TOWARDS MORE EFFECTIVE RESIDENTIAL RETROFIT INTERVENTIONS

Exploring an alternative monitoring approach to drive the effectiveness of residential energy efficiency retrofit interventions

M.Wolf

P5 | M.Sc. Graduation Thesis
BOLD Cities Graduation Laboratory
Management in the Built Environment
Delft University of Technology

TU Delft

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Humanity is facing large scale environmental challenges emerging from the anthropogenic climate change. Greenhouse gas emissions (GHG) are widely considered to be the main driver of the changing climate. With the built environment currently being accountable for about 40% for our total GHG emissions there is a great urgency to act and change our current consumtion patterns. Whereas new buildings are already mostly able to achieve a high energy efficiency the biggest potential for CO2 reductions lies in retrofitting the existing housing stock. Yet current interventions aimed at retrofitting our built environment often seem to remain below their expectations. Actual solid evidence on their performance is scarce and inaccurate. One reason for the lack of information is seemingly the rather simplified and therfore inadequate approach to generate feedback. In order to provide more accurate evidence and thereby facilitate more effective decision-making this research investigates an alternative approach based on a more holistic thinking and the use of data innovation.

Keywords: *Anthropogenic climate change, GHG emissions reduction, energy efficiency, retrofit, data innovation, monitoring, systems thinking*

COLOPHON

Title	Towards more effective residential retrofit interventions: Exploring an alternative monitoring approach to drive the effectiveness of residential energy efficiency retrofit interventions
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PREFACE

This report is the final result of the BOLD Cities graduation laboratory (AR3R010) and presents my research on monitoring residential energy efficiency retrofit interventions. The research was carried out at the department of Management in the Built Environment (Faculty of Architecture) at the University of Technology Delft.

The Big, Open, Linked Data (BOLD) Cities graduation lab aims to bring together the perspectives of big data, architectural and planning information, smart cities, information technologies, urban area development and governance into clear demonstrations that explain the potential of the emerging approaches. Choosing this graduation lab gave me the opportunity to combine both my interests in architecture and technology into one graduation project and broaden my perspective beyond the boundaries of the building sciences and towards the wider socio-economic context.

For me the past months have been an interesting journey through a vast amount of new topics and lead to a lot of new insights on a variety of different topics related to this research. This is especially valuable because I believe that complex challenges like the energy transition in the building sector are only to be managed if they are approached with a holistic understanding of the many interrelated factors and specific context in which they are embedded. This however requires us to collaborate across the traditional boundaries of our professional domains. By choosing this graduation project I hoped to have laid the foundation for my own contribution in this transformational process.

At this point I would like to thank my interview partners for their time, ideas, feedback and overall valuable contribution to this research. Moreover I would like to especially thank my mentors Alexander Koutamanis and Andrea Mauri for their great support, guidance during and interesting conversations during this time.

I hope you will enjoy reading this report!

Delft, January 2019
Malte Wolf

EXECUTIVE SUMMARY

Humanity is facing large scale environmental challenges emerging from the anthropogenic climate change. Greenhouse gas (GHG) emissions released in particular through the use of fossil fuels are widely considered to be the main driver of the changing climate. This has diverse negative impacts such as rising sea levels, increased risk of flooding, drought and other extreme weather events.

A major step in acknowledging the problem and creating a global plan and shared commitments towards changing our current energy consumption patterns was made in the 2016 Paris Climate Agreement. The central aim of this agreement is to response to the threat of climate change by keeping the global temperature rise in this century well below 2 degrees Celsius (UNFCCC, n.d.). With the built environment currently being accountable for about 40% of the final energy consumption and 36% of the GHG the sector plays a crucial role in the success of these efforts (EC, 2011b).

Especially the existing residential housing stock is considered to offer a vast potential for reductions in particular through energy efficiency (EE) retrofit interventions (IEA, 2014). Yet recent progress assessments show that current retrofit interventions are having problems in delivering their ambitious reduction targets (UN, 2018). Problems like the comparably low take-up rate of related programmes as well as the gap between anticipated and actual performance of EE interventions in many projects clearly show that there is a need for optimisations. Solid evidence on the actual performance of most interventions is however scarce.

