higher than at other times. The Triads charges are introduced during colder months (November – April) and they generally occur between 16:00 and 19:00, when industrial demand overlaps with domestic demand. They are calculated in retrospect but utility contractors can predict when they will occur and provide advice for their clients in advance. In an attempt to mitigate the impact of these higher charges, the Building Services Manager at Leeds Beckett University chose to shut down the AHUs in the Rose Bowl between 17:00 and 18:30 on weekdays from the beginning of December 2016 until the end of January 2017.

Although the main aim of the field trial was to reduce cost, it also offered the opportunity to explore the implications for energy flexibility. This introduced two further objectives: to quantify the reduction in power demand achieved through the simulated ADR events; and to evaluate the impact of the demand response AHU shut down on the thermal comfort of occupants. The methods employed to achieve these objectives are described in the next section. Numerous published studies aim to characterise and/or quantify energy flexibility, but there are limited examples of how this affects occupants in real buildings, especially non-domestic buildings.

Analysis of the data made available through this field trial was influenced by the broad scope of IEA EBC Annex 67 (Jensen et al., 2017) and in particular explores the potential for flexibility in HVAC systems and the impacts of this on users. In terms of underlying assumptions, this work aligns with concept described by (Reynders et al., 2018) that "…energy flexibility is a deviation from a reference profile due to an external incentive". This case study also uses nomenclature developed in the two aforementioned papers (Jensen et al., 2017) and (Reynders et al., 2018) and from a further paper defining the extent of Key Performance Indicators (KPIs) when characterising energy flexibility in buildings (Junker et al., 2018).

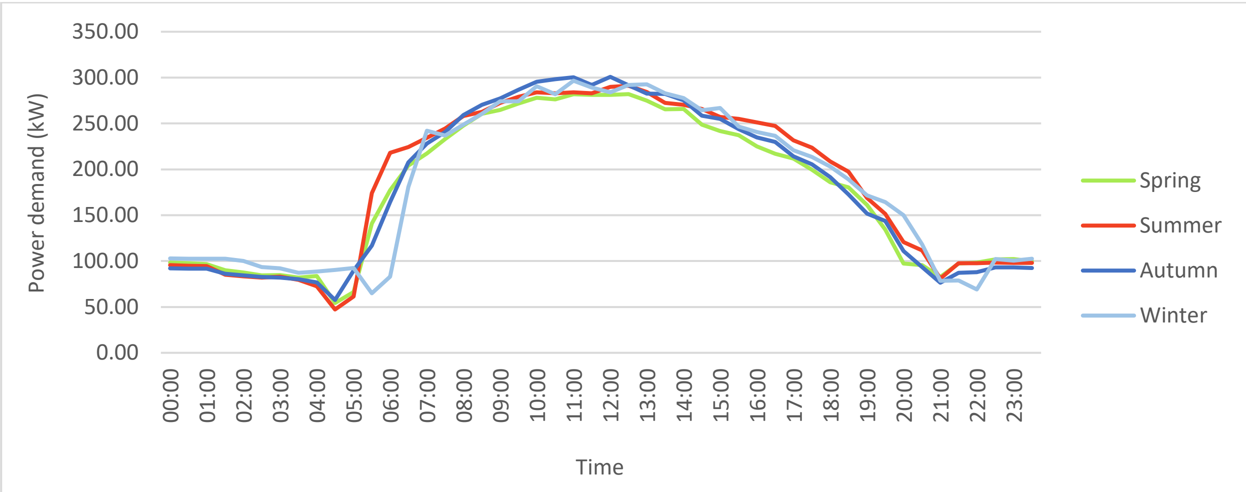
12.3. Method

The Building Energy Management System (BEMS) was used to shut down the AHUs between 17:00 and 18:30 on weekdays during the trial period; weekend days and closure days (such as Christmas periods and national holidays) were all omitted from the analysis described in this work. The trial period ran between December 2016 and January 2017. Half-hourly electrical power demand data covering the period from Thursday 5 May 2016 up until Friday 21 December 2018 were provided by the Leeds Beckett University Estates Building Services Manager as a basis for the analysis presented here. These data were used to quantify the reduction in power demand during the trial period by creating reference demand profiles against which the profiles including the flexible operation could be compared. This was the most practical method of normalising data for comparison with the available data set. It is important to note that the data are from the main incoming electricity feed and not from the specific sub-meter associated with the AHUs, the demand profiles, therefore, include all electrical loads within the building. Further work will evaluate the impact of sub-metred loads specific to the AHUs when data become available.

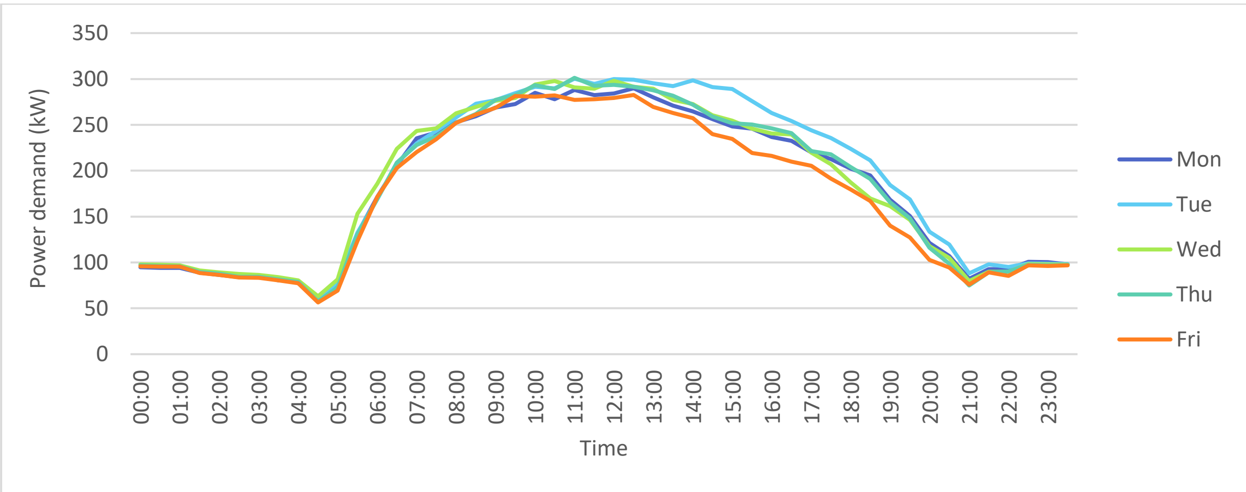
For the first section of data analysis, a sample week in December (12^{th} – 16^{th} December 2016) is used to illustrate and quantify the impact of the flexible operation. The second section of analysis then presents results calculated for the full trial period. Reference demand profiles were created for each weekday during the winter periods to facilitate the comparison between normal (referred to throughout as the 'reference' load) and flexible operation. This was necessary as there is some variation between the average profiles for the different seasons as can be seen in Chart (a) in Figure 12.2 (these average profiles omit data from the trial period.) There are also slightly different profiles for the different weekdays; an example of this with mean values for weekdays in December 2017 is used to illustrate this in Chart (b) of Figure 12.2.

As part of IEA EBC Annex 67, calculation methods and key performance indicators (KPIs) have been developed that provide an effective means of visualising and quantifying results. Where relevant, the impact of the flexible operations in this case study were analysed using these methods and KPIs. The KPIs include: β (Time) The total time of decreased energy demand; Δ (Power) The maximum change in demand following the penalty change; A (Energy) The total amount of decreased energy demand; and B (Energy) The total amount of increased energy demand (Junker et al., 2018). The theoretical extents of each measure are illustrated in Figure 12.3.

Due to limitations in the control strategy employed in the field trial and the granularity of available data (i.e. main electricity meter), the value of calculating all of the metrics noted above was not always significant. For example, the total time of reduced energy demand (β) was fixed, so is of no import in this example. In addition, it was not relevant to calculate the increase in demand (B) due to the control parameters; this is explained further in the results section below.



(a) Average seasonal power demand profiles



(b) Average daily power demand profiles

Figure 12.2 Average power demand profiles between 5 May 2016 and 21 December 2018.

Although the impact of flexible operations has been calculated for this case study, it is the thermal comfort of occupants during the simulated ADR events that offers a more original contribution to knowledge. As this trial was carried out in an operational building, it offers some insight into the scope for flexibility in existing buildings, as well as how flexible operation affects the comfort of occupants. When using the building HVAC system in flexible operations, the thermal comfort of occupants represents the main boundary condition within which the strategy must operate. Internal temperature data at a half-hourly resolution was used to evaluate the impact on thermal comfort during the sample week in December 2016. The comfort ranges recommended by the Chartered Institute of Building Services Engineers for different thermal zone types were used to define acceptable boundary conditions (CIBSE, 2015). Internal air temperature data were available for a sample set of 61 rooms, which represents approximately 40% of the conditioned floor area within the building. For each room, the proportion of time spent outside the boundary conditions during the trial periods has been calculated.

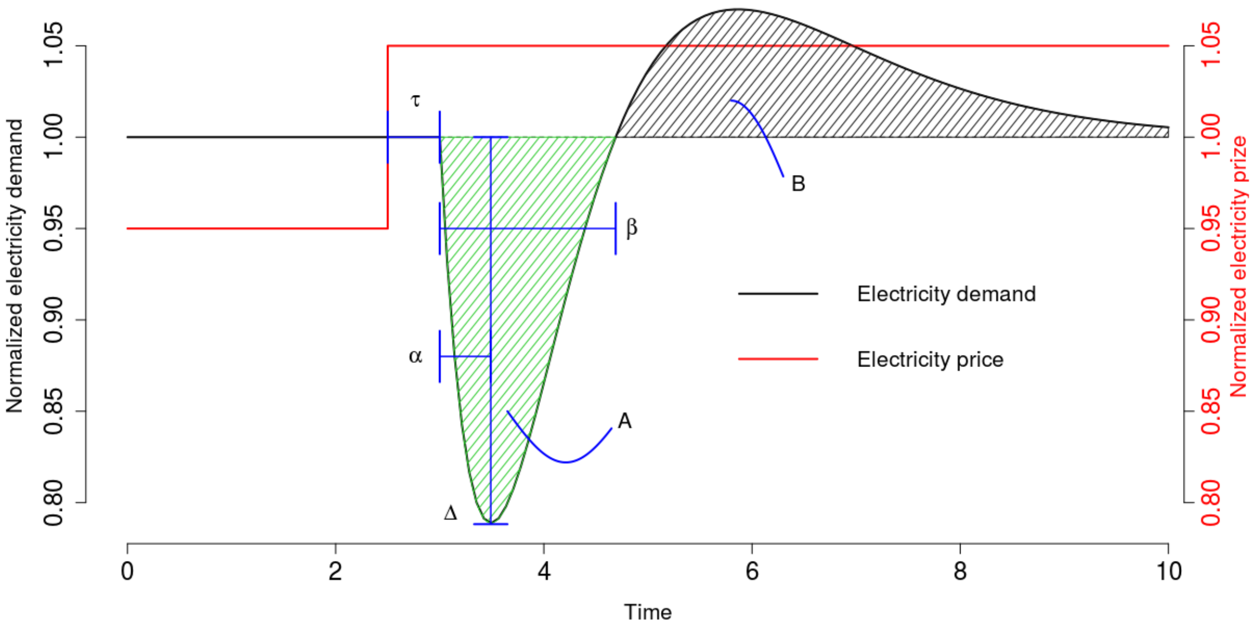
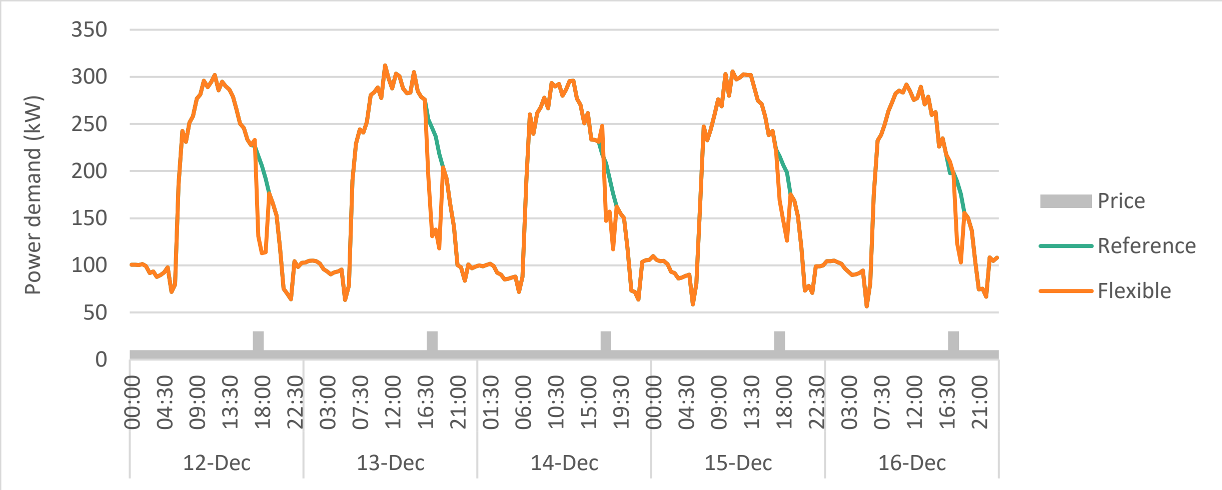


Figure 12.3 Theoretical extent of metrics used to measure energy flexibility (Junker et al., 2018).

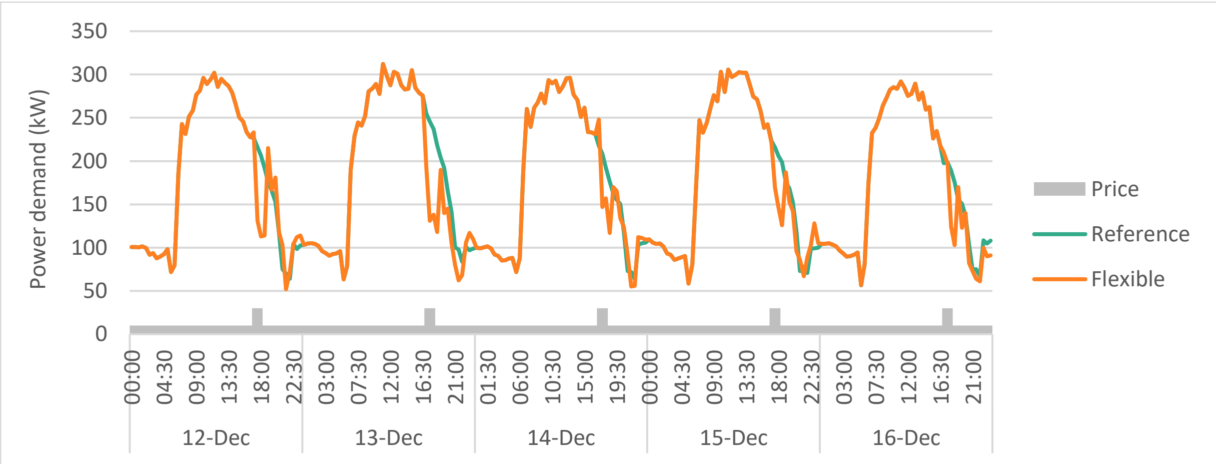
12.4. Results

12.4.1. Power demand and load shedding

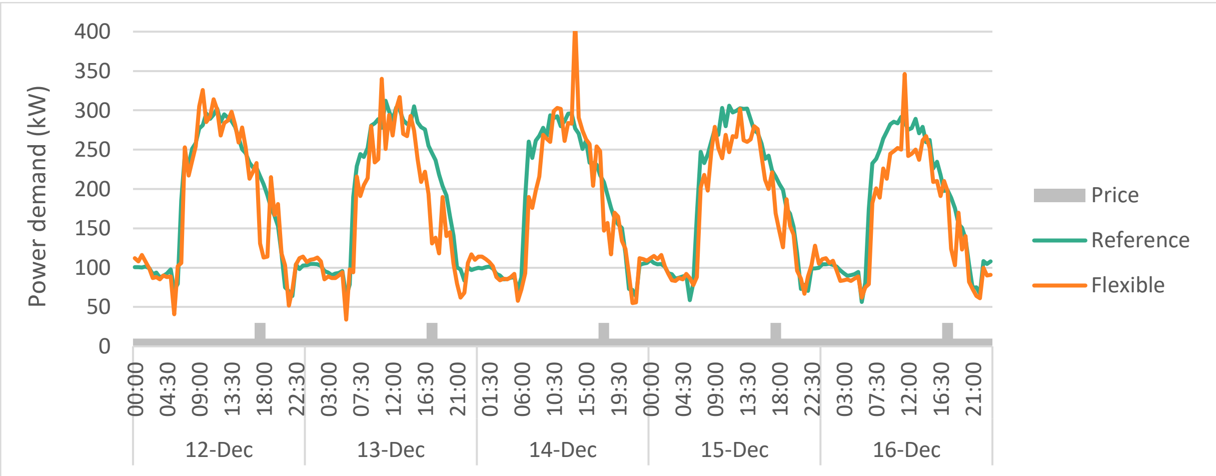
The power demand profiles for the sample week of 12th – 16th December are shown in chart (a) of Figure 12.4. The reference profile was compiled using average values for each half-hour time step for all winter months, and for each weekday, outside of the trial period. In chart (a), the flexible profile was created by using the actual demand during the penalty period (Triads increase in electricity tariff); outside of the penalty period, the flexible profile follows the same pattern as the reference profile. This provided the simplest means of quantifying and visualizing the shift in demand during these times. However, this does not account for any increase in energy demand ('B' in the chart shown in Figure 12.3). This increase would most commonly be associated with bringing the internal temperature set point back to the desired levels. However, this is not entirely consistent with the trials that were carried out in this instance, as is explained later in this section. Despite this, charts (b) and (c) have been included to help illustrate the potential difficulty of quantifying all of the relevant KPIs when using real metered data only, and following the methodology developed as part of IEA EBC Annex 67.



(a) Reference and flexible loads 12th – 16th December 2016 (ADR periods only).



(b) Reference and flexible loads 12th – 16th December 2016 (ADR event until midnight each day).



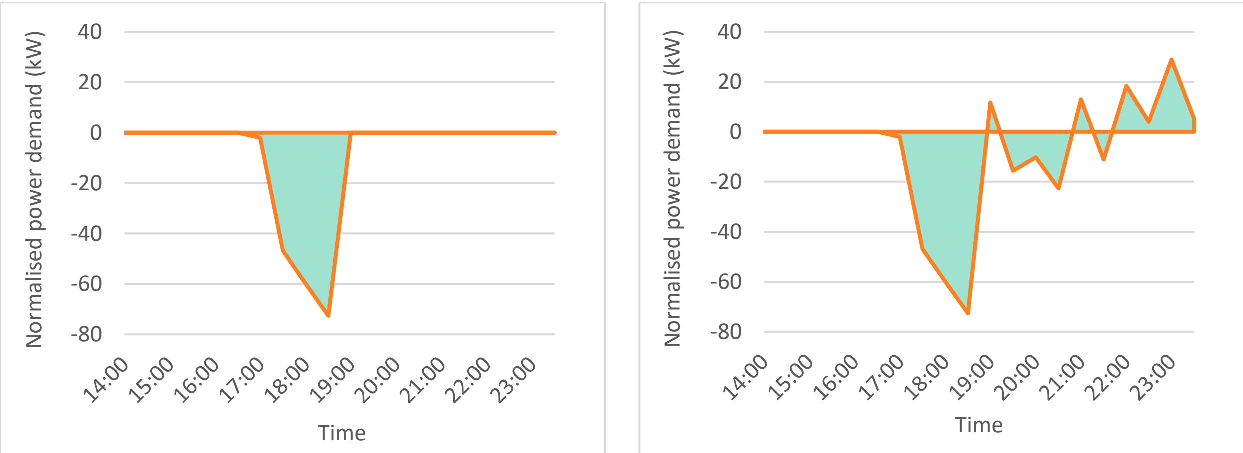
(c) Reference and flexible loads 12th – 16th December 2016.

Figure 12.4 Comparison between reference and flexible loads 12th – 16th December 2016.

As stated above, the three different curves for the same period have been shown here to emphasise the complexity of quantifying and visualising flexibility using real metered data. In all charts, the reference profile is the average for winter weekdays in the Rose Bowl building. It is the composition of the curves related to flexible operation that differ; in chart (a), the flexible curve is created by following the same pattern as the reference profile for all times apart from the period of time covered by the ADR event only, where actual demand data have been inserted (17:00-16:30). In chart (b), the flexible curve is created in the same way but inserting actual demand data from the beginning of the ADR event until the end of the day (17:00-24:00); this was done to explore whether there was any increase in demand following the ADR event. In chart (c) the flexible curve is created using actual demand data at all times; this was done to demonstrate the need to normalise demand to achieve meaningful comparison, as is emphasised below.

In chart (b), an increase in demand following the ADR event can be observed for some of the days but not for others. There are two possible reasons for this, the first is that the data are for total demand and other loads could influence this increase. The second is that, although the AHUs are used to help condition the spaces, they are controlled to deliver a set rate of fresh air and, as such, do not increase their demand to return the spaces to previous conditions following the ADR event. Chart (c) illustrates the stochastic nature of demand on specific days and how comparing full diurnal demand profiles with the reference profiles does not produce any meaningful insight when using the described methodology to quantify impact. This is because the deviation away from the reference load during times outside of the Triads are not related to flexible operation. All charts shows the price step during the Triads charges.

When using the average daily profiles as the reference load, it is possible to normalise the change in load based upon the metered data. This allows the ADR event to be visualised in the same format as that used in Figure 12.3. However, in this instance, the problem remains that when attempting to account for the potential increase in demand following the ADR event, the increase does not necessarily relate to the flexible operation, and therefore provides an unreliable result. A comparison between these two approaches is presented in Figure 12.5 using data from Thursday 15 December 2016 as an example.



(a) Decrease only

(b) Decrease and increase

Figure 12.5 Normalised demand profiles comparing data for ADR period and ADR until the end of day.

Despite the limitations of the control strategy and data set available, it is possible to calculate the savings indicator based upon the cost function, the maximum change in demand following the penalty change (Δ) and the total amount of decreased energy demand (A) for both the sample week and full trial period. The cost of electricity is set at 0.09 €/kWh outside of the Triads penalty period and 0.27 €/kWh during the Triads (this is based upon indicative costs provided by the Building Services Manager). For the sample week, the saving indicator was 6.7%, the maximum change in demand was 114.72 kW, and the total decrease in demand was 553.54 kWh. The total decrease in demand equates to a cost saving of just under €150 during the sample week.

The average profiles shown in Figure 12.6 illustrate a clear decrease in demand throughout the entire trial period when compared with the reference case. Using the same methodology to calculate KPIs for the full period, the saving indicator is considerably lower for the full period at 2.9%, the maximum change in demand was 120.67 kW, and the total decrease in demand was 6,292.75 kWh. Over the full trial period, a saving of €1,699 was achieved when compared to the expected cost.

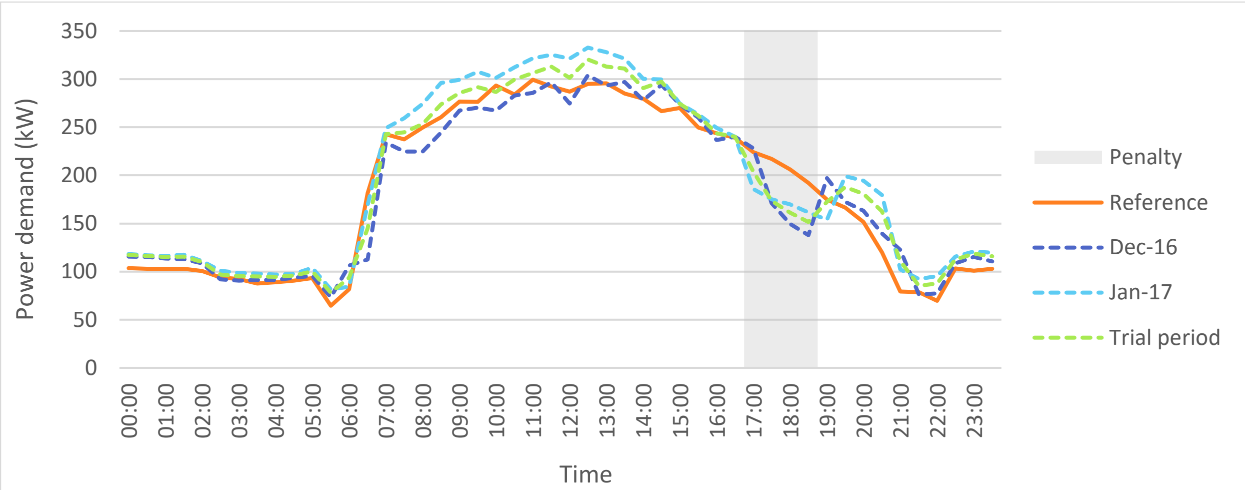


Figure 12.6 Average power demand profiles for reference and flexible load profiles.

12.4.2. Thermal comfort of occupants

Although the power demand data offer some indication of the savings that can be achieved using simple BEMS controls, the room temperature data from the trial period offers a more useful insight in the context of IEA EBC Annex 67. The CIBSE Guide A (CIBSE, 2015) environmental design criteria were used to set upper and lower limits for room temperature in different thermal zone types. These limits were then used to calculate the proportion of time that room temperatures were outside of the recommended range. Due to the time of year that the trial took place, it would be intuitive to assume that there would only be a problem with rooms falling below the recommended temperature. However, as the AHUs provide heating, cooling and fresh air, it was important to include an upper limit to identify any instances where internal heat gains and reduced air changes led to overheating. Results for the hours during the ADR event over the full two-month trial period are shown in Table 12.1. The column named "% out" refers to the total percentage of time that room temperature was outside of both the upper and lower recommended limits.

The majority of rooms did not exceed either the lower or the upper limits of recommended comfort at any point during the field trial. In total, 40 of 61 rooms could be deemed comfortable at any time (66%). Of the 21 rooms that fell outside of the limits, only four exceeded the upper limit at any time, although none of the rooms exceeded both limits at any stage. Approximately 65% of the rooms that were deemed too cold during the trial period were below the limit for at least 50% of the time or more, with four of the rooms being too cold for 80% of the time or more. Reference to the building floor plans, along with anecdotal evidence, suggests that there may have been causal reasons for this. For instance, five of the meeting rooms in this group were unoccupied throughout the trial period (RB407, RB408, RB504, RB508 and RB509); they are referred to as offices in Table 12.1 as this is their designated thermal zone type in CIBSE Guide A. They are all also on the northeast facing façade of the building and therefore receive very low solar gain during winter months. Room RB204 is also on the northeast façade but was partially occupied during the trial period.

Table 12.1 Percentage of hours during trial period when room temperatures were beyond recommended ranges for specific zone types.

Room	Zone	Range	% out	% above	% below
RB102a	Atrium	19-25	0%	0%	0%
RB139	Office	21-24	70%	0%	70%
RB148	Office	21-24	0%	0%	0%
RB149	Office	21-24	0%	0%	0%
RB150	Office	21-24	0%	0%	0%
RB151	Office	21-24	0%	0%	0%
RB152	Corridor	19-23	20%	20%	0%
RB204	Office	21-24	70%	0%	70%
RB205	Classroom	19-23	0%	0%	0%
RB206	Classroom	19-23	0%	0%	0%
RB207	Classroom	19-23	0%	0%	0%
RB208	Classroom	19-23	0%	0%	0%
RB209	Corridor	19-23	0%	0%	0%
RB241	Lecture	19-23	50%	0%	50%
RB262	Classroom	19-23	0%	0%	0%
RB263	Classroom	19-23	0%	0%	0%
RB304	Office	21-24	20%	20%	0%
RB305	Office	21-24	15%	0%	15%
RB306	Office	21-24	0%	0%	0%
RB307	Classroom	19-23	0%	0%	0%
RB308	Classroom	19-23	0%	0%	0%
RB310	Classroom	19-23	0%	0%	0%
RB355	Classroom	19-23	20%	20%	0%
RB356	Classroom	19-23	0%	0%	0%
RB357	Office	21-24	0%	0%	0%
RB358	Office	21-24	0%	0%	0%
RB404	Office	21-24	0%	0%	0%
RB405	Office	21-24	5%	0%	5%
RB406	Office	21-24	0%	0%	0%
RB407	Office	21-24	65%	0%	65%
RB408	Office	21-24	60%	0%	60%
RB412	Office	21-24	20%	0%	20%
RB414	Office	21-24	0%	0%	0%
RB415	Office	21-24	15%	0%	15%
RB418	Office	21-24	0%	0%	0%
RB425	Office	21-24	0%	0%	0%
RB463	Office	21-24	10%	0%	10%
RB464	Office	21-24	0%	0%	0%
RB465	Office	21-24	0%	0%	0%
RB466	Office	21-24	0%	0%	0%
RB503	Office	21-24	0%	0%	0%
RB504	Office	21-24	100%	0%	100%
RB505	Office	21-24	0%	0%	0%
RB507	Office	21-24	60%	0%	60%
RB508	Office	21-24	85%	0%	85%
RB509	Office	21-24	100%	0%	100%
RB510	Classroom	19-23	0%	0%	0%
RB511	Corridor	19-23	0%	0%	0%
RB513	Classroom	19-23	80%	0%	80%
RB515	Classroom	19-23	0%	0%	0%
RB516	Office	21-24	0%	0%	0%
RB517	Office	21-24	5%	0%	5%
RB518	Office	21-24	0%	0%	0%
RB519	Office	21-24	0%	0%	0%
RB520	Office	21-24	0%	0%	0%
RB522	Office	21-24	40%	0%	40%
RB524	Office	21-24	0%	0%	0%
RB561	Office	21-24	0%	0%	0%
RB562	Office	21-24	0%	0%	0%
RB563	Office	21-24	10%	10%	0%
RB564	Office	21-24	0%	0%	0%

The proportion of rooms within specific temperature ranges for Friday 16 December are shown in Figure 12.7, which was the day with the coldest average external air temperature during the trial period. Very few rooms drop below 20°C during the penalty period; this suggests that comfort can be maintained under normal occupied conditions. Trials that include information on occupancy and room use would, however, need to be completed to confirm this assumption.

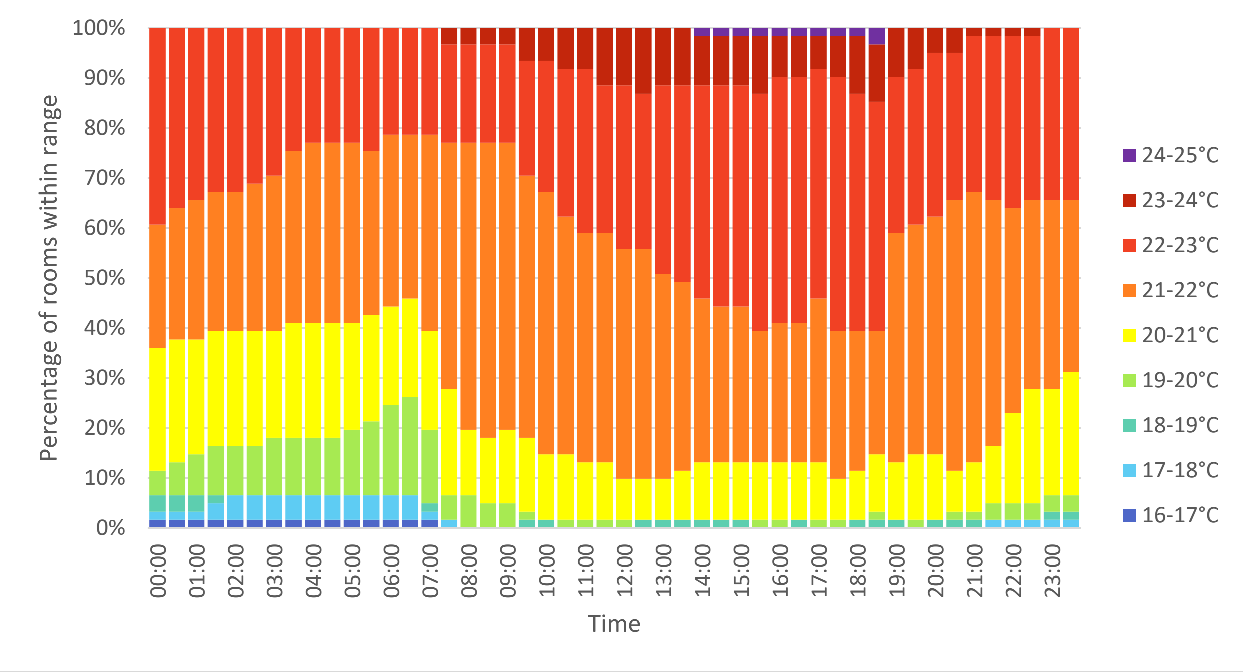


Figure 2.7 Percentage of sample rooms within temperature ranges from Wednesday 14 December 2016

12.5. Conclusion

From a holistic perspective, this case study demonstrates that some flexibility can be achieved in existing buildings with relatively simple controls. It also conversely demonstrate the limitations of introducing energy flexibility into existing buildings that do not include sophisticated controls, particularly over specific rooms and zone types. This is emphasised by the zoning of AHUs in the case study building and the comfort levels within each room. There are only five AHUs serving the entire building, which means that the scope for flexibility will be limited by the lowest common denominator. In practice, this would mean that a single occupied room that falls below the comfort threshold could restrict the shutdown of an AHU that serves one fifth of the building's rooms. This has important implications for retrospectively introducing flexibility strategies and emphasises the need to consider the resolution of control in larger buildings, and not just the sophistication of the building control algorithms. Monitored room temperature data from this particular building does however suggest that this type of strategy could be introduced without having a significant impact on thermal comfort. Results presented do however only offer a limited sample of the impact on thermal comfort. There is the need for more detailed appraisal of the relationship between comfort and flexibility in future work.

