Energy in Buildings and Communities Programme

International Energy Agency, EBC Annex 58

Reliable building energy performance characterisation based on full scale dynamic measurements

Report of Subtask 4b: Towards a characterisation of buildings based on in situ testing and smart meter readings and potential for applications in smart grids

Dirk Saelens, Glenn Reynders

EBC is a programme of the International Energy Agency (IEA)

International Energy Agency, EBC Annex 58

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cover picture: Tailored heating experiment performed for one of the industrial partners of the Annex 58-project to determine the overall heat loss coefficient of a newly built dwelling based on on-site measured data. (source: Geert Bauwens, KU Leuven)

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 29 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 international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes. 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 (*):

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 & CO2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy & CO2 Equivalent 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
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Annex 68: Design and Operational Strategies for High IAQ in Low Energy Buildings

Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale

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 (*)

IEA EBC Annex 58: Reliable Building energy performance characterisation based on full scale dynamic measurements

Annex 58 in general

To reduce the energy use of buildings and communities, many industrialised countries have imposed more and more stringent requirements in the last decades. In most cases, evaluation and labelling of the energy performance of buildings are carried out during the design phase. Several studies have shown, however, that the actual performance after construction may deviate significantly from this theoretically designed performance. As a result, there is growing interest in full scale testing of components and whole buildings to characterise their actual thermal performance and energy efficiency. This full scale testing approach is not only of interest to study building (component) performance under actual conditions, but is also a valuable and necessary tool to deduce simplified models for advanced components and systems to integrate them into building energy simulation models. The same is true to identify suitable models to describe the thermal dynamics of whole buildings including their energy systems, for example when optimising energy grids for building and communities.

It is clear that quantifying the actual performance of buildings, verifying calculation models and integrating new advanced energy solutions for nearly zero or positive energy buildings can only be effectively realised by in situ testing and dynamic data analysis. But, practice shows that the outcome of many on site activities can be questioned in terms of accuracy and reliability. Full scale testing requires a high quality approach during all stages of research, starting with the test environment, such as test cells or real buildings, accuracy of sensors and correct installation, data acquisition software, and so on. It is crucial that the experimental setup (for example the test layout or boundary conditions imposed during testing) is correctly designed, and produces reliable data. These outputs can then be used in dynamic data analysis based on advanced statistical methods to provide accurate characteristics for reliable final application. If the required quality is not achieved at any of the stages, the results become inconclusive or possibly even useless. The IEA EBC Annex 58-project arose from the need to develop the necessary knowledge, tools and networks to achieve reliable in situ dynamic testing and data analysis methods that can be used to characterise the actual energy performance of building components and whole buildings. As such, the outcome of the project is not only of interest for the building community, but is also valuable for policy and decision makers, as it provides opportunities to make the step from (stringent) requirements on paper towards actual energy performance assessment and quality checking. Furthermore, with the developed methodology it is possible to characterise the dynamic behaviour of buildings, which is a prerequisite for optimising smart energy and thermal grids. Finally, the project developed a dataset to validate numerical Building Energy Simulation programs.

Structure of the project

Successful full scale dynamic testing requires quality over the whole process chain of full scale testing and dynamic data analysis: a good test infrastructure, a good experimental set-up, a reliable dynamic data analysis and appropriate use of the results. Therefore, the annex-project was organised around this process chain, and the following subtasks were defined:

Subtask 1 made an inventory of full scale test facilities available all over the world and described the common methods with their advantages and drawbacks for analysing the obtained dynamic data. This subtask produced an overview of the current state of the art on full scale testing and dynamic data analysis and highlighted the necessary skills.

Subtask 2 developed a roadmap on how to realise a good test environment and test set-up to measure the actual thermal performance of building components and whole buildings in situ. Since there are many different objectives when measuring the thermal performance of buildings or building components, the best way to treat this variety has been identified as constructing a decision tree. With a clear idea of the test objective, the decision tree will give the information of a test procedure or a standard where this type of test is explained in detail.

Subtask 3 focused on quality procedures for full scale dynamic data analysis and on how to characterise building components and whole buildings starting from full scale dynamic data sets. The report of subtask 3 provides a methodology for dynamic data analysis, taking into account the purpose of the in situ testing, the existence of prior physical knowledge, the available data and statistical tools,… The methodologies have been tested and validated within different common exercises, in a way that quality procedures and guidelines could be developed.

Subtask 4 produced examples of the application of the developed concepts and showed the applicability and importance of full scale dynamic testing for different issues with respect to energy conservation in buildings and community systems, such as the verification of common BES-models, the characterisation of buildings based on in situ testing and smart meter readings and the application of dynamic building characterisation for optimising smart grids.

Subtask 5 established a network of excellence on 'in situ testing and dynamic data analysis' for dissemination, knowledge exchange and guidelines on testing.

Overview of the working meetings

The preparation and working phase of the project encompassed 8 working meetings:

Meeting	Place, date	Attended by
Kick off meeting	Leuven (BE), September 2011	45 participants
Second preparation meeting	Bilbao (SP), April 2012	46 participants
First working meeting	Leeds (UK), September 2012	44 participants
Second working meeting	Munich (GE), April 2013	53 participants
Third working meeting	Hong-Kong (CH), September 2013	26 participants
Fourth working meeting	Gent (BE), April 2014	49 participants
Fifth working meeting	Berkeley (USA), September 2014	37 participants
Sixth working meeting	Prague (CZ), April 2015	39 participants

During these meetings, working papers on different subjects related to full scale testing and data analysis were presented and discussed. Over the course of the Annex, a Round Robin experiment on characterising a test box was undertaken, and several common exercises on data analysis methods were introduced and solved.

Outcome of the project

The IEA EBC Annex 58-project worked closely together with the Dynastee-network (www.dynastee.info). Enhancing this network and promoting actual building performance characterization based on full scale measurements and the appropriate data analysis techniques via this network is one of the deliverables of the Annex-project. This network of excellence on full scale testing and dynamic data analysis organizes on a regular basis events such as international workshops, annual training,... and will be of help for organisations interested in full scale testing campaigns.

In addition to the network of excellence, the outcome of the Annex 58-project has been described in a set of reports, including:
Report of Subtask 1A: Inventory of full scale test facilities for evaluation of building energy performances.
Report of Subtask 1B: Overview of methods to analyse dynamic data
Report of Subtask 2: Logic and use of the decision tree for optimizing full scale dynamic testing.
Report of Subtask 3 part 1: Thermal performance characterization based on full scale testing: physical guidelines and description of the common exercises
Report of Subtask 3 part 2: Thermal performance characterization using time series data – statistical guidelines.
Report of Subtask 4A: Empirical validation of common building energy simulation models based on in situ dynamic data.
Report of Subtask 4B: Towards a characterization of buildings based on in situ testing and smart meter readings and potential for applications in smart grids
IEA EBC Annex 58 project summary report

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IEA, EBC Annex 58, Report of Subtask 4b

Towards a characterisation of buildings based on in situ testing and smart meter readings and potential for applications in smart grids

Dirk Saelens, Glenn Reynders

June 2016

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SYMBOLS AND UNITS

A	m^2	Area
A_{sol}	m^2	Solar aperture
C	J/K	Effective heat capacity of a space or building
g	-	Total solar energy transmittance of a building element
H	W/K	Heat transfer coefficient
H_{tr}	W/K	Transmission heat transfer coefficient
H_{ve}	W/K	Ventilation heat transfer coefficient (including infiltration)
I_{sol}	W/m^2	Solar irradiance
Q	J	Quantity of heat
q	W/m^2	Heat flow density
R	m^2K/W	Thermal resistance
T	K	Thermodynamic temperature
t	s	Time, period of time
U	W/m^2K	Thermal transmittance
θ	°C	Centigrade temperature
Φ	W	Heat flow rate
Φ_P	W	Thermal power

ABBREVIATIONS

BES	Building energy simulation
RMSE	Root mean squared error
PV	Photo-voltaic system
HVAC	Heating ventilation and air-conditioning
DSM	Demand side management
MPC	Model predictive control
nZEB	Nearly zero energy building
EPC	Energy performance certificate
ZCB	Zero carbon building
ADR	Active demand response
FMU	Functional mock-up unit
FMI	Functional mock-up interface

1. Preface

This report summarizes the activities that were carried out in the framework of Subtask 4 of IEA EBC Annex 58. Subtask 4 dealt with the application of the developed concepts in the other subtasks of Annex 58 – as summarized in the structure of the project – and shows the applicability and importance of full scale dynamic testing for different issues with respect to energy conservation in buildings and community systems. Subtask 4 is divided into 3 activities:

ST4.1. Verification of common building energy simulation models based on in situ dynamic data

In this activity a well-documented, high-quality data set for verification and validation of numerical building energy simulation (BES) codes is developed. This is a valuable addition to the existing BESTEST [1] and several validation standards, which only performed an intermodel comparison. The results of this activity are described in a separate document [2]

ST4.2. Towards a characterisation of buildings based on in situ testing and smart meter readings

This activity investigates how the methods that were developed in Subtask 3 [3, 4] can be used to characterise the thermal performance of buildings. The activity looks at the developed methods, used them and tried to improve them by analysing the measurement data that were available and identifying what data could improve the accuracy of the results. This was done with real and virtual data. The final aim is to develop a real energy performance characterisation of a building based on on-site gathered information and to develop reduced order building models for use in software tools modelling smart grids and model based controllers.