Currently EE interventions are reduced to their carbon benefits (GHG reductions) and often assessed in isolation which makes them look rather unattractive compared to other investment options (IEA, 2014). Recent research indicates however that broadening the perspective beyond the environmental aspects of EE can help to make interventions look much more attractive and thereby stimulate a higher take-up. In particular it was shown that interventions in EE have the potential to act as a tool for social and economic development (IEA, 2014). The understanding of these unintended spin-off effects however is yet rather limited due to a lack of data and an adequate approach illustrate and understand the trade-offs of the different factors.

„Data is the lifeblood of decision-making and the raw material for accountability. Without high-quality data providing the right information on the right things at the right time, designing, monitoring and evaluating effective policies becomes almost impossible„

United Nations (2014)

This leads to uncertainty and increases the risk of unintended negative effects, missed opportunities in aligning goals and ineffective resource allocations. In order to better understand the complex interrelations between the different factors and determine the actual effect of an intervention an alternative approach to capture the effects of EE interventions might be helpful. Even though the knowledge in this area is growing it is yet rather fragmented. This research aims to contribute to the closing of this gap by exploring, collecting and aggregating existing knowledge

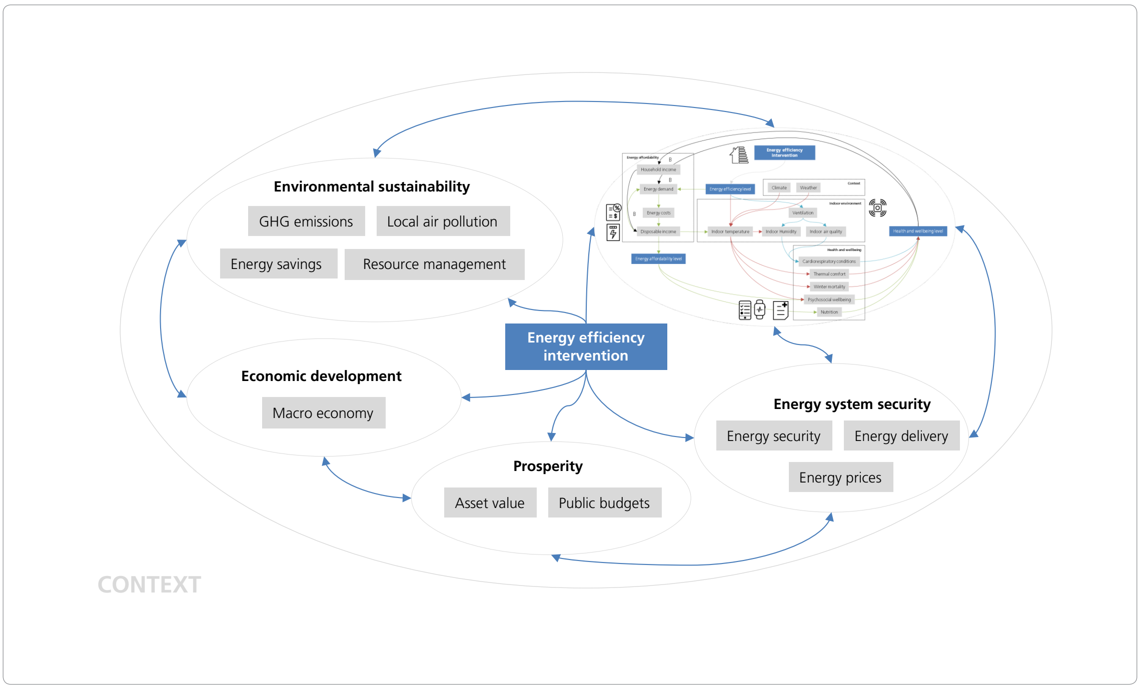

Figure 1: Proposed alternative systems understanding of energy efficiency interventions (own illustration)

as well as new ideas and thereby add valuable information to the academic body of knowledge. Keeping in mind the fact that the global population and at the same time the global urban infrastructure is about the double within the next thirty years there is a great urgency in getting things on the right track. The decisions taken today will determine if people will be locked into their current resource intensive lifestyles or if they enable people to change. The central problem statement was posed as follows: *How can we monitor the performance of residential energy efficiency retrofit interventions more accurately to facilitate more effective decision-making?*

The research project was carried out as an exploratory research using a qualitative multi-method design making use of literature study, expert interviews and a model development in order to explore the subject.