It is important to note the limitations of this case study and the need for further work. The next stage to this work is to gather data from relevant sub-meters so that the loads related to thermal comfort can be considered in isolation. This raises another important point when analysing data in this context; in many larger non-domestic buildings, sub-meters are not always reserved for single load types. A well-designed sub-metering strategy can aid the analysis from future flexibility trials (in addition to the established benefits of energy management and conservation). It will also be important to include air quality measurements in any future work related to AHUs. No reliable room CO_2 concentration data were available for this work, but this is another environmental parameter that could limit the scope for flexibility in the AHU load. In the context of carbon emissions and future grid carbon intensity, it will also be useful to design trials that respond to alternative penalty signals (i.e. carbon intensity) and at different times of the day and year.

12.6. Acknowledgement

The field trials described in this work and related monitoring data were provided by Glyn Cash, the Building Services Manager in the Estates team at Leeds Beckett University.

13. 2nd Life EV battery storage

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13.1. Abstract

This example demonstrates that storage systems consisting of second life Electric Vehicle (EV) Lithium Ion (Li-Ion) batteries, coupled with loads and local renewable generation, managed by an ICT platform can deliver energy flexibility in buildings. The use of second life EV batteries has four benefits, environmental, cost, safety and scalability. Costs of existing and future battery systems are summarised. An overview of the battery storage systems installed at 6 pilot sites as part of the ELSA project is given, with a detailed example for one pilot site. Smart grid use cases demonstrated include peak shaving, energy arbitrage and Demand Response - Cost Minimisation. For the example building, the ICT based Energy Management System (EMS) predicts the load and Photovoltaic (PV) generation to charge and discharge the 2nd life battery system during use case demonstration, offering flexibility to a simulated aggregator.

13.2. Background and objectives

Li-Ion EV batteries are expected to have an operating life of 8 - 10 years in vehicles. After this period has elapsed, while the battery may not be reliable enough for the demands of automotive applications, they still have the ability to charge and discharge and hold storage capacity. Building storage applications are much less demanding. The battery may only be required to charge and discharge once or twice a day, it is not subjected to extreme temperature variations, which can reduce its useful life and the system is less safety critical e.g. issues with the battery won't cause a traffic accident if it is installed in a building. With the expected increased uptake in EVs globally, encouraged in Europe by some EU member states offering incentives such as reduced vehicle tax, it is predicted that in the medium to long term, there will be large numbers of 2nd life EV batteries becoming available. The EU Battery Directive 2006/66/ec (EU, 2006) requires that manufacturers recycle batteries. However, it would be advantageous from both an environmental and a cost perspective if EV batteries could be put to an alternative use before recycling. The use of second life EV batteries addresses the challenge of cost competitiveness, identified as one of the four challenges for increased deployment of energy storage (Gyuk et al., 2013). Re-using the batteries contributes to the whole life cycle sustainability of EV, as it maximizes their use before the requirement to recycle the batteries. In addition, EV batteries are both safe and scalable. EV batteries meet stringent safety standards as they are built to survive traffic collisions. Given their modular nature, the number of 2nd life batteries may be scaled up to meet the needs of an individual building or district.

Storage systems are one element required by the smart grid in order to meet the challenges of grid balancing, hosting capacity and stability. With EU targets for renewable generation driving increased wind and solar capacity on electricity grids, storage is one of the technological solutions which can help balance the intermittency of this generation. Battery storage systems have the ability to provide a range of services to the grid. At transmission level, battery storage systems can be used for services such as providing operating reserve, temporary re-dispatch measures, and innovative starting assistance for power plants to restore power to the grid and to compensate forecast errors. At the distribution level, battery storage systems can enable efficient grid expansion, balancing of load flows to reduce losses and maintain grid voltage within required tolerances. At building level, battery storage systems can reduce peaks in power consumption, reduce the operational risk of power cuts and increase self-consumption and energy autonomy in combination with on-site renewable generation, for example, a PV system.

There are two elements to any battery storage system, the lithium-ion batteries and the battery management system. For a 2nd life EV battery storage system to be cost competitive, the cost of the 2nd life batteries must be less than first life batteries both for stationary batteries and for new EV batteries. In addition, the cost of the entire system, i.e. the batteries and the battery management system, must be competitive with stationary storage systems, the most common type being PV storage systems. In general, for stationary battery storage systems, the cost of the batteries is estimated to be approximately one third of the total system cost (Nykvist et al., 2015). Li-ion PV storage systems were in the range 750 - 1,250 €/kWh in 2015 (VDE 2015). EV batteries are more expensive than standard Lithium-ion cells due to their stringent manufacturing requirements and safety standards, but costs have reduced from €700/kWh in 2009 to 150 – 175 €/kWh in 2018 (Mosquet et al., 2018) making them competitive with stationary storage batteries. Future costs for PV storage systems are estimated to be between 430 – 860 €/kWh in 2020 and 250 - 500 €/kWh in 2025 (VDE 2015). For a 2nd life battery storage system to be competitive, its cost must be in this range.

This work was done as part of the EU Horizon 2020 project Energy Local Storage Advanced system (ELSA, 2017). The aim of the ELSA project is to mature a 2nd life EV battery storage solution for buildings and districts to provide services to the grid using local ICT-based energy management systems to manage the storage and combine it with other sources of energy flexibility in the building such as loads and renewable energy. There are 10 partners and 6 pilot sites in the ELSA project. Renault and Nissan provided the second life EV batteries while Bouygues Energies and Services developed the battery management system in conjunction with Renault and Nissan. United Technologies Research Centre Ireland (UTRC), ENG, EGRID and RWTH Aachen developed building and district energy management systems. The pilot sites were provided by EGRID, ASM Terni, RWTH, Nissan, Gateshead College and the Ampère building, Paris. In this example, an overview of the battery storage system is given and detailed results from the Gateshead College Skills Academy for Sustainable Manufacturing and Innovation (SASMI) building are presented.

13.3. Method

To deliver services to the grid, an Energy Management System (EMS) coordinates loads, renewable generation and the 2nd life battery storage system. Use cases are selected to demonstrate how services may be delivered to a simulated aggregator or Distribution System Operator (DSO).

The storage system developed in the ELSA project is shown in Figure 13.1. Two Nissan Leaf 2nd life batteries are shown on the left of the picture while the battery management system developed by Bouygues in cooperation with Renault and Nissan is shown on the right. The battery management system, known as the B4B (Batteries for Buildings), controls and co-ordinates the charging and discharging of the individual batteries. It consists of inverters, PLCs (Programmable Logic Controllers) and a PC hosting dedicated management software with a graphical user interface. The capacity of the system and the maximum charge and discharge rates are dependent on the number of 2nd life batteries in the system.

Figure 13.1 ELSA 2nd Life Battery Storage System.

The six 2nd life EV battery storage systems deployed at the pilot sites are listed in Table 13.1. The Energy Management Systems (EMS) were developed by a range of partners. UTRC developed a building scale EMS for commercial buildings, the other EMSs are for district, residential and sub-station applications. At some pilot sites, a number of versions of the storage system were installed. DT3 (Définition Technologique) was the first prototype at TRL 5/6 (Technology Readiness Level), DT4 and DT5 are later prototypes, bringing the system to TRL 8. In some pilot sites, the number of EV batteries was also increased when later prototypes were installed.

An ICT platform for Building Energy Management was developed by UTRC Ireland and deployed at SASMI, Sunderland and Ampere, Paris sites. Control and optimization algorithms manage the storage on site to provide flexibility services to the building, an aggregator or the grid, in response to simulated requests. The battery management system communicates with the Building Energy Management System (BEMS). The SASMI pilot site system architecture is shown in Figure 13.2. The system architecture for this ICT platform was developed by UTRC Ireland and successfully deployed on previous projects (Valdivia et al. 2014) and (Monti et al. 2017). Meter and equipment data is extracted from the site Building Management System and may be read in real time. In addition, this data is continuously stored in a database. Set points are sent from the control and optimization algorithms running in the BEMS layer to equipment in the building such as the battery system. The control algorithm uses historical data for load prediction in order to control the battery system to deliver the services required by the use cases.

Table 13.1 2nd Life Batteries Storage system installed at the 6 pilot sites.

	EMS	First capacity installed	Version	Final capacity Installed	Version
Ampère, Paris, FR	UTRC	6 kW charge 24 kW discharge	DT3	96 kW charge 96 kW discharge	DT5
SASMI, Sunderland, UK	UTRC	9 kW Charge 36 kW Discharge	DT3	-	-
Aachen, DE	RWTH	18 kW Charge 72 kW discharge	DT3	72 kW charge 72 kW discharge	DT5
Kempten, DE	EGRID	18 kW Charge 72 kW discharge	DT3	-	-
Terni, IT	ENG/ASM	72 kW charge 72 kW discharge	DT4	-	-
Hajime, Paris, FR	NISSAN	144 kW Charge 144 kW discharge	DT5	-	-

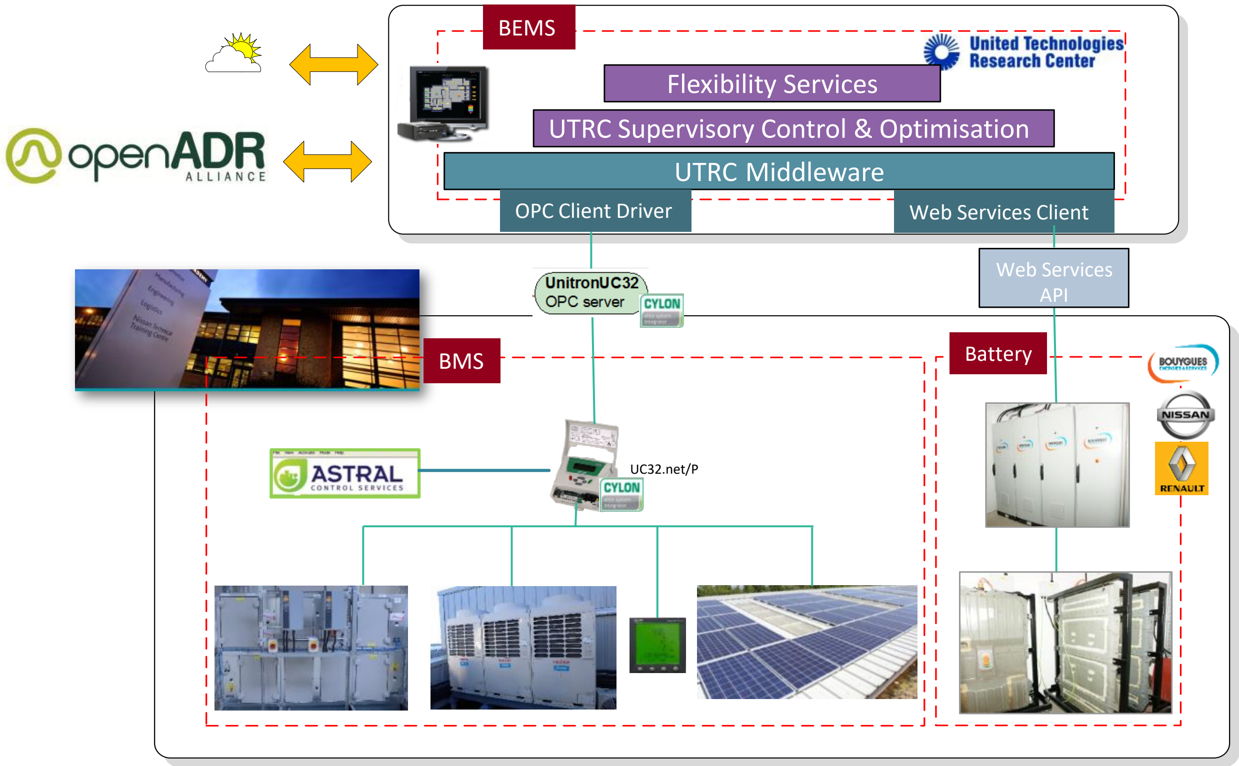

Figure 13.2 Energy Management System for example building, SASMI.

The example building is the Gateshead College Skills Academy for Sustainable Manufacturing and Innovation (SASMI). It is a 5,700 m^2 building consisting of classrooms, offices and workshops and is located adjacent to the Nissan manufacturing site in Sunderland, UK. The peak power load of the building is approximately 140 kW and its base load at evenings and weekends is between 20 kW and 40 kW.

To demonstrate the range of services which the 2nd life EV battery system can deliver, five use cases were selected for the example building, SASMI. These consisted of: Peak Shaving; Energy Purchase Time Shifting (also known as Arbitrage); Demand Response – Auto Consumption; Demand Response - Cost Minimisation; and Demand Response – Other. The objective of Peak Shaving is to limit the peak demand from the grid and thus reduce electricity costs for the building, defer infrastructure investment or upgrade for the utility, and assist the utility in maintaining lower power generation costs during peak periods. Energy Purchase Time Shifting (Arbitrage) aims to buy and store electricity when the energy price is low and use it when the price is high and thus minimising the energy cost for the building. The objective of Demand Response – Auto Consumption is to consume renewable generation on site and not allow export to the grid. Demand Response Cost Minimisation aims to minimise the cost of electricity for the building in response to a varying price signal. Demand response – Other is a general category to support the implementation of incentive based demand response services. For example, the building responds to a request from an aggregator by modifying its load consumption profile within the available flexibility range to provide grid support.

13.4. Results

The UTRC BEMS, the Graphical User Interface (GUI) of which is shown in Figures 13.3 and 13.4, demonstrated the use cases at the example building, SASMI. The control and optimisation algorithm in the BEMS uses model predictive control to predict the load profile of the building over an eight hour horizon based on historical data. In 2.3, the top graph shows the real demand for the building on the left in blue and the predicted demand on the right. Electricity price is shown in red. The lower graph shows charging and discharging of the battery system (B4B) with power in blue and State of Charge (SOC) in red. The use case demonstrated is Demand Response – Cost Minimisation.

Figure 13.3 shows the prediction just before the Demand Response event, Figure 13.4 shows the actual demand and load profiles just after the Demand Response event. In Figure 13.4 the forecast demand (dark blue icons) and forecast load (light blue icons) are responding to a forecast cost decrease (dashed red line) starting at 12.00. In Figure 13.4, it can be seen the actual demand (dark blue line) and forecast load (light blue line) increased as predicted during the event. This demonstrates that the BEMS controls the battery system to charge when the cost of electricity in €/kWh is low. The battery is then later scheduled to discharge in order to be prepared for the next charge cycle. The prediction accuracy of the forecasted demand and load was of the order of +/-5%.

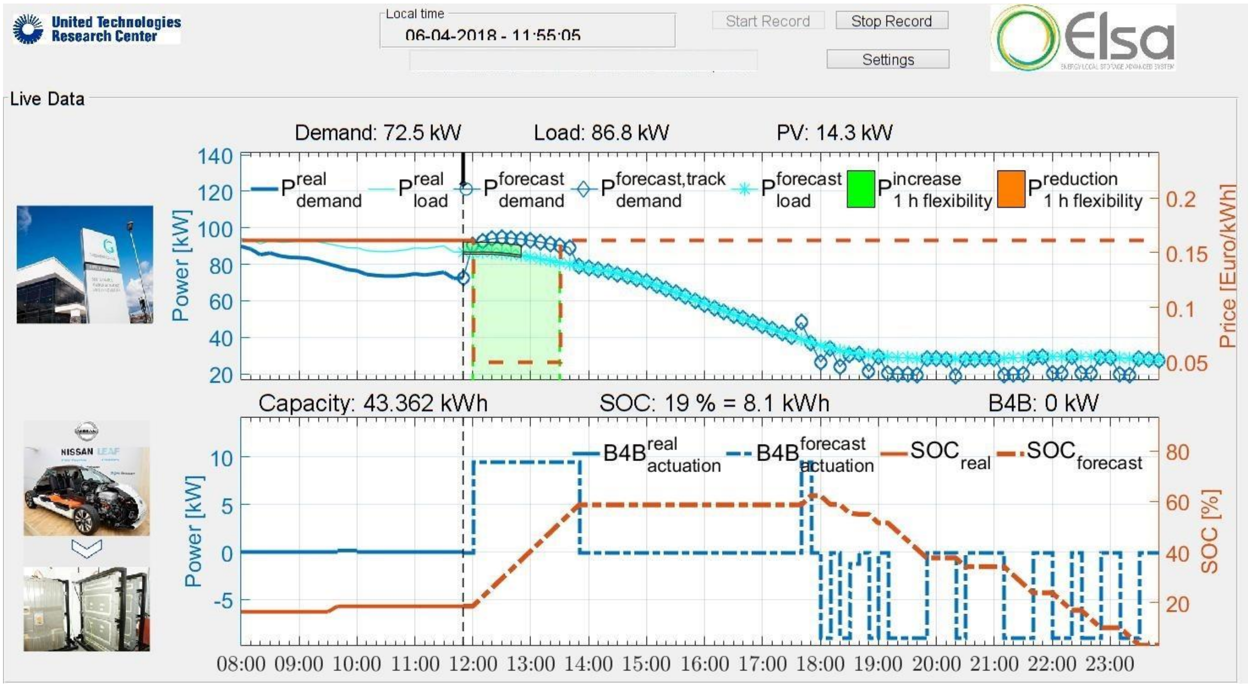

Figure 13.3 Before Demand Response – Cost Minimisation Use Case.

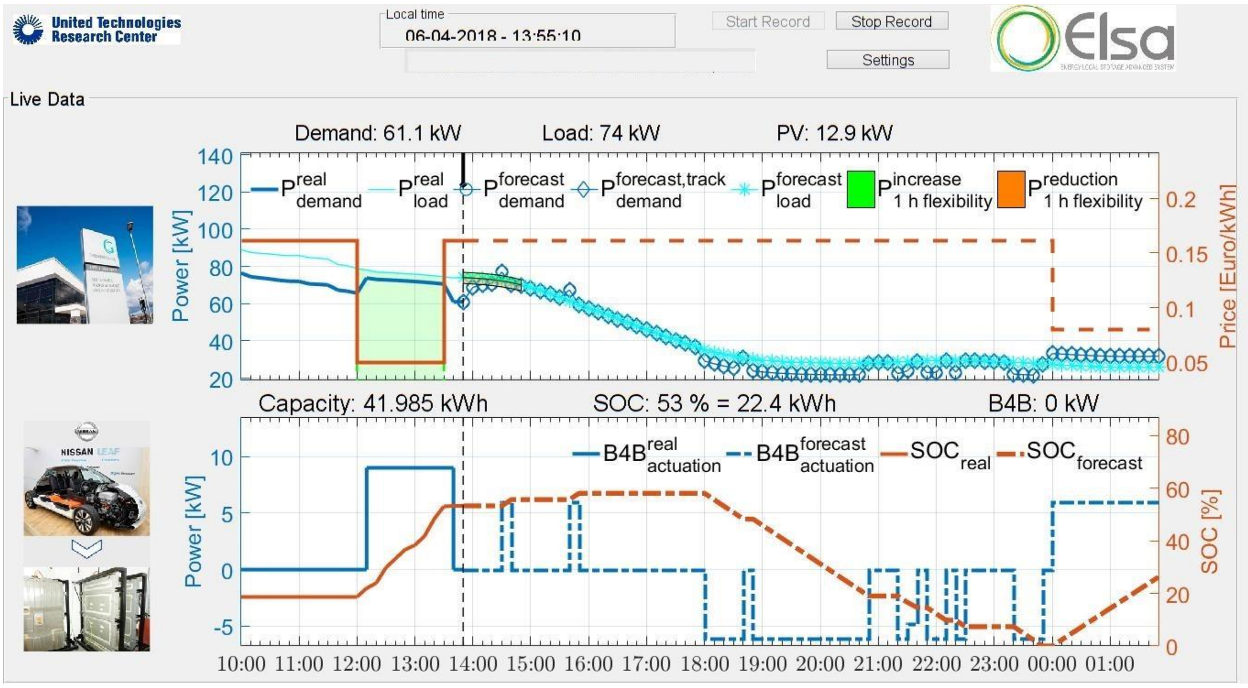

Figure 13.4 After Demand Response – Cost Minimisation Use Case.

Target Key Performance Indicators (KPIs) for each of the use cases for the example building, SASMI are shown in Table 13.2. The KPIs are target reductions for each of the areas, power, energy, cost and CO_2. The Power KPI is expressed as a percentage of building peak load (kW) reduction to be achieved using the 2nd life EV battery storage system. The Energy KPI is a percentage of building energy (kWh) reduction over a 24-hour period. The Cost KPI is a percentage energy cost reduction (€/kWh) in utility bills for the building, which is linked to the Energy KPI reduction. The CO_2 KPI is a percentage reduction in CO_2 emissions for the particular use case, also linked to the Energy KPI reduction.

Table 13.2 Example building target use cases KPIs using the 2nd life EV battery system. T stands for Target, which is based on the estimated capacity of the 2nd life batteries, while **A** is the actual measured values for the five different investigated Use cases.

Project KPI	**SASMI Building**									
	Use Case 1		Use Case 2		Use Case 3		Use Case 4		Use Case 5	
	Peak Shaving		DR - Auto Consumption		Energy Purchase Time Shifting		DR - Cost Minimization		DR – Other	
	T	**A**	T	**A**	T	**A**	T	**A**	T	**A**
Power	32 %	**30 %**								
Energy	2 %	**1 %**	16 %	**27 %**	2 %	**1 %**	-16 %	**-21 %**	16 %	**5 %**
Costs			16 %	**27 %**	2 %	**1 %**	-16 %	**-21 %**		
CO_2 Emissions			16 %	**27 %**			-16 %	**-21 %**		

KPIs based on experimental tests at the example building are shown in the table above. T denotes target values and A is achieved values. For Energy services, the use case DR – Auto Consumption and DR – Cost Minimisation achieved higher actual values, with associated cost and CO_2 emissions reductions. The Peak Shaving use case was the only one providing power flexibility and the achieved value of 30% was just below the target value of 32%.

Detailed results for the five other use cases and their associated KPIs are available in the ELSA public deliverable D6.3 which may be downloaded from the ELSA website elsa-h2020.eu.

13.5. Conclusion

Based on the work to date, the following conclusions were reached:

- Storage needs to be managed by a supervisory control system, in this case the EMS, to co-ordinate it with loads and renewable generation in order to provide useful services to the grid.
- Prediction control to within +/-5% was achieved by the EMS enabling accurate forecasting of flexibility for intra-day events.

- The example given has demonstrated the technical feasibility of using 2nd life EV batteries in buildings to provide flexibility, achieving close to or above the target KPIs in power and energy for peak shaving and auto consumption use cases.

The target cost for the ELSA battery storage system is competitive with predicted 2020 costs for Lithium-ion PV storage systems.

To give a broader perspective on the future of 2nd life EV batteries the following scenarios illustrate their future availability and ability to provide services to the grid. The capacities of the 2nd life batteries deployed in the ELSA project were approximately 11 kWh for Renault Kangoo.

- Scenario 2025 - Theoretically, 300,000 2nd life batteries can provide most of the operating reserve (primary, secondary, minute reserve) that will be required in France.
- Scenario 2035 - 9 million 2nd life batteries have the potential to guarantee almost all of the French maximum national power demand for 1.35 hours continuously.
- Scenario 2050 - 43 million 2nd life batteries have the potential to guarantee almost all of the French maximum national power demand for 5.15 hours constantly. In addition, 2nd life batteries from a fully electrified national vehicle fleet will have the potential to meet all the short-term storage requirements for one hour for an electricity grid receiving all of its power from PV and wind. (ELSA, 2017)

13.6. Acknowledgement

The work was done as part of the project Energy Local Storage Advanced system (ELSA) which received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 646125. (ELSA-h2020.eu). Funding was also provided by the Sustainable Energy Authority of Ireland under the ‘National Participation in IEA TCP – Task Participation’ programme.

14. Building energy flexibility by using DC power and distributed electricity storage

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14.1. Abstract

The energy flexibility of buildings can be greatly enhanced through the use of Direct Current (DC) power and electricity storage, i.e. batteries. When compared with the commonly used Alternating Current (AC) power, DC power supply in buildings has the advantages of higher power distribution efficiency, reduced losses when converting power, and a higher penetration of renewable energy. Furthermore, larger battery capacities can provide a greater range of energy flexibility. However, larger battery capacity requires greater capital investment, therefore, optimal design of the battery capacity is required for these technologies to be financially viable. Additionally, the optimal control for the battery charge and discharge requires detailed study.

The research presented in this example investigates the feasibility of DC power supply and distributed electricity storage in buildings, including the benefits, costs, and technologies required for further development. The optimal designs for the DC power supply system topology and battery capacity are also discussed in this work. Finally, results are presented from a series of experiments carried out on an installed DC power supply system in a small office building.

Analysis shows that the DC power supply and distributed electricity storage system is an effective means for shifting building electricity demand and can achieve a high degree of energy flexibility. Cost-benefit analysis shows that it can be cheaper to discharge 1 kWh of stored electricity than to purchase electricity from the grid during peak load periods. The experimental results of the demonstration DC power supply system show that it can provide a constant power supply, demand response, and minimum electricity cost.

14.2. Background and objectives

Electricity is the main energy source in cities and electricity use in civil buildings accounts for nearly 40% of the total electricity use in cities (Beijing Municipal Bureau of Statistics 2015). The profile of electricity use in buildings commonly has large differences between peak and off-peak demand, which is the main cause of problems associated with management of the grid, such as low distribution efficiency, high capital investment cost, and curtailment of renewable energy. Figure 14.1 presents an example of the typical electricity use measured in an ordinary residential community (Zhou 2015), which shows electricity use during peak periods can be up to four times as high as use during off-peak periods. For the purpose of solving the problems caused by the large differences between energy use during peak and off-peak periods, this research proposes a novel power system for buildings, which uses direct current (DC) power supply and a distributed electricity storage system. The objectives of this power system are to achieve large potential of energy flexibility in buildings by electricity storage, high power distribution efficiency by DC, and more renewable energy utilization. The following sections of this example evaluate the feasibility of using the DC power supply and distributed electricity storage in buildings from the viewpoint of technologies and cost. Furthermore, performance test results of the proposed DC power supply and distributed electricity storage system in a small office building are introduced to demonstrate the in-use performance of the proposed power system.

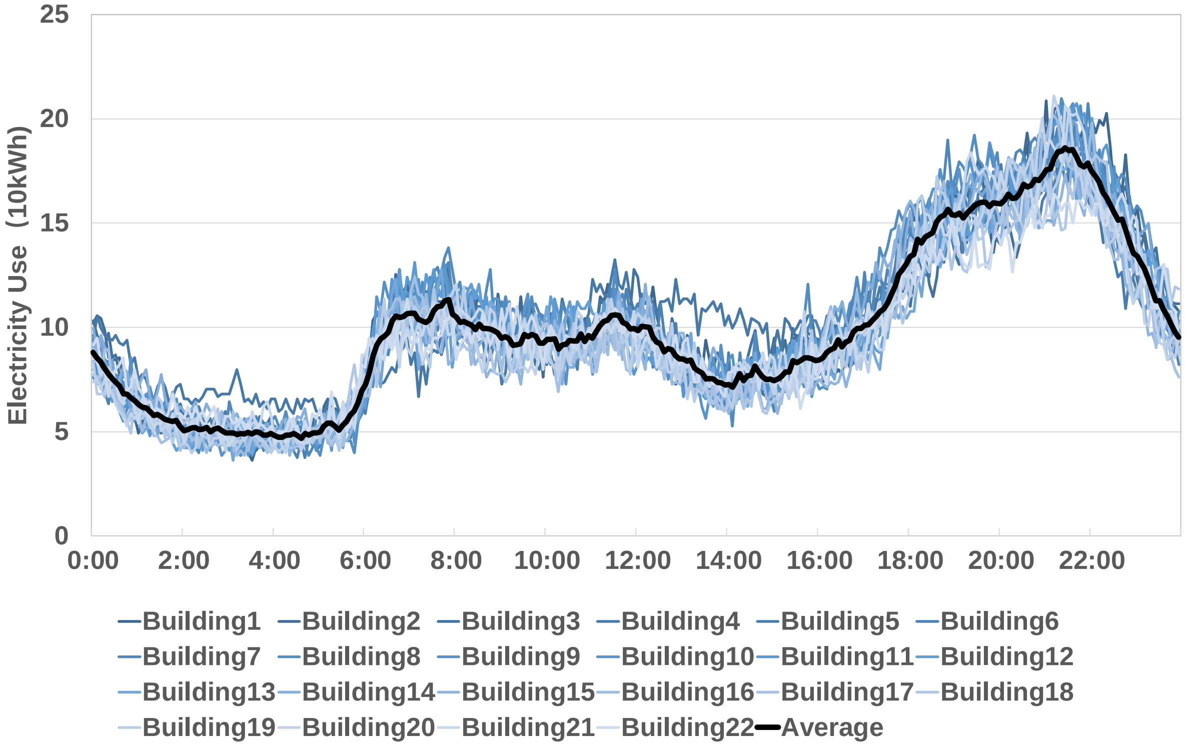


Figure 14.1 Hourly electricity use measured in an ordinary residential community

14.3. Method

14.3.1. Feasibility Analysis

Terminal electricity users

Currently, almost all appliances in buildings use DC power, for example, Light Emitting Diode (LED) lamps, Liquid Crystal Display (LCD) monitors, and computers. For the motor-driven machines, such as air-conditioning units, pumps, fans, and chillers for example, the use of DC motors is expanding rapidly as well. As for the Alternative Current (AC) power driven motors, if they are equipped with Variable Speed Drive (VSD) by inverters, the inverters actually achieve speed change by using a rectifier that converts the AC power to DC and then changing the DC power pulse duty ratio. Therefore, in the context of appliance operation, there is no barrier to using DC power supply in buildings instead of AC.

Compared with AC power, the benefits of using DC power in buildings include:1) low investment cost by eliminating AC/DC converter and DC/AC inverter; 2) low wire cost because of higher effective current and low line loss; and 3) building space saving because the size of DC/DC converters are smaller than AC/DC converters. Lawrence Berkeley National Laboratory (LBNL) has built a DC powered small scale data centre test-bed and showed that the DC power system can improve the power distribution efficiency by 7%, reduce investment cost by 6%, save building space by 33%, and double the reliability when compared with the most advanced AC power system (Huang and Lu. 2013). A United States company has developed a DC power solution for data centres, which can reduce investment costs by 15%, running costs by 33% and building space by 33% (Geary 2012). A Japanese research group has built a DC powered house and by measurements compared the electricity used of a full DC powered house and a full AC powered house. The comparison showed that the DC powered house reduce electricity consumption by 10.8% (Panasonic, 2011).