ST4.3. Application of dynamic building characterisation for optimising smart grids

This activity has the objective of demonstrating that reliable dynamic characterisation of the energy use in buildings is beneficial for modelling smart grid solutions – demand side management, minimising import/export of energy, analysing energy supply and demand options – from the perspective of the grid operator and the building owner. As such this subtask is not focused on optimizing and designing District Energy Systems, but rather on how to use building characterisation for instance by using the data that are collected within this grid.

The present report focuses on activities 4.2 and 4.3 and gives an overview of the presented work. Essentially, the main findings are listed and references to different papers and presentations that were presented during the expert meetings in the frame of activity 4.2 and 4.3 are given to guide the reader to more detailed information. The emphasis of the work done was on the characterisation of the buildings and hence on activities 4.2.

The general outline of the report is listed below:

Chapter 1: Preface

Chapter 2: Introduction

Chapter 3: Characterisation of buildings

Chapter 4: Application of characterisation results

Chapter 5: Summary and outlook for future work

2. Introduction

Reduction of the energy use in the built environment offers a key opportunity for reducing the global energy use and mitigate the related environmental issues. This may be achieved by reducing the energy demand of buildings by better insulating and making buildings more air tight, by introducing renewable energy sources and by increasing the efficiency of the use of fossil fuels. Past efforts on the three previous aspects mainly have focused on renovation and increasing energy efficiency on building level. However, recent evolutions focus on a larger scale and tackle the energy system as a whole – coupling demand and supply side. This increase of scale is essential as the evolution towards nearly zero energy buildings changes the way the buildings interact with energy distribution grids. Buildings no longer only use energy, but can also act as distributed renewable energy sources by integrating rooftop photovoltaics for instance. At the same time, other sources of renewable energy pop-up and have to be integrated in a network with distributed generation and use of energy. As an example Figures 1 and 2 show the massive increase of distributed energy sources in Denmark and Germany over time. These illustrations focus on electricity, but a similar evolution can be identified in thermal applications. Figure 3 for instance shows a fourth generation thermal network where different buildings can make use of a central geothermal storage and use thermal energy from distributed sources.

Increasing wind generation & CHP units in Denmark

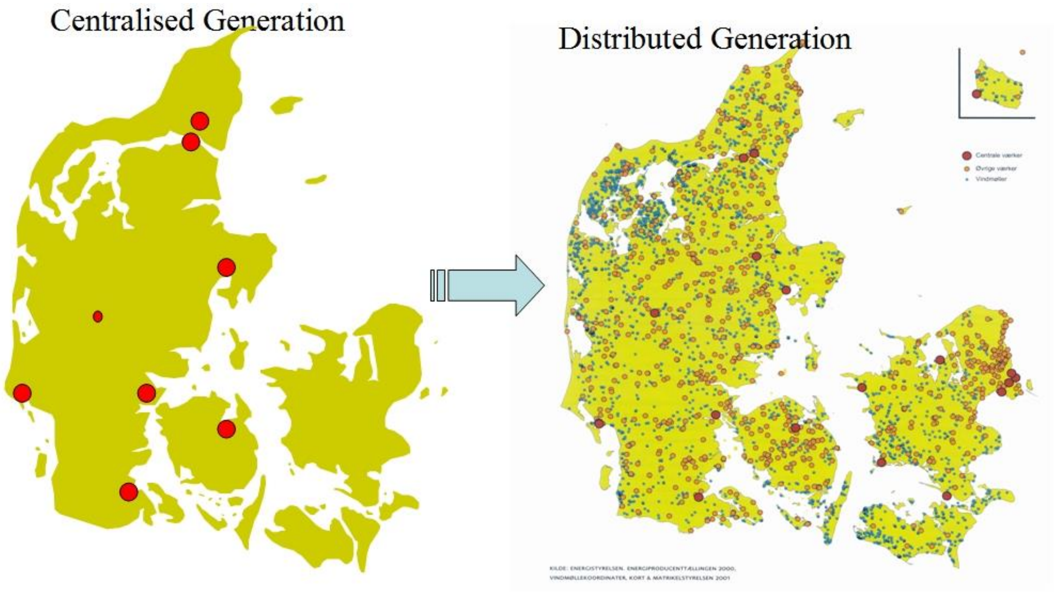
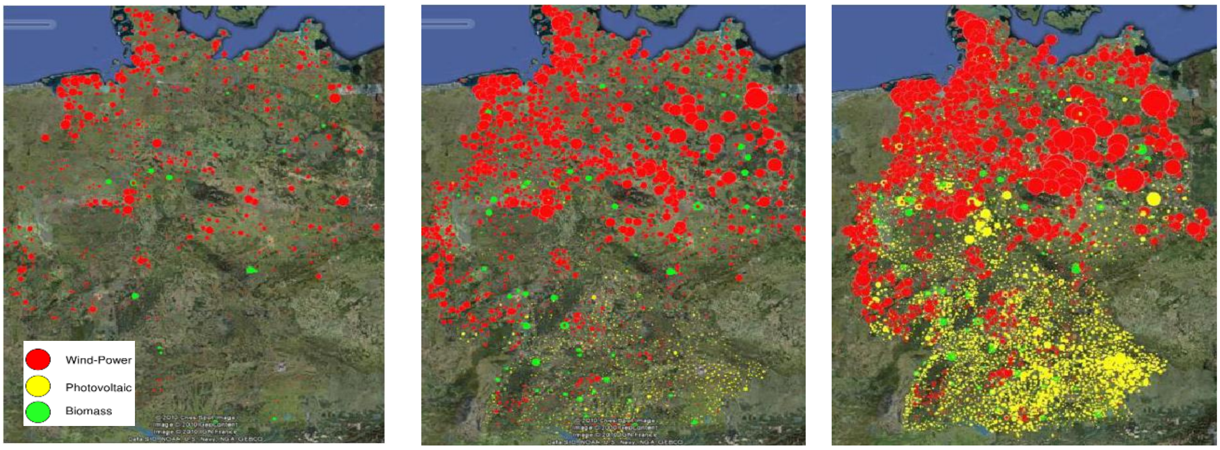


Figure 1 Increase of distributed generation of renewable energy and combined heat and power in Denmark [5]



Year 2000
~30.000 power plants

Year 2005
~221.000 power plants

Year 2010
~750.000 power plants

Figure 2 Increase of generation of distributed generation of renewable energy from wind and solar power and biomass [6]

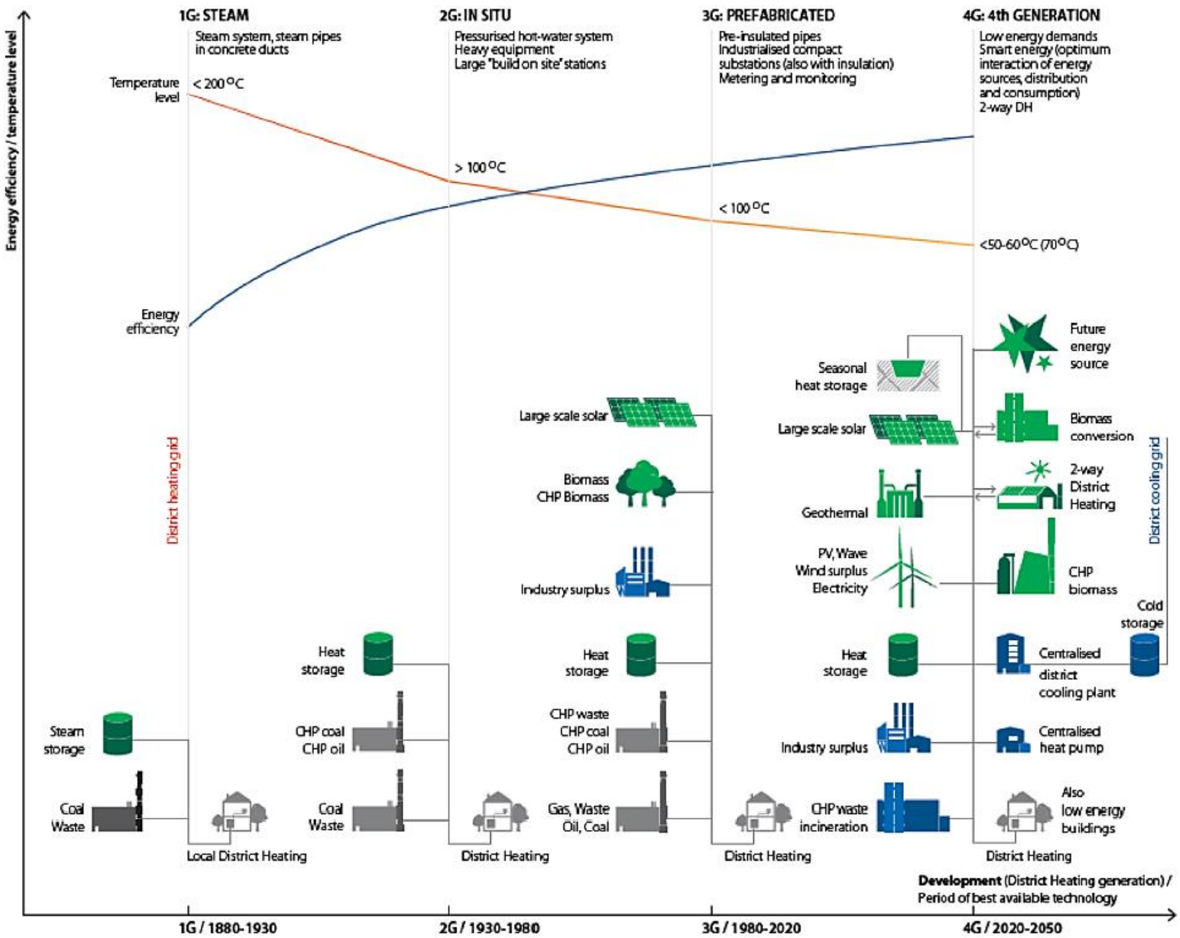


Figure 3 Evolution of different generations of thermal networks [7]