The proposed alternative approach is based on (1) a more holistic perspective and (2) driven by data innovation. This combination is considered to offer major advantages over the conventional linear and simplified approach. Regarding the more holistic perspective the following areas and factors were identified to be worth further consideration:

- Environmental sustainability (e.g. energy savings, GHG emissions, resource manage ment)
- Social development (e.g. health and well-being, poverty alleviation, employment)
- Economic development (e.g. macroeconomic impacts)
- Prosperity (e.g. asset value, public budgets)
- Energy system security (e.g. energy security, energy prices, energy delivery)

Due to the complex relationships and interdependencies between the different factors the conventional linear thinking approach was considered to no longer be adequate. Instead a system thinking approach was suggested and introduced that enables decision-makers to determine trade-offs between the different factors and the wider context and an overall better understanding of their dynamics. Moreover the evidence presented showed that innovative data sources and collection methods emerging from recent technological developments such as mobile sensors and self-phones may help to overcome these obstacles by supplementing conventional methods. Interesting could be in particular their contribution to the following areas:

- Improving the understanding of the intervention context which may include among other economic, social, political, cultural, demographic and ecological factors;
- Improving the data collection by providing less cost-intensive and more timely data;
- Monitoring process and behavioural change by providing continuous data about certain phenomena;
- Evaluating complex interventions by collecting data on a larger number of variables and analysing interactions among them.

However even though the seemingly vast opportunities of data innovation it was also shown that these technologies give rise to new challenges in particular regarding the questions of causality, data privacy, data accessibility and the role of theory. This is why opportunities may arise in particular from the combination of conventional and non-conventional into mixed methods approaches and thereby adding additional depth to the findings.

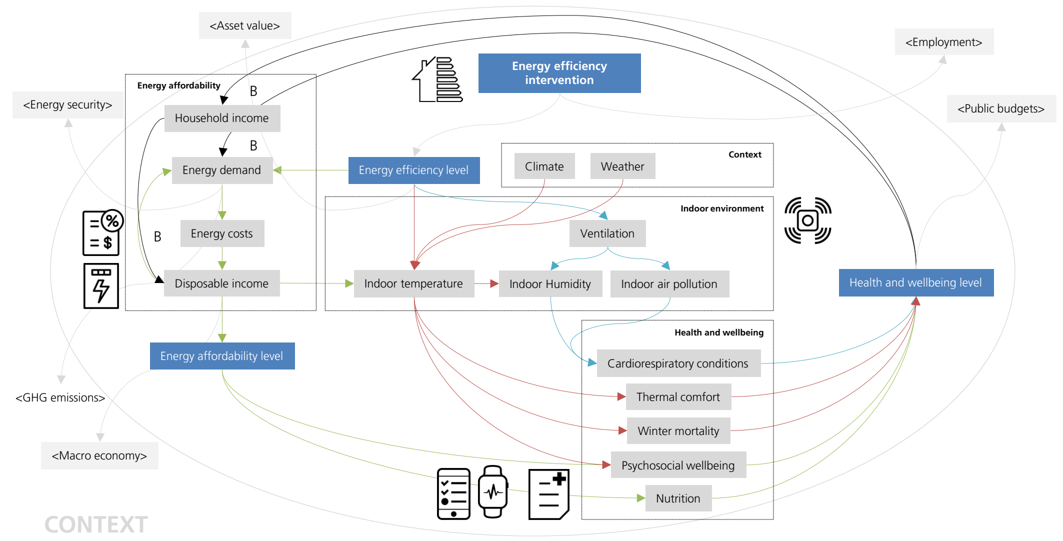

Figure 2: Proposed conceptual model (own illustration)

READERS GUIDE

This report is divided into seven chapters:

CHAPTER 1: INTRODUCTION
Introduction of the background and contextual information for the research as well as the central problem statement and related research questions

CHAPTER 2: RESEARCH APPROACH
Justification of the research methodology, the research design, the data collection techniques as well as the process and scope of the research project

CHAPTER 3: LITERATURE STUDY
Evidence that illustrates the performance problems and underlying limitations of current retrofit interventions and the conventional feedback approach and explores opportunities for an alternative more holistic approach driven by emerging technological developments

CHAPTER 4: EXPERT INTERVIEWS
Interviewee selection and explaination of the process and main findings of the qualitative interviews