Cost issue of battery

To achieve a shift away from peak electricity demand, electricity storage is essential. The cost of batteries has a direct influence on whether the storage system is financially viable. Battery technology is developing rapidly; key performance indicators (KPI), such as battery cost, reliability, charge/discharge efficiency, life span, and safety are all continuously improving. Considering the present battery cost and life span (i.e. charge/discharge times), the cost of 1 kWh electricity supplied by battery can be 0.1 US dollars if using a lead-acid battery and 0.2 US dollar if using a lithium-ion battery. These electricity prices are lower than the cost of grid electricity during peak periods and similar to the off-peak grid electricity price. This suggests that, in a financial context, it is cheaper to use batteries to store and supply electricity than purchasing power from the grid only. Furthermore, the cost of batteries will decrease continuously in line with the development of battery technologies. Therefore, the benefits of charging batteries during off-peak periods and discharging them during peak periods will increase.

14.3.2. Study case

The case study building used to investigate the proposed power system is a small office with 658 m^2 of floor area. It was retrofitted from the original AC power system to the proposed DC power and distributed power storage system. A photo of the case study building is shown in Figure 14.2.

The topology of the power system in the case study building is shown in Figure 14.3. The power source includes an AC/DC converter to change the AC power to DC power from the city grid and a photovoltaic (PV) panel array on the roof of the building. A set of batteries are used to store and supply electricity, serving as both energy source and sink. The electricity consuming equipment includes a set of multi-indoor-unit air-conditioners, personal computers, and LED lights, amongst other appliances. The main information about the case study building is summarized in Table 14.1.

Figure 14.2 A photo of the case study building.

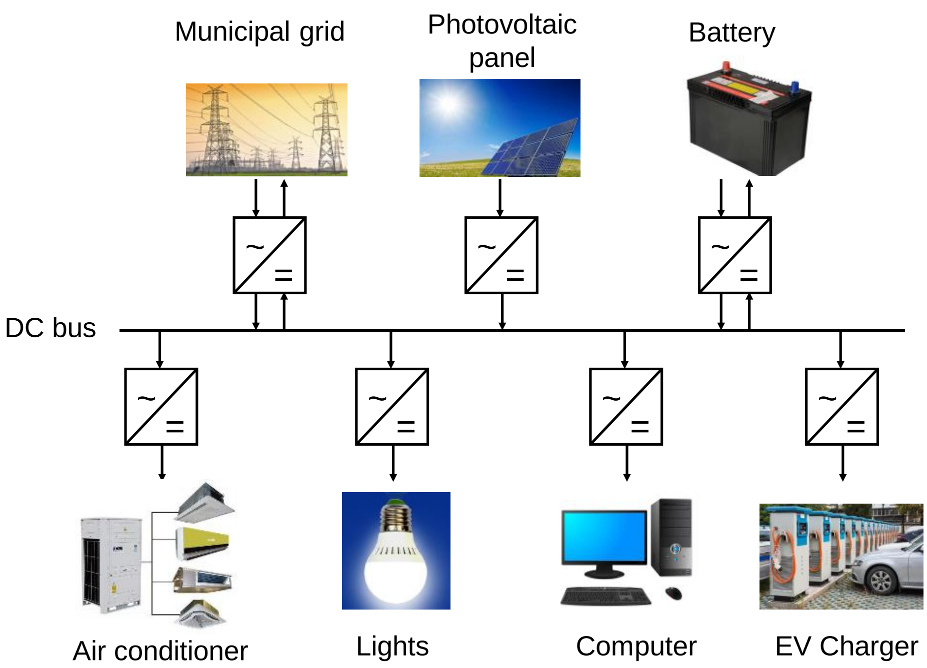


Figure 14.3 Power system topology of the case study building.

Table 14.1 Characteristics of the case study building.

	Parameter(s)
Building floor area (m²)	658
PV panel capacity (kW)	12.88
Battery	12 V, 125 AH, 30 kWh
AC/DC converter	AC 380 V-DC 500 V, 20 A, 10 kW
Air-conditioner	Cooling capacity 28 kW; Power input 370-900 V DC, 12.5 kW
LED lights (kW)	1.5
Plug load (kW)	3

14.3.3. Control strategy for energy flexibility of the building

The principle of the control strategy for energy flexibility used in this study, is to store electricity in the batteries when there is an excess of renewable energy production or grid power is cheap, and then supply electricity from the batteries when energy production from renewable energy sources is insufficient or grid power is expensive. The applied time-of-use tariff is shown in Figure 14.4.

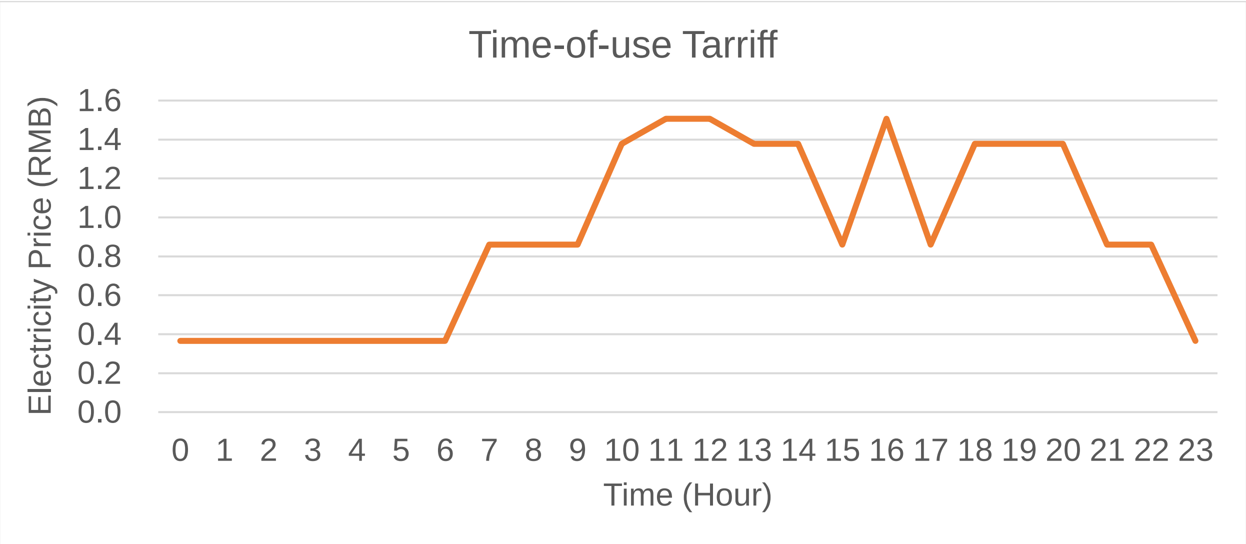


Figure 14.4 Time-of-use tariiff for the case study building.

Two control strategies are studied, the first draws constant power from the grid and the second is a demand response mode. The basic objectives of these control strategies are to achieve peak load shaving and valley load filling – i.e. a shift of consumption in time. The difference of the two control strategies is that the set points of the power from the city grid are different.

Constant power from grid

This control strategy aims to maintain a constant power induction from the grid, so that the peak-valley gap can be totally eliminated if all buildings use this control strategy. The method to maintain the power introduced from grid is to constantly adjust the battery charge/discharge power to make up the gap between power load and power introduced from grid.

The first step of the control strategy is to predict the electricity load of the next day. Either artificial neural network analysis or detailed simulation modelling of buildings can be used to predict the electricity loads.

The second step of this control strategy is to decide the set point of power introduced from grid, as shown in Equation 14.1. The control objective is to maintain constant power introduced from the grid, so the set point of the power from grid is the average of the predicted loads.

$$P_{gridset} = \kappa \frac{\int_0^T P(t)dt}{T} \tag{14.1}$$

Where: $P_{gridset}$ = set point of power from grid (kW)
$P(t)$ = predicted load at time t (kW)
k = line loss factor (-)
T= time cycle of control (hour)

The third step is to control the battery charge/discharge power, according to Equation 14.2, to make up the gap between the power load and power introduced from grid.

$$P_{bat} = P_{gridset} - P(t) \tag{14.2}$$

Where: P_{bat} = battery charge/discharge power (kW)
P_{gridse}t = set point of power from grid (kW)
$P(t)$ = predicted load at time t (kW)

Demand response mode

Demand response is characterised by the grid operators sending a signal in the form of e.g. power limitation, the end-users then reduce their demand (by switching off appliances for example) to meet the limitation (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2016). Demand response is an efficient way of shifting demand. However, switching off some appliances might decrease the satisfaction levels, and even productivity, of some end-users. In contrast to demand response, the DC power supply and distributed electricity storage system can meet the demand limitation requirement without sacrificing the users' satisfaction levels and productivities.

The demand response control strategy is to change the set point of power introduced from grid according to the grid power limitation signals, and to adjust the discharge of battery to make up the gap between demand and grid power supply. The set point of power introduced from the grid is calculated as shown in Equation 14.3 and the battery charge/discharge power is calculated using the same method as shown in Equation 14.2.

$$P_{gridset} = \eta P(t) \tag{14.3}$$

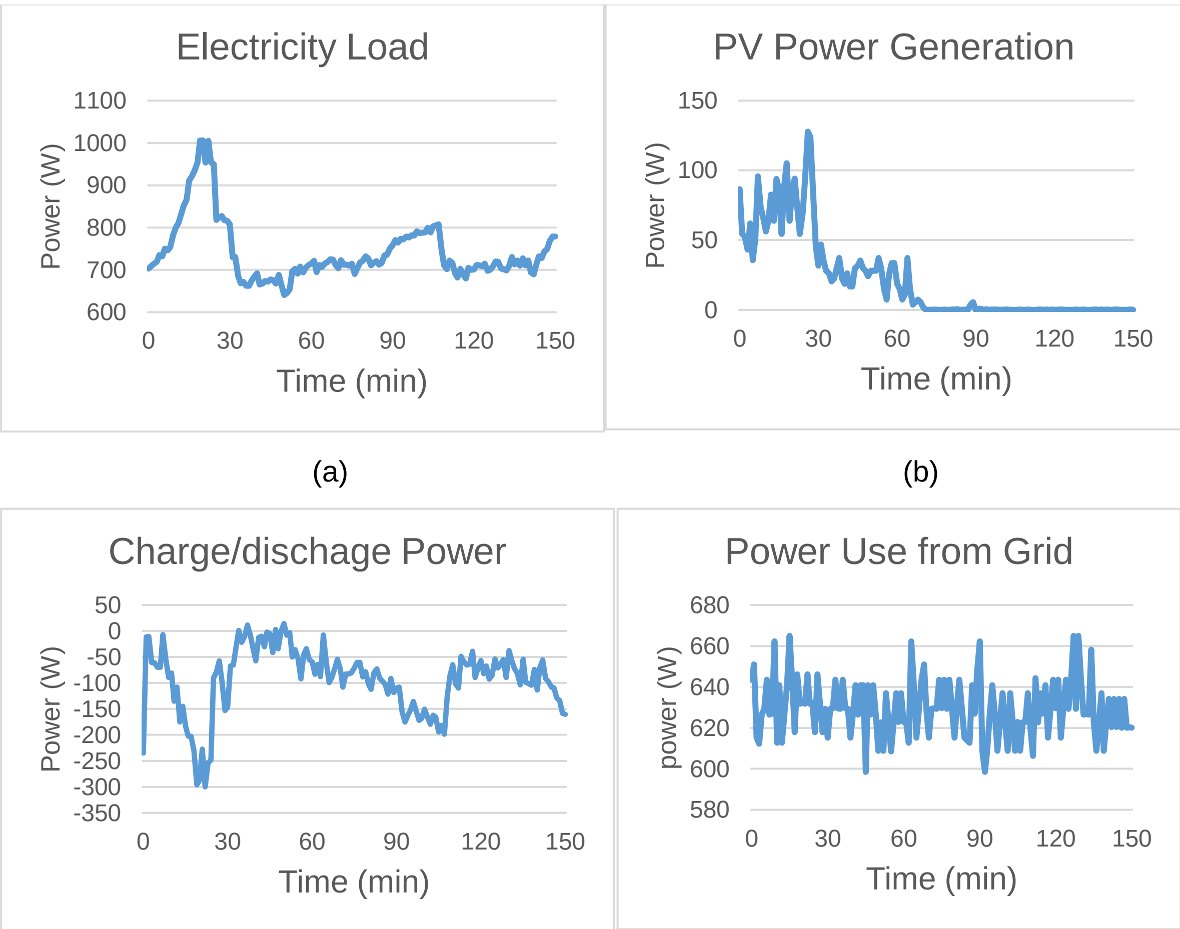
Where: $P_{gridset}$ = set point of power from grid (kW)
$P(t)$ = load at time t (kW)
η = demand response factor (-)

14.4. Results

The two control strategies, constant power introduced from grid and the demand response mode, were studied using the case study building.

Constant power from grid

The experimental results for the constant grid power strategy are shown in Figure 2.4. From Figure 14.5, it can be seen that although the electricity loads varied between 600 and 1000 W and the PV power production varied between 0 and 130 W, depending on the battery discharging, the electricity consumed from the grid was controlled within a range between 600 W and 660 W, showing an acceptable control accuracy of ±5%. It should be noted that during this experiment the set point of constant power from the gird was relatively small, so most of the time the battery was in a state of discharge, as shown by the minus values in the subfigure c of Figure 14.5. As for a daily span, the electircity load is small during the night time, where the battery will be in the state of charging.



(a) (b)

(c) (d)

Figure 14.5 Experimental results during constant power from grid.

Demand response mode

The experimental results for the demand response control mode are shown in Figure 14.6. For the purpose of verifying the control performance in a short peorid, the electriciy price was same as shown in Figure 14.4. It can be seen that the electricity loads varied between 500 and 1040 W and the PV power production varied between 0 and 310 W. The demand response factors *η*, shown in Equation 14.3, changed from 1, 1.01, 1.75, and 4.12, which are determined corresponding to the electricity price steps of time-of-use tariff shown in Figure 14.4. Accordingly, the battery discharged when the power introduced from the grid was small, i.e. from time 0 to time 500 min, and charged when the power introduced from the grid was large, i.e. after time 500 min. From Figure 14.6 it can be seen that by reacting to demand response requirements, the control strategy can tune the battery charge/discharge power rationally to fulfil the demand response requirements.

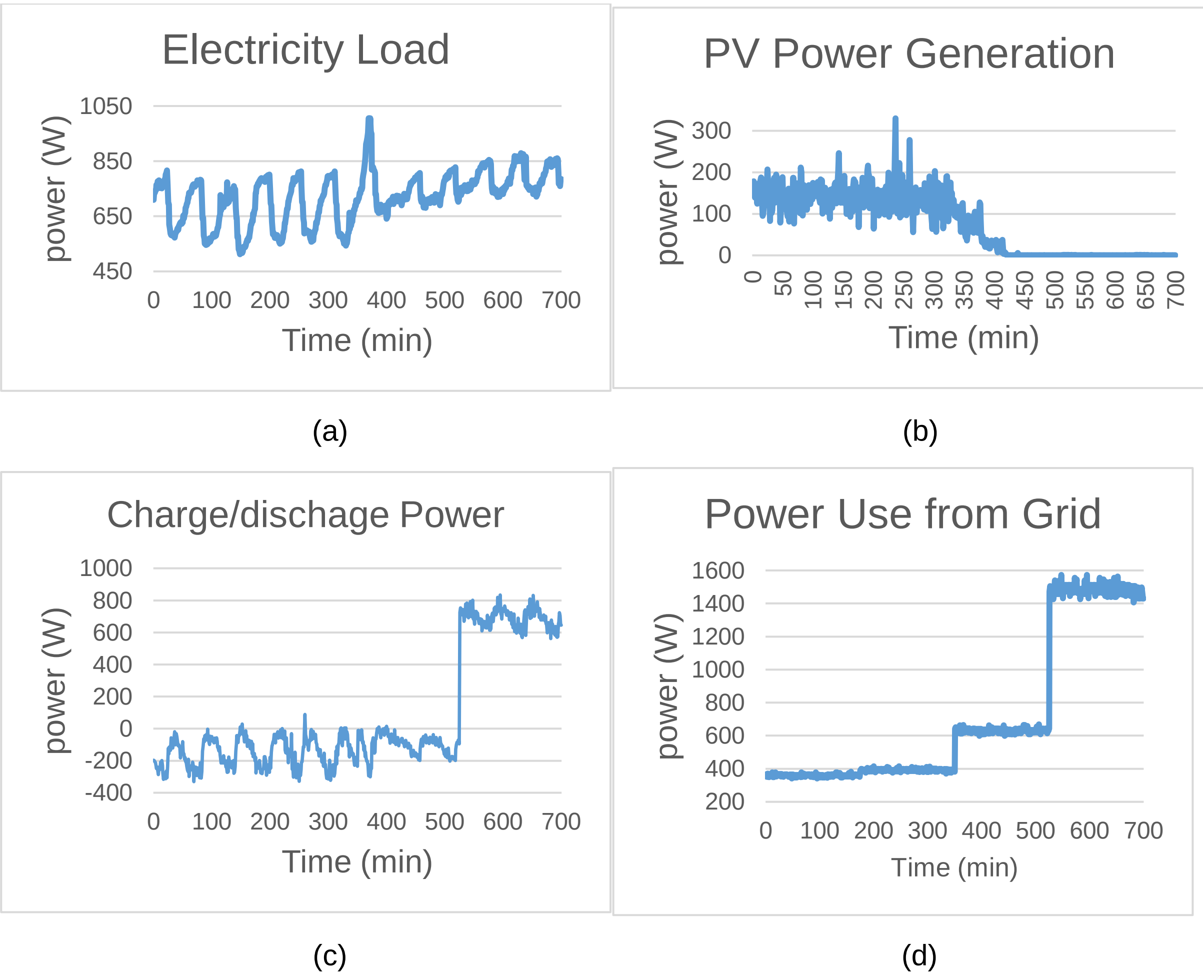


Figure 14.6 Experimental results from the demand response mode.

The proposed DC power supply and distributed electricity storage system can achieve large energy flexibility in buildings. By using the control strategy of constant power from the grid, the gap between the building's peak and off-peak import of electicity from the grid can totally be elliminated. Buildings may in this way become stable elecitricy users and can, therefore, contribute very much to an efficient operation of the gird. Furthermore, by using the control strategy of demand response, the DC power supply and distributed electricity storage system can provide much more demand shift than can be achieve by utilizing the thermal storage for shifting the load of air-conditioning.

14.5. Conclusion

DC power supply and distributed electricity storage is an effective way to achieve demand shift and flexible energy use, while maintaining a comfortable indoor environment and building users' productivity. A small office building's power system was retrofitted with the proposed DC power supply and distributed electricity storage system. In the retrofitted building, two control strategies were studied to evaluate how much flexibility the energy system could achieve using the DC power supply and distributed electricity storage. The first control strategy draws constant power from the grid, regardless of the fluctuations in the building's electricity load and renewable energy production. A second control strategy was designed to activate demand response, by controlling the power use from the grid according to grid commands. The two control strategies were verified in the case stud building. The case study results show that the two control strategies can achieve the objective of demand shifting with an acceptable control accuracy. Further studies will be conducted to determine the economic benefit of using the investigated DC power and distributed electricity storage system. The potential economic benefit lies in utilizing the electricity time-of-use tariff by charging batteries using grid power during low price periods while discharging the batteries during the high price periods.

14.6. Acknowledgement

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15. Solar XXI

Laura Aelenei, National Laboratory of Energy and Geology and Daniel Aelenei, NOVA University of Lisbon, Portugal

15.1. Abstract

Solar Building XXI, built in 2006 (Gonçalves and Cabrito, 2006) at 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 by 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 energy generation and consumption and improve grid interaction by the integration of Battery Energy Storage Systems (BESS). Results are reported regarding scenarios which are developed from monitoring data obtained during 2016 and from numerical simulations on the use of distributed power through integration of BESS with storage capacities ranging from 13.5 kWh to 54 kWh. The results show that employing energy flexibility in this way may improve the load matching provided by a BESS up to 17% with a storage capacity of 13,5 kWh.

15.2. Background and objectives

Statistics show that buildings are responsible for 40% of energy consumption in the EU and U.S. (Pérez-Lombard et al., 2008). In this context, it is of fundamental importance to identify strategies for the building stock to meet the objectives in terms of energy efficiency and climate change set by different countries (Aelenei et al., 2014).

Unlocking the potential of energy efficiency in the building sector is a priority for EU countries. One of the most important legislative instruments aiming at this is the directive 2010/31/EU (European Commission, 2010) which requires Member States to draw up national plans for increasing the number of nearly zero-energy buildings (nZEBs). A “nearly zero-energy building” refers to a high energy performance building of which annual primary energy consumption is covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby (Garde et al., 2017). One such building is the Solar XXI office building located in Lisbon, Portugal, which integrates a variety of energy efficiency measures and strategies and which has installed on the South façade a BIPV (12 kWp) and an additional photovoltaic roof system in a nearby car park facility (12 kWp) for electricity generation – see Figure 15.1.

Solar XXI has a proven record of high performance with respect of 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 15.1 SOLAR XXI.

Given the increasing interest in passive solar office buildings, this study reports on the electrical energy performance of the Solar XXI building and the associated considerations that are critical when similar renewable energy systems and energy flexibility options are considered in the same climate context. This study is also considered essential given the recent renewed strategic interest of the European Community in pursuing a clean energy transition with innovative solutions for the management of energy flexibility, among other strategies (European Commission, 2016). The main aspect investigated in this study is the potential for energy flexible demand in an office building which integrates two different PV technologies, a façade BIPV and a photovoltaic roof system in a nearby car park facility. To address the mismatch between energy production and consumption, and improve the resulting grid interaction, the integration of Battery Energy Storage Systems (BESS) with capacities ranging from 13.5 kWh to 54 kWh was studied, aiming to provide a certain degree of flexibility (Aelenei et al., 2018).

15.3. Solar XXI building description

The Solar XXI building is considered as a very high efficient building, from the national regulation point of view, with a difference in its energy performance ten times better compared with the Portuguese office reference building. Solar XXI combines energy efficiency measures and strategies with a BIPV system integrated on the main building façade (South oriented) together with a PV roof system in a nearby car park facility to reach a Net Zero Energy performance. Figure 15.2 shows the layout the Solar XXI building (right) and an interior view of the circulation space at the ground floor level (left). The main building characteristics of Solar XXI are summarized in Table 15.1.

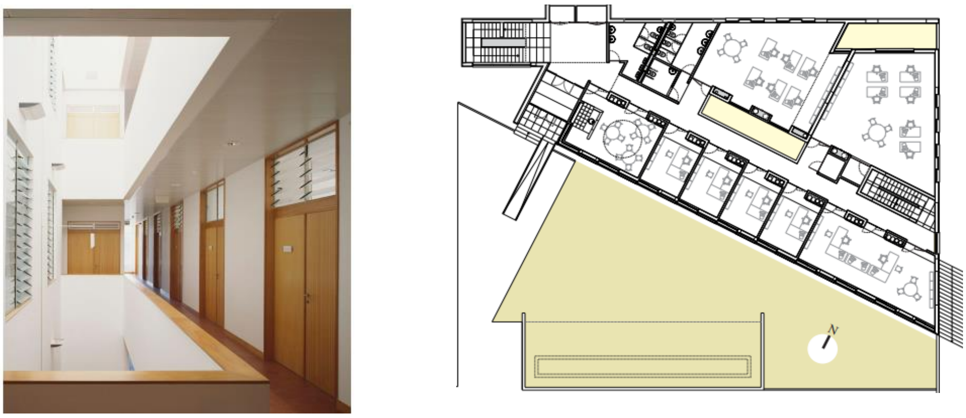

Figure 15.2 The Net-Zero energy building Solar XXI at the LNEG campus: interior view of the circulation space at the ground floor level (left); building layout at ground level (right).

Table 15.1 Solar XXI main characteristics.

SolarXXI Characteristics, components & features				
Building Characteristics	Gross Floor Area	1500 m^2	Net Floor Area	1030 m^2
	External Walls Area	400 m^2	External Roof Area	480 m^2
	Windows Area (South)	80 m	Windows Area (other)	100 m^2
	Floors above ground	2	Floors underground	1
	Climate	Mediterranean	Köppen Climate	CSA
HVAC	Heating (main)	Solar energy (Solar thermal collectors)	Heating (auxiliary)	Gas boiler
	Cooling	-	-	-
	Ventilation	-	-	-
Passive strategies	Heating	Direct gain through large window areas	Heating (auxiliary)	Indirect gain through BIPV recovery
	Cooling	Natural ventilation	Cooling (auxiliary)	Ground-cooling system
Renewable systems	PV façade	12 kWp	Technology	76 PV multicristalline silicon
	PV car parking roof	12 kWp	Technology	100 PV amorphous silicon + 150 CIS thin-film
	Solar thermal (heating)	11 MWh	Technology	Compound Parabolic Concentrator

The BIPV system in the south façade includes 100 m^2 of photovoltaic modules, resulting in a 12 kWp generation capacity, which equals the 205 m^2 PV modules capacity installed in the parking roof. The PV generation of both systems is firstly consumed within the building, the generation surplus (when available) is supplied to the existing distribution grid of the campus. South oriented large windows and a solar thermal system backed up by a gas boiler are used to meet the comfort requirements during heating season. In addition, the BIPV modules are mounted at a distance of 10 cm from the insulated masonry wall, allow the 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).

The building has no HVAC system and relies on external shading devices to prevent overheating; natural ventilation and buried ducts to provide temperate fresh air to the occupants including cooling during summer nights.

15.4. Actual electric energy performance

The actual operation of Solar XXI is characterized by the electricity demand and generation profiles depicted in Figure 15.3. These profiles were acquired during a 1-year measuring campaign and exhibit a 1 hour resolution.

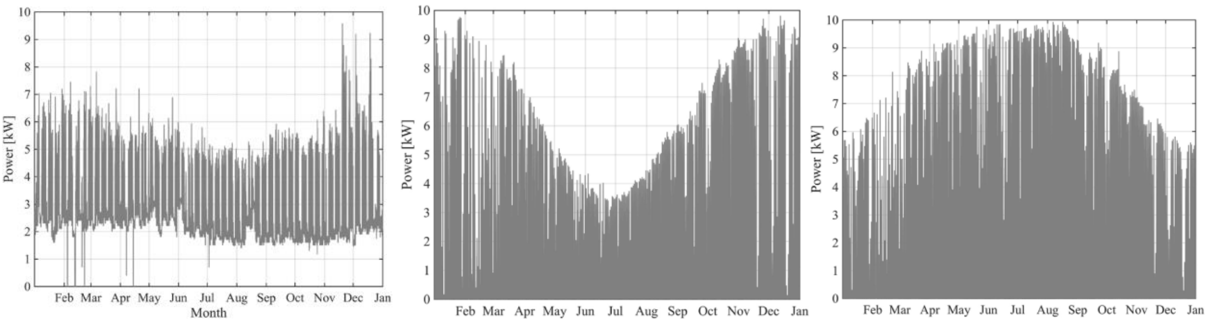

Figure 15.3 SolarXXI's electricity demand (left), Solar XXI's PV façade generation (middle), and Solar XXI's PV car park generation (right) (Aelenei et al., 2018).

A better picture of the building´s energy performance can be seen in Figure 15.4, which shows the electricity power load and generation for a typical winter day and summer day as average daily values. The typical winter day and summer day depicted in Figure 15.4 show a constant electricity power load outside the building occupancy period and peak loads during working office hours. With regard to the electrical power generated, BIPV shows significantly higher values in winter when compared with summer due to the vertical position of the PV panels, which improve their performance when solar radiation is at its lowest.

15.5. Storage Approach Scenario

15.5.1. Rationale and Assumptions

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 kWh, 27 kWh, 40.5 kWh 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 kW 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).

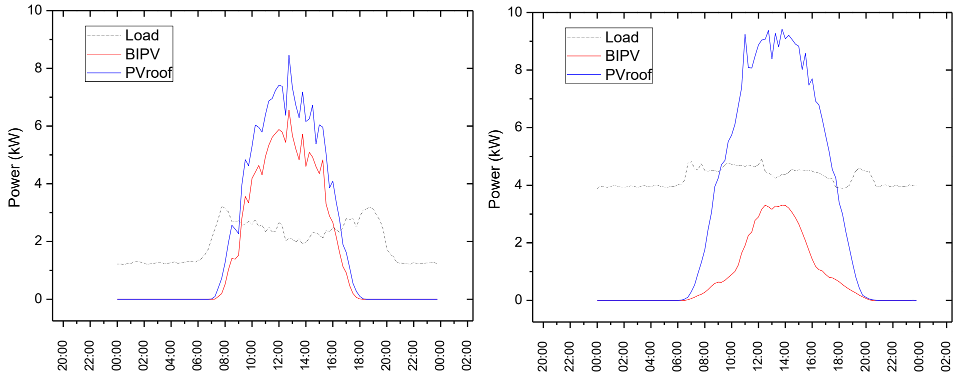

Figure 15.4 Average load and energy generation from BIPV and parking lot PV during typical winter (left) and summer (right) days.

15.5.2. Load matching design approach

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 and SS ratios are given by Equations 15.1 and 15.2, respectively, where n1 and n2 delimit the period of analysis. Equation 15.1 measures the amount of the building's on-site generation that is instantaneously matched by the building's electricity demand, while Equation 15.2 measures the amount of the building's electricity demand that is instantaneously matched by the building's on-site generation, both over the period defined by n1 and n2. Since the improvement of SC and SS ratios also impacts the grid interaction, this study considers that the resulting net load profile is given by Equation 15.3.

$$SC = \frac{\sum_{n=n_1}^{n_2} min(D(n),G(n))}{\sum_{n=n_1}^{n_2} G(n)} \cdot 100, \sum_{n=n_1}^{n_2} G(n) > 0 \tag{15.1}$$

$$SS = \frac{\sum_{n=n_1}^{n_2} min(D(n),G(n))}{\sum_{n=n_1}^{n_2} D(n)} \cdot 100, \sum_{n=n_1}^{n_2} D(n) > 0 \tag{15.2}$$

$$net(n) = \begin{cases} D(n) - G(n), first\ scenario \\ D_{mod}(n) - G(n), second\ scenario \end{cases} \tag{15.3}$$

where D(n) is the original electricity demand profile depicted in Figure 15.3 (left), G(n) refers to Solar XXI total PV generation and D_{mod}(n) is the modified electricity demand profile.

15.6. Results

15.6.1. Grid interaction

Figure 15.5 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. As it can be seen from Figure 15.5, the electricity demand profile reflects the building's occupancy characterized by a reduced value during the night, followed by a morning peak between 7 am and 8 am due to cleaning operations. Such electricity demand increases as a result of the lighting needs and cleaning equipment operation (e.g. vacuum cleaners). After this demand peak, the electricity demand of Solar XXI slowly increases until reaching the midday peak, when most of the occupants are working. The demand profile remains constant throughout the remaining of the day, until around 6 pm when people are starting to leave.

When BESS is considered as a single battery, the demand modified profile is changed significantly with regard to the original profile. As it can be seen in Figure 15.5, the daily average demand profile of Solar XXI increases during the morning because of battery charging. The demand increase introduced by the BESS is attenuated until it eventually reaches a null value when the battery reaches its maximum capacity. Then, the energy stored throughout the day is discharged later (around 5 pm), reducing the electricity demand.

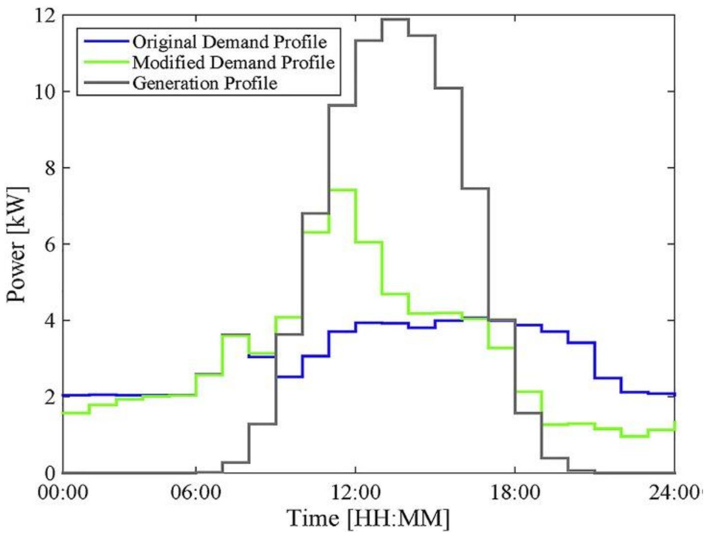

Figure 15.5. Original and modified (13.5 kWh BESS) daily average demand profile of Solar XXI, together with its daily average generation profile.