To indicate the variety of energy vectors (electricity versus thermal) and to emphasize the importance of a whole-system approach the term "energy systems" is preferred as a container term that covers both electrical and thermal systems. This in contrast to the term "grids" which has a more electrical connotation. In light of the evolution towards the use of more renewable energy sources, future energy systems should be capable of following features:

- Possibility to integrate energy from local and central energy sources.
- Integrate flexibility at demand and supply side
- Exchange of energy between buildings
- Provide means to store different forms of energy

Figure 4 illustrates these features for an energy system on a city level.

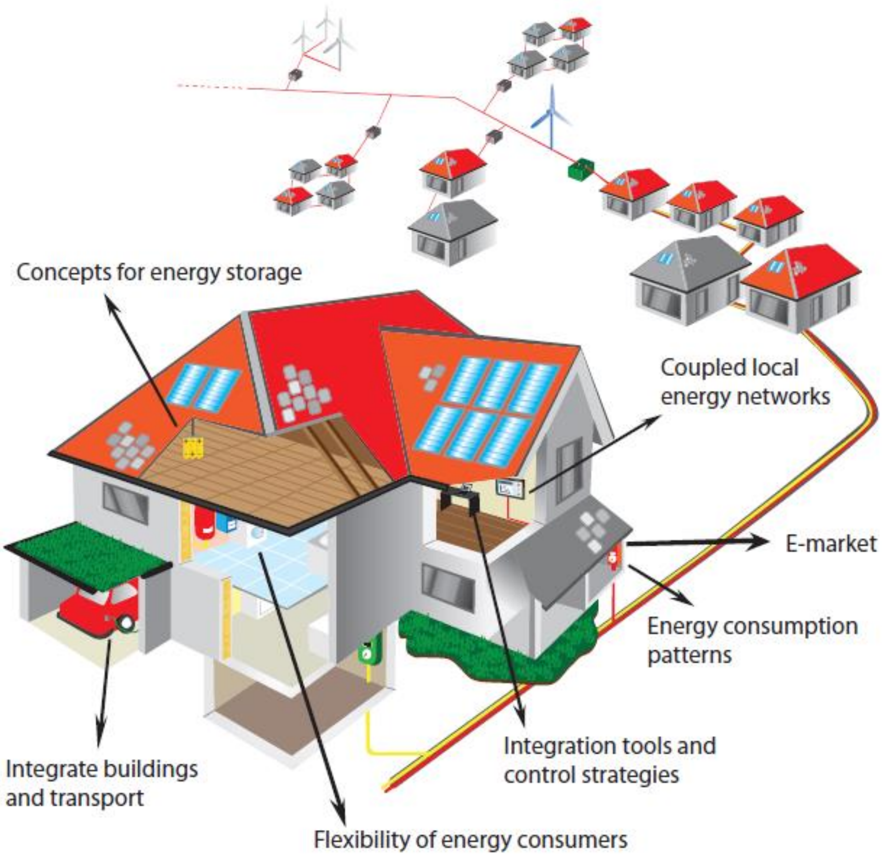


Figure 4 generation of renewable energy (source: Linear project, KU Leuven)

One of the main challenges regarding the control and operation of energy systems with large shares of renewable energy sources are the intermittency and mismatch between supply and demand of energy. To overcome this, energy systems should be equipped with technologies to balance supply and demand effectively. The required load matching can be achieved by considering many techniques like Demand Side Management (DSM) and storage of thermal or electrical energy, but requires flexibility of the users or producers of energy together with some form of intelligence to match both. In electrical energy systems this intelligence is often reflected by using the term smart grids, but the same considerations are valid for thermal energy systems as well. These smart systems are often referred to as Smart Energy Networks.

The intelligence relies on algorithms that can be either rule-based or optimisation-based. For the last category of a key feature is the characterisation and prediction of the dynamic behaviour of the different components within this system. As illustrated in previous figures, these components can be attributed to different functions including:

- Production of energy – which can be distributed or not,
- Use of energy in buildings, industry or other processes – coupled to the energy system,
- Storage of energy – which can be distributed or not.

In the context above, buildings are identified as:

- Potential suppliers of distributed energy,
- Users of electricity and thermal energy,
- Potential suppliers of flexibility to the energy system. This can be achieved through demand side management or energy storage.

Within Annex 58, the focus is on "Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements" and hence it is analysed how the identification and characterisation techniques that result mainly from Subtask 3 [3, 4] can be applied in the context of intelligent energy networks to characterise the dynamic behaviour of buildings. An accurate characterisation of the dynamic behaviour of buildings will prove to be essential for a reliable design and operate of smart grids.

In order to control and guide this balancing between supply and demand of energy, intelligent control systems need to be implemented. An interesting example of how such control can be implemented has been presented by [8]. In this work, a market-based multi-agent control algorithm is used which allows an effective distribution of the power consumption across the different thermal energy storage possibilities in the neighbourhood. The optimal control algorithm is essentially model-based and hence requires the identification of a suitable model of the buildings in the neighbourhood.

Essentially, the aim is to identify suitable models for describing the dynamic energy characteristics of a building or group of buildings. These can be used to optimize the operation and control of energy systems such as smart grids, smart controllers in residential applications and controllers implemented in building energy management systems for larger buildings. These models for dynamic energy characteristics are also useful to increase the simulation speed in district energy system simulations.

3. Characterisation of buildings in a smart grid context

3.1 Introduction

With a widespread integration of distributed renewable energy sources and the electrification of the energy demand for heating, cooling and ventilation (HVAC), the electricity grid faces new challenges in terms of peak load, decentralization and reverse flow. Baetens et al. [9] demonstrated using detailed bottom-up simulations of a residential neighbourhood that 14–47 % of the expected local PV production is wasted at feeder level by inverter curtailing when all dwellings are intended to achieve a level of net zero energy. At building level, these losses may rise up to a fraction of 41–68 %. At the same time, Xue Xue et al. [10] state that buildings are the major cause of variability in the electricity demand and account for more than 90 % of the electricity in Hong Kong. They impose not only a significant challenge for the grid, but also show important opportunities to increase the overall energy efficiency on a district level by intelligent load management. It was demonstrated that by using intelligent control strategies such as model predictive control (MPC), that take into account the flexibility in the energy demand of buildings and the available thermal (or electrical) storage systems, buildings also show a significant potential for demand-side management (DSM) to reduce the power imbalance and improve the power reliability [11,12].

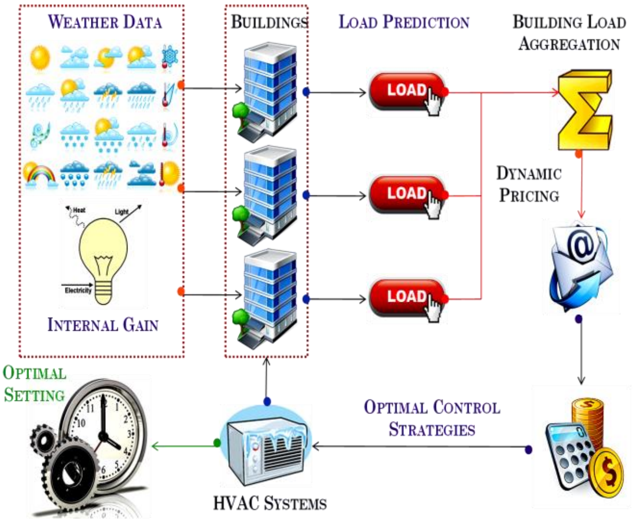


Figure 5 Principle scheme optimal control [9]

In order to enable DSM using the flexibility of buildings, characterisation is needed for two main aspects: (i) design and planning, (ii) operation and control. Therefore, this report provides an overview of the progress in the field of characterisation of whole building energy performance

Figure 6 Principle scheme optimal control [9]

and identification of dynamic reduced-order models that are suitable for:

- **Short-term prediction** of the heat demand and thermal response on a short prediction horizon (e.g. for MPC application)
- **Long-term simulation** of the heat demand and thermal response of dwellings (e.g. for implementation in district simulations)
- **Characterisation** of the main thermal properties of a dwelling (e.g. for the evaluation of the storage efficiency)

For the application in MPC – which requires short-term predictions of the heat demand and the indoor temperature variations typically in the range of 15 min to 2 days – the modelling requirements are mainly focused on capturing the short-term dynamics of the dwelling [13]. In contrast, for the application of reduced-order models in long-term simulations – typically over a whole year, e.g. for the simulation of the energy use for heating on an aggregated district of even national level [14, 15] – models should also capture long-term effects such as the heat transfer to the ground.
Characterisation of the thermal properties goes a step further. In order to estimate e.g. the contribution of different building components (e.g. roofs, windows and exterior wall) in the effective thermal capacity of the dwelling, the identification process should be able to separate the thermal dynamics of the different components. For this type of characterisation, the identifiability of the model parameters is critical. As will be shown further, whether a parameter can be uniquely estimated – i.e. if a parameter is identifiable – given a certain data set and model structure, is closely related to the model structure and the design of experiment.