CHAPTER 5: MODEL DEVELOPMENT
Integration of the findings of the literature study and the qualitative interviews into an exemplary conceptual model in order to identify opportunities and challenges of the alternative apporach

CHAPTER 6: RESEARCH FINDINGS
Summary of the findings of the research and discusses the potential added value as well as challenges and limitations of the new approach and indicates further research opportunities

CHAPTER 7: REFLECTION
Elaboration on the process as well as the societal, professional, scientific relevance and transferability of the research findings

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GLOSSARY OF TERMS

Intervention is used in the context of this report as an umbrella term to describe an action taken in order to achieve higher energy efficiency. This includes interventions on different levels such as policies, programs or individual projects.

Monitoring can be defined as a regular assessment in which stakeholders obtain feedback on the progress made towards achieving a certain objective (UNDP, 2009). Its purpose is to track and determine to which level the objective planned has been reached and thereby enable corrective measures if necessary.

Evaluation is defined as a more in-depth independent analysis of completed or ongoing activities to determine the performance (using specific indicators) of certain actions in achieving a certain objective (UNDP, 2009) . The process of evaluation may also include the validation and verification of an action.

Validation describes the evaluation process that aims to determine the appropriateness of an action in order to achieve a specific goal (e.g. are we doing the right thing?).

Verification on the other hand aims to determine if the action that was taken was executed correctly (e.g. are we doing the thing right?).

Performance indicators are used to determine the status or results of a specific action (e.g. effectiveness, efficiency or impact)

Effectiveness is defined as the level to which an action contributes to its predefined purpose (e.g. reducing GHG emissions or energy demand. This can be related to a variety of different factors.

Efficiency on the other hand considers the amount of resources needed to reach the predefined purpose (e.g. how much money was paid to achieve a specific reduction of GHG emissions).
Impact is the extent to which an action leads to long-term changes. An intervention could for example be effective on the short term but do net lead to a long-term change.

Data innovation is used as an umbrella term covering innovative new approaches of data collection and analytics

ABBREVIATIONS AND ACRONYMS

EE	–	Energy efficiency
BD	–	Big Data
M&E	–	Monitoring and Evaluation
ICT	–	Information and Communication Technology

1. INTRODUCTION

In the following chapter the necessary background information for this research is introduced. This includes not only the introduction of the topic, the central problem statement and related research questions but also a justification of the scientific and societal relevance of the research.

Research background

Today humanity is facing large scale environmental challenges emerging from the anthropogenic climate change. With about 40% of the final energy consumption the built environment is one of the major causes (36%) for the emission of greenhouse gases (EC, 2011b). Researchers around the world agree that with the rapid urbanization and the related resource intensive urban lifestyles this percentage is likely to grow even further (Becchio, Corgnati, Delmastro, Fabi, & Lombardi, 2016). Even though many countries have formulated goals and implemented various interventions to reduce our energy consumption and facilitate the change towards renewable energies the results seem to be yet far from optimal (UN, 2018).

„What gets measured gets managed“

Drucker (1955)

A major step in acknowledging the problem and creating a global plan and shared commitments towards changing our current energy consumption patterns was made in the Paris Climate Agreement which entered into force on November 4th 2016. The central aim of this agreement is to response to the threat of climate change by keeping the global temperature rise in this century well below 2 degrees Celsius and purse efforts to limit the temperature increase even further to 1.5 degrees Celsius (UNFCCC, n.d.).

The precise GHG reduction targets to achieve this objective differ from country to country. The European Member States (MS) have agreed upon shared targets with specific shares for each major sector. According to this planning the GHG emissions in the building sector are to be cut by 80-95% (compared to 1990 levels) by the year 2050 with intermediate targets to be achieved in 2030 (40%) and 2040 (60%) (EC, 2011b).

With about three quarters of the total floor space in Europe being residential and about 75% of the sub-sector currently being classified as inefficient the existing residential housing stock is of special importance for the success of the energy transition. This is especially important as the biggest part of these buildings will still be standing in 2050. Yet despite major efforts to stimulate citizens to engage in energy retrofits the annual renovation rate across Europe is on a rather low level of 0.8-1.0%. However, to reach the 2050

CO_2 reduction goal this level would have to rise above 2.0% (Becchio et al., 2016; EC, 2011b). In an attempt to encourage more building renovation and improve the energy efficiency in buildings the EU ambassadors have just recently agreed upon an amendment of the Energy Performance for Buildings Directive (EPBD) the main European legislative intervention regarding the energy performance of buildings (EC, 2018b; EU, 2016). Actual evidence on the process and performance of these interventions is however very scarce meaning that only the future can tell if the improved interventions will be more successful in achieving its ambitious objectives.