It should be noted that the battery charging is completely ensured by both PV systems while discharging contributes to a reduction of the energy imported during the periods with lower solar resource availability. On average, the annual exported electricity decreases by 26.1 % whereas the amount of electricity imported from the distribution grid is reduced by 31.3 %.

The results obtained in terms of grid interaction for all BESS storage capacity scenarios are summarized in Table 15.2.

Table 15.2 Summary of grid interaction results.

Number of Tesla walls	Storage Capacity [kWh]	Average daily positive net peak load [kW]	Average daily negative net peak load [kW]	Annual electricity import [kWh]	Annual electricity export [kWh]
0	0	3.4	-8	14401	17228
1	13.5	3.3	-7.3	9900	12737
2	27	2.4	-4.4	6170	9008
3	40.5	1.6	-4.1	5022	7864
4	54	1.4	-4.1	4807	7659

As it can be seen, the major improvement per additional Tesla Powerwall is achieved when one (13.5 kWh) or two batteries (27 kWh) are integrated, depending on the metric under analysis. On one hand, the amounts of imported and exported energy are reduced by 4501 kWh and 4491 kWh, respectively, when one battery is integrated, whereas an additional reduction of 3730 kWh and 3729 kWh is achieved when the second battery is considered. On the other hand, the average daily positive and negative net peak loads are reduced by 0.9 kW and 2.9 kW when the second Tesla Powerwall is added, respectively, comparing to a reduction of 0.1 kW and 0.7 kW when Solar XXI is equipped with only one battery of 13.5 kWh.

15.6.2. Load matching analysis

When analysed throughout the year, the actual energy performance of Solar XXI suggests a positive net energy balance. The instantaneous load matching between the building generation and demand, however, is far from being perfect, with yearly SC and SS ratios around 40.9 % and 45.3 %, respectively. The reasons for this low yearly SC ratio are related with an unbalanced ratio between the PV systems' power output and the Solar XXI power demand during periods with higher solar resource availability and with the lack of PV generation during periods with electricity demand (e.g. night period).

The results obtained following the integration of BESS, in terms of SC and SS ratios, for all considered battery capacities, are shown in Table 15.3. The collected results show that these ratios are significantly increased when the batteries are integrated into Solar XXI. As it can be seen from Table 15.3, the major improvement per additional battery is achieved when only 1 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).

15.7. Conclusion

The Solar XXI building combine energy efficiency measures and passive solar design with on-site renewable energy generation to achieve a Net Zero-Energy balance over an average year.

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 annual 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 a difficult task due to the absence of electrical heating/cooling equipment, which could allow deviation from their normal consumption patterns in response to high renewable generation periods. For this reason, the approach followed in this work to address the mismatch between energy production and consumption relied on the use of BESS with storage capacities ranging from 13.5 kWh to 54 kWh to provide the required energy flexibility.

This study has shown that the limited options for energy flexibility of passive solar energy with on-site renewable energy can be managed with the use of BESS and that the implementation of such systems could be further investigated in conjunction with nearly-zero energy buildings which are expected to become much more common in the near future following the introduction of energy efficiency requirements in national building codes, in line with the Energy Performance of Building Directive (EPBD).

Table 15.3. Summary of load matching related metrics.

Number of Tesla walls	Storage Capacity [kWh]	SC [%]	SS [%]
1	0	40.9	45.3
2	13.5	56.3	62.4
3	27	69.1	76.6
4	40.5	73.0	80.9
5	54	73.7	81.7

16. Quantitative potential evaluation of different flexibility and storage options for grid-supportive operation of a generic office building

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16.1. Abstract

The ability of building energy systems to adapt their load and generation trajectories to the relative 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, this study evaluates and compares four different flexibility and storage options (batteries, fuel switch, 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. For this purpose, new control strategies that build upon conventional building controllers are developed. 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. In comparison to other options, batteries are technically attractive in terms of grid support, efficiency and ease of implementation, whereas fuel switch is easy to implement, but does not offer significant benefit. Water tanks, with a capacity of about two full operation hours, offer nearly the same flexibility as much larger tanks, but negatively influence the efficiency of heat pump systems. The building thermal mass can be used effectively and efficiently for thermal storage, particularly in the heating season, but this is technically challenging to realize.

16.2 Background and objectives

A large amount of intermittent renewable energy in the energy system is a major challenge, since supply and demand must match at any time. A high level of flexibility on the demand side can greatly facilitate and promote the reliable and efficient integration of renewable energy sources into the power grid at a local, district or national level. The focus of this evaluation is on the electricity load and generation caused by heating and cooling systems with heat pumps and chillers in non-residential buildings. Heating and cooling systems in buildings are worth investigating because the cumulative load shifting potential in the heating and cooling sector is quite large, considering the high energy consumption and thermal storage potential of the building stock.

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 a grid signal:

- Fuel switch involves a change in the sequencing of different heat and cold generators in bivalent 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.
- Batteries can create a time shift between the net power load and the net power demand of the building.
- Water tanks can introduce a time shift between heat generation and heat delivery.
- The building thermal mass can be used for thermal storage by modifying the heat delivery trajectory.

It is generally not well understood how much load shifting potential each of these energy flexibilities and storage options provides, how this potential relates to the type and sizing of the energy flexibility and storage options, as well as the available thermal generators, during what times of the day and year the desired flexibility is available, and how the performance of the heating and cooling system is affected by load shifting. Answers to these questions are essential for defining the possible role of energy flexible buildings in an integrated sustainable energy system, and to understand how buildings can contribute to the conservation of energy resources and optimization of energy processes at a system level.

16.3 Method

16.3.1 Evaluation criteria

One of the fundamental motivations for load shifting is the variable quality, i.e., (economic or ecological) “cost”, of electricity over time considering intermittent renewable power generation. This factor is reflected by the non-renewable cumulative energy consumption (CEC). In this study, the projected residual load and the projected CEC of the electricity mix of Germany in 2023, shown in Figure 16.1, are used as grid signals. The residual load provides a quantitative indication of the relative demand for conventionally generated electricity at a given time and is highly correlated with the EPEX Day-ahead stock exchange electricity price (Klein et al., 2016).

For the evaluation of grid flexibility, two new indicators are introduced (Klein et al., 2016): absolute and relative Grid Support Coefficients (GSCabs and GSCrel). GSCabs weights a time-resolved electricity consumption profile with a time-resolved grid signal. It indicates whether additional loads occur at times with a relative electricity demand above or below average, which allows an evaluation of the grid impact of a building from the energy system perspective. One advantage of this indicator is that it does not require a reference operation trajectory. In general, values close to zero are grid-supportive while values larger than one can be interpreted as grid-adverse. The precise range of the indicator depends on the technical constraints of the analysed system. They are taken into account by the additional metric GSCrel, which relates the achieved value of GSCabs to the worst and best possible, on a scale of -100 to +100. Consequently, it can be used to assess the optimization potential for the operation of the heating and cooling system.

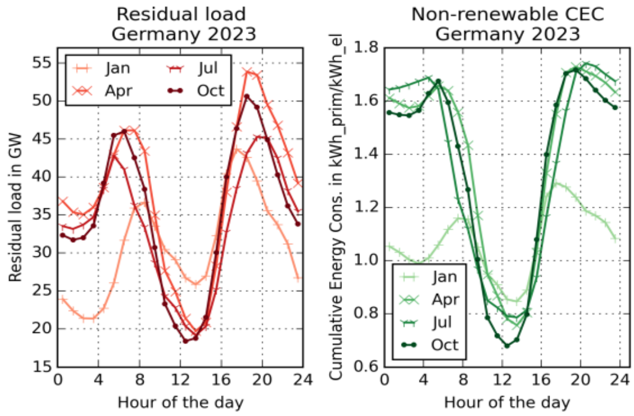


Figure 16.1 Daily profiles of the residual load and the CEC for Germany, projections for 2023. The data sources and assumptions used for calculation are in (Klein et al., 2016).

In addition to the evaluation of grid flexibility, energy efficiency is assessed by the final energy consumption (i.e. the sum of gas and power consumption) per usable floor space and the CEC of the developed grid-flexible strategies are compared to the reference operation.

The internal environment is considered to be thermally uncomfortable when the room temperature is outside of the tolerance band defined in European Standard (EN 15251, 2012). Accordingly, interior temperatures of 22°C ± 2 K are acceptable in the heating season, and interior temperatures of 24.5°C ± 1.5 K are acceptable in the cooling season.

16.3.2 System description and modelling

The considered building 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 7 am and 6 pm 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. They are both sized to match the reference heating and cooling loads 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 battery is modelled with a constant round-trip watt-hour efficiency factor of 83.9% as suggested by (Weniger et al., 2014). Static loss of charge and degradation of the battery are not considered. The discharging power is assumed to be identical to that of the heat pump load. The hydraulic layout is illustrated in Figure 16.2: 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.

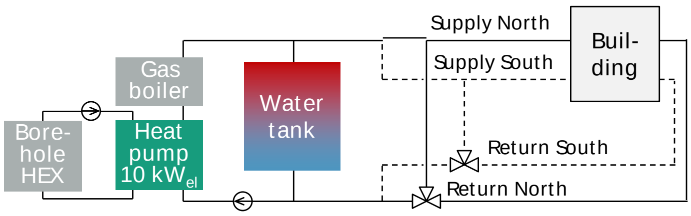


Figure 16.2 HVAC system and hydraulics.

The considered building is first modelled as a detailed white-box model using nine types of three-zone segments, with each zone based on a resistor-capacitor model. Due to its large number of states, a simplified grey-box model is subsequently calibrated based on the simulated thermal energy consumption of the detailed model. A full description of the employed model can be found in (Klein et al., 2017).

16.3.4 Control

The developed novel control concept is based on the combination of a low-level control and a high-level control. The low-level control is based on conventional control concepts for keeping the supply temperature close to the set-point by regulating the heat generators, circulation pumps and mixing valves. The high-level control is responsible for activating the flexibility and storage options so that the net load trajectory of the building becomes more grid-supportive. For this purpose, it determines the sequencing of the thermal generators ("fuel switch"), the charging and discharging schedule for the batteries ("batteries"), the overheating or undercooling temperature ("water tanks") and the target heat delivery schedules into the heat emission system circuit of each zone ("building thermal mass").

The workflow (Figure 16.3) used to obtain the results is as follows: first, the reference system is simulated in a Dymola simulation environment with the low-level control; the high-level control algorithm, which is implemented in Python (programming language), calculates input signals to the low-level control based on the grid signal; finally, the simulation of the complete system is repeated, but this time, the input signals are considered by the low-level control.

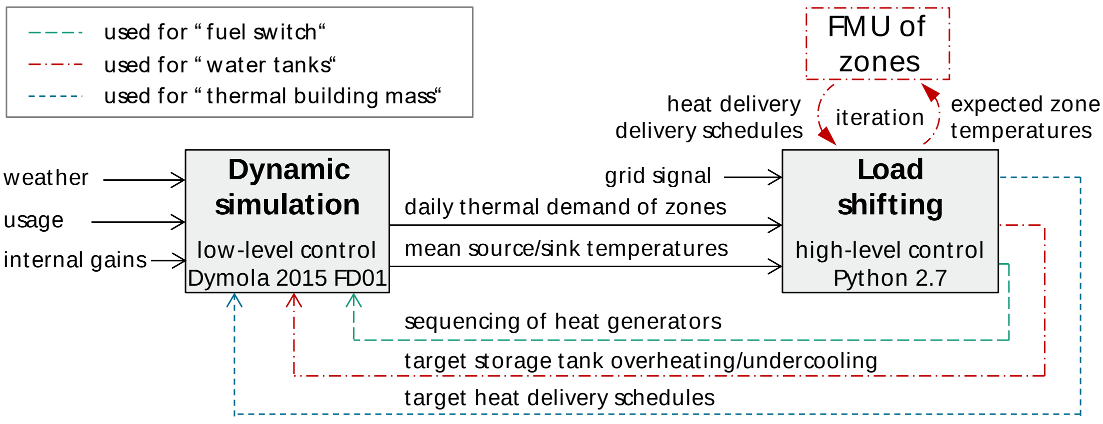


Figure 16.3 Overview of the data and signals involved in the load shifting process (FMU = functional mock-up unit) (Klein et al., 2016).

Fuel switch

The approach of fuel switch refers to a variation of the sequencing of heat generators in the low-level control. The decision when to switch between the different heat generators depends on the grid signal – the residual load in this study. The reasoning is that a high residual load signal is an indicator of a peak electricity demand situation and 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 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. For other options to select appropriate switching signals, we refer to (Klein et al., 2017).

Water tanks

This approach calculates the overheating or undercooling temperature in the tank compared to the set-point supply temperature according to the heating curve. The goal is to temporarily increase or decrease the operation of the thermostatically-controlled generators of heating and cooling energy. The developed load shifting algorithm determines the most suitable times for charging the tank, based on a grid signals by determining the locally optimal heat storage schedule. It makes use of a single-node state-of-charge model of the water tank, which additionally takes the thermal storage losses into account. For a successful implementation, precise forecasts of the heat demand and of other factors which influence the heat pump efficiency are required.

Batteries

Load shifting with batteries is accomplished by a simplified version of the load scheduling algorithm for water tanks. Because electricity is stored directly, the relation between thermal and electrical energy does not have to be taken into account. The battery is discharged by the variable load (heat pump or chiller) and charged from the grid when the residual load is low. The round-trip efficiency of the battery is considered after scheduling of battery charging or discharging is complete.

Building thermal mass

The algorithm used to control the water tanks cannot be applied to the building mass to control thermal storage, because the state of charge (i.e. temperature) and the discharge rate (i.e. heat flow rate to the zone) are coupled. Instead, another algorithm is used, which is described in detail in (Klein et al., 2017). For a successful implementation, precise forecasts of the load, weather, gains and usage are required. In short, both the grid-optimal delivery trajectory based on the grid-optimized heat pump operation and the conventional delivery trajectory to the zones are calculated first. Using a low-order FMU model of the building, the room temperatures resulting from the two delivery trajectories are tested for compliance with the comfort requirements. Due to the large time constant of the heat emission system, exceedances may extend to the following day and it is necessary to evaluate comfort for more than one day at a time. Finally the grid-optimal profile is applied if it satisfies the comfort requirements; otherwise a trade-off with the conventional profile is used.

16.3.5 Technical implementation

Batteries can be installed and operated independently of the hydronic system. Fuel switch is also fairly straightforward to implement since it only affects the sequence in which the heating and cooling systems are activated. However, in combination with thermal load shifting, the activation and deactivation criteria for the thermal generators must be tuned carefully, as additional thermal generators may become unintentionally activated when too much thermal load is scheduled. Whether or not water tanks can be used for load shifting depends strongly on the hydraulic topology. Particularly in the case of low-temperature heat emission systems such as concrete core conditioning, it is essential that the supply temperature to the heat distribution circuits can be regulated independently of the tank temperature, e.g. by mixing the supply water with return water using three-way valves. Otherwise, load shifting might affect the thermal comfort negatively. The building thermal mass is the most technically challenging of the flexibility and storage options considered in this work. Transferring this concept into application is expected to be challenging, as precise weather, load, occupancy and usage predictions, as well as accurate zone models, are required to ensure thermal comfort, particularly in the cooling season. Moreover, the circulation pumps of the individual zones need to be centrally controlled and the thermal energy delivered to each zone needs to be monitored precisely.

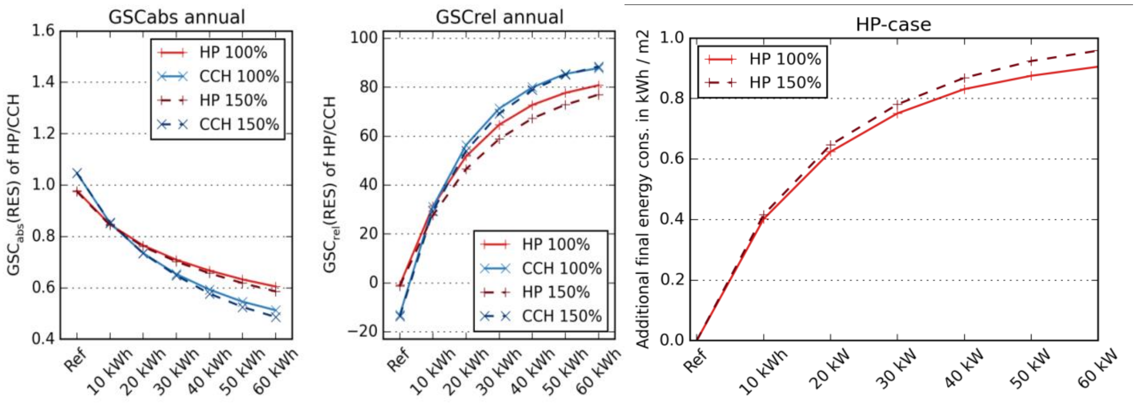
16.4 Results

In the reference operation, the building consumes 21 kWh/m^{2}a of final energy and 26 kWh/m^{2}a of primary energy, respectively. The comfort temperature range is between 20 and 24°C (heating season) and between 23 and 26°C (cooling season), respectively. 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 consumption. The latter is given as the sum of additional gas consumption and additional power consumption. A more in-depth interpretation of the following brief summary of results is provided in (Klein, 2017).

16.4.4 Batteries

The results illustrated in Figure 16.4a and b show that a higher absolute grid support can be achieved with larger batteries. However, the benefit of additional battery capacity decreases with increasing battery size. Oversized thermal generators with 50% more nominal power (labelled as “HP/CCH 150 %”) do not improve grid support compared to standard sizing (“100 %”). GSC_{rel} is also improved; however, the results are not directly comparable to the other flexibility options, since batteries can be operated simultaneously with the coupled variable load or generator such that their electric powers add up.



a b c

Figure 16.4 Batteries: grid support and energy efficiency for different battery sizes.

The use of batteries causes electrical losses of 0.3 – 0.95 kWh/m^{2}a depending on the battery size (Figure 16.4c), which is significant compared to the annual heat pump consumption of 7 kWh/m^{2}a. According to the applied operation strategy, the battery accumulates between 195 and 564 full charge cycles in one year depending on the battery size. Assuming a battery life time of 5,000 full charge cycles, this translates into an approximate lifetime of 10 – 20 years (Kairies et al., 2015).

16.4.5 Fuel Switch

Figure 16.5 illustrates the grid support coefficient and energy consumption for different switching signals – here given as percentiles of the residual load as explained in the previous section. Smaller switching signals indicate an earlier signal to switch from the heat pump to the gas boiler as primary heat generator. Consequently, gas consumption increases while electricity consumption is reduced, which also improves grid support. However, this happens at the expense of an increase in final energy consumption 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 consumption are almost directly proportional to the defined switching signals. GSC_{rel}, which reflects how well a variable load or generator is scheduled with respect to a grid signal on a daily basis, is only moderately improved, since heat generation is not actually rescheduled, but partially re-distributed among the different heat generators.

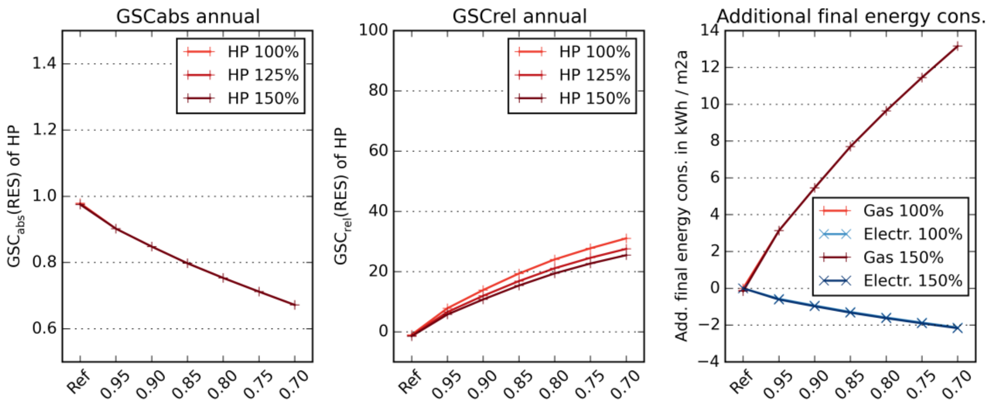


Figure 16.5 Fuel switch: grid support and energy efficiency for different switching signals. Switching signals designated as “0.95” refer to the 95th percentile of the grid signal residual load.

16.4.6 Water tanks

As evident from the upper chart in Figure 16.6, the operation of the heat pump is shifted towards the middle of the day and the night hours (darker red in the graph). The applied algorithm schedules the heat pump such that the tank is nearly fully charged when the residual load reaches its daily peaks (morning and evening – darker red in the graph) and discharged during the peak residual load periods (lower diagram of Figure 16.6). The tank is typically charged and discharged twice per day.

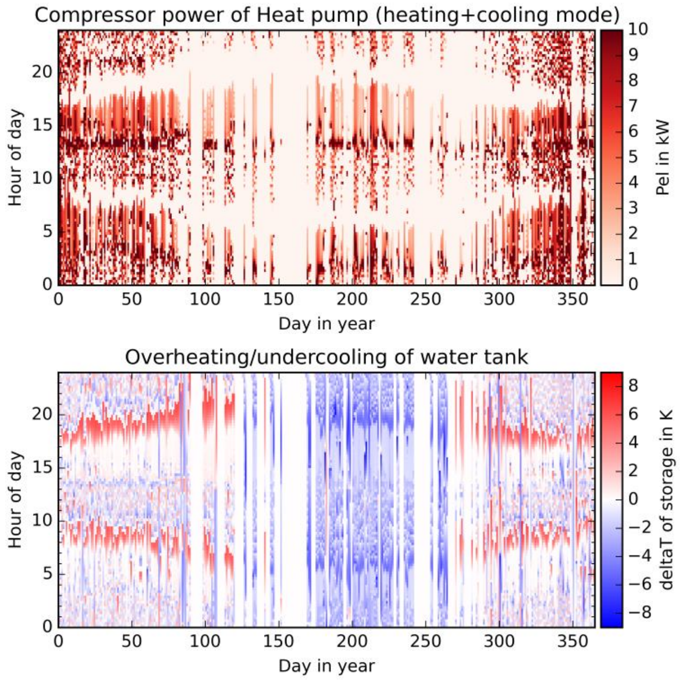


Figure 16.6 Power of the heat pump in heating and cooling mode and state of charge of the water storage tank in carpet plot diagrams.

In Figure 16.7, the influences of different sizes of the water tank and thermal generators are presented.

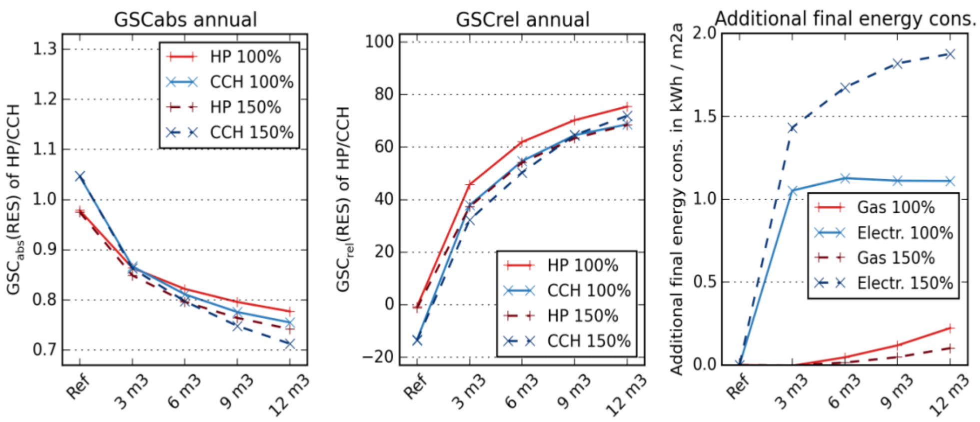


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Figure 16.7 Water tanks: grid support and energy efficiency for different tank volumes. The tank water is overheated and undercooled by 10 K.

Absolute and relative grid support is continuously improved by increasing the tank size. With increasing tank size, more powerful heat generators can outperform the conventionally sized systems. Heat losses from the tank to the environment (not shown in the diagram) increase with tank size, but account for less than 1% of the annual thermal energy demand of the building. The efficiency of the heat generation is thus more significant for end energy consumption than the storage losses.

Figure 16.8a and b illustrate the trade-off between improved grid support and lower heat pump efficiency when increasing the overheating temperature difference with a tank of 3 or 6 m³.

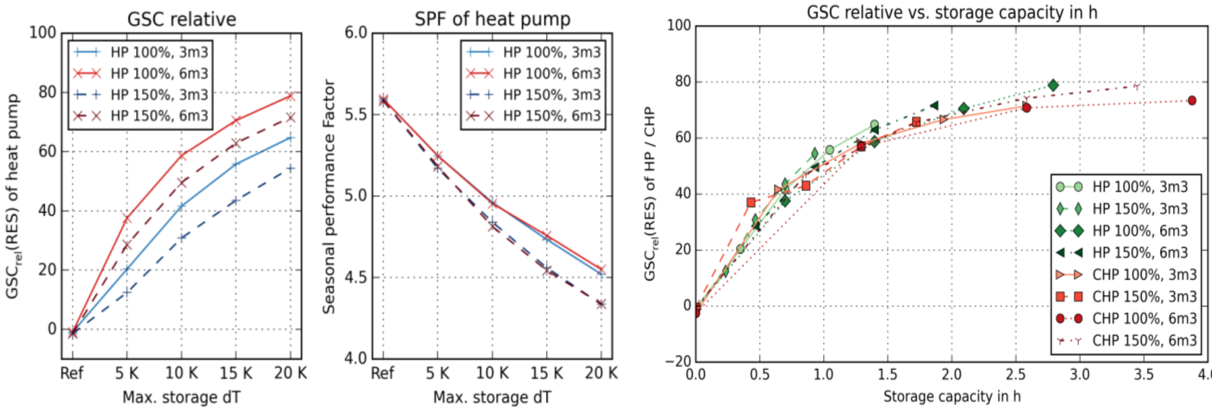

Figure 16.8 a: GSC_{rel} and b: SPF of the heat pump depending on water tank overheating temperature. c: GSC_{rel} as a function of the storage capacity in full operation hours.

The combination of tank size and overheating temperature defines the thermal capacity of the storage. Figure 16.8c shows that GSC_{rel} is continuously improved with increasing storage capacity, provided here in full operation hours of the thermal generator. However, following a storage capacity of two hours of full operation, a “saturation effect” occurs and a further increase of the tank size has only limited benefit.

16.4.7 Building thermal mass

According to the applied load shifting algorithm, the building thermal mass can only be used for storing or extracting heat as long as it does not result in a reduction of thermal comfort compared to the reference case. Its availability for storage depends on all parameters affecting the room temperature such as occupancy, internal and solar heat gains, and ambient temperature. The north-facing zone is better suited for load shifting than the south-facing zone, since it is affected less by solar gains and, therefore, has less variable room temperatures. The ability to perform load shifting in summer can further be enhanced by increasing the discomfort tolerance such that small exceedances up to 2 Kelvin-hours (Kh) per day and zone are accepted.

As can be seen in Figure 16.9, applying the load shifting algorithm leads to a significant improvement in grid support over the reference case: even without an additional discomfort tolerance (0 Kh), GSC_{rel} of the primary heat generator can be improved to 80. While a small discomfort tolerance improves GSC_{rel} for both heat and cold generation, larger comfort tolerances only enhance grid support in the cooling season. Oversized systems (150%) allow for better absolute grid support (GSC_{abs}) because of their ability to generate the required thermal energy in shorter periods, which allows them to utilize the thermal storage capacity provided by the building mass better.

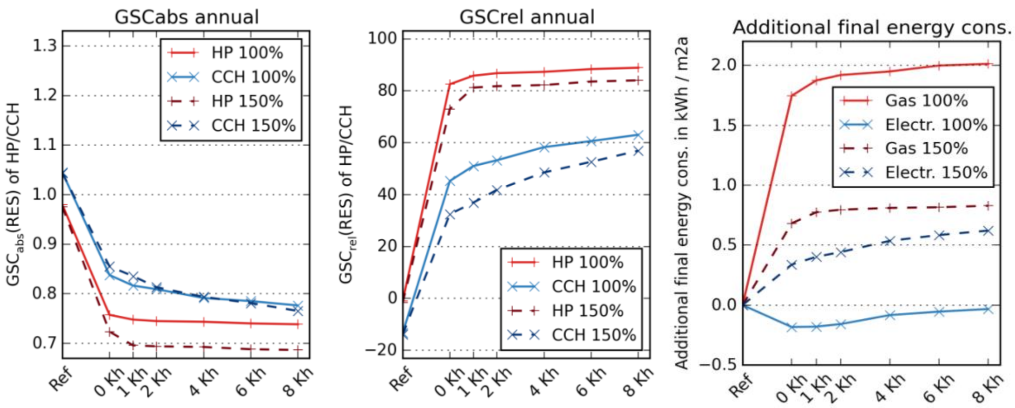

Figure 16.9 Building thermal mass: grid support and energy efficiency for different comfort tolerance settings.

16.4.8 Comparison and economic discussion

The benefit of the load shifting is illustrated through a comparison between grid support and efficiency (Figure 16.10). Improved grid support is indicated by a lower value of the proposed metric GSC_{abs}. Energy efficiency is determined in the form of lower mean final energy consumption (Figure 16.10a) and lower mean CEC (x-axis in Figure 16.10b) per consumed electricity unit.

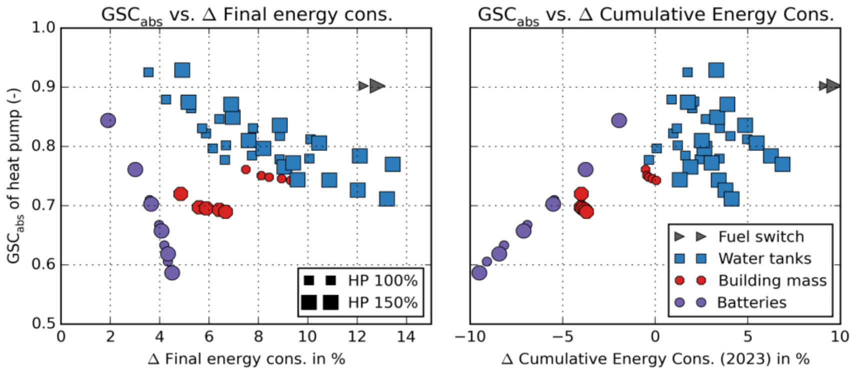

Figure 16.10 Comparison of flexibility and storage options. Each option is considered for standard and over-sized heat generators (illustrated by small and large points) and varying sizings and parameters as presented in the previous section.

Out of the considered flexibility options for heat pump systems, batteries achieve the lowest GSC_{abs} values with the least additional final energy consumption. 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 consumption.

However, due to the resulting favourable timing of the heat pump, the increase in CEC is much smaller. Fuel switch improves grid support only marginally at the expense of a very large additional final energy consumption 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 consumption 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 systems, fuel switch may provide a more effective and capable option.

In the following economic discussion, the question of whether the current electricity price can reward grid flexible operation in the considered scenario is investigated. For this purpose, the gas price is assumed to be 0.05 €/kWh. For the mean wholesale electricity price for end customers, a value of 0.218 €/kWh on average is considered (EWI, 2014), which contains a time-variable price component (EPEX Day-ahead stock electricity price) as well as fixed fees and taxes. Table 16.1 presents the results. While load shifting with water tanks and the building thermal mass leads to the heat pump consuming electricity at a lower average electricity price, it increases the consumption and thus the operating cost over the reference case. In conclusion, the assumed price signal does not offer sufficient variation to reward grid-supportive operation sufficiently to generate savings that exceed the additional operation cost due to increased final energy consumption. Therefore, a compromise between grid support and efficiency must be found, which ultimately depends on the monetary incentive of load shifting.

Table 16.1 Mean electricity price, final energy consumption, and operating cost for water tanks (6 m^3 volume, ΔT=10 K) and building mass (1 Kh tolerance).

	Reference	Batteries	Water tank	Building mass
Electr. Price for HP load in €/kWh	0.218	0.212	0.214	0.212
Final energy consumption in kWh/m²a	21.0	21.7	22.1	23.0
Cost in EUR/m²a	4.58	4.68	4.76	4.63

16.5 Conclusion

The aim of this study was to investigate the technical load shifting potential of non-residential buildings with a heating and cooling system based on a bivalent system consisting of a heat pump and a gas boiler. For this purpose, new control strategies which enhance grid-supportive operation of the energy supply system of the building were developed. The control concepts were designed to remain compatible with traditional controllers to ensure an easy technical integration in conventional building control systems. For a generic modern office building, the energy flexibility and storage options were analysed using detailed numerical simulation and compared in terms of grid support and energy consumption using parameter studies.