As a specific aspect of Subtask 4.2 – in contrast to the work in Subtask 3 – is that measurement setups should be simple and low-cost to enable a widespread implementation in control and smart grid applications. Thereby data obtained during the operational phase of the buildings using sensors that may already be available in smart meters or building automation systems for other monitoring and control purposes, are expected to be a valuable data source for this type of applications. Hence one of the main goals in this subtask was to investigate to what extent smart meters in combination with information obtained from Building Automation Systems (BAS) can be used to identify reduced order models and characterise the energy performance and energy flexibility of buildings.

The characterisation of this flexibility has been carried out on two levels. On building level, dynamic reduced-order models have been identified using data collected from detailed building energy simulations as well as full-scale dynamic experiments. On a district level, smart meter readings of over 8500 residential users have been analysed to identify the main drivers that govern the variability in the users' electricity behaviour. While most of the work within the annex-project was focused on the building level, the following two sections give an overview of the lessons learned on both levels.

3.2 Characterisation of buildings on building level

In order to obtain a reliable and robust characterisation of the dynamic behaviour of buildings, focusing on the flexibility obtained by structural thermal energy storage, i.e. the activation of the thermal mass embedded in the building fabric, a 4-step approach has been followed in this subtask.

As summarized in the scheme of Figure 6, the identification approach started from detailed building energy simulations, referred to as white-box simulations. The use of these detailed simulations has proven to be a comprehensive research tool as it allows for a large flexibility in dynamic experiments that could be simulated. These simulations were used as virtual measurements in the second step to identify grey-box models using the methods established in Subtask 3. Thereby, grey-box models refer to models that combine physical knowledge about the system with statistical system identification methods in order to identify accurate, dynamic reduced-order building models.

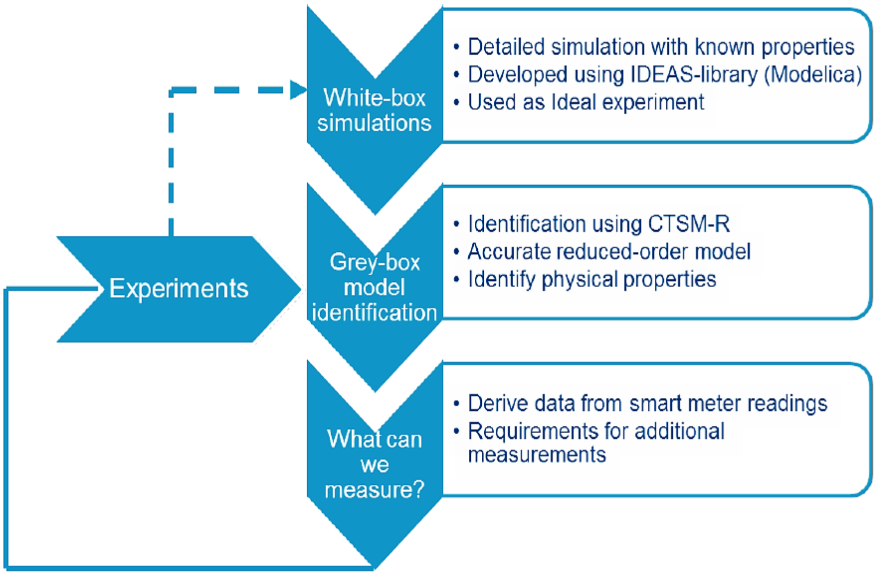


Figure 7 Overview of identifcation approach [16]

Specifically in the context of this Subtask 4.2, the flexibility of the use of virtual measurements is exploited to analyse the impact of the experiment design and proposed model structure on the accuracy of the identified grey-box models. Based on these results minimal requirements for the input data are formulated in the third step of this subtask. As stated above, the main focus has been on analysing to what extent smart meter readings and building automation systems may provide adequate information for the identification of accurate grey-box modelling.

Using this identification approach, important insight was obtained into the opportunities and challenges for a large-scale implementation of grey-box modelling for characterisation of the energy performance of buildings and the identification of reduced-order building models. To structure the lessons learned, the following paragraphs first show the simulation-based proof of concept. Thereby, the focus is on analysing the accuracy that may be expected from the identified grey-box models, comparing the results for data obtained from dedicated experiments as well as data obtained during operation.
Secondly, the flexibility of using virtual data is exploited to describe minimum requirements for measurements used for the identification of grey-box models.
Finally, in the third part of this section, the link with current state-of-the-art in building automation and monitoring is presented.

a. Simulation-based proof of concept

To investigate the relation between the design of experiment, the proposed model structures and the obtained accuracy of the grey-box models, the grey-box modelling framework developed in Subtask 3 [3] has been applied on detailed building energy simulations [14]. Thereby a wide range of residential building types and insulation qualities have been covered in order to analyse if the same approach and same model structures can be applied for a wide range of building typologies.
Moreover, buildings equipped with radiator and floor heating systems have been compared since they significantly differ in the way they activate the thermal mass and thus result in different dynamic excitations of the building. Cooling systems and office buildings have not explicitly been analysed, although the established methodology can be readily extended to these applications.

The detailed simulations have been carried out using the IDEAS-library in Modelica [17] as presented in Reynders et. al. [14]. Although the methods have been demonstrated on multi-zone dwellings as well [15], the main example used to develop the methodology consisted of a single zone building. The building was modelled in detail using a control volume approach, resulting in over 400 states, and simulated for the heating dominated climate of Belgium. Climate data and stochastic occupancy profiles are used as input with a time resolution of 10 minutes, i.e. the same resolution that was used for the virtual measurements.

Two specific experiments have been analysed in order to assess the impact of the experiment design: (i) a dedicated identification experiment using a pseudo-random binary signal (PRBS) for the heating power and (ii) a virtual experiment of the building in-use, applying a thermostatic control with night setback. The former is specifically designed to guarantee persistent excitation of the thermal mass. Thereby it is important to note that parameters of the PRBS signal have been chosen to have excitation in the frequency band that corresponds to the main time constants of the building.
The identification on in-use data has been investigated as it corresponds to a scenario where a building automation system (BAS), or controller, is installed in an existing building and needs to learn the dynamic behaviour of an occupied building. The latter can be expected to become standard practice in many smart grid applications [12].

For both experiments different combinations of input signals and observation measurements have been used to identify grey-box models. The solar gains, internal gains, heating power and outdoor temperature are used as input signal. The indoor air temperature is always used as observation measurement. Depending on the level of complexity allowed for the measurement campaign, surface temperatures and heat flux measurements are included.

Figure 8 gives an overview of the input and observation measurements for the in-use experiments carried out for an insulated and uninsulated detached dwelling. The experiments are shown for winter data for which in general a more robust identification is obtained as a result of the high difference between indoor and outdoor temperature and the high level of excitation by the heating system. Moreover the figure differentiates between models that are identified using ‘effective gains’ that are obtained from the detailed simulations and ‘alternative measurements,’ such as the domestic electricity use, which are more likely to be available in an operational setup. As explained further (Figure 10) these different input signals have been compared to analyse the impact on the model accuracy when moving from the ideal test setups that were used in Subtask 3 [4] to more realistic scenarios for energy performance characterisation in a smart grid context.

Different model structures have been evaluated in a forward selection process, whereby the model complexity is systematically increased based on the analysis of the residuals and the noise model which give insight in the model deficiencies [14]. As an initial model structure a first-order model (Figure 9.a) is used whereby all thermal mass is lumped to a single state, or capacity, that is couple to the outdoor temperature by a thermal resistance corresponding to both the transmission losses and the ventilation losses. For the second-order model a distinction is made between the relatively low thermal capacity of the indoor air and furniture, and the high thermal mass of the building structure. For the third order model an additional capacity is included corresponding to the thermal mass of the interior walls. Finally, in the 4^{th} order model (Figure 9.b) the thermal capacity for the ground floor is included, which is adjacent to the ground temperature rather than the outdoor air temperature.