When looking at the findings of research in the field their actual performance must at least be doubted. The so called 'performance gap' for example describes the discrepancy between the anticipated and the actual post-occupancy energy consumption of a retrofitted building. Multiple researchers showed that the actual energy consumption of buildings is often far from the pre-retrofit calculations (Gram-Hanssen & Georg, 2018; Hong, Yan, D'Oca, & Chen, 2017; Steg, Perlaviciute, & van der Werff, 2015; van den Brom, Meijer, & Visscher, 2018). In practise this means that simulations often overestimate the energy wasted in pre-retrofit (inefficient) buildings and vice versa underestimate the potential savings in post-retrofit (efficient) buildings. (Gram-Hanssen & Georg, 2018; Hong et al., 2017; Steg et al., 2015; van den Brom et al., 2018).

The uncertainty about their actual performance emerging from a rather narrow and technical perspective in combination with the general data scarcity is believed to lead to ineffective resource allocations and performance losses throughout the intervention process (planning, design, implementation, evaluation) and is thereby at least partially the reason for their results to remain below expectations (IEA, 2014). In combination with the long assessment cycles an effective management of the interventions, not to mention timely follow-up optimisations of specific interventions, is rather difficult if not impossible. The limitations of the conventional feedback approach can be divided into (1) design challenges meaning the simplified linear understanding of the process neglecting the complex dynamics and interdependencies with a variety of related factors and (2) data challenges meaning the inability to collect up-to-date high quality data on the process as well as contextual factors.

„Everything should be made as simple as possible, but no simpler"

Einstein (n.d.)

After all it can be concluded that the progress being made towards a carbon-neutral housing stock might after all be not as positive as stated by official assessments and that the lack of evidence puts the ambitious GHG reduction targets at great risk. In order to facilitate the design of more fine-grained and goal-orientated interventions evidence is required that provides a more robust understanding of energy retrofit interventions.

Given the importance of decisions taken today to set the stage for future developments there is a great urgency in developing a more adequate feedback approach that is able to generate the evidence needed for effective decision-making. This is supported by an assessment of the Building Performance Institute Europe (BPIE) which emphasized on the need for more solid information on the policy level but also to the lower programme and individual building level (BPIE, 2014). Being able to effectively manage the process will decide whether people are locked in their current resource-intensive lifestyles or if they are enabled to change.

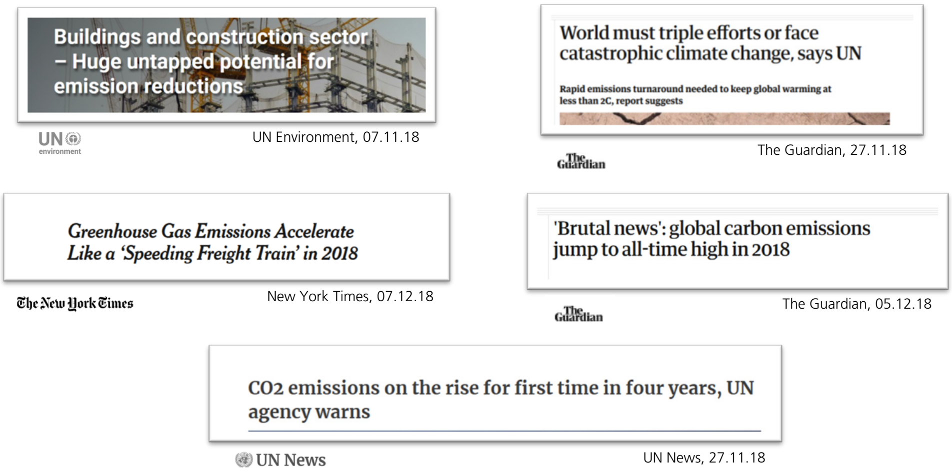

Figure 3: Recent news headlines indicating the urgency to reduce GHG emissions (own illustration)