It has been 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. Regarding water tanks, it was shown that the achievable improvements of the grid support largely depend on the relation between the thermal storage capacity and the thermal power of the heat generator. Tanks with a capacity of approximately two full operation hours proved sufficient to realize most of the optimization potential in grid support. Regarding the building thermal mass, the evaluated system with a high-inertia heat emission system (concrete core conditioning) proved capable of storing large amounts of thermal energy with small temperature differences during the heating season, which provides a very attractive storage option for heat pump systems, the efficiency of which is highly sensitive to increases in the temperature of the heat emitting system. However, during the cooling season, thermal storage using the building mass is restricted by comfort constraints. Furthermore, it is technically challenging to implement.

Further work is needed to increase the application maturity of the developed concepts. The applied algorithms are partly based on heuristic rules and do not lead to a numerical optimum. Simpler, more easily implemented rule-based strategies might be sufficient to provide significant improvements in the grid support. Moreover, the developed control methods require reliable predictions of load, and for using the building mass also weather, gains and usage, for successful activation of the flexibility options. Very accurate predictions, however, are challenging to realize in real buildings, e.g., due to the large influence of user behaviour on the thermal load, particularly in a well-insulated building. This challenge could be met by self-calibrating models and methods for dealing with model uncertainty. If the technical realization allows, more advanced model-predictive controllers, which are able to take model and prediction errors into account, may provide better load shifting schedules.

16.6 Acknowledgement

The authors acknowledge the financial support by the German Federal Ministry of Economics and Energy in the project "flexControl" (project code: 03ET1359A). This chapter is an extract from (Klein et al., 2017).

17. Influence of penalty amplitude on the flexibility measures in model predictive control applications

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17.1 Abstract

The study presents an analysis of the influence of energy penalty signals on the flexibility characteristics in a building controlled using Model Predictive Control. The results were obtained through a simulation-based experiment using a simplified grey-box model of a building. The heat supply in the building was optimized using a multiple-shooting optimization algorithm (in-house code developed at the University of Southern Denmark). The results show that the penalty amplitude has a significant influence on the flexibility characteristics. Moreover, the relationship between the flexibility parameters and the penalty amplitude is nonlinear. Finally, there exists a theoretical limit of downward flexibility, affected by the efficiency of the energy shifting strategy.

17.2 Introduction

The increasing share of renewable energy sources, characterized with unstable production profiles, creates new challenges for energy grids and energy systems. One of the ways to limit the pressure on the energy grid is by increasing the energy flexibility of buildings and other energy consuming systems. Buildings, however, have traditionally been designed as passive energy consumers. Typically, the only control objectives implemented in building HVAC systems are the maintenance of indoor thermal comfort and the minimization of energy consumption.

Hence, there is a need for new types of controllers that could utilize the building dynamic properties (thermal inertia) in order to increase the energy flexibility. One such controller type is Model Predictive Control (MPC), in which a building performance model and a chosen dynamic optimization algorithm are used to minimize a predefined cost function, the energy price for example. It is, however, nontrivial to describe the flexibility potential of MPC-equipped buildings. The building's response depends e.g. on the penalty (e.g. price) signal profile.

Hence, this study analyses the influence of the penalty signal amplitude on the building flexibility characteristics. Six flexibility characteristics defined by (Junker et al., 2018) and shown in Figure 17.1 are considered:

- τ (time): the delay from adjusting the energy price and seeing an effect on the energy demand,
- Δ (power): the maximum change in demand following the penalty change,
- α (time): the time it takes from the start in change in demand until it reaches the lowest level,
- β (time): the total time of decreased energy demand,
- A (energy): the total amount of decreased energy demand,

B (energy): the total amount of increased energy demand.

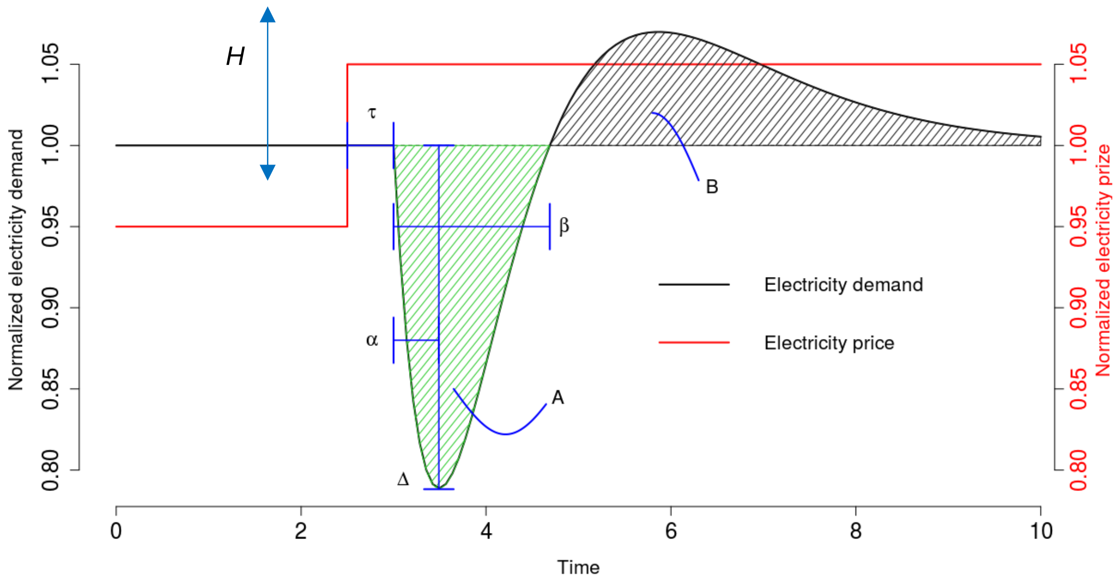


Figure 17.1 Example of the response of a building's eletricity demand to a step change in a penalty signal (Junker et al., 2018).

17.3 Method

The influence of the penalty signal amplitude H on the flexibility characteristics is studied based on simulation results using a simplified building energy model. The model represents a single-zone building and is based on the RC thermal network (linear time-invariant system), which is a low-order model in which a zone is represented by a network of resistors and capacitors. Resistors describe the conductive properties of zone partitions, whereas capacitors represent their thermal inertia. The zone model used in this study is based on the R3C3 (3 capacitors, 3 capacitors) model from Arendt et al. (2018). The capacitors represent the (1) indoor air, (2) internal thermal mass (internal walls and floors), and (3) external thermal mass (external walls, floors, roofs). The resistors represent the thermal resistance of the external walls (2 resistors) and internal walls (1 resistor). The model inputs are divided into disturbances and controlled inputs. The disturbances include outdoor temperature T_{out} [°C], solar radiation Q_s [W/m^2] and the number of occupants n [-]. The only controlled input is the heating power q [W].

The model parameters are calibrated based on measured data from one of the zones in the OU44 teaching building situated at University of Southern Denmark (Santos and Jørgensen, 2019), but slightly adapted to better represent a standalone building (mainly by limiting the infiltration).

In this study, constant boundary conditions are assumed: T_{out} = 0, Q_s = 0, n = 0. The heating power is optimized to minimize the following cost function:

$$\min \int_t (pq)^2 \, dt, \tag{17.1}$$

where: p is the penalty signal [-]
t is time [s]

The penalty signal assumed in this study is dimensionless, however from the cost function point of view, Equation (17.1) is equivalent to the energy price if we assume that the heating of the building is based on electricity (e.g. heat pump). The optimization is performed using the multiple shooting algorithm (Arendt, 2019).

Nine different penalty signals are analyzed with amplitudes H equal to 0, 1, 2, ..., 8. The penalty step lasts for 2 h. In all cases the penalty signal is equal to 0 for 48 h before the step change and for 24 h after the step change (Figure 17.2).

Finally, in all the considered cases it is assumed that the indoor temperature should stay within the range 21-24 °C and the maximum heating power is 4000 W (optimization constraints).

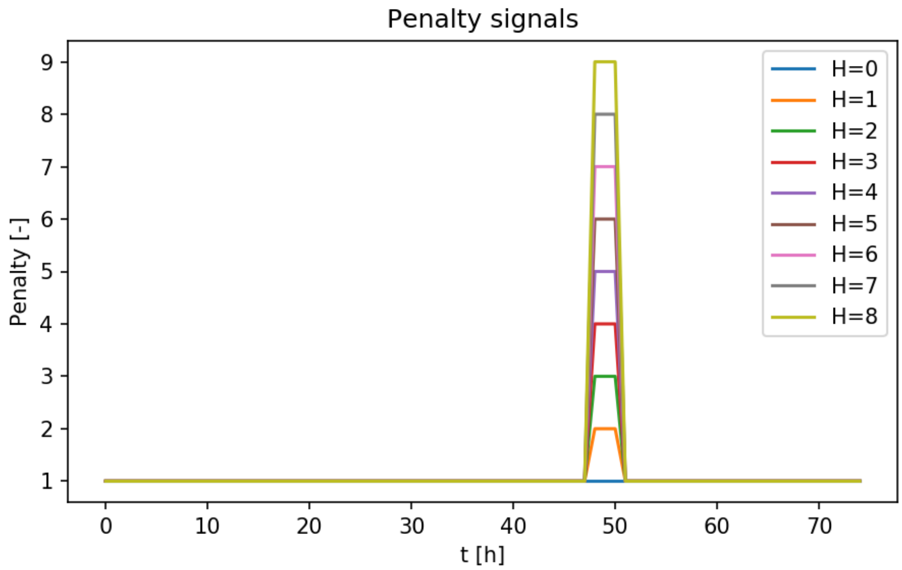


Figure 17.2 Nine considered penalty signals with amplitudes from H=0 to H=8.

17.4 Results

The heating profiles in all the considered cases are presented in Figure 17.3. As shown, the penalty amplitude has a clear impact on the heating profile. The higher the penalty amplitude, the earlier the heating occurs, in order to preheat the building without violating the constraints (maximum heating of 4000 W and temperature within 21-24 °C). In the case with a flat penalty signal (H = 0), the heating power stabilizes at a level of around 2600 W (steady state reached).

The heating profiles relative to the case H = 0 are presented in Figure 17.4. Due to the temperature constraints (Figure 17.5), the peak power during the pre-heating stage decreases with the increasing penalty amplitude. Since the indoor temperature cannot exceed 24 °C, the heating is distributed over a longer time period (Figure 17.4) to also heat up the building thermal mass. The absorbed heat is subsequently used during the increased penalty period. Due to the heat losses during the pre-heating cycle (energy shifting), more heat is used during the pre-heating period than released during the increased penalty period. Hence, the penalty amplitude drives the building response.

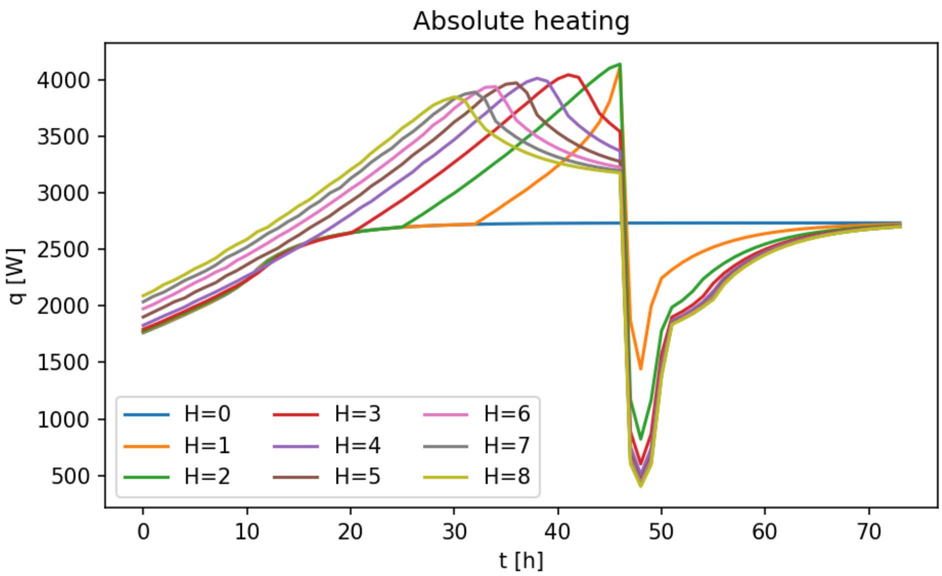


Figure 17.3 Absolute heating profiles (optimized by MPC).

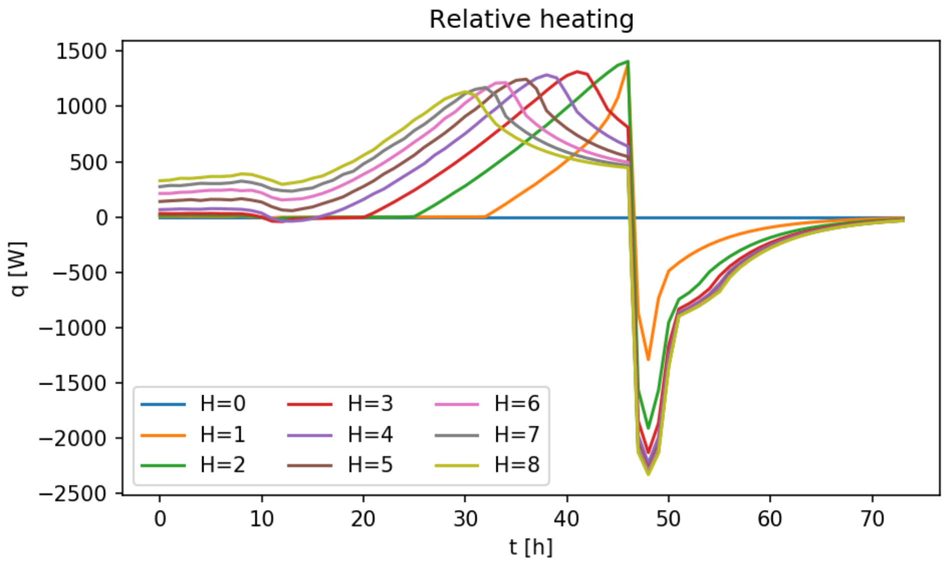


Figure 17.4 Relative heating profiles (optimized by MPC).

Based on the relative heating profiles it is possible to calculate the flexibility characteristics τ, Δ, α, β, A, B. In MPC applications, the penalty increase can be anticipated. In such case, B (the increased energy demand), occurs before the penalty increase (Figure 17.4). The calculated parameters are presented in Table 17.1.

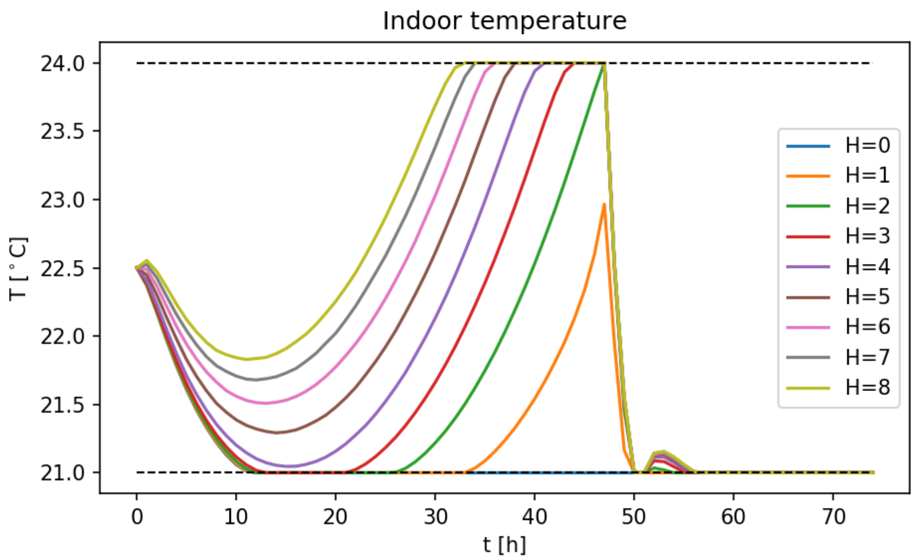


Figure 17.5 Indoor temperature profiles (constraints marked with dashed lines).

Table 17.1 Calculated flexibility characteristics

Step size H [-]	τ [h]	Δ [W]	α [h]	β [h]	A [kWh]	B* [kWh]
1	0	736,55	1	24	3,88	5,46
2	0	1568,86	1	24	7,72	11,49
3	0	1868,15	1	24	9,36	14,88
4	0	1995,92	1	24	10,07	17,12
5	0	2066,68	1	24	10,46	19,11
6	0	2104,43	1	24	10,66	20,59
7	0	2127,46	1	24	10,79	21,70
8	0	2140,64	1	24	10,86	22,58

A nonlinear relationship is observed between three flexibility characteristics (Δ, A, B) and the penalty amplitude (Table 17.1). The nonlinearities are due to the heating power and temperature constraints as well as due to the heat losses in the pre-heating cycle. As shown in Figure 17.6, the penalty signal can be effectively used to control the downward flexibility only to a certain level. In the given example, any further increase in the penalty amplitude would have minimal effect on the parameter A, because most of the heat used to increase the temperature of the building thermal mass would be lost. In other words, there is a limit of how much energy can be effectively used during an increased penalty period.

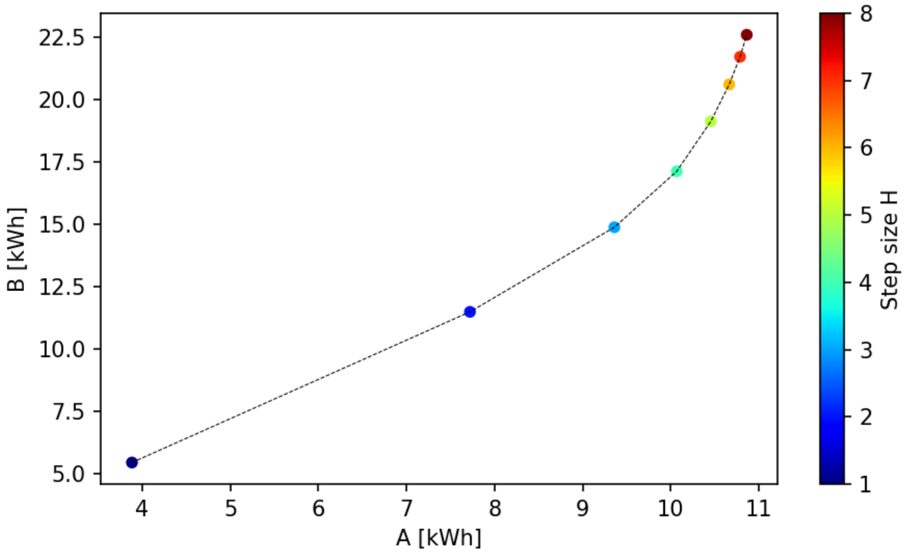


Figure 17.6 Decreased consumption A [kWh] vs. increased consumption B [kWh] for different penalty amplitudes (from H=0 to H=8).

The remaining characteristics are constant in this case study. The parameter τ is equal to 0, because MPC anticipates the penalty rise and adapts the heat supply accordingly. The parameters α, β depend on the building thermal mass (inertia) and in this example are equal to 1 h and 24 h, respectively.

17.5 Conclusions

A building's response to a penalty amplitude depends on the allowed comfort range, boundary conditions, time to the penalty step, duration of the step, initial building state, building properties, and the control objectives (cost function). In this study, to isolate the influence of amplitude, all other factors were kept constant.

The main conclusions from this work are that the penalty signal has a significant influence on the flexibility of an MPC-equipped building. In addition, there exists a theoretical maximum potential of downward flexibility in cases with an upper indoor temperature constraint. The downward flexibility can be effectively controlled by the penalty amplitude only to a certain level, above which the energy shifting becomes very inefficient. This happens because (1) MPC distributes the heat supply over a longer period of time and (2) it limits the peak supply to avoid overheating of the indoor air.

18. Experiences of asset managers for the adoption of energy flexibility

Erwin Mlecnik, Faculty of Architecture and the Built Environment, Delft University of Technology, The Netherlands

18.1 Abstract

It is expected that future buildings will be able to manage their demand and generation according to, not only local climate conditions and user needs, but also to changing grid requirements. This development will introduce new challenges for asset managers, which need to be understood in detail. This example identifies key opportunities and barriers for asset managers from a case study: an assembly of buildings on a university campus in the Netherlands, where changing grid conditions and heating optimization strategies were introduced. The case illustrates the changing viewpoint of the asset managers towards the adoption of energy flexibility, from initial theory to experiences when simulating and testing options.

18.2 Background and objectives

Different examples in this publication illustrate technological advances and economic optimisation strategies for achieving energy flexible buildings. However, the adoption of energy flexibility in buildings depends largely on the principles being accepted socially and commercially. It is important to understand political, economic, social, technological, legal and environmental factors that influence the decision processes of stakeholders. The adoption of energy flexibility in buildings implies that buildings will react to changing grid requirements. To make this happen building users must see the benefits of such a strategy and must be able to eliminate barriers for implementation.

Amongst all building users, asset and facility managers are amongst the most important stakeholders, as they can decide if energy flexibility will be implemented in buildings and districts. Asset and facility managers are responsible for the strategic management of entrusted buildings and surroundings and can influence strategy decisions and property developments. It is thus important to understand the viewpoint of these stakeholders regarding the adoption of energy flexibility. Moreover, their experiences and viewpoints can change once they start experimenting with the implementation of energy flexibility.

This example describes the barriers and opportunities that asset managers encounter during such an innovation trajectory. The work is based on a follow-up of asset managers' experiences during the implementation of changing heat grid requirements on a specific assembly of buildings in a district, the campus of the Delft University of Technology (TU Delft) in the Netherlands.

18.3 Method

As energy flexibility is perceived as a new concept by asset managers, it can be investigated from the viewpoint of adoption of innovation. Innovation theories were introduced during the 1960s and have been applied on hundreds of adoption problems (Rogers, 2003), including the adoption of energy-saving and environmental technologies, concepts and demonstration buildings (Mlecnik, 2013). For example, innovation theory provides models for researching decision processes and for understanding how stakeholders perceive the characteristics of innovations.

Not much is known about the perception of energy flexibility by stakeholders, particularly asset managers. In-depth knowledge from demonstration cases and involved stakeholders is still needed for the design of asset management strategies. Real-world case studies can unravel important contextual conditions for the adoption of energy flexibility. Methodologically, this example used a case study approach (Yin, 2014), supported by a literature review, semi-structured stakeholder interviews and (procurement) action research to investigate adoption barriers and opportunities related to the adoption of the concept of energy flexibility and its effect on asset management strategy, using the experiences from asset managers from a university campus in the Netherlands.

The TU Delft campus (see Figure 18.1) is like a small village with its own heat generation and distribution network, using a high temperature water grid with supply temperatures of approximately 100 to 130 °C, 3 heating plants, 2 cogeneration plants and 101 heat exchangers. Figure 18.2 shows the original situation of the campus heat grid before any flexibility strategies were introduced; a power plant delivered the same supply temperature in multiple branches. In the original scenario, the buildings were controlled individually based on current outdoor temperature.

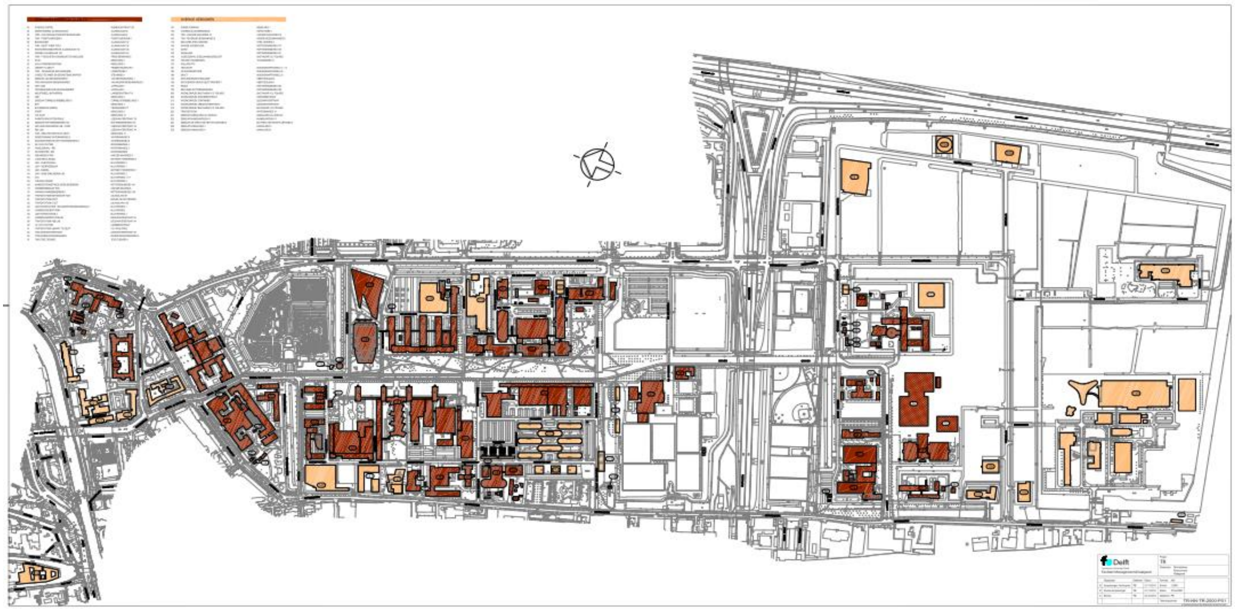


Figure 18.1 Site plan of the TU Delft campus.

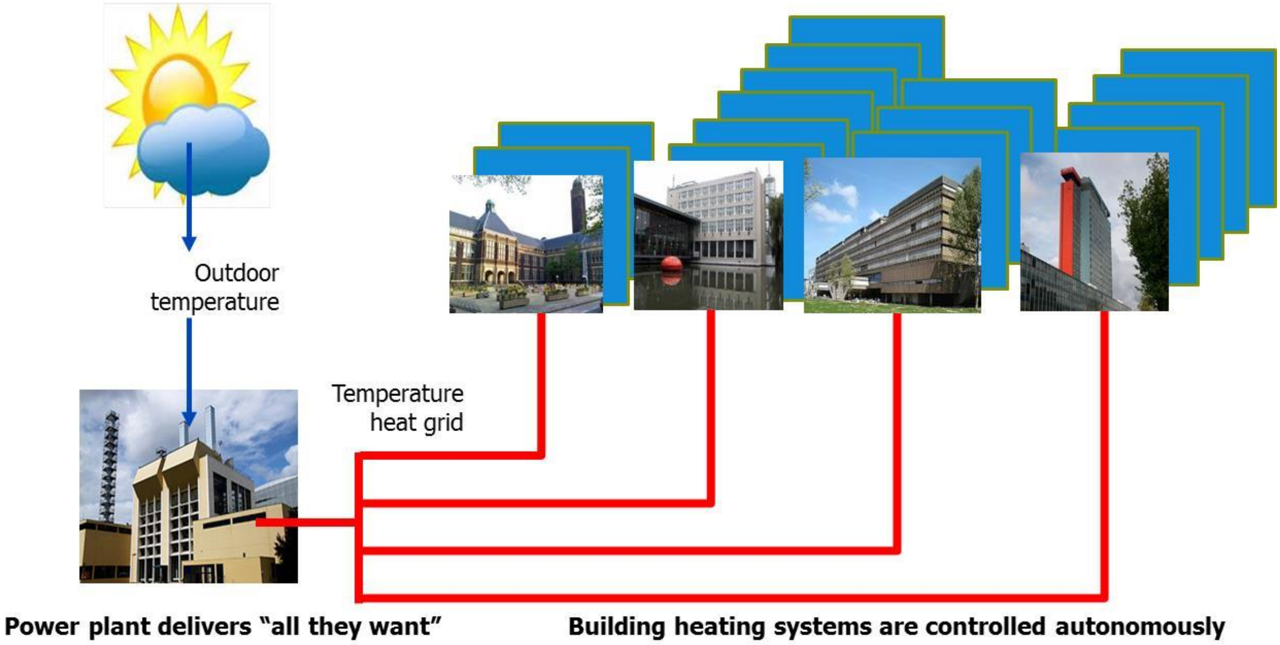


Figure 18.2 Existing branching and control strategies in the TU Delft campus district heat network (Deerns, 2015).

In addition to the asset and facility managers, other important stakeholders on the campus regularly intervene or consult on building use and development. These include related real estate managers; researchers engaged in energy system and building development; and stakeholders involved in the TU Delft heat grid or smart campus development and the development of innovation incubator zones.

User experiences were collected from such stakeholders in the period 2014-2018, coinciding with the development of technical experiments to test the applicability of smart control systems on the heat grid on the campus. One of the aims of this Intelligent Heat Grid project was to check the feasibility for reducing the heat supply temperature to campus buildings to save energy and CO_2 emissions. The project included some modifications of the heat grid and the control systems and software. A model-predictive control system was developed with industry partners, while linking the building management systems to the power station's software. Five-day weather forecasts, updated every hour, were used for predicting and controlling the required heating supply to buildings without loss of comfort. The technical experiences from this Intelligent Heat Grid project were previously reported (Stoelinga et al., 2016 and 2017) and the user experiences have been described (Mlecnik et al., 2018). Here, a brief overview is provided of the main stakeholder experiences during different phases of the innovation adoption trajectory.

18.4 Results

The example describes the experiences of the asset managers during the four consecutive stages of the Intelligent Heat Grid Project:

1. The initiation phase, when the need and feasibility of changing grid requirements on the campus was discussed;
2. The simulation phase, when simulations were used to establish a better understanding of the performance of buildings and the heat grid to address the effect of changing grid conditions;
3. The building testing phase, when a model predictive control system was tested on one building;
4. The grid testing phase, when the control system was tested on multiple buildings connected to one branch of the heat grid;

The following sections describe the main barriers and opportunities encountered in each phase.

18.4.1 Initiation phase

There were concerns that the adoption of changing heat grid supply conditions on campus could be hindered by the various characteristics of the buildings. For example, the gross floor area of the buildings linked to the heat grid varies from 3,072 to 46,860 m^2. The installed power varies from 407 to 13,410 kW. There are substantial differences between the energy consumption of the various buildings. These differences are mainly due to the age of buildings and/or their level of maintenance, but also due to the building functions. Currently only the larger buildings have a programmable building management system that allows for climate control and detailed information about the energy use of various indoor comfort systems. This information cannot be requested centrally and is mostly related to building wings, spaces and rooms instead of specific end-use or systems such as lighting, cooling, ICT, and so on.

The asset managers had drafted a comprehensive strategy regarding energy saving on campus. The strategy addresses the needs for achieving overall energy saving targets, for including energy saving in regular maintenance, for low-energy retrofit, for replacement of buildings with a poor performance, and for a transition of the energy grid to include more renewable energy sources.

From the viewpoint of the asset managers, only the latter argument was guiding action towards the adoption of energy flexibility. As it is not feasible to have all buildings deeply renovated or replaced by 2020, TU Delft is looking towards a transition of the heat grid and energy sources to reach its goals. For example, investments were planned for a new cogeneration plant and for developing the use of deep geothermal energy. To facilitate the introduction of sustainable solutions such as heat and cold storage in aquifers, the current heat grid needs to work on lower supply temperatures. The changing grid conditions also were expected to lead to needed changes in the connected buildings.

The transition from a gas-fired heat network to a hybrid network operating with lower heat supply temperatures was thus one of the measures that sparked interest in energy flexible buildings. The asset managers found that R&D competencies and resources are needed to check the viability of this idea. They engaged in the Intelligent Heat Grid project (Agentschap.NL, 2013) together with industrial partners and consulting engineers to test the feasibility of lowering the heat grid supply temperature, for which innovation demonstration funding was received.

18.4.2 Simulation phase

To enable the development of a heat supply control strategy, building comfort and heat grid energy simulations were used to try to understand the effect of changing grid conditions on the operation of buildings. During these simulations, the asset managers were presented with new observations.

The simulation research examined various scenarios. The simulation results illustrated that conventional building control strategies, based on a simple linear relationship between supply temperature of the district heat grid and outdoor temperature, do not offer the opportunity to lower the supply temperatures without a loss of thermal comfort. The scenario analyses led to the conclusion that a dynamic heat grid control system is required. This control system needs to determine the set points, the data communication and the control of the heat generation plant and central heating systems of the buildings.