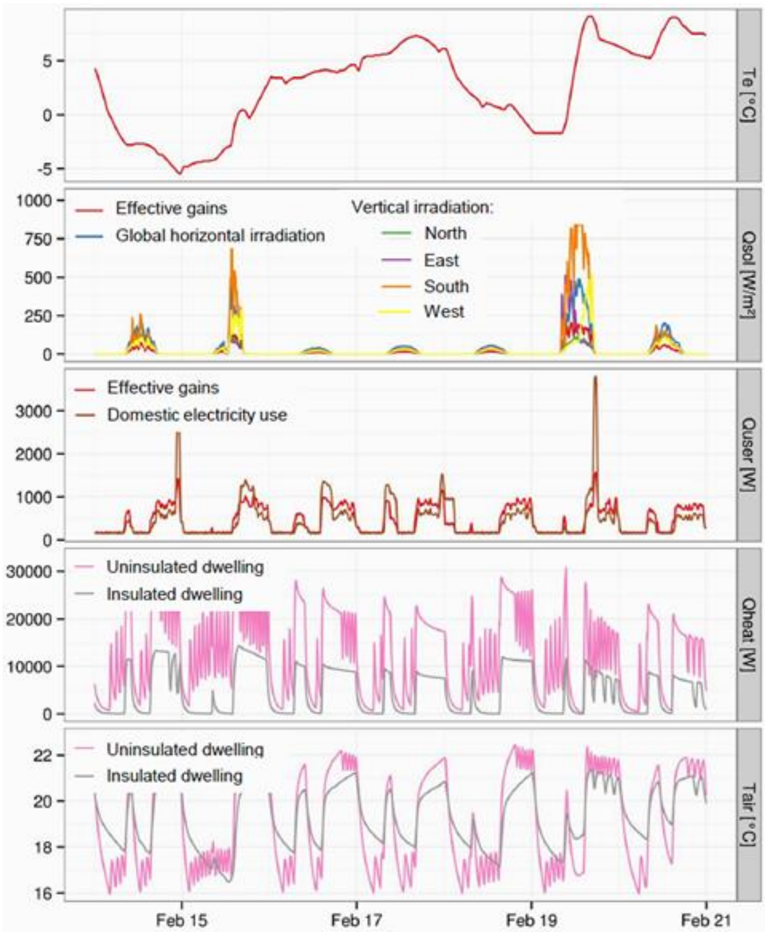


Figure 8 Input and observation measurements for the identification of grey-box models

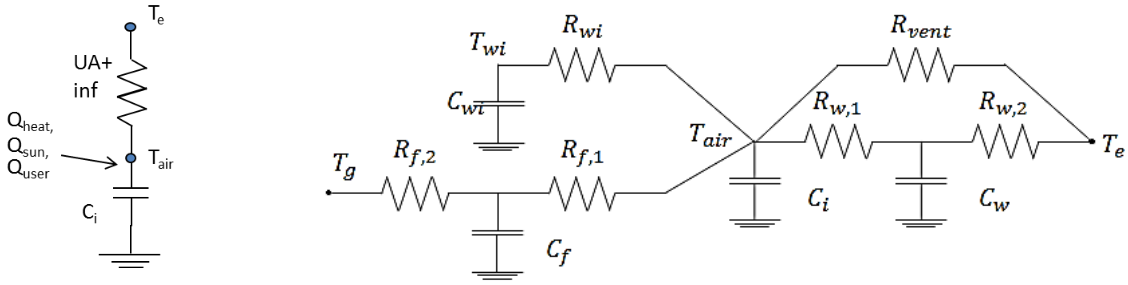
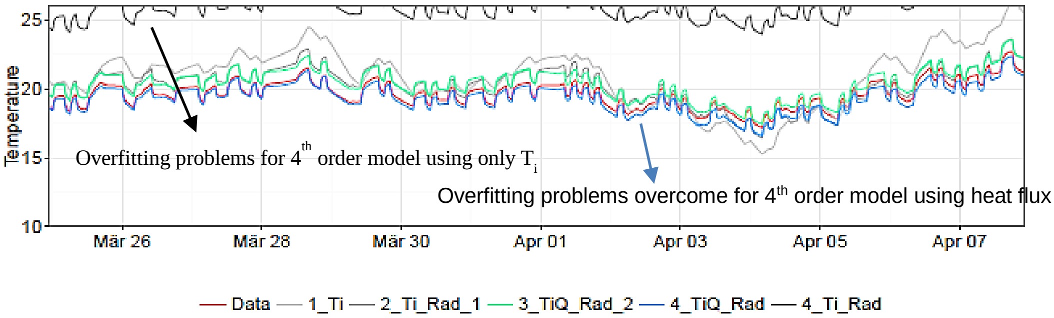
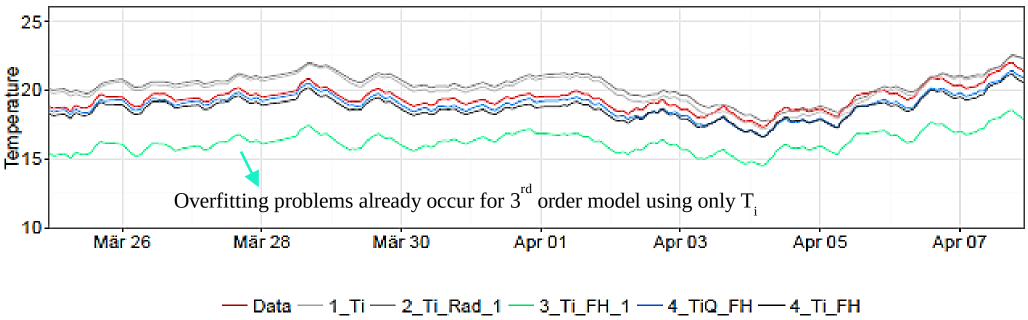


Figure 9 Electric analogy of the (a) 1st order model and (b) 4th order model using thermal resistances (R) and thermal capacitors (C)

For each of these models the identification process has been carried out using different combinations of input and observation measurements. For the latter the distinction was made between a ‘simple’ measurement approach - whereby only the indoor air temperature was used as an observation which can be expected to be available in control and building automation systems – and an ‘advanced’ measurement approach – whereby heat flux sensors and surface temperature measurements are included. Three important conclusions were



(a) radiators



(b) floor heating

Figure 10 Simulation results for (a) radiator and (b) floor heated buildings as function of the model type [18]

drawn from this analysis. First, it was found that lower-order models (1th and 2nd order for floor heating, 2nd order for radiators) show adequate performance for short-term predictions (prediction horizon ranging from minutes up to a day) that are typically required in control applications. For long-term simulations, as shown in Figure 10, typically higher-order models are required to give accurate simulation of both the high- and low-frequent thermal dynamics of the dwelling. Nevertheless, as shown for model 4_Ti_Rad in Figure 10**Error! Reference source not found.**.a – which is the 4th order model using only indoor temperature observations – overfitting problems may jeopardize the model performance in absence of adequate information in the observation measurements. A thorough model validation, as proposed in ST3 [3], is therefore a prerequisite, including a statistical residual analysis, cross-validation and verification of the estimated physical properties.

Including heat flux measurements to the different components in a more advanced experiment setup, e.g. model 4_TiQ_Rad and 4_TiQ_FH in Figure 10, is found to be an effective measure to avoid overfitting problems. Moreover, the study shows that these measurements are also a prerequisite when one is interested in characterising the disaggregated thermal properties of the different building components [18].

In practice heat flux measurements are however difficult to obtain for in use buildings and may only be possible in dedicated, “enhanced” measurement setups. In absence of such detailed measurement setups, it is advised to limit the complexity of the model or use physical prior knowledge about the building to limit the amount of unknown parameters. The latter is demonstrated in [10, 19, 20] using a genetic algorithm based identification of the buildings internal mass.

Finally, it is important to note that whereas previous example shows the application of grey-box modelling for common building components using linear time invariant models, the methodology can also be extended to non-linear models. As such, the methodology also allows the characterisation of innovative building concepts such as building integrated PV systems or ventilated facades [21, 22].

Scenario	Solar gains	Internal gains
A	Effective gains	Effective gains
B	Global horizontal irradiation	Effective gains
C	Oriented vertical irradiation	Effective gains
D	Effective gains	Domestic electricity
E	Oriented vertical irradiation	Domestic electricity
F	Effective gains	No input

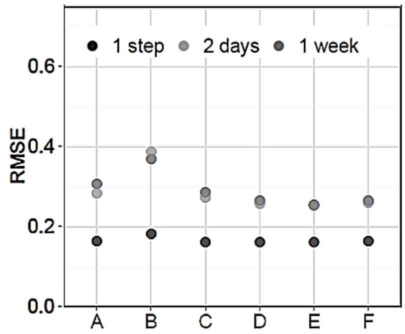


Figure 11 Impact of alternative input scenarios on the accuracy of the identified models expressed by the root mean squared error (RMSE) for 1-step, 2-day and 1-week ahead predictions [14]

b. DATA REQUIREMENTS - ALTERNATIVES FOR OPERATIONAL DATA COLLECTION

The studies described in the previous section demonstrated the relation between the requirements for the experiment design, the level of detail in the model structure and the applicability of the models (i.e. prediction, simulation or characterisation). While the previous results were obtained for idealized simulation inputs, this section describes to what extent smart meter readings and information for the building automation systems may be used as inputs in the identification process instead of the idealized measurement setup used in subtask 3 and the example above.