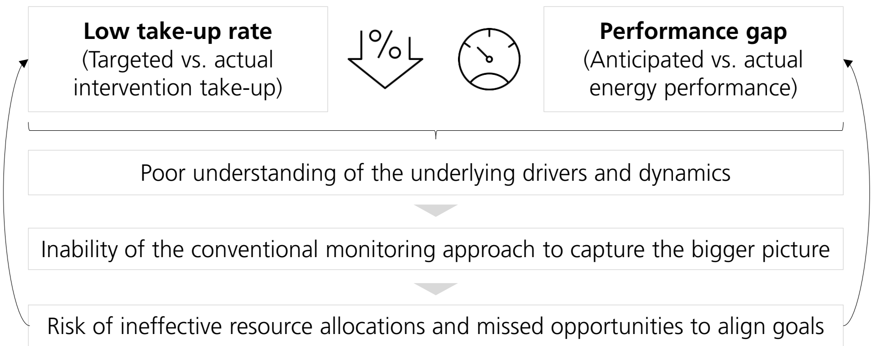

Figure 4: Challenges faced by current interventions (own illustration)

Research question(s)

Based on the introduced information and scope the central problem statement of this research is formulated as following: *How can we monitor the performance of residential energy efficiency retrofit interventions more accurately to provide better evidence for decision-making?*

To approach the central question and structure the research two sub-questions concerning the design as well as the data problem were formulated as following:

Q1: Which additional non-carbon factors are influenced and could provide a more holistic understanding of residential EE retrofit interventions and which alternative thinking approach could help to illustrate the complex relationships and dynamics of these factors?

Q2: Which additional or alternative sources could be used to provide more timely and accurate data on these factors and which methods could be used to collect the data?

Research scope

In the context of this research the focus will be put especially on the post-implementation monitoring. The process of monitoring (what is happening?) is being defined as a regular assessment in which feedback on the state of implementation and progress made towards achieving a certain objective is obtained (UNDP, 2009). In this sense it is however also the necessary precondition to provide data for downstream in-depth evaluations (why is something happening?).

Due to the scale of the topic and the various perspectives from which the topic can be approached the research is also guided by the following boundaries:

Target:	Existing residential housing stock
Level:	Project
Type:	Energy efficiency
Perspective:	Policy-maker
Process:	Monitoring
Stage:	Post-implementation

Research relevance

In the next years ongoing trends like the growing global population and the rapid urbanization are going to increase the problems of the anthrophonic climate change. Changing our current energy consumption patterns therefore becomes increasingly urgent. This change however can only be managed effectively if decision-makers have a solid understanding of the dynamics of certain interventions and are provided with accurate information on their performance. This research aims to contribute to a better understanding by exploring the various factors involved as well as methods and tools on how they could be measured and illustrated. By choosing a more holistic approach on the topic this might also offer valuable insights into how energy efficiency interventions are interrelated with other major challenges of today and thereby enable decision-makers to align goals, discover synergies and increase the performance of their interventions. This offers the potential to significantly strengthen the performance of certain interventions for example as tool for social and economic development.

Even though there is a significant amount of literature on subjects related to this research the information is yet rather blurry and fragmented especially when it comes to the use of new thinking approaches emerging from recent technological developments in the context of energy retrofit interventions. These developments however might offer opportunities to overcome the limitations of most conventional and thereby offer valuable insights for the design of feedback systems that are more suitable for the requirements of the complex world we are living in today.

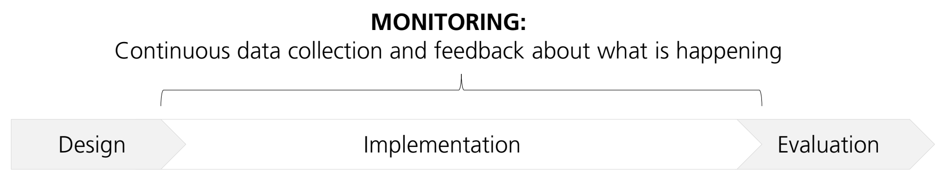

Figure 5: Process focus (own illustration)