The simulations further showed that it would be feasible to reduce the heat supply temperature to many buildings (using a five-day weather forecast to optimize the heat supply). The implementation of a smart control system could theoretically lower the heat network supply temperature. However, such a control strategy would have to, as a consequence, begin heating individual buildings earlier than normally required. Technical modifications of hardware, devices, buildings and systems would also be required for the control strategy to be viable. The prediction of required energy flexibility is also challenged by possibly unpredictable occupancy rates of buildings.

Simulation results from individual buildings also showed the need to redefine the branching of the heat grid to make sure that buildings with a similar heating demand are connected to the same branch of the heat grid. In the initial situation, one supply temperature was distributed in four branches (see Figure 18.2). However, as part of the revised branching of the network, it was decided to have different supply temperatures for each of the four branches (see Figure 18.3).

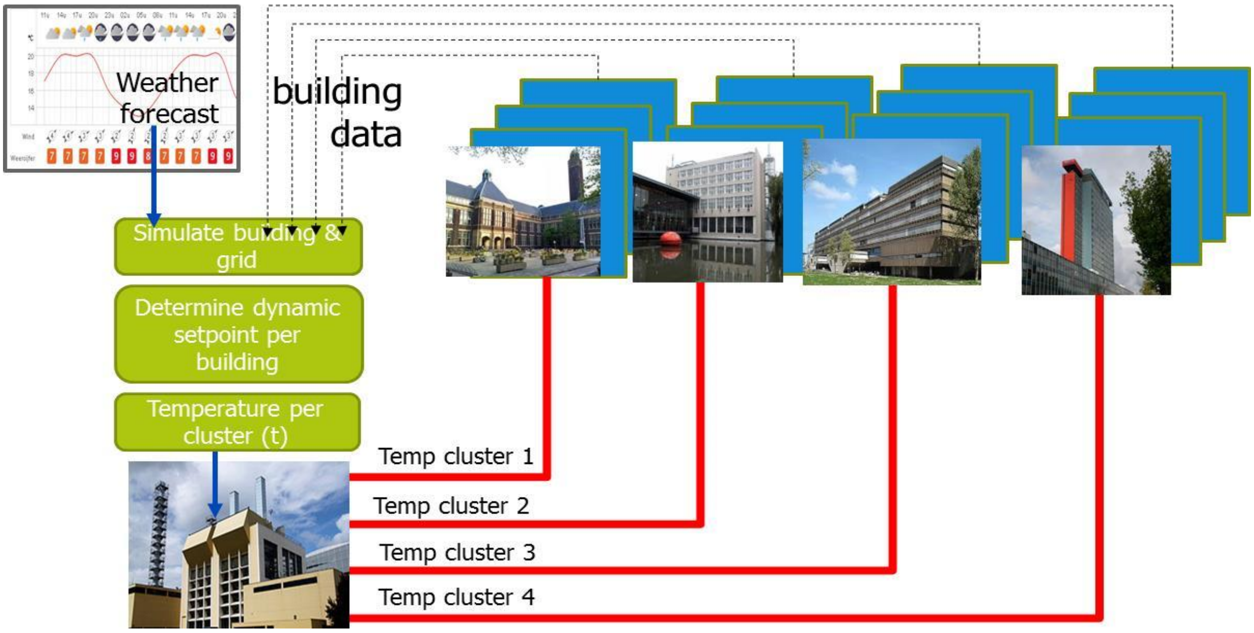


Figure 18.3 Expected changes in the TU Delft campus district heat network: branching and control strategies (future situation) (Deerns, 2015).

The proposed control system for the testing phase is also illustrated in Figure 18.3. This differs considerably from the initial control strategy shown in Figure 18.2. In the testing phase, building and weather forecast data should be used to simulate and optimize the expected performance of buildings and grids. This control strategy implies that an algorithm can change a buildings' operation of indoor climate systems based on the expected heat supply from the grid.

The transition from a high to a medium supply temperature of the TU Delft campus heat grid thus appeared to have far-reaching consequences on facility management of the buildings and for the redevelopment of the heat grid.

18.4.3 Building testing phase

The project partners further developed a model-predictive control system and tested it on one building.

The data coupling and the robustness of the simulation systems had to be tested for use in a control environment. As the building had to be kept in operation during the test, stakeholders preferred to do the testing in a low-risk period. A test was done in spring 2016 on one building (see Figure 18.4), without coupling to the control systems of the heat grid. The data coupling between the heat grid control, the building simulation and the new control system could be implemented after solving some technical and data storage problems which following allowed for initial reference checks. The system sometimes predicted an unnecessary heating demand, for example because it didn't take into account holidays. It is however particularly important to note that there were no comfort complaints during this period.

The adoption of the control system was somewhat hindered by the need to keep buildings in operation all the time and by a lack of interoperability of the building simulation, control and data systems. Some technical changes were required. Overall, the first test provided, however, the asset managers with confidence that a smart control system can work effectively in a building.

Figure 18.4 Tested building on the TU Delft campus.

18.4.4 Grid testing phase

The project partners further tested the model-predictive control system by coupling it to the heat grid control systems for one branch of the heat grid using the building connected to this branch as a reference. The tested heat grid branch and buildings are shown in Figure 18.5. This testing was done in a low-risk period (November 2016).

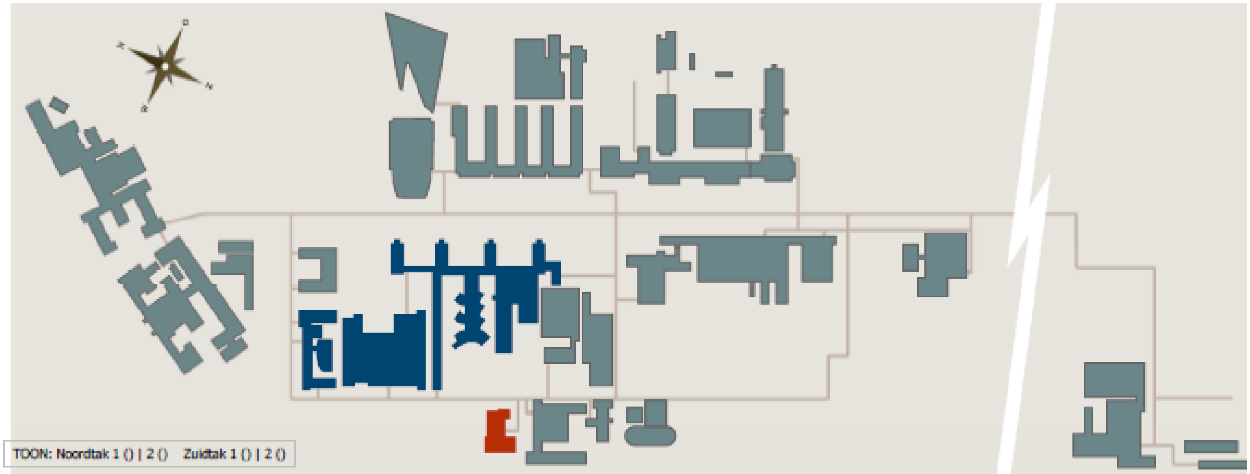


Figure 18.5 Tested heat grid branch of the TU Delft campus. Red: power plant; blue: connected building (TU Delft, 2017).

The implementation of the dynamic control system required some technical changes, such as the integration of servers, the placement of district heat grid controllers at each station, communication equipment for the data coupling between the simulation environment and the control of the heat generation, the heat grid and the buildings' heating systems. The practical modifications took over a year to implement.

There were concerns that a variety of data sources from different manufacturers had to be connected, such as those from simulation tools, various building management systems, installation controllers, meters, campus energy monitoring system and meteorological data.

There were some differences between simulated/predicted and measured heating demand and heat flow data. The increased complexity of the problem made it difficult for the asset managers to interpret the results. However, the results convinced them that the supply temperature from the heat grid can be effectively lowered using the predictive control model. The asset managers perceived that cogeneration and geothermal energy systems can be used to support the development of the heat grid.

18.5 Conclusion

It is expected that future energy flexible buildings will be able to manage their demand and generation, according to not only local climate conditions and user needs, but also related to changing grid requirements. While many studies refer to the technical challenges, this example shows that adoption of energy flexibility can be facilitated or hindered by various adoption factors.

This example shows that the operation of buildings connected on a heat grid can be simulated and tested to convince the asset managers to adopt energy flexibility. However, such an innovation trajectory requires dedicated time including research and development resources.

The successful adoption of energy flexibility can be facilitated when the asset managers perceive a relative advantage of the energy flexibility strategies, for example when being able to introduce more renewable energy systems in a district, or when energy flexibility solutions fit with their own energy or CO_2 saving asset strategies.

The perceived complexity of required building and grid changes can be a significant barrier to the adoption of energy flexible buildings. When introducing energy flexibility, additional operational activities are required, such as the installation, testing and managing of controllers, data servers, interfaces, sensors, back-up heating units, and so on, both in buildings (management and energy using systems) and networks (generation plant, controllers and branches).

Overall, the example illustrates that – when a district is owned and managed by one main stakeholder – the asset managers can be progressively motivated to integrate principles of energy flexible buildings.

18.2 Acknowledgements

This contribution was prepared by TU Delft with the support of the Dutch Enterprise Agency (RVO). The development of the intelligent heat grid was previously done with the support of the Dutch Smart Grid Innovation (IPIN) programme (supported by RVO).

Teasers on how to control of energy flexibility in buildings

19. Multi-objective genetic algorithm for model predictive control in buildings

Krzysztof Arendt and Athila Santos, Centre for Energy Informatics, University of Southern Denmark

19.1. Abstract

The study presents a multi-objective model predictive control framework and its implementation in the OU44 building located at the SDU Campus Odense (Denmark). The framework is modular and consists of a multi-objective genetic algorithm (MOGA) as the optimization algorithm, grey-box building models for predicting the effects of various control strategies, and an archiver and communication platform.

A detailed description of the study is included in the IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings (annex67.org/publications).

19.2. Building and system description

OU44 is a teaching/office building of 9,600 m^2 spread over three floors and a basement constructed at the campus of University of Southern Denmark. The building is designed as a benchmark pilot project for energy efficiency and automated performance testing. It has been operational since 2015 and was built according to the Danish Building code BR2015 with a $18.5 million budget. The purpose of OU44 was to establish a living lab for improving the energy efficiency of public buildings based on Information and Communications Technology (ICT) solutions that also account for the behaviour of occupants. The building is equipped with a balanced ventilation system controlled based on indoor CO_2 concentration, hydronic heating system (district heating), occupancy-driven lights dimmed based on the indoor and outdoor illuminance, and moving blinds controlled according to outdoor illuminance.

19.3. Method and modelling tools

The planned controlled strategy will be implemented as a direct control over ventilation dampers, radiator valves, set points for the air pressure in the ventilation duct system, ventilation air temperature (heating only), and light systems. The system objectives are to maximize indoor thermal comfort, minimize energy consumption and minimize energy costs. In addition, the system can react to the Demand Response (DR) events by temporarily sacrificing other objectives. The system utilizes simulation models predicting indoor environment conditions and energy consumption based on the weather and occupancy forecasts. These predictions can be used to minimize the negative effect of DR events, because the system will be able to optimize the overall strategy to the DR event. The exemplary strategies the system can apply are related to the building dynamics, e.g. pre-heating, pre-cooling, pre-ventilating. The simulation models are based on the grey-box modelling approach, e.g. the zone models are based on RC thermal networks. The framework is planned to be tested in the actual building and in a virtual simulation-based setup.

20. Deep reinforcement learning for optimal control of space heating

Hussain Kazmi, Enervalis and KU Leuven, Belgium

20.1. Abstract

The study investigates the efficacy of different controllers in the context of space heating in residential buildings. More specifically, it compares the performance of a novel reinforcement learning based controller with classical variants employing rule based control and model predictive control. Different price signals were used to optimize operational performance in a simulated environment, while considering the impact on occupant comfort. Additionally, the robustness of different controllers in the face of changing constraints and operating conditions was also explored.

A detailed description of the study is included in the IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings (annex67.org/publications).

20.2. Building and system description

The case study uses a building simulator to test and benchmark the learning characteristics and abilities of different controllers. The simulator constitutes an equivalent thermal parameter model (ETP), which simulates the heating of a building interior as a function of a limited number of lumped parameters, such as outdoor temperature and characteristics of the heating equipment (a modulating air-source heat pump). The building model is a deterministic second order model, which takes into account the heat being stored in the building envelope and how the building cools down in case of an outdoor temperature drop, or in the absence of heating to the building.

The objective of the controller is to leverage the energy flexibility inherent in the thermal inertia of the building to either preheat or postpone heating of the building in a way that minimizes the energy costs, while simultaneously preserving (or improving) occupant comfort. A number of different factors influence the control problem including ambient temperature, building envelope and indoor temperature, and the heat pump control actions.

20.3. Method and modelling tools

The different controllers considered in this case study were implemented using different packages in the programming language Python. A traditional rule based controller operates on a strict if-then-else basis using the indoor temperature to control the actions of the heat pump. In doing so, it does not consider the incurred energy costs. It therefore provides the lower bound against which a smarter control algorithm can be benchmarked. A model predictive controller, on the other hand, is assumed to be in possession of the building model, which allows it to choose the theoretically optimal control actions to minimize cost and maximize occupant comfort. This controller therefore forms the upper bound on performance. The proposed reinforcement learning controller presented in this example is a balance between the naive but simple rule based controller and the optimal but computationally expensive model predictive controller. It does so by directly learning optimal control actions from observed states. This makes it computationally very efficient when first developed. A different version of reinforcement learning based controller takes the form of model-based reinforcement learning, which is closer to the model predictive controller. However, for this case, the model is not assumed to be known by the controlling agent and is rather learned on the fly from observation data. The controlling agent then uses this model to optimize the performance of the heat pump. Typically, a model-based reinforcement learner would also engage in some form of policy side learning, however this was not implemented in this study.

20.4. Conclusion

By shifting consumption from times when prices are high to times when prices are low means that the building under consideration can be used for energy storage. The exact extent of this usage and its implications on using building thermal mass for providing services to the electric or thermal grid is an area for future consideration. However, this study demonstrates that it is possible to reduce energy costs by between 5 and 10%. For most households, this translates to savings of hundreds of kilowatt-hours. Likewise, this energy flexibility can also be translated more directly into providing grid services such as congestion management for the local grids with increasing electrification of heat etc.

The study shows the strengths and weaknesses of different control strategies. Model-free controllers tend to under-perform their model-based counterparts: this is especially true when it comes to cost optimization where the difference in savings can be, on average, close to 5%. However, computational complexity is one avenue that might cause model-free algorithms to become more attractive for control as it allows them to execute instructions much faster. This will become an increasingly attractive property, especially in distributed settings in the future.

21. A model predictive controller for multiple-source energy flexibility in buildings

Reino Ruusu and Ala Hasan, VTT Technical Research Centre of Finland, Finland

21.1. Abstract

Different sources of energy flexibility can exist in a building's energy system, which together can work towards a specific objective for the benefit of the building's owner (minimizing the operating energy cost), the needs of the grids (shift loads to off-peak times) or mitigate the impact of energy use (reduction of CO_2 emissions). A smart controller is needed to optimize the operation of the components of the energy system and to best exploit the multiple sources of energy flexibility. The controller should be able to take into account the current and future status of the energy system, fluctuations in the input data (e.g. energy price) and forecasts of the weather that can significantly affect the future demands and the power generated from renewable sources.

A detailed description of the study is included in the IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings (annex67.org/publications).

21.2. Experiments and Results

This contribution is about an energy management system that uses a developed Model Predictive Controller (MPC) to find optimum operation of a building's energy system for minimizing the operational energy cost. The components of the building's energy system are shown in Figure 21.1. The flexibility sources include best management of the onsite generated renewable energy (from PV panels, wind turbine and solar-thermal collectors) by using energy storage (electricity in a battery and heat in a hot water storage tank - HWST), operation of a Ground Source Heat Pump (GSHP) and electric heating element, as well as interaction with the electricity grid and district heating network.

As a conclusion, the developed MPC method is shown to be fast, needed manageable computational time and is suitable for use in detailed simulation-optimization evaluations of multiple flexibility sources. The MPC performance is found to be affected by the quality of the forecasting data of the energy demand and generation in the next time steps. However, the MPC was shown to have a better performance than a traditional rule based controller (RBC) without forecast. Energy matching of onsite-generated energy with the demand is shown to be a suitable control method when the energy export price is lower than the import price.

The description in the aforementioned Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings includes results from the operation of the MPC and the performance of different components of the energy system as well as lessons learnt form the operation of the test facility.

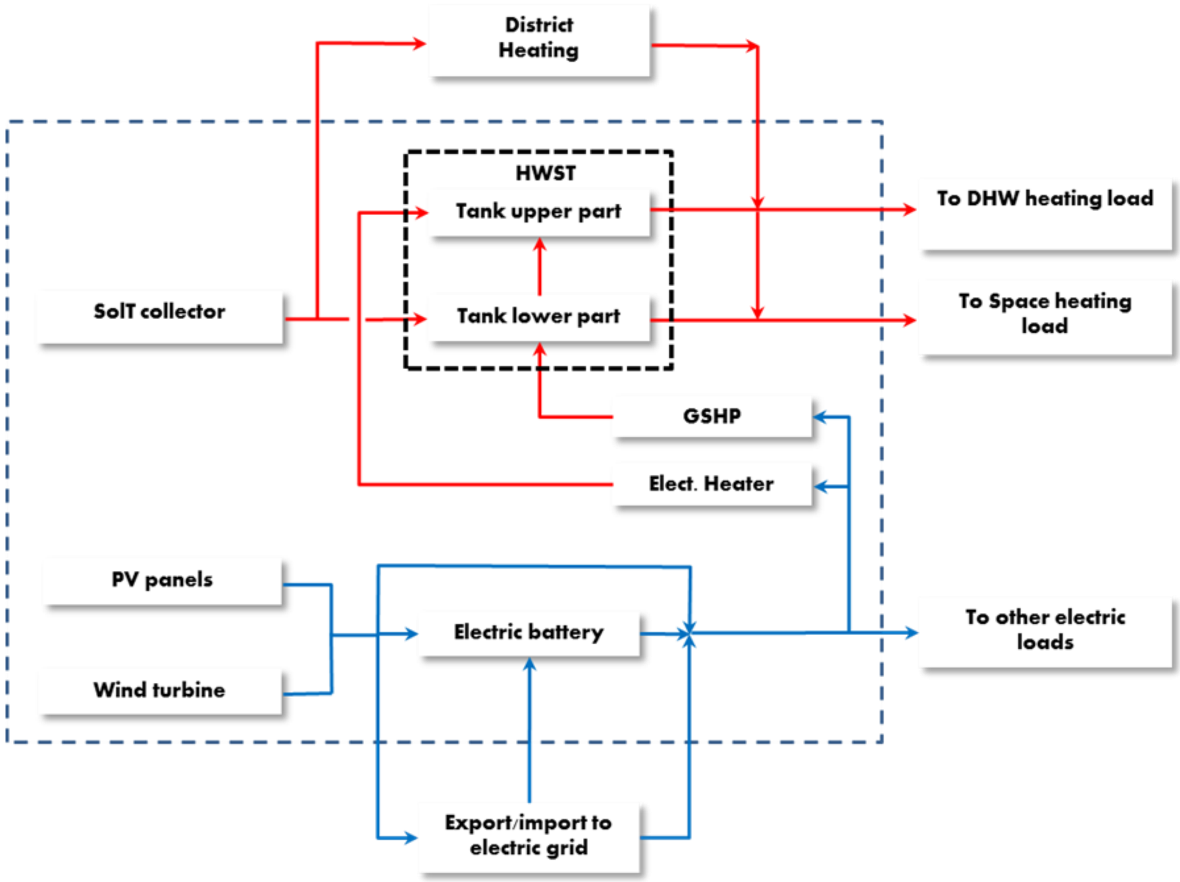


Figure 21.1 Components of the building's energy system.

22. Model predictive control for carbon emissions reduction of residential cooling loads

Thibault Péan, Catalonia Institute for Energy Research, Spain

22.1. Abstract

A model predictive control (MPC) strategy aiming at reducing the operational CO_2 emissions of heat pump cooling loads is tested on a residential building. Through a co-simulation study on a 3 day summer period, the performance of the controller is evaluated in cooling mode: it enables savings of 19.1% in CO_2 emissions compared to a standard thermostatic control.

A detailed description of the study is included in the IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings (annex67.org/publications).

22.2. Building and system description

The control strategy is tested on a residential building situated in the Mediterranean area of Spain, where the total cooling and heating loads are balanced across the year. The present study focuses on the exploitation of the flexibility potential in the summer season and thus only with the cooling and domestic hot water (DHW) loads. The eight rooms of the studied flat are air-conditioned with Fan-Coil Units, which are supplied by an air-to-water heat pump. The occupancy pattern by the 4 occupants of the dwelling is modelled stochastically, and the DHW tapping deterministically from a standard profile. The whole building and its systems are modelled in TRNSYS.

The air-to-water heat pump is reversible and used for space cooling and production of DHW in the summer season. Its performance in both modes is evaluated through black box models created from the results of static tests performed in a laboratory setup. The following parameters were varied during these tests: outdoor air temperature (controlled in a climate chamber), supply and return water temperatures (controlled by the heat pump itself and in a thermal bench). The derived model thus covers a wide range of operating conditions.

22.3. Methods and results

To test the control strategy, a co-simulation framework was set up. The TRNSYS building model serves as a substitute of the real building, and the heat pump MPC controller is developed and executed in MATLAB to benefit from its optimization features.

The MPC controller primarily aims at minimizing the CO_2 emissions related to the heat pump use. It includes additional subobjectives and constraints to guarantee users comfort and ensure a proper functioning of the heat pump by avoiding too frequent switching. To be able to project the behaviour of the building in the future (prediction horizon of 24 hours), the MPC requires simplified linear models of the heat pump and of the building envelope. The former is evaluated with the black-box model previously mentioned, while the latter is modelled by a simplified grey-box resistance-capacity (RC) network, derived from the more detailed TRNSYS model. To minimize the CO_2 emissions, a signal indicating the carbon intensity of the electricity grid used by the heat pump is also necessary. In the present case, the marginal emissions were utilized, as they represent better the emissions savings resulting from demand-side management actions as presented here.

Figure 22.1.1 presents the following time series of the co-simulation results: the input CO_2 signal, the power draw of the heat pump in the MPC case and in a reference case where the heat pump is controlled by a standard thermostat, the difference between these two power curves, and the cumulated marginal CO_2 emissions savings. It can be observed that in the MPC case, a large portion of the heat pump operation occurs during periods of low emissions, and thus results in emissions savings of 19.1% compared to the reference case.

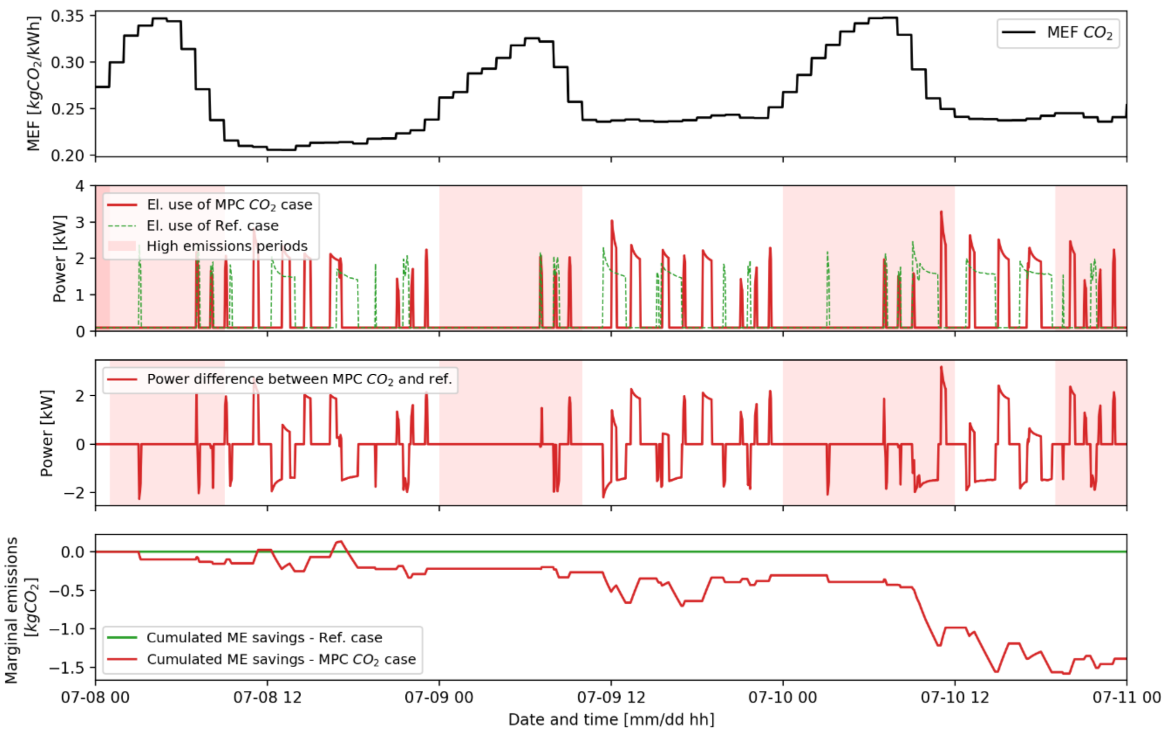


Figure 22.1 Time series of the marginal emissions factor (MEF) penalty signal, the electrical use of the heat pump in the reference and MPC CO_2 case, power difference between these two cases, and finally the cumulated marginal emissions (ME) savings.

22.4. Conclusion

A MPC strategy aiming at minimizing the carbon footprint of space cooling in a residential building was investigated. Through a co-simulation study over a 3 day summer period, emissions savings of 19.1% were observed. The results are satisfactory although the savings are mainly due to a reduction of the energy use, less from the load shifting, and the comfort conditions are slightly degraded (however remaining within acceptable levels). Such MPC strategies present great potential to reduce operational costs or emissions for space cooling or heating provided by heat pumps. However, their high development and implementation cost still slow down their deployment at a large scale.

23. Investigation of the energy flexibility of a residential building involved with the hybrid energy storages in Hong Kong

Yuekuan Zhou and Sunliang Cao, The Hong Kong Polytechnic University, HKSAR, China

23.1. Abstract

The study presents the results from an investigation of the energy flexibility of a hybrid energy system in the cooling dominated region, Hong Kong. An energy management system considering the bidirectional energy interactions was modelled, including the building-to-vehicle (B2V) and the vehicle-to-building (V2B). A quantification methodology was developed using the nonlinear impulsive responsive function of the nonlinear energy system. The impact of hybrid thermal storages, a static battery and a battery of an electrical vehicle (EV) on the dynamic energy flexibility of a building has been investigated. Moreover, technical solutions have been proposed to enhance the building energy flexibility via the operation of the hybrid energy storages.

A detailed description of the study is included in the IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings (annex67.org/publications).

23.2. Building and system description

The studied building is a two story single-family house of 100 m^2 situated in Hong Kong. The energy flexibility sources in the hybrid building energy system include the chiller systems, hybrid thermal storages (the air handling unit cooling storage, the space cooling storage and the domestic hot storage), the PV-grid system and the hybrid electric storages. Depending on the on-site renewable generation and the building energy demand, the building services systems are operated to generate more or less energy according to the requirement, which is called the REe-demand penalty responsive control. The following principles were applied:

1) In the REe-demand penalty responsive control, during the renewable surplus period, the surplus renewable energy can be either stored in the batteries or the thermal storage systems via the diversified energy conversions, to reduce the amount of electricity exported to the grid. During the renewable shortage period, the storage systems can be discharged to meet the building demand, and to reduce the amount of electricity imported from the grid. By implementing both the thermal and the battery storages, the REe-demand penalty responsive control can generate energy flexibility by shifting the surplus renewable energy from the renewable surplus period to the renewable shortage period for the domestic usage;

2) The static battery and the EV battery are implemented to enhance the building energy flexibility of the hybrid energy system with respect to different energy forms and diversified energy conversions.

The energy flexibility is here defined as the maximum fluctuation range of the difference between the energy generation and the building energy demand. Regarding various energy forms in the hybrid energy system, the flexible energy in this study is analysed using the same energy form, i.e. the electricity. Parametric analysis has been conducted following the rule-based control principle of the energy management system.

23.3. Method and modelling tools

A rule-based control modelling for the building energy management system (EMS) was developed using TRNSYS 18 – see Figure 23.1. The dynamic energy flexibility of the nonlinear system is characterized by the nonlinear impulsive responsive function. The energy flexibility of the hybrid EMS is affected by the renewable system, the hybrid energy storages, the smart grid and the electric vehicle. A series of building energy flexibility indicators, which systematically combine the renewable system, the building energy demand, hybrid energy storages, and different energy forms together with diversified energy conversions, are proposed for the energy flexibility assessment. The rule-based control strategy for the energy management of the system is flexible, in that the hybrid storages can be flexibly managed to shift energy from the renewable surplus periods to the renewable shortage periods.

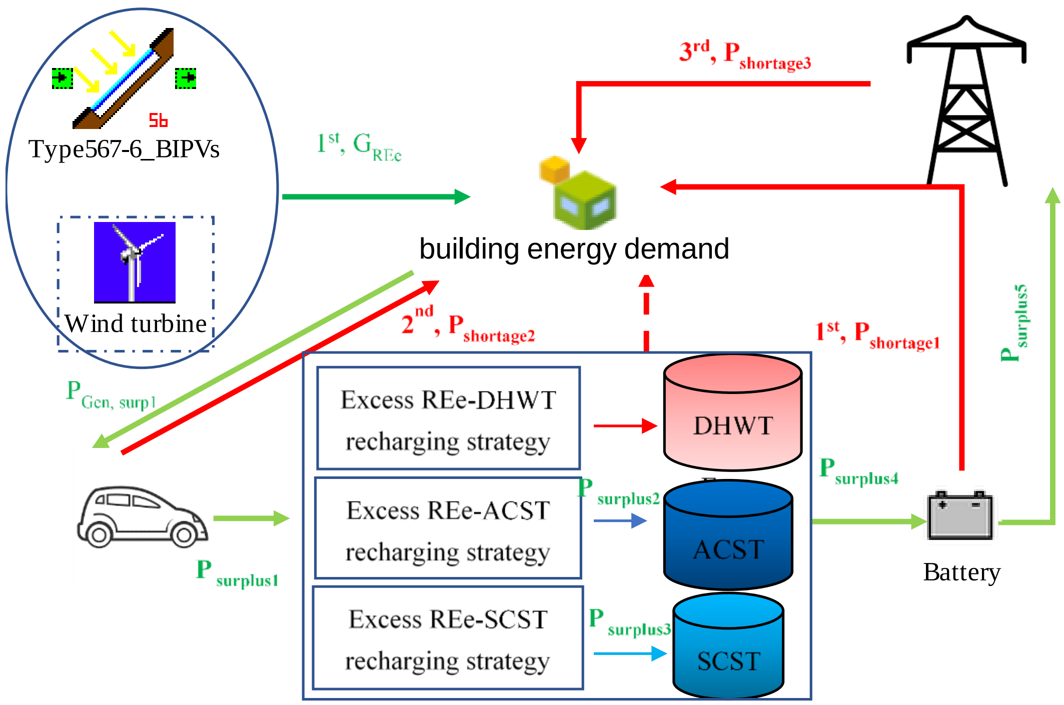


Figure 23.1 The configuration and the control principle of the EMS. (The excess REe-DHWT, the excess REe-ACST and the excess REe-SCST are abbreviations of the domestic hot water tank, the air handling unit cooling storage tank, and the space cooling storage tank)

23.4. Conclusion

The building energy flexibility can be acquired via the adoption of the excess renewable-recharging strategies, the integration of an electric vehicle, and the enhancement of both the rated capacity of the on-site renewable system and the storage capacity of the hybrid energy storage systems. The impact of the battery-based electric vehicle on the building energy flexibility is dependent on various factors, such as the time-duration of the B2V and the V2B interactions, the storage capacity and the discharging condition of the EV's battery. In the scenario when a 48 kWh EV is integrated with a residential building at daytime, regarding the energy interactions in the B2V and the V2B networks, 87.2% of the annual total energy charged to the EV (including the energy from the on-site renewable system and the electric grid) is from the on-site renewable system. Meanwhile, 71.7% of the annual total energy charged to the EV can be discharged to cover the building energy demand, and 55% of the annual energy demand for the travelling purpose can be covered by the on-site renewable system.