Concerning climate data, detailed and local measurements, especially for the solar irradiation, is often difficult to obtain. One of the main challenges thereby is to capture the angular dependent relation between the solar irradiation and the effective solar gains that are absorbed in the building. As shown in Figure 11, the root mean squared error (RMSE) clearly increases if global solar irradiation on the horizontal plain, typically measured in simple measurement setups, is used as input for model (scenario B). As described in more detail in [14], an interesting work around is to pre-process the solar irradiation measurements using a solar processor to calculate the solar irradiation on vertical surfaces along the different cardinal orientations (scenario C). Using this work around measurements of the output of the photovoltaic system as an input signal to calculate the solar gains is suggested as an alternative to provide local solar data in a cost-effective way.

Similarly, the use of smart meter readings and information of the building automation system – as shown in the following paragraph – is suggested to provide important input information about the occupant behaviour. As shown on Figure 11, using the measured time series data for the domestic electricity use (scenario D) as an improvement of the model performance compared to the models that had no information about occupant behaviour (scenario F).

c. COLLECTING DATA FROM SMART METERS AND BUILDING AUTOMATION TECHNOLOGIES

As shown in previous paragraphs, accurate reduced-order models for prediction, simulation and characterisation may be obtained using time series data collection during operation. Thereby, options for support from implemented home and building automation systems and smart meters have been identified in an extensive review of basic and state-of-the-art principles of home and building automation systems. This paragraph summarizes the main conclusions obtained from the review as

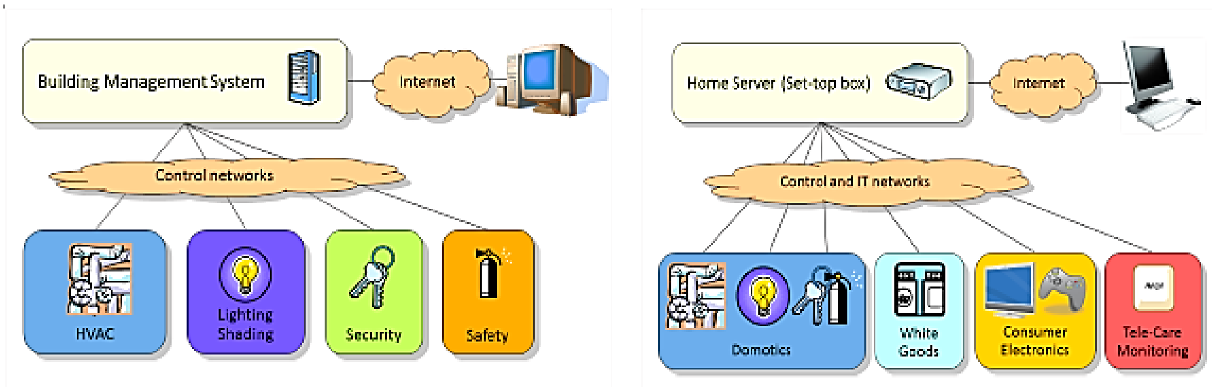


Figure 12 Information potential through automation technologies in buildings (left) and homes (right) [4]

described in [12]. Although this review was focused on home automation and smart metering in Austria, findings can be generalized to a wider context.

To identify the information potential provided by building automation systems a distinction is made between *buildings* (i.e. offices, large apartment blocks, schools, hospitals…) and *homes* (i.e. smaller residences). This distinction is made as automation and monitoring systems show significant differences in architecture, technologies and history.

The objective of building automation is to ensure acceptable quality and energy-efficiency of building operational functions, with minimum requirements for related system components and services specified in DIN EN ISO 16484 [23]. Early developments focused on systems for heating, ventilation and air-conditioning (HVAC) [24] with optional integration of independently operating building services [25]. The challenge then was interoperability of products from different manufacturers and information exchange between the individual components enabling centralized access to information and controls for facility management [26]. Therefore, the most frequent information found in building automation systems relates to HVAC operations. For the purpose of energy management, automation of lighting systems including shading can be added (Figure 12). In addition, security and safety information from systems for fire and access control can be found. Some building management systems are linked to PC-based information systems commonly found in office management for e.g. special analytics, maintenance dispatch or accounting tasks. Nevertheless, given the size of the building, the complexity of the systems and the historic goal of interoperability, building automation systems are typically designed as integrated systems for robustness and quality of service of the control operations.

In contrast, home automation systems have grown from a large number of heterogeneous devices, resulting in stand-alone solutions, different systems for different services and communication solutions that tend to be proprietary and closely linked to manufactured products. Taking into account that integrated systems today are often also more expensive than specific stand-alone solutions, fewer homes are equipped with integrated solutions. For example independent automations systems are used for shading and for security or home entertainment.

In the context of data collection for grey-box modelling two fundamental issues can be identified. Firstly, existing sensor data are not readily available. Given the use of proprietary and diverse communication protocols it is difficult to obtain the full set of measurements, including temperature readings, heating system operation, ventilation rates, electricity use… As shown in previous paragraphs, such complete input of all energy vectors is a prerequisite for accurate characterisation of the energy performance of buildings. The development of open communication protocols such as KNX, which is specifically aimed at intelligent home management, are identified as important steps forward. Also cloud-based solutions may contribute significantly in making data more generally available in so-called "connected homes." In addition to computer firms such as Apple or Google, electronics companies are among the providers of these internet-based, proprietary automation solutions.

A second fundamental difficulty results from the historic background of building automation systems. The automation systems are designed for operation of the specific devices installed, and the sampling strategies are totally optimized and simplified, because automation processes do not rely on the sensors in the same way as the envisioned applications of IEA Annex 58. For example, to control the supply temperature and flow rate of the ventilation system typically the return air temperature rather than the room air temperature is measured for control. Consequently, even in detailed building automation systems, the variables needed for the identification frameworks developed in this annex may not be directly available, may have to be newly commissioned (minor effort), or require additional programming (potential major effort). With the on-set of "smart" home solutions that can be configured by users, energy efficiency also became a driver for home automation. Related solutions can be characterised as modular, often wireless components that are internet-based, and have a proprietary operating system for integration of services. Recently, they are also energy-efficient in their electricity consumption, and emphasize software and interoperability with existing infrastructure [27, 28]. This evolution suggests that also in small residential applications, the amount of sensors related to the energy consumption and as such related to the work of Annex 58 may become increasingly available in the near future, particularly in residences participating in smart grid operations like demand response and load shifting programs.

3.3 Characterisation of buildings on smart grid level

In addition to the characterisation on a building level, top-down and bottom-up approaches to characterise the building performance on a district – or smart grid – level have been presented [29].

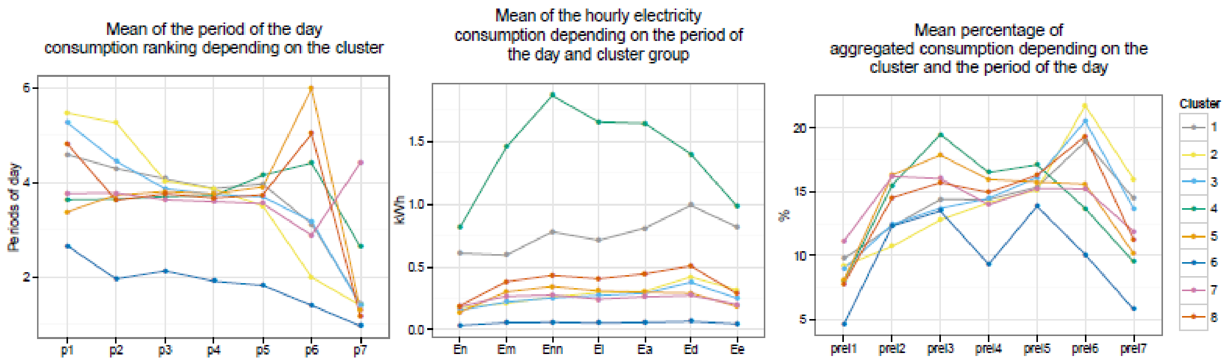


Figure 13 Analysis of electricity use patterns for identified clusters [29]

A clustering analysis on data from over 8500 smart meters was applied to identify relevant indices or parameters related to the hourly electricity use profiles that can define user's electricity behaviour. In the procedure different performance indicators have been defined and quantified for each of the dwellings. The performance indicators cover energy consumption indicators, user behaviour indicators, weather dependency indicators and complementary indicators. After selecting the relevant indicators that describe the dataset, (Self-Organizing Maps) SOM and K-means clustering was applied for the segmentation of groups of dwelling with similar energy characteristics. As shown in Figure 13, each of these clusters thus represents a group of buildings characterised by different load profiles. As such, this methodology not only allows to support decision-making regarding energy conservation measures and user awareness campaigns. The method also allows modelling of the energy use of a large amount of buildings.

Alternatively to this data-driven top-down approach, bottom-up detailed building energy simulations have been used to evaluate the impact of net zero energy buildings (net ZEB) - equipped with heat pump and photo-voltaic systems - on a distribution grid level. Figure 13 shows the obtained effective level of net ZEB as function of the design level of net ZEB for different feeders. A design level of net ZEB equal to 1 thereby represents a neighbourhood where all buildings have been designed individually to have their annual electricity demand covered by local PV production. The effective level of net ZEB is what was actually achieved on a neighbourhood level taking into account Ohmic losses, PV curtailing… The study shows (Figure 13) significant efficiency losses, reflected values of effective net ZEB levels below the design level, that mainly as a result from curtailment losses due to the mismatch between local electricity demand and supply [9]. These efficiency losses are typically not accounted for in the evaluation of net zero energy buildings (nZEB) on a building level. Nevertheless, as shown in Figure 13 significant losses may occur for weak feeders.