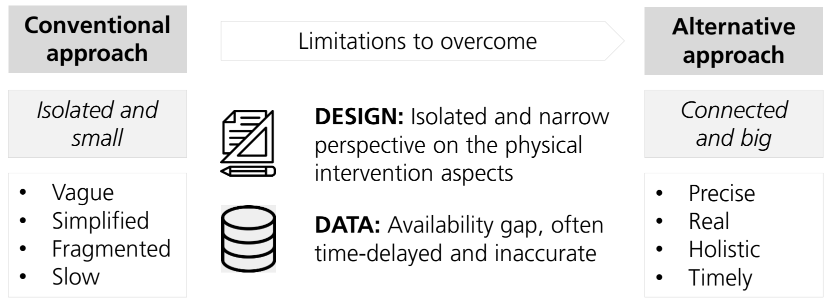

Figure 6: Research approach (own illustration)

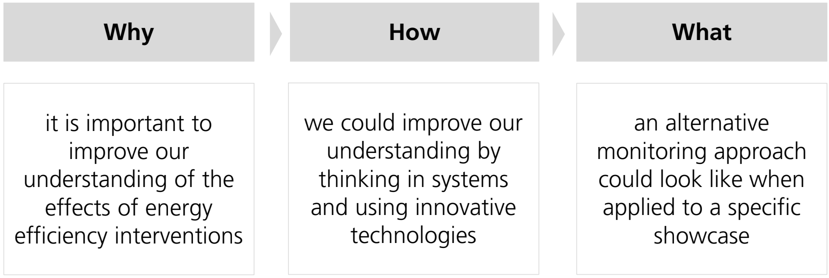

Figure 7: Underlying structure that the research follows (own illustration)

2. RESEARCH APPROACH

In the following chapter the research approach including the methods used and related data collection and analysis techniques are introduced and justified. Furthermore information on the research data plan as well as ethics is provided.

2.1. Type and design

Even though the body of knowledge on subjects related to the research, upon others for example energy efficiency, human behaviour or data innovation is expanding rapidly there is yet a lot of fragmentation regarding the information and uncertainty due to a lack of solid data. It seems that especially in the building sciences systematic large-scale collaboration across multiple research domains is rather unusual. Due to this reason an exploratory research type was chosen to approach the topic. This will not only ensure the flexibility of the research to adapt to changes during the process but also emphasise on the discovery of new ideas and insights on the topic (Kothari, 2004). The research design is based on multiple qualitative methods of data collection.

Using a multi-method approach offers the chance to explore the research topic in depth from different angles and can offer new insights. Furthermore the use of different methods and data sources leads to the triangulation of data which makes the findings more robust (Bryman, 2016). Especially in regards to the iterative process of this research this approach offered the possibility to complement information at any time of the research. This means that areas of interest that were identified during the use of one method could be explored also using another method. After all each method has its unique strength and weaknesses and by using a multi-method design the reliability and validity of the research is strengthened.

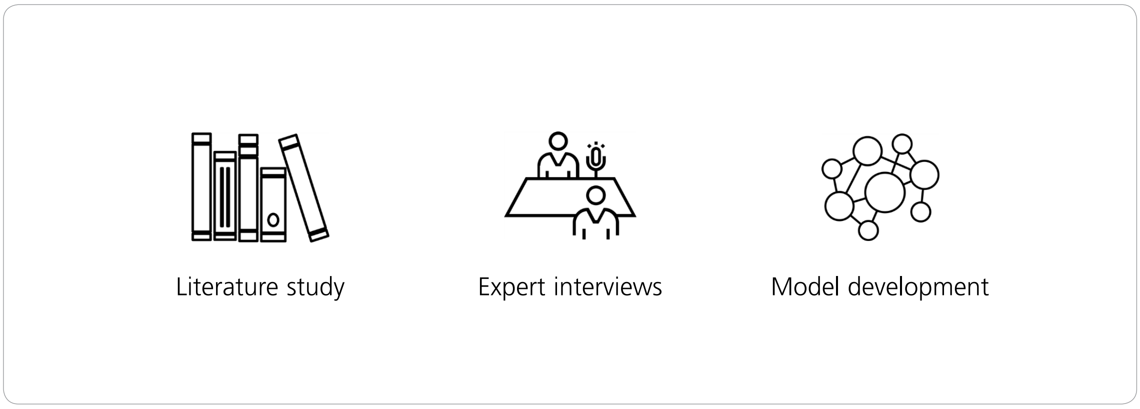

Figure 8: Research method