24. Rule-based load shifting with heat pumps for single family houses

Young-Jae Yu, Fraunhofer Institute for Energy Economics and Energy System Technology IEE, Germany

24.1. Abstract

The study is aiming at increasing the load shifting potential of decentralized heat pumps by introducing a rule-based control (RBC) coupled with different thermal energy storages in a single family house. The local residual load (energy demand not covered by renewable energy sources (RES)) is used as external signal for the RBC and a flexibility strategy based on set-point modulation depending on the local residual load was applied to the heat pump control. Besides the analysis of the RBC, the study presented the impact of load shifting with RBC regarding energetic and economic aspects in comparison to the conventional heat pump operation (heat-driven) with heat pump blocking times (3x2 hours a day). During the blocking times, the operation of heat pumps can be blocked by grid operators in order to avoid peak loads.

A detailed description of the study is included in the IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings (annex67.org/publications).

24.2. Building and system description

In this study, the investigation of the flexibility potential of the decentralized heat pump operation is investigated based on the local electricity data of the city Wolfhagen in Germany. Wolfhagen is a small town of ca. 14,000 (2018) residents in an area of 112 km² located in the Kassel District of the Federal State of Hesse. Wolfhagen´s 100 percent renewable strategy is essentially based on a newly installed wind park with a rated capacity of 12 MW and a PV park with a rated capacity of 12 MW. For the simulation study, a single family house is modeled with multiple thermal zones using TRNSYS type 56. The building model has two floors with a total floor area of 160 m² and consists of 11 thermal zones representing a typical single family house in Germany. The single family house is equipped with a ground source heat pump (GSHP). The ground source heat pump model has a COP of 4.5 in the specified test conditions (source inlet temperature of 0 °C and load outlet temperature of 35 °C).

24.3. Method and modelling tools

The flexibility of buildings for space heating and domestic hot water (DHW) supply can be controlled in different manners. This study focuses the straightforward RBC, which aims at increasing the consumption of RES during peak periods with predefined rules. In general, RBC provides non-mathematical concepts and conditions into a control solution. Typically, there is a programmable fuzzy logic controller (e.g. thermostat) with a predefined control scheme that is executed based on the external data (electricity price signal). The RBC continuously receives the information about the electricity price to make decisions in order to adjust new set point temperatures of the thermal energy storage (TES) based on the new information received from the grid operator. Thereby, RBC uses different TES in the building such as, building mass, buffer storage for the space heating and domestic hot water (DHW) storage as shown in Figure 24.1 and compare this with a conventional heat pump operation.

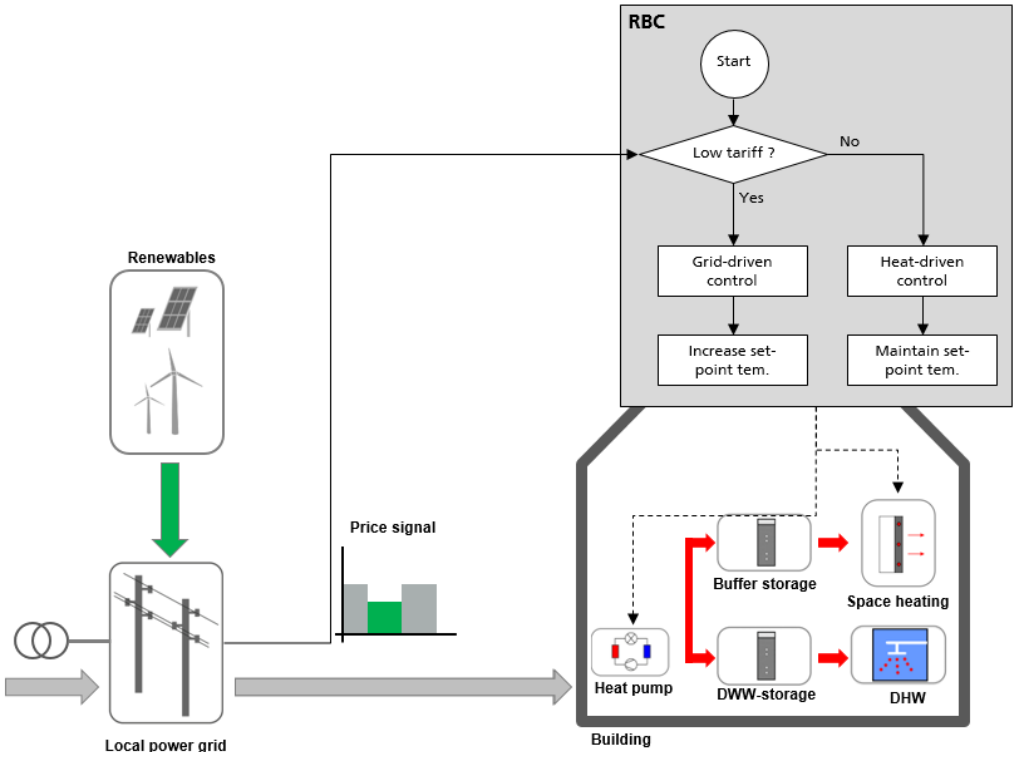


Figure 24.1 Schematic diagram of the RBC.

24.4. Conclusion

The operation of the heat pump with RBC is evaluated regarding energetic and economic aspects. From an energetic point of view, the load shifting of the heat pump with a RBC provides disadvantages such as additional electricity demand and reduced the coefficient of performance (COP) and seasonal performance factor (SPF) of heat pump if the energy balance boundary is limited to final energy use. The expansion of the system boundary from the final energy input to the system to the primary energy input (primary energy ratio - PER) can enable the evaluation of the surplus electricity utilization for load shifting more properly, regarding the energy chain from generation to consumption. For this reason, the heat pump operation should be evaluated, in the future with a high share of renewable energy sources, with the PER besides SPF. From an economic point of view, the heat pump operation with RBC for load shifting provides saving potential of the operating costs if the price difference between low and high tariffs is higher than 0.12 €/kWh. The utilization of the building mass can enable economic benefits, if the surplus electricity price is very low or delivered for free, in order to avoid urgent grid congestions.

25. Predictive rule-based control for heating demand response in Norwegian residential buildings

John Clauß, Norwegian University of Science and Technology, Norway

25.1. Abstract

Four demand response (DR) strategies for heating a Norwegian single-family house are investigated: two strategies are based on the electricity spot price, and two strategies use the average $CO_{2eq.}$ intensity of the electricity mix as a control signal. The DR measures are implemented into predictive rule-based controls (PRBC) that vary temperature set-points (TSP) for space heating (SH) and domestic hot water (DHW) heating depending on the control signals. Results show that, in Norway, price-based controls typically lead to increased annual emissions. Furthermore, it is challenging to achieve cost and emissions savings in the investigated Norwegian bidding zone because there are only limited daily fluctuations in the spot price and the $CO_{2eq.}$ intensity of the electricity mix.

A detailed description of the study is included in the IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings (annex67.org/publications).

25.2. Building and system description

The building geometry is based on the ZEB LivingLab which is located in Trondheim, where two different building insulation levels are used in this study. These insulation levels comply with the Norwegian building standards from 2010, TEK10, and with the Passive House Standard for residential buildings NS3700, PH. A model of the building is created in IDA ICE Version 4.8. Electric radiators are used for SH, which are the most common SH system in Norwegian houses. There is one electric radiator in each room with a power equal to the nominal SH power of the room at design outdoor temperature of -19 °C. DHW is produced in a storage tank, which is equipped with an electric resistance heater with a capacity of 3 kW. The charging of the DHW storage tank is controlled by two temperature sensors that are installed in the bottom and in the top of the tank.

25.3. Methodology: control strategies

The energy flexibility potential of four different PRBCs is evaluated; two strategies are based on the electricity spot price and two scenarios are based on the average $CO_{2eq.}$ intensity of the electricity mix. The respective control strategies are based on different principles. The main objective of the control strategies is to shift the load away from peak hours and at the same time aiming at reducing costs or carbon emissions. Figure 25.1 illustrates the principle of one of the carbon-based control strategies for the TEK10 building during 48 h of the heating season in the Norwegian bidding zone NO3.

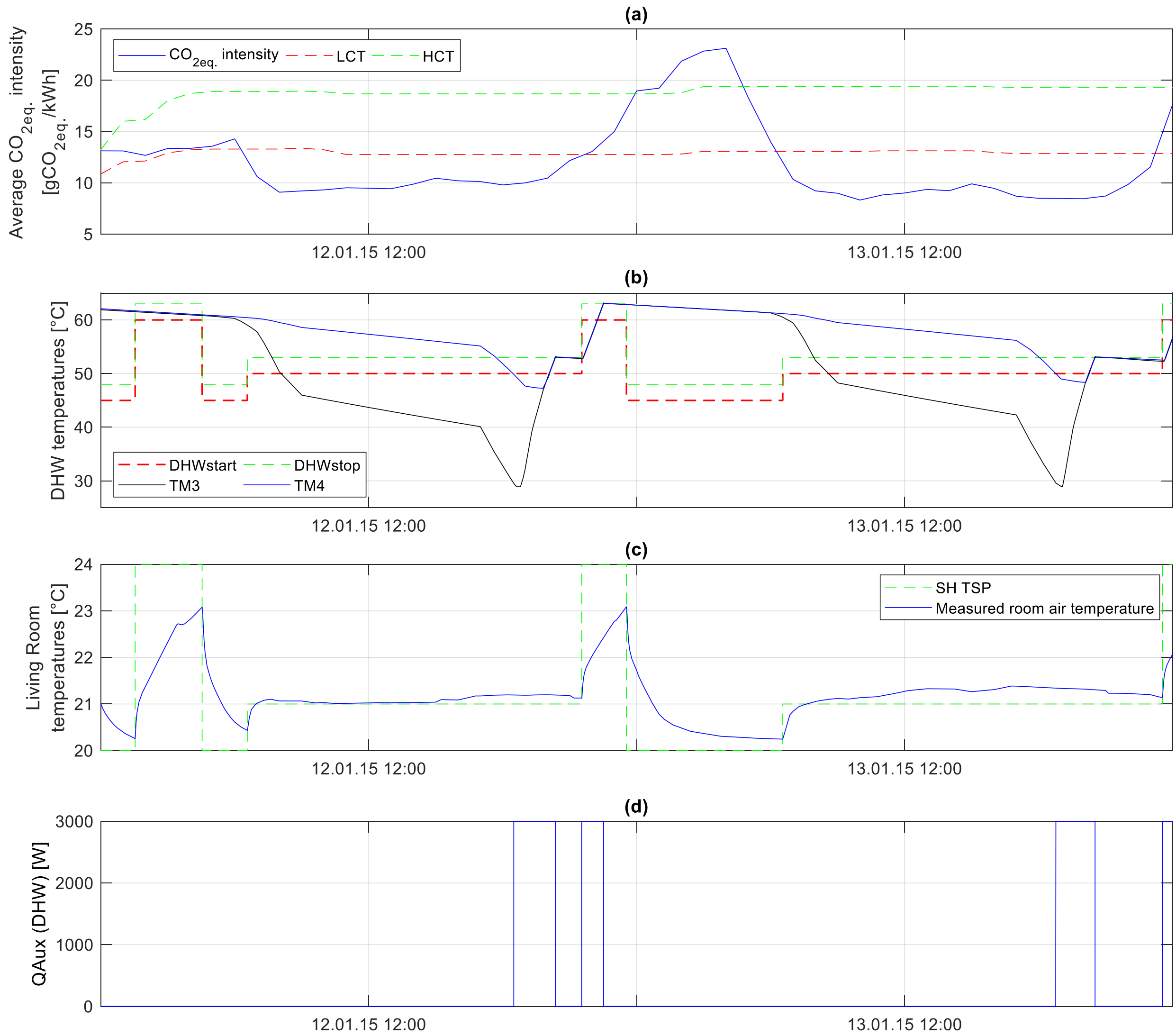


Figure 25.1 Illustration of a carbon-based control principle for NO3 for a TEK10 building during a 48 h period (LCT is Low-carbon threshold, HCT is High-carbon threshold, DHWstart and DHWstop are the start and stop temperatures for DHW, TM is two temperature measurement in the water tank).

25.4. Results and conclusion

The electricity use increases for all cases. It is found that the CO_2-based and price-based control strategies lead to contradictory results: if the aim is to reduce emissions (CO_2-based controls), costs are increased and if the aim is to reduce costs (price-based controls), emissions are increased significantly. This is due to the typical daily profile for Norwegian spot prices and $CO_{2eq.}$ intensities, because $CO_{2eq.}$ intensities are low, when spot prices are high and vice versa.

Therefore, a trade-off between the objectives has to be made to satisfy both aims. Similar trends for annual costs and emissions are visible for both building insulation levels. It should be investigated whether the absolute maximum savings could be increased with advanced controls such as model-predictive control. Furthermore, the potential emission and cost savings would be stronger in locations with higher daily fluctuations of the spot price and average $CO_{2eq.}$ intensity. Due to limited fluctuations for price and $CO_{2eq.}$ intensity within one day in bidding zone NO3, potential cost and emission savings from load shifting are outweighed by the increased electricity use for heating independent of the building insulation level.

26. CO_2-aware heating of indoor swimming pools

Rune Grønborg Junker, Department of Applied Mathematics and Computer Science, Technical University of Denmark

26.1. Abstract

In this case study, economic model predictive control is used to control the heating of indoor swimming pools. The objective is to minimise the CO_2 emission caused by the power plants producing the electricity used by the heat pumps of the swimming pools. The case study shows how flexibility successfully can be utilized by simply having varying penalty signals describing the cost of electricity in time.

A detailed description of the study is included in the IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings (annex67.org/publications).

26.2. Building and system description

The study is dealing with indoor swimming pools located in Danish summer houses. The swimming pools are heated by air-to-water heat pumps, which are controlled to activate the energy flexibility associated with the thermal inertia of the water in the swimming pools. In total 30 houses are controlled. To simplify the setup and protect the hardware, the heat pumps are activated using the temperature set point. The set point is increased to turn the heat pumps on and vice versa to switch them off. The air temperature is not controlled in this project, but left as is with standard thermostatically controlled heating. The summerhouses are rented on a weekly basis, so the test period includes both periods without any residents using the pool and periods where it is used. When the summerhouses are not rented, the temperature of the pools is reduced to limit energy consumption. Since the heat loss of the swimming pools depends on the ambient temperature, the power consumption does as well. Thus, the varying weather condition and occupancy of the summerhouses impacts the heating of the swimming pool, and thus also the available energy flexibility.

The control of the heat pumps is performed by an economical model predictive controller (MPC) based on weather and demand forecast and with a penalty signal as input. The penalty signal has been both the CO_2-intencity in the power grid and the price of electricity on the Danish regulation market.

26.3. Conclusions

It was shown that the energy flexibility varies tremendously in time, both due to seasonal changes in weather conditions, and especially due to changes in occupancy. This is even more pronounced due to the summerhouses having many periods with no occupancy, where the temperature of the swimming pools is lowered in order to save energy. During the transition between being occupied and not occupied and vice versa, it was shown that it almost never was profitable to be flexible.

27. Economic model predictive control for demand flexibility of a residential building

Christian Finck, Eindhoven University of Technology, Netherlands

In this study, an economic model predictive control (EMPC) was validated and tested to optimise demand flexibility. The operational costs of energy usage were associated with demand flexibility, which was represented by three flexibility indicators: flexibility factor, supply cover factor, and load cover factor. The results from a day-long test showed that these flexibility indicators were maximised when the EMPC controller's demand flexibility was compared to that of a conventional proportional-integral (PI) controller. The EMPC framework for demand flexibility can be used to regulate on-site energy generation, grid consumption, and grid feed-in and can, thus, serve as a basis for overall optimisation of the operation of heating systems to achieve greater demand flexibility.

A detailed description of the study is included in the IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings (annex67.org/publications).

27.1. Method and modelling

A Dutch residential building was used as a testbed to conduct the experimental case study. The dwelling was located in the city of Utrecht, the Netherlands, representing a typical old row house from 1910. The house has a floor area of 75 m^2 divided on three floors (kitchen on first floor, living room on second and bedroom on third). During cold periods, when heating was required, the room temperature was controlled by one thermostat located on the second floor. The annual heating energy usage was about 0.47 GJ/m^2, which was delivered by a gas-fired condensing boiler. For modelling of the heating system and the building, artificial neural network (ANN) models were identified from measurements. The ANN models were validated and implemented in the MPC framework. The validation of the ANN-MPC was conducted based on the heating consumption. The MPC was modified to EMPC, the heating system was modified to a virtual heat pump, and photovoltaic (PV) panels were virtually installed at the building to simulate on-site electricity generation (Figure 27.1).

27.2. Conclusion

An ANN-MPC approach was used to represent the dynamical behaviour of the heating systems and the building. Another ANN model was developed for weather forecasting to obtain global and horizontal solar radiation. All ANN models and the ANN-MPC were validated and tested, showing good prediction performance. The application of ANN models can be recommended for future identification of the dynamics of buildings and heating systems and for weather forecasting. The application of ANN-MPC can be recommended as a generic approach for optimal control of energy usage in energy systems in residential buildings.

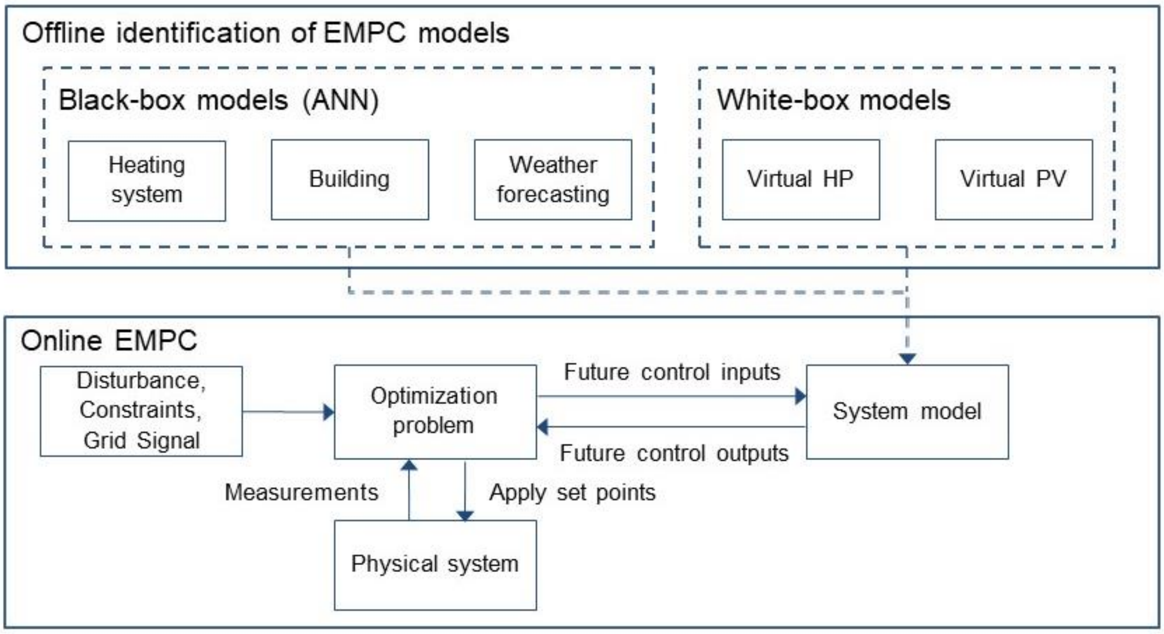


Figure 27.1 Methodological framework of the economic model predictive controller (EMPC).

An EMPC approach was introduced to optimise demand flexibility. For this approach, operational costs of energy usage were associated with demand flexibility, which was represented by three flexibility indicators: flexibility factor, supply cover factor, and load cover factor. The operational costs were (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. By taking into account the operational costs of energy usage, one objective function can be created, and demand flexibility can be optimised. As an example, assuming positive prices for electricity consumption from the grid, negative prices for electricity consumption from on-site PV generation, and negative prices for grid feed-in from on-site PV power generation resulted in an increase of the flexibility factor, the supply cover factor (self-consumption), and the load cover factor (self-generation). This generic approach offers the possibility to regulate on-site generation, grid consumption, and grid feed-in. The methodology can be adapted to flexibility indicators which are associated with the costs of energy usage.

28. Implementation of demand response strategies in a multi-purpose commercial building

Despoina Christantoni, Mohammad Saffari, Mattia De Rosa, Donal P. Finn, University College Dublin, Ireland

28.1. Abstract

Improving demand-side energy flexibility in more advanced ways can help to increase the overall capacity of the power systems to integrate variable renewables and to help reduce the overall systems costs. Demand response (DR) techniques can be used to provide the necessary flexibility to the grid. The current study aims 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. Simulation results have shown that considerable reductions of electrical power demand when targeting centralized loads such as chillers can be achieved.

A detailed description of the study is included in the IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings (annex67.org/publications).

28.2. Description of Case Study

A mixed used commercial building, the Student Learning Leisure and Sports Facility located on the University College Dublin (UCD) campus in Dublin (Ireland), was chosen as a demonstration site. The selected building exhibits a strong commercial profile including a wide range of HVAC systems, space usage and occupancy patterns. Moreover, a Building Energy Management System controls and monitors all the primary and ancillary equipment of the building. Electricity, gas and district heating meet the energy demand of the building, thereby providing a flexible combination of energy vectors for DR analysis. The building has an 11,000 m^2 floor area and consists of three floors. It contains a gym, a 50 m x 25 m swimming pool, leisure rooms, meeting and seminar rooms, studios, health facilities, offices, shops and a cafe space. Additionally, it contains spaces dominated by different loads and occupancy patterns which facilitate the evaluation different DR strategies for different loads and zones. For example, the swimming pool and lesisure spaces exhibit large occupancy fluctuations on an hour-to-hour basis, while the offices have almost constant occupancy during their operational hours. The main objectives of the present study are:

- to develop adaptive DR strategies that maintain occupant comfort but still meet varying utility / aggregator requirements under different boundary conditions,
- to apply different available DR strategies, targeting building HVAC systems, which were developed to maximize building flexibility by providing the requested load with the lowest impact on occupant comfort,
- to analyse the potential of DR as a possible measure to enhance renewable energy systems penetration.

28.3. Results

Regarding demand reduction of the electrical power, the chilled water temperature control strategy provides the largest reduction by up to 14.2 % of the baseload (see Figures 28.1). In addition, delivery equipment, (i.e., fans and pumps) on/off control constitutes a significant DR load, but it requires careful planning to ensure occupant comfort in zones is maintained, especially where considerable heat gains occur. Furthermore, load reduction was observed to be highly affected by the time of day at which the strategy is implemented, this is especially true for air temperature set point adjustment.

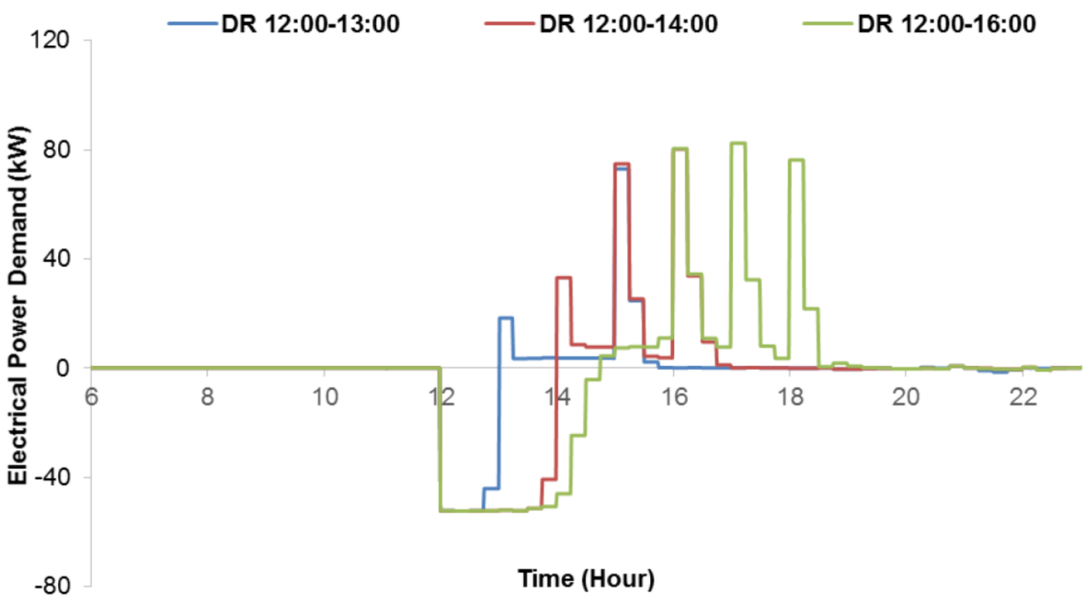


Figure 28.1 Difference in the building electrical load demand for the chilled water temperature strategy (July, 15-minute intervals) (Christantoni et al., 2016).

It can be seen from the results that even for temperate climate conditions, as exhibited in Ireland, there is a considerable DR potential in the commercial building sector, which can be utilised to provide additional flexibility to electricity end-use demand profiles, thus promoting the integration of renewable energy system. After the DR event, significant rebound behaviour is evident, which increases with the duration of the event. Although the rebound effects are significant, the overall energy consumption of the building is reduced when implementing the DR strategy.

28.4. Conclusion

A combined evaluation of the capabilities of different demand response strategies to maintain occupant indoor thermal comfort while simultaneously meeting utility/aggregator requirements regarding the immediacy and the duration of the load reduction is presented in the aforementioned IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings. For further information please refer to this report.

Increasing the chilled water temperature proved to have the largest DR potential. It can provide up to 14.2 % load reduction in summer, when most of the analysed zones required cooling, without any significant effect on occupant comfort.

Simulation results have shown that when there is a considerable cooling demand in the building, the strategy is capable of providing a load reduction only for a limited duration. Specifically, for summer events commencing at noon and of a duration longer than 2.5 hours, the electrical power demand was increased in comparison with the base case.

Delivery equipment on/off control constitutes also a significant DR load, but it requires careful planning to ensure occupant comfort in zones is maintained, especially where considerable heat gains occur. In addition, it was observed that longer duration demand response events are more likely to disrupt occupant comfort.

29. Experimental assessment of energy flexibility potential of a zone with radiant floor heating system

Ali Saberi Derakhtejani, José Candanedo and Andreas Athienitis, Civil and Environmental Engineering, Concordia University, Montreal, Canada

29.1. Abstract

The study investigates the potential energy flexibility of a hydronic radiant floor heating system embedded in a concrete slab. The energy flexibility potential of the radiant floor was estimated from experimental measurements for a specific change in the zone air set point profile. The study was carried out in an experimental room designed to simulate the conditions of an office space near a window.

A detailed description of the study is included in the IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings (annex67.org/publications).

29.2. Building and system description

The case study was performed in a test cell located at Concordia University's solar simulator/environmental chamber (SSEC) laboratory. The temperature of the SSEC can be controlled within a wide range (between -40 °C and +50 °C) and, thus, allow for a great deal of flexibility in terms of testing conditions. The test cell is a 3m×3m×3m office placed inside the environmental chamber and it has a radiant floor heating system. The energy flexibility of the radiant floor is defined as the difference between the energy consumption of the baseline radiant floor heating load profile and the increase/decrease of the heating profile due to increase/decrease of set point of the zone air temperature.

29.3. Highlight of results

It was observed that relatively small adjustments of the zone air temperature set point result in significant changes in the heating load, and thus provide a certain energy flexibility potential. This flexibility, along with applicable strategies in response to a specific price signal profile, are evaluated as shown in figure 29.1. It was observe that with the chosen set point modulation the radiant floor heating system offers about 4 hours of power shifting potential.

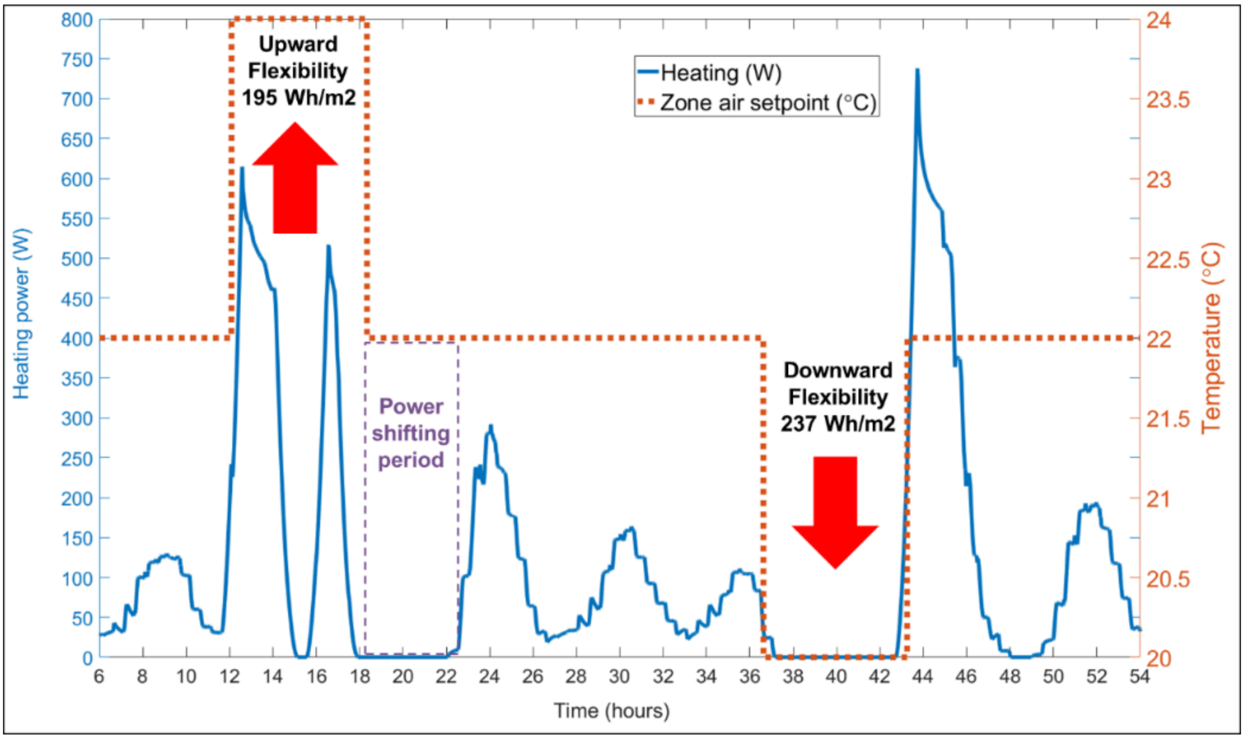


Figure 29.1 Heating power of the radiant floor system and the calculated upwards/downwards energy flexibility.

30. Aggregation of energy flexibility of commercial buildings

Anjukan Kathirgamanathan, Killian Murphy, Mattia De Rosa, Eleni Mangina, and Donal Finn, University College Dublin, Ireland

30.1. Abstract

Commercial buildings are able to provide energy flexibility through a variety of mechanisms, whether through shifting consumption of HVAC systems, utilising active thermal energy storage, active electric storage in the form of batteries, shifting to onsite generation or through a combination of these measures. The question then arises for the building energy manager on how to optimally provide flexibility, given different efficiencies and costs associated with each strategy. Current approaches often only focus on individual strategies as opposed to the total available flexibility of a building.

A detailed description of the study is included in the IEA EBC Annex 67 report Control strategies and algorithms for obtaining energy flexibility in buildings (annex67.org/publications).

30.2. Description of Case Study

This example investigates the issue of calculating the total energy flexibility through the use of a US-DOE (United States Department of Energy) large commercial building archetype model as a virtual demand response (DR) testbed building. The 'Large Office' reference building has a gas boiler for heating, water-cooled chillers for cooling and a multizone variable air volume system for air distribution. The archetype model was modified to add a lithium-ion battery to provide a means of energy storage and source of energy flexibility. Finally, a solar PV array was also added to the building to provide a further flexibility source. For further details on the reference building model please see the aforementioned Annex 67 report.