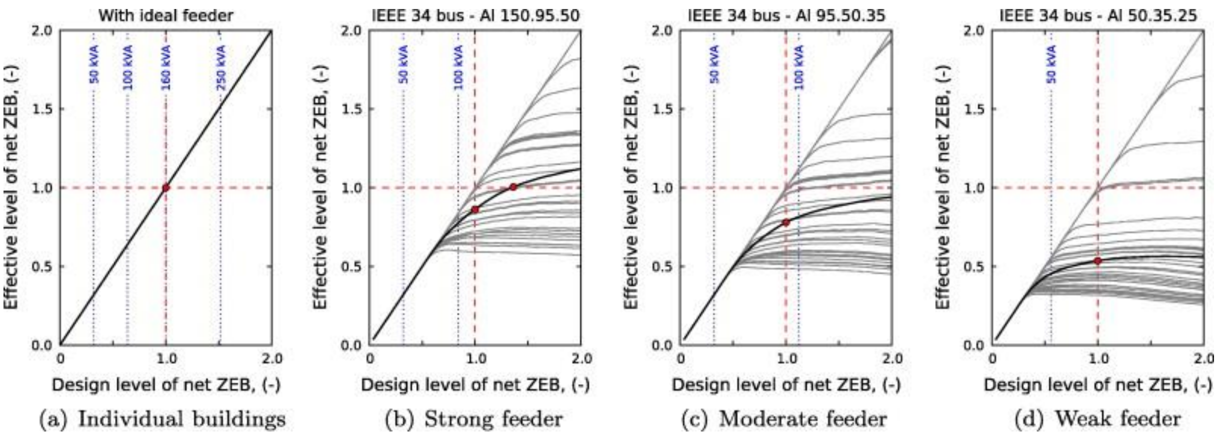


Figure 14 Obtained level of "net ZEB," taking into account the grid constraints for different feeder qualities on a neighbourhood level. A design level of net ZEB of 1 corresponds to a neighbourhood where all dwellings are designed to have an annual net electricity demand of 0 kWh. [9]

In a next step, a Monte Carlo method is applied to characterise the relation between building and neighbourhood parameters and the grid performance indicators related to these efficiency losses, such as the Ohmic losses, maximum transformer load and the characteristic daily voltage peak deviation [30]. Figure 14 represents these relations by showing the Spearman's correlations of 21 neighbourhood parameters to 3 grid performance indicators, i.e. Ohmic losses, transformer load and maximum voltage. Thereby it is shown (Figure 15) that mainly the aggregated volume (16: $\sum Vol$), UA-value (17: $\sum UA$) and gA-value (18: $\sum gA$) as well as the total nominal heat load (19: $\sum Q_{des}$) and annual heat pump demand (20: $\sum E_{HP}$) are dominant characteristics and can be considered as good candidates to be used in meta-modelling of the resulting loads, the occurring voltage fluctuations and Ohmic losses in the low voltage grid. Due to this bottom-up characterisation of meta-models on a neighbourhood level, these identified meta-models show important potential to support the evaluation of building performance optimization or the integration of storage systems from a grid perspective.

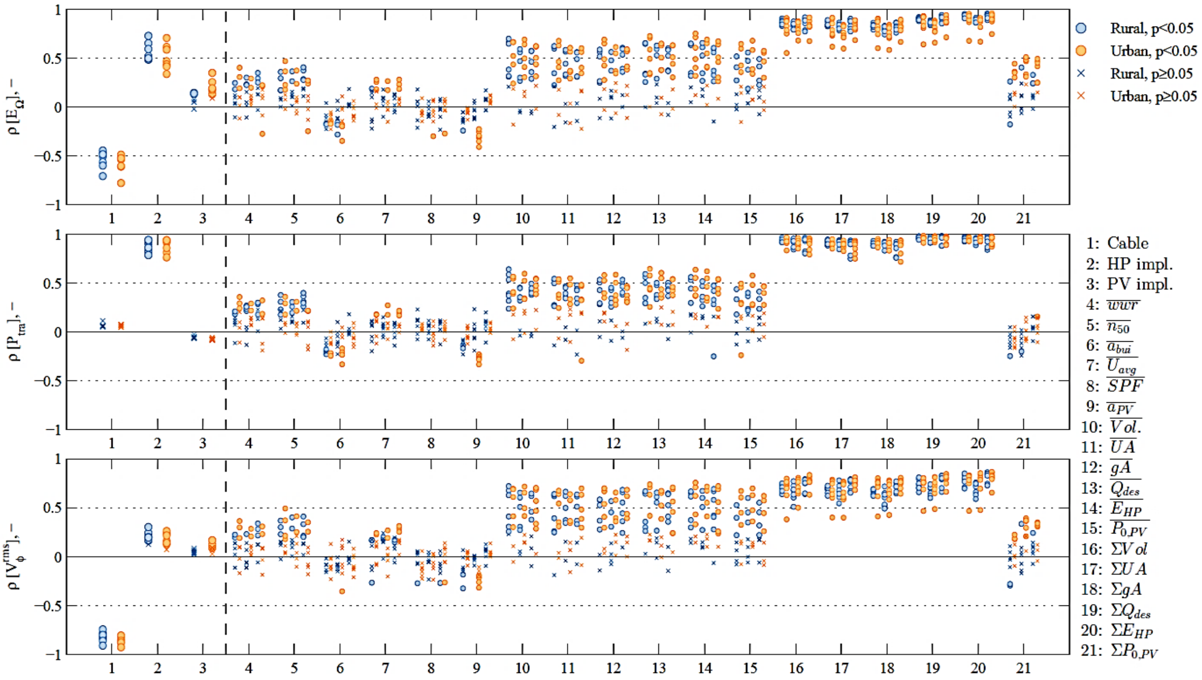


Figure 15 Spearman's ρ correlation coefficients of all neighbourhood parameters for the Ohmic losses $\rho[E_\Omega]$, the transformer load $\rho[P_{tra}]$ and the voltage fluctuations $\rho[V_\phi^{rms}]$ based on the simulation set, feeder configuration and cable type. [30]

4. Application of characterisation results

As outlined in Chapter 2, the evolution towards nearly zero energy buildings and the integration of renewable energy sources changes the way the buildings interact with energy distribution grids. Buildings no longer only use energy, but also act as distributed renewable energy sources. As a result, an optimized operation of energy networks is essential to balance demand and supply of energy.

The aim of subtask 4.3 is to identify suitable applications for models for describing the energy dynamics of buildings. There are different ways to use the characterisation results of buildings. Of the many possible applications, performance compliance checking can be cited as a very interesting addition to Energy Performance Certification (EPC) checks or for commissioning purposes. Another important field of applications is the development of models for control purposes.

In this subtask, the emphasis was put on using the dynamic characterisation in the context of energy networks. Annex 58 participants were encouraged to submit free papers and presentations demonstrating the opportunities offered by the use of characterisation results. The submitted papers mainly focused on the use of characterisation results to aid in the optimization of the operation of energy grids. In the following a brief summary of the contributions is outlined. The text is based on the presented papers and presentations.

The presentation “Demand Side Management and Grey Box Models for Smart Grids: As seen from a Danish perspective” by Henrik Madsen presents a comprehensive overview of the potential of dynamic characterisation within Demand Side Management applications for the specific situation in Denmark with high shares of wind and solar energy. A hierarchy of optimization/control problems based on grey-box models with integrated forecasting for both direct and indirect control have been described as well as an approach for integrating large fractions of wind/solar power in smart grids. The presented optimization problems were illustrated with examples of smart grid applications such as control of electrical heaters in 20 family houses, control of supermarket cooling and control of heat pump and thermal solar collector system for a family house. Other Danish applications have been presented in the paper “Results from measurements on a wide range of Danish single-family houses with heat pumps”, Lars Olsen, Søren Østergaard Jensen, Christian Holm Christiansen.

In the paper “Using dynamic models and comfort intervals for balancing the fluctuating wind and solar power production” Henrik Madsen, Gianluca Dorini, Olivier Corradi, presented during the 2012 Bilbao meeting some of the earlier stated principles are further outlined and the existing market structures and balancing strategies are challenged. In a real-time electricity pricing context – where consumers are sensitive to varying prices – having the ability to anticipate their response to a price change is valuable. The paper outlines models for the dynamics of the price-response, and shows how they can be used to control the electricity consumption using a one-way price signal. The estimation of the price-response is based on data measured at grid level, removing the need to install sensors and communication devices between each individual consumer and the price-generating entity. Two applications to real-life price-responsive heating systems were also presented.

Researchers form the Hong Kong Polytechnic University further provided examples of applications. During the Hong Kong Meeting the first zero carbon building (ZCB) in Hong Kong was presented (Lu Yuehong, Wang Shengwei, Xiao Fu, Li Guiyi, Experimental and Analytical Investigations on Energy Demand and Generation of Hong Kong Zero Carbon Building (ZCB) Expert Meeting Hong Kong, 2013). The principle aim of this study is to demonstrate how to optimize the design with single- and multi-objective optimization techniques and to develop an optimal control strategy for the ZEB which ensures indoor air quality, reduces operational cost and minimizes the negative impacts on the grid.

The same research group also analysed an interactive building power demand management strategy that was developed for the interaction and optimization between commercial buildings and the smart grid. The method used a building thermal model based on a battery analogy which was developed to characterise the dynamic behaviour of buildings for the use of grid interaction and optimization. It was demonstrated how the building's thermal mass could be used to help relieving grid power imbalance caused by renewable generations. ("An Interactive Building Power Demand Management Strategy for Smart Grid", Shengwei Wang, Xu Fiao, Isso Xue Xue, Yongjun Sun, 2013 Expert Meeting Holzkirchen Germany). The paper "Using structural thermal energy storage in dwellings" (Glenn Reynders, Thomas Nuytten, Dirk Saelens, 2012 Bilbao) also demonstrated the use of structural thermal mass for demand side management to increase the cover factor of the energy generated from the PV and to reduce the peak load of the building. Thereby, the authors emphasize the need for a model-based control which is shown to outperform simple rule-based control.

The above examples all emphasize the importance of a good characterisation of the (dynamic) behaviour of the buildings. Some papers and presentations reported on different methods to determine this characterisation results in the field and gave suggestions to define smart meter configurations. The presentation "Some possibilities for use of Smart Meter data" (Henrik Madsen, Henrik Aalborg Nielsen, Peder Bacher, Carsten Rode, Søren Østergaard) presented at the Annex 58/Dynastee Workshop Ghent, April 2014 showed different uses for Smart Meter data. During the following Berkeley meeting the presentation "What can we learn from data?" (Madsen, 2014 Berkeley meeting) demonstrated the use of different models that were used for different purposes. For instance RC-networks, Lumped, ARMAX and grey-box models, can be used to derive building characteristics from smart meter data (Annex 58), Markov chain models, Generalized linear models are used in Annex 66 to deduce user behaviour. Non-parametric, conditional-parametric and semi-parametric models were identified as suitable upgrades for future research.

In the paper "Grey-box building models for model order reduction and control" by Roel De Coninck, Fredrik Magnusson, Johan Åkesson and Lieve Helsen and presented during the 2013 Holzkirchen meeting, ongoing developments and first results of data-driven grey-box modelling for buildings were presented. It was reported how a Python toolbox coupled to a Modelica library was developed and coupled to the optimization framework JModelica.org to characterise buildings. The results of a system identification and parameter estimation study for an office building in Brussels were outlined. Also the papers "Building dynamic characterisation for use in smart grids" Gabriel Masy and Philippe André presented during the Hong Kong meeting (2013) and "Development of a building performance evaluation method in climate chamber using a building occupant emulator and with application to smart grids", Imane Rehab, Elisabeth Davin, Philippe André presented during the Prague meeting (2015) demonstrated how experiments could be used in practice to apply in Smart grids.

Despite the interesting presentations, a demonstration of the opportunities that are enabled by a dynamic characterisation do not proof to be straightforward as it requires a full multidisciplinary approach, which is both in experimental set-ups and simulation environments rarely available. The European research project FIEMSER (Friendly Intelligent Energy Management System for Existing Residential Buildings) however gives a nice example of an approach where a control system in a residential application is developed and applied in an experimental study, which tries to adapt the local energy consumption profiles on the local generation of renewable energy sources. More details on the project where the energy management system even tries to influence the user behaviour can be found in www.fiemser.eu. The project was presented during the Holzkirchen meeting (2013).

5. Summary and Outlook

5.1 Summary

This report first identifies some of the problems which we will face when massively integrating renewable energy sources. The main issue is the mismatch of supply and demand of the highly intermittent distributed renewable energy sources. Demand side management and storage of energy are important means to overcome this issue. To deploy these techniques it is necessary to be able to characterise the dynamic behaviour of buildings and stocks of buildings.

Subtask 3 and subtask 4.2 provide useful information for developing models for Model Predictive Control (MPC) and Active Demand Response (ADR) in the context of intelligent energy networks such as smart grids and 4th generation Thermal Networks.

In the second chapter, which is the main body of this report and the work done within activities 4.2 and 4.3, the importance of characterisation of the dynamic response and the energy performance of buildings in a smart grid context has been emphasized. Thereby, three main application domains for identification are highlighted: (i) short-term predictions for control optimization, (ii) long-term simulations for the evaluation of new energy concepts on a building or neighbourhood level and (iii) the characterisation of the main thermal properties of buildings.

The simulation-based approach proposed in this subtask showed a high degree of flexibility for the identification of different buildings and different experiment setups. As such, it was demonstrated that different degrees of model complexity are required for the different applications. Low-order models, which could be identified using simple measurement data of in-use buildings, showed accurate performance for prediction. The required input and observation measurements for these low-order models can be obtained from smart meters and state of the art building automation systems. An extensive review of the state-of-the-art in building automation systems revealed that while a lot of data potential is already available, lack of open communication standards are currently one of the limiting factors.

Higher-order models that allowed to separate the heat flow paths to different boundary conditions (outdoor air, ground, adiabatic…) are needed for a detailed long-term simulation as well as for a reliable physical interpretation of the identified thermal properties of the individual components. Nevertheless, it was emphasized that to guarantee a reliable and robust identification process for these higher-order models, adequate measurement data are required including heat flux measurements. If these advanced measurement data are not available, it is suggested to limit the complexity of the model and only interpret the overall building thermal properties. Using additional prior physical knowledge to reduce the amount of unknown parameters was also suggested to assure the identifiability.

In addition to these studies on the characterisation on building level, different studies were presented on the characterisation of the energy performance of buildings on a smart grid level. Thereby, clustering analysis was found to be an interesting top-down approach to identify different drivers that govern the electricity demand profiles in large districts. Additionally, a bottom-up assessment of zero energy neighbourhoods revealed that as a result of the mismatch between local demand and supply important renewable production losses occurred. A Monte-Carlo analysis was carried out to characterise dominant building and grid parameters which are candidate inputs for meta-models on district level. As such these district level models can be an important next step into a district level optimization of smart grids and buildings in a smart grid context.

In the third chapter, some applications of the framework have been listed. Participants provided free papers and presentations that demonstrated the importance and opportunities of characterisation in intelligent energy networks. Both application is simulations as real life cases were shown. It was clear that the multi-disciplinary approach which is necessary to demonstrate all benefits of the application of dynamic characterisation in the context of District Energy Systems is not yet fully present. Simulation environments for DES-simulation are continuously improving but fully featured environments where complete neighbourhoods with energy networks (electrical and thermal) including sophisticated control strategies can be assessed are not yet available. Also comprehensive data sets (including building and occupancy descriptions) and operational data (energy use, control signals) from fully operational real energy networks are hardly accessible (because of e.g. privacy issues) or available. Nevertheless, some interesting applications demonstrating characterisation based on experimental data amongst which data from smart grids were shown.

5.2 Outlook

The presented examples showed the initial benefits of the framework in the context of intelligent energy networks. With a growing interest in building and home automation systems the availability of valuable time series data is expected to grow. The application potential for on-line identification and characterisation of the dynamic thermal performance of buildings using the methods presented in this Annex is therefore expected to increase, enabling the harvesting of energy flexibility in buildings and optimize energy efficiency on a district level. Nonetheless, the work is obviously not finished.

The methods developed within the framework of this Annex proof to be valuable (1) to organize the operation of energy systems by generating models that can be used to quantify the dynamic response and the flexibility available in different buildings or blocks of buildings and (2) to develop models that are useful in simulation environments to assess different designs at increasing scale, i.e. from building to district level. The latter is especially interesting in co-simulation tools developed to assess the design and operation of District Energy Networks.

These opportunities and applications can be linked to running and upcoming IEA EBC Annexes:

- Focus on characterising the dynamic thermal behaviour of the building
  → possible link to Annex 67 "Energy Flexible Buildings"
- Focus on the description and characterisation of user behaviour
  → possible link to Annex 66 "Definition and Simulation of Occupant Behaviour in Buildings "
- Focus on the identification of building characteristics and reduced-order models for implementation in co-simulation tools (e.g. FMU/FMI) in District Energy Simulations (DES).
  → link with Annex 60 "New generation computational tools for building and community energy systems based on the Modelica and Functional Mockup Interface standards"

The results may also be beneficial for:

- Annex 63 "Implementation of Energy Strategies in Communities"
- Annex 64 "Optimized Performance of Community Energy Supply Systems with Exergy Principles"

On a longer perspective the focus could be on using the building energy signatures in District Energy Systems. Possible research questions and applications include:

- The characterisation of the aggregated dynamic behaviour of blocks of buildings.
- Identify occupancy induced fraction of energy demand to enable building specific energy labelling or certification using on-line measured energy use data.

- The automatic generation of reduced order models from smart meter and building automation data including the definition of the minimum measurement requirements to generate these forecasting models.
- Linked to the above: the development of new kinds of smart meters that can be applied in electrical and thermal grids.
- Increasing availability and quality of sensor data in building and home automation systems by open communication standards.

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