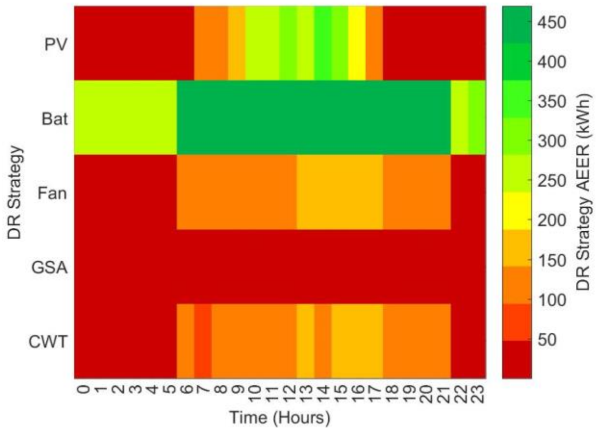
The research questions can be summarised as follows:

- Can a suitable framework be identified that considers the various demand response strategies available in a commercial building?
- Can the various demand response strategies be aggregated to calculate the total flexibility that a building can offer?

This study considers four demand response strategies (chilled water temperature adjustment (CWT), global setpoint adjustment (GSA), fan modulation (FAN) and battery (BAT)) for a summer design day case using the typical meteorological year (TMY) data for Dublin, Ireland. A flexibility window of one hour in duration is considered which allows a daily profile to be created of the flexibility available. Two sets of energy flexibility indicators are specified in this study, both modified from that existing in literature to be directly applicable from a grid perspective. The first indicator is the "Available Electrical Energy Flexibility" (AEEF) and is a measure of the quantity of flexibility available. AEEF essentially calculates the total deviaiton in energy consumption between the DR case and the reference case over the duration of the DR event. The second indicator is the storage efficiency (η_{AEEF}) which captures the magnitude of any "unwanted effects" to the electricity demand profile from applying a demand response strategy.

30.3. Results

First, considering all the demand response strategies individually, the daily profiles of available electrical energy flexibility (for downwards flexibility) is illustrated in Figure 30.1 (left). This shows the capacity for shifting load given a DR event of 1 hour for each hour of the day. Figure 30.1 (right) shows the efficiency of all the demand response strategies as a daily profile, again given a DR event of 1 hour. Using this information, the different strategies can be ranked in terms of efficiencies. A building operator can use the information from both these graphs to act for a given demand response event. The case where a combination of strategies has to be used to obtain the required amount of energy flexibility is investigated and presented in the aforementioned Annex 67 report.



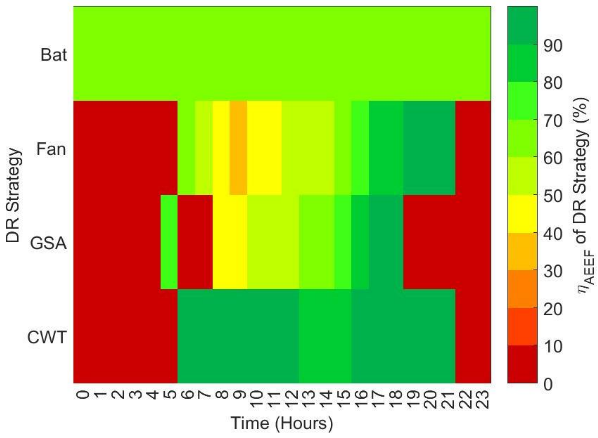


Figure 30.1 Left: AEEF – All DR Strategies (Down Flex) – Daily Profile. Right : η_{AEEF} – All DR Strategies (Down Flex) – Daily Profile.

30.4. Conclusion

A methodology to quantify and present the available electrical energy flexibility from the various strategies as well as the total energy flexibility available from a typical commercial building has available from various demand response strategies cannot be simply summed and simulation is required to calculate the total flexibility in these cases. Modified energy flexibility indicators that are been illustrated. When strategies interact due to coupling of the systems, the energy flexibility more generalised to the various demand response strategies available in a commercial building and the provision of both down and up flexibility are presented. These indicators are also more relevant directly to the grid as they consider the electrical load rather than the thermal load.

Teasers on how to model energy flexibility in buildings and clusters of buildings

31. Development of a data driven approach to investigate the energy flexibility potential of building clusters

Rongling Li, Department of Civil Engineering, Technical University of Denmark

31.1. Abstract

The study investigates a data driven approach to simulating a generic building cluster that could resemble any mix of building archetypes and occupancy. The energy flexibility potential of clusters of apartment building was estimated by using data from surveys and available statistics in Denmark for the worst case scenario, i.e. when the end users do not allow any disturbance when they are at home, so that energy flexibility is only available when residents are not at home. The uncertainty of the energy flexibility potential due to uncertain occupancy and various archetypes was quantified for different scales of building cluster. The resulting hybrid-model is a combination of a building model and an occupancy model and includes the different factors that influence the potential energy flexibility of buildings.

For a more detailed description of the study, please see the IEA EBC Annex 67 report Modelling of possible Energy Flexibility in Single Buildings and Building Clusters (annex 67.org/publications).

31.1. Building and system description

Heat pumps are assumed to be used for space heating to provide energy flexibility. The following principles were applied:

- Heat pumps can be controlled for flexible electricity usage only during the time period when occupants are away, i.e. when the home is unoccupied. This is the worst case scenario, i.e. the minimum amount of flexibility offered by a apartment assuming that end users do not allow any disturbance of their energy supply when they are at home, so external control can only be applied when they are not at home.
- The occupancy pattern is considered at the household level.

The energy flexibility is thus defined as the adjustable range of heat pump power during the period the apartments are unoccupied. Due to the stochastic nature of occupancy in households, the energy flexibility in this study is a probabilistic distribution with uncertainties instead of a determined number. The uncertainty of energy flexibility can be defined as the degree of dispersion of the distribution. Our hypothesis is “The stochasticity of occupancy declines with the scaling-up of a building cluster, as does the uncertainty of energy flexibility”.

31.2. Method and modelling tools

A data-driven approach was developed to model the energy flexibility of a building cluster, using MATLAB. The energy flexibility of a given building cluster is greatly influenced by the physical characteristics of the building and the occupancy pattern of individual households. A hybrid-model approach was used that consists of two parts: Thermal resistance and capacity (RC) models for the buildings with each building represented as one RC node, and occupancy models for buildings considering occupancy at the household level (Figure 31.1). The construction of the model is flexible, in that a building cluster can in principle be modelled with any mix of parameters such as the number of buildings, building types and construction year.

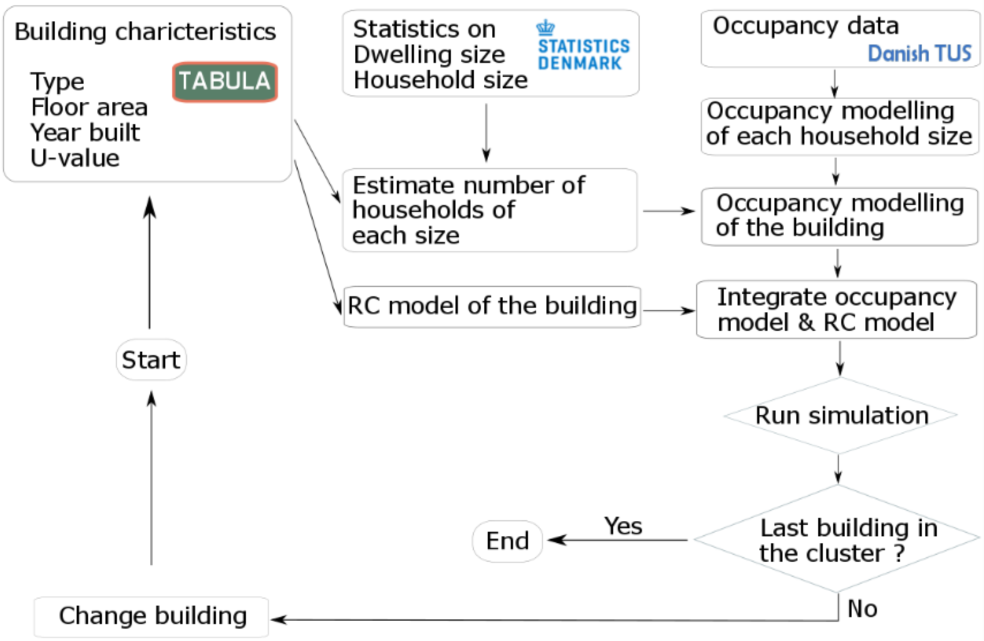


Figure 31.1 Flow diagram of quantification of building cluster energy flexibility using a data-driven approach.

31.3. Conclusion

The uncertainty of the building energy flexibility potential caused by the stochasticity of occupancy patterns was evaluated. It was found that when the size of a building cluster was scaled up, the uncertainty became negligible. In other words, the uncertainty of the occupancy decreases when the aggregated number of residents increases. The uncertainty of energy flexibility was less than 10%, when about 700 households were aggregated. In comparison with new buildings with good thermal insulation, older buildings have higher energy flexibility potential. In addition, it was found that the older the building is, the higher the energy flexibility it has. The model can be a tool for simulating the potential of energy flexibility from building for district or even regional energy planning when using the available flexibility to address various challenges caused by fluctuations in the power available from renewable energy sources.

The developed method may be useful for a number of practical applications, e.g. to support the design of flexibility service products in the electricity and heat markets; to help aggregators in creating a building-based portfolio that has a statistically steady and predicable performance; and to facilitate city and network planning by providing improved prediction of building clusters' energy profiles.

32. Flexibility analysis for smart grid demand response

Sarah O’Connell, National University of Ireland, Galway, Ireland

32.1. Abstract

The aim of the study is to generate models to define the flexibility ranges for contracts between buildings, aggregators and grid operators. Flexibility ranges are then visualised through scenario generation. The scenarios visualise the quantity, in power (kW), and duration (time) of the available flexibility for a building. Two sets of sample scenarios for flexibility are generated. The first is for a one-hour flexibility event, the second is a four-hour flexibility event. Flexibility is denoted as a percentage of total peak load. The scenarios are then validated by conducting one and four-hour experiments at the pilot building, which was modelled.

For a more detailed description of the study, please see the IEA EBC Annex 67 report Modelling of possible Energy Flexibility in Single Buildings and Building Clusters (annex67.org/publications).

32.2. Building and system description

The building that is modelled in this study is a 5,700 m^2 mixed use building with classrooms, offices and workshops. The peak power load of the building is approximately 140 kW and its base load at evenings and weekends is between 20 kW and 40 kW. The systems modelled for flexibility are a second life Electric Vehicle battery system with a 48 kWh capacity, a PV array and HVAC loads such as Air Handling Units (AHUs) and a Variable Refrigerant Flow (VRF) heat pump system.

32.3. Method and modelling tools

Scenario modelling using flexibility characterization was conducted. The flexibility characterization process, shown in figure 32.1, is represented as a flowchart through which to navigate the significant amount of data such as equipment specifications, drawings and documents available for buildings which are required to assess the power and energy flexibility of a building. The objective of the flexibility characterisation process is the elimination of non-flexible systems and identification of key parameters for flexible storage, on-site generation and loads. These key parameters are then captured in a flexibility matrix. The output of the modelling process is a visualisation of the available power flexibility in kW against a standard daily load profile for one-hour and four-hour scenarios.

Validation of the predicted results was conducted through on-site testing using the equipment in the building. The scenario modelling proved to be accurate for the HVAC systems but high frequency variations in PV output and technical issues with the prototype battery system resulted in the validated flexibility differing from the modelled flexibility.

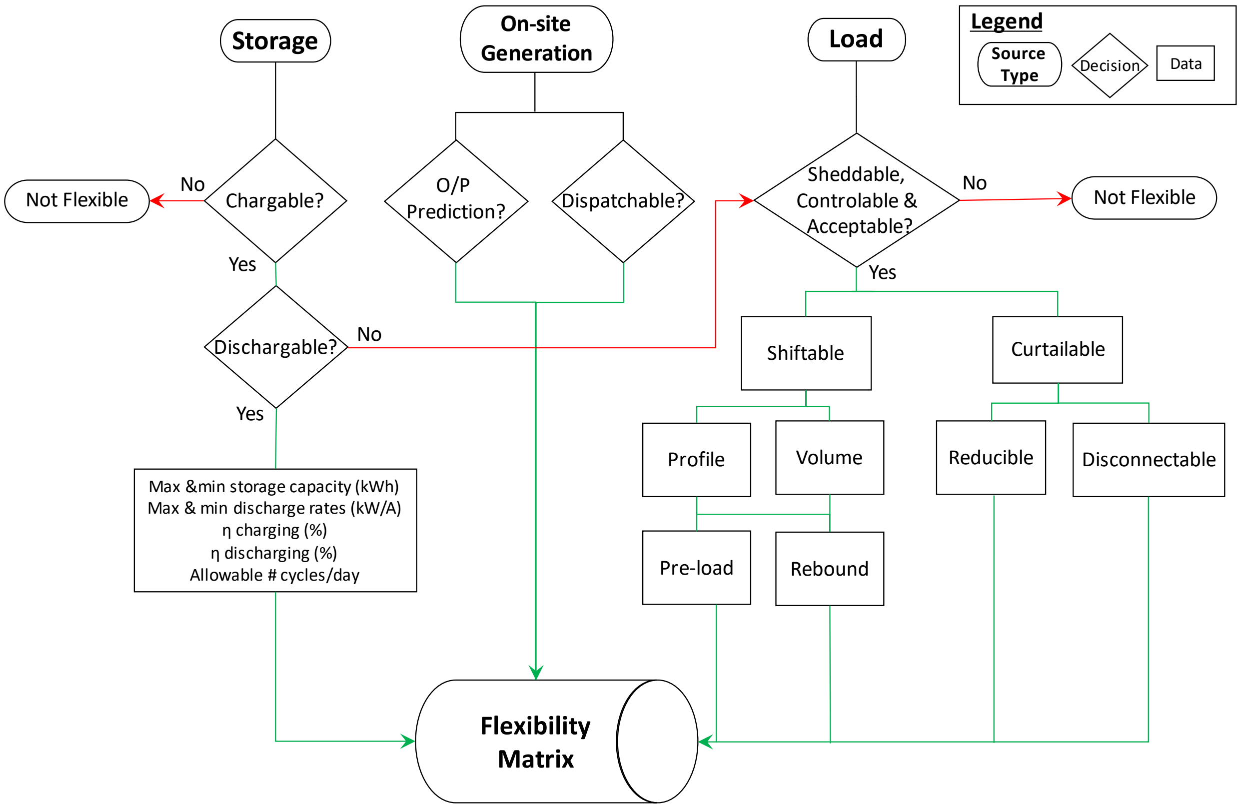


Figure 32.1 Flexibility Characterization Process.

For further information on the applied modelling methodology and graphs of the scenarios generated, please see the aforementioned IEA EBC Annex 67 report Modelling of possible Energy Flexibility in Single Buildings and Building Clusters.

32.4. Results & Conclusions

The two test cases modelled are a) activating the flexibility of the battery system by itself and b) activating two types of HVAC load - Air Handling Unit (AHU) fans and Variable Refrigerant Flow (VRF) heat pump system along with PV renewable generation. These scenarios were modelled using the scenario modelling method and validated through experiments in the building. The results, expressed as a percentage of building peak load, predict second life battery flexibilities of 26 % for a one-hour flexibility event and combined PV & HVAC flexibilities of 19 %. For the four-hour event the predicted flexibilities are 8% for the second life battery system and 20% for the PV & HVAC.

In conclusion, the results demonstrated that the capacity and maximum discharge rate of the battery system had a significant impact on the available flexibility, particularly for the one-hour scenario. It was further shown that during longer events, such as the four-hour scenario, load sources such as HVAC become much more significant, doubling the flexibility range of the building. The applied method demonstrates the effectiveness of the scenario modelling in predicting the available flexibility at a building.

33. Investigating the energy flexibility of typical Canadian homes: the potential of building thermal mass and photo-voltaic system with battery storage

Kun Zhang, Department of Mechanical Engineering, Polytechnique Montreal, Canada

33.1. Abstract

The study investigates the energy flexibility potential of typical Canadian houses. Two types of storage technologies are studied separately: building thermal mass and electrical energy storage. The flexibility provided by the thermal mass is achieved by set point temperature modulation. Simulation results show that the amount of flexible energy is quite significant, especially during colder weather. The implemented control strategy saves about 20% of energy for a demand response duration of 2 hours without thermal comfort compromise.

The flexibility analysis for a photovoltaic system shows that yearly self-generation and self-consumption can be greatly improved by adding batteries to a conventional grid connected PV system, with a saturation effect for larger battery capacities. Conventional inverter control strategies, such as grid-support and Uninterruptible Power Supply, present results at the two opposite ends of the spectrum: the UPS strategy offering the highest hourly downward flexibility (reduction of energy use) and the grid-support strategy offering the highest hourly upward flexibility (increase of energy use).

For a more detailed description of the study, please see the IEA EBC Annex 67 report Modelling of possible Energy Flexibility in Single Buildings and Building Components (annex 67.org/publications).

33.2. Case Study Buildings

To investigate the energy flexibility of Canadian residential buildings, the case study described here used the twin houses at the Canadian Centre for Housing Technology (CCHT) shown in Figure 33.1. Built in 1998 according to the Canadian R-2000 building standard, they represent common three-story single-family Canadian homes with a basement, a living floor and a sleeping floor. They are constructed in a typical North-American style, with a timber frame structure and brick veneer as exterior finish. The thermal mass is relatively low compared to some European heavy-weight houses. The time constant for a response to heating power is in the order of 18 hours.

Figure 33.1 The CCHT twin houses.

33.3. Experiments and Results

Based on the studied house, energy flexibility simulations were conducted separately for space heating and PV with a battery system. Simulation results show that the energy flexibility potential of using thermal mass is significant by modulating the thermostat set point up or down 2 °C. The studied house shows a median decrease of the energy use (downwards regulation) by 6.5 kWh during the night (see Figure 33.2) but only 2 kWh at noon for a 2 hour Demand Response (DR) event. The flexibility depends on the time of day that the DR event occurs, and is largely affected by weather conditions (illustrated with the coloured dots in Figure 33.2) and building operation. The flexible energy amount is higher during colder weather because the house has a higher energy demand during these periods. Similar results are obtained for the possibility to increase the energy use (upwards regulation) with a median of 7.5 kWh and nearly no variation over the day for the median.

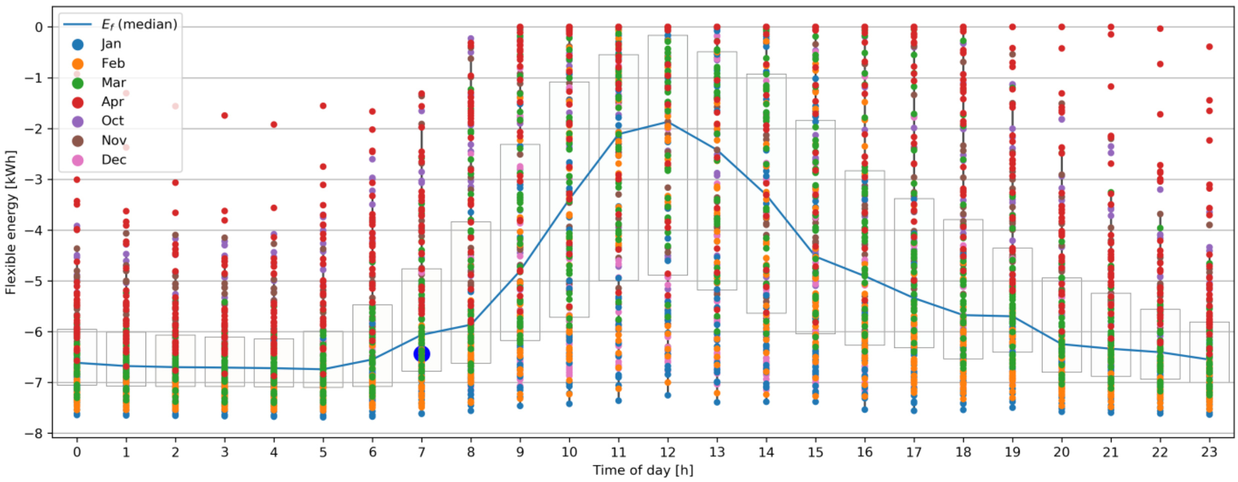


Figure 33.2 The results from the downward flexibility simulations. The possible reduction of the energy use is shown depending on time of the day and year.

The available flexibility by adding batteries to a conventional grid connected PV system is also significant, shown by yearly Key Performance Indicators (KPIs) such as self-generation and self-consumption. However, the added flexibility shows a saturation effect when the battery capacity is higher than 4 kWh/kWp (see Figure 33.3).

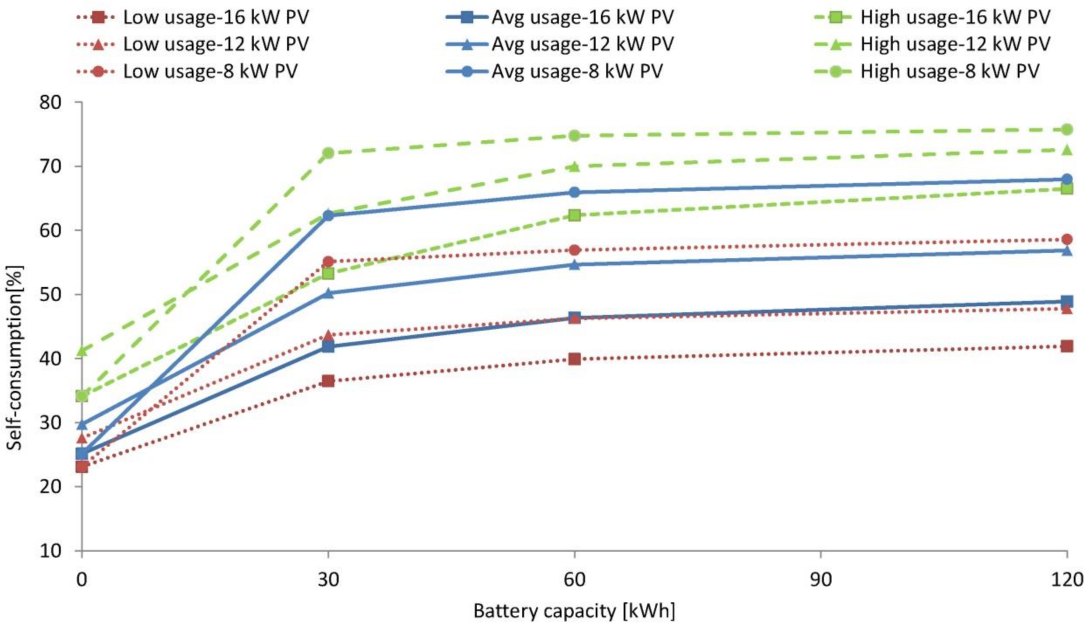


Figure 33.3 Self-consumption vs battery capacity.

Dynamic KPIs calculated for 1 hour upward and downward flexibility events show that there is a large variability in available flexibility, depending on the day and time of the year and on the inverter control strategy. The Uninterruptible Power Supply (UPS) mode, which results in the lowest yearly self-generation and self-consumption, presents a significant downward flexibility potential, limited by the maximum battery discharge current. Its upward flexibility results from the ability to shut down PV generation and is entirely dependent on solar radiation. On the other hand, the grid-support (or PV priority) operation mode, which already minimizes grid imports, offers no potential for downward flexibility under the current assumptions. Its upward flexibility is variable between 0 and 12 kWh in this study, with a relatively constant median value around 5 kWh.

34. Few-shot learning: data-driven modelling of hot water systems with extremely limited data

Hussain Kazmi, Enervalis and KU Leuven, Belgium

34.1. Abstract

The study investigates a data driven approach to modelling hot water systems in a completely automated and generalizable manner. It uses transfer in deep learning models to not just enable, but vastly accelerate model learning. The study shows that it is possible to learn far more accurate models in a shorter period of time than would otherwise be possible using real world data from net-zero energy buildings in The Netherlands. All of the considered houses make use of heat pump hot water systems. The models learned in this way can be used for a number of different tasks, including estimation of flexibility potential, and using these flexibility estimates to optimize operation, and provide ancillary services to the grid or recommendations to building occupants.

The proposed methodology overcomes the difficulties traditionally associated with different modelling paradigms for hot water systems. These include white box methods which make use of human domain knowledge, and are consequently constrained by the expertise and availability of the human modeller. The sheer number of hot water systems to be modelled especially makes it impractical to consider every single one individually. An alternative is to use black box methods which rely on sensor data to model system behaviour. These methods, while avoiding the costly dependence on human domain expertise, rely on detailed sensing of the system to model the system accurately. Where the data being gathered does not fully reflect (or capture) the internal state of the system, these methods break down or require a very long data collection period before attaining a reasonable model accuracy. Using transfer learning, this study shows that it is possible to reduce both the reliance on sensor data and human expertise.

For a more detailed description of the study, please see the IEA EBC Annex 67 report Modelling of possible Energy Flexibility in Single Buildings and Building Components (annex 67.org/publications).

34.2. Building and system description

Two different net-zero energy neighbourhoods in the Netherlands are considered in this case study. All the houses (in both projects) employ air-source heat pumps which are used to provide both the hot water and the space heating in the building. A 200 litre storage tank installed in each house is used for domestic hot water provision. However, the hot water system is identical only for houses belonging to the same project. There are considerable differences in the hot water system between the two projects (most important of which is the completely different orientation and dynamics of the storage as well as the way the heat pump interacts with it). The identical hot water systems are referred to as homogeneous, while non-identical systems are considered heterogeneous. As the case study focuses on data-driven modelling of the hot water systems, it makes use of data from the following sensors: (1) temperature measurements in the storage vessel; (2) ambient temperature measurements; (3) hot water flow in litres; and (4) electricity consumed by the heat pump for hot water production.

34.3. Method and modelling tools

The data-driven learning framework used to model the hot water system was implemented in Keras, an open source Python library. This framework used the data collected above to learn a system dynamics model for the hot water system, which further comprised of a storage model and a heating model. The purpose of the storage model is to estimate the state of the storage (i.e. its state of charge) at any given instant, while the purpose of the heating model is to estimate the amount of energy required by the heating element (heat pump in this case) to reheat the storage from an initial to a final state of charge. This information is essential to estimate the flexibility that can be offered by the hot water system as a whole.

The study shows that it is possible to combine data from different homogeneous and heterogeneous devices to vastly accelerate model improvements using different forms of transfer learning. When compared with models which do not make use of transfer learning, transfer learning can improve the initial and asymptotic performance, and the learning rate as a function of available training data. This information is highlighted in Figure 34.1, where the typical black-box learning case corresponds to learning without transfer. Most notably, two forms of transfer learning are employed in this study: transduction is found to be helpful when combining data from homogeneous hot water systems, while induction is more suitable for the case of heterogeneous devices.

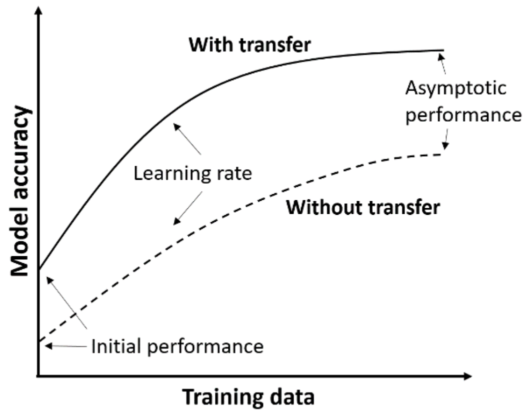


Figure 34.1 A graphic representation of the potential benefits of transfer learning.

34.4. Conclusion

The model performance of the hot water system was evaluated as a function of increasing data collection period and the number of hot water systems used for modelling purposes. It was found that increasing the number of considered households employing identical hot water systems had the same influence on model performance as increasing the data gathering period in a single household, i.e. performance scaled linearly. This meant that instead of collecting data for a year with a single household, the same model performance could be obtained in a week with roughly

50 households. Transferring across non-identical devices, on the other hand, required the neural network to be initialized with knowledge already gathered during previous projects, which allowed the model to retain its thermodynamic knowledge while making device specific adjustments to its model.

The proposed methodology can be applied to any hot water system with minimal sensing requirements to model it and estimate its flexibility potential. These models can be a tool for optimizing the efficiency of hot water systems (with demonstrated improvements of up to 20%). They can also be used to better understand the energy flexibility potential of hot water systems for energy planning with increasing heat electrification and distributed generation. For a practical example of this, please see the IEA EBC Annex 67example 'Determinants of flexibility in residential hot water systems' in the present report.

35. Simulation-based design optimization of houses with low grid dependency

Zahra Mohammadi, Department of the Built Environment, Technical University of Eindhoven, The Netherlands

35.1. Abstract

In this study, a performance optimization of various residential building designs with differences in energy demand, on-site energy generation and storage sizes is carried out considering future policy scenarios. The objective is to minimize the dependency to the nearby energy grid and maximize the self-consumption. To achieve this, a performance-based design support framework is proposed. The framework is able to optimize the building performance under various future scenarios while considering energy flexibility. A simulation framework is presented to conduct the performance assessment. The developed methodology is demonstrated using a Dutch residential house that needs to be renovated.

For a more detailed description of the study, please see the IEA EBC Annex 67 report Modelling of possible Energy Flexibility in Single Buildings and Building Clusters (annex 67.org/publications).

35.2. Building and system description

A typical Dutch residential, semi-detached terraced house from 1975, is chosen as the case study building. The building is a heavyweight three-floor construction. Heating is supplied by an air source heat pump and the building is ventilated with balanced mechanical ventilation with a heat recovery unit. Natural ventilation (free cooling) is used in summer instead of mechanical cooling.

In order to satisfy different building standards, design options related to building envelopes such as window type, insulation level of envelopes and infiltration rates are altered at the same time and formed different renovation packages. Hence, the air to water heat pump system is sized for each building envelope package. Other design options such as size of the PV system, size of the electrical battery and type of the domestic hot water (DHW) system are varied for all building envelope packages.

Two different systems are assumed to meet the DHW needs, one is a standalone solar domestic hot water system with an electrical auxiliary heater and the other is a gas boiler. Both solar thermal collectors and photovoltaic panels are placed at a tilt angle of 43° facing south, which is also the slope of the roof.

35.3. Methods and results

The proposed design optimization approach consists of three main steps. These steps are presented below:

1a: Identify the decision makers' preferences and define the relevant performance indicators including energy matching and grid interaction indicators.
1b: Define the design space, e.g., define the possible renovation measures that should be considered (variations in building envelope properties, HVAC systems, size of onsite-energy generation system and storage systems).
1c: Formulate the future scenarios. This study is e.g. based on the various support schemes.
2: Predict the performance of each design solution in the design space using building performance simulation and calculate the performance indicators across all future scenarios.
3: Analyse and present future-proof building designs with low grid dependency using multi-criteria decision making.

Due to the conflicting nature of most indicators, a set of Pareto optimal solutions is obtained for each scenario. This enables the decision maker to perform a trade-off among alternative design solutions based on the preferred performance indicators. Depending on the selected performance indicators, the set of Pareto optimal solutions can vary per scenario. It is assumed that the probabilities of the occurrence of the scenarios is unknown and hence, it is essential to assess the performance robustness of the design solutions considering all scenarios. The minimax regret method is used to calculate the performance robustness of each Pareto. The Pareto solutions are presented using scatter plots and box plots to show the values for each design parameter. These plots are shown and explained in the IEA EBC Annex 67 report Modelling of possible Energy Flexibility in Single Buildings and Building Clusters.

35.4. Conclusion

The performance of the design space for different policy scenarios is assessed by using building performance simulations with multiple energy flexibility, performance indicators and corresponding performance robustness. The methodology is demonstrated using a case study with a homeowner as decision maker. The results show that the proposed methodology provides a homeowner information to economically compare improving the building envelope with other design options like electrical storage and PV system. In addition, the homeowner can choose design options that are more robust to the preferred performance indicators.

The proposed approach also provides the decision makers with information about the energy flexibility of the design space. This case study shows e.g. that energy flexible designs that are able to provide higher self-consumption and lower dependency to the grid are more expensive for homeowners specifically in scenarios with incentives to sell on-site produced energy. Considering variations in the operational cost due to different policy scenarios, designs with high insulation levels [8.5 m^2K/W], large PV systems [25 m^2] and high storage capacities [15 kWh] are dominating solutions obtained with self-consumption and grid dependency objectives. However, because of the high additional investment cost these solutions might not be the homeowner's preferred design solutions.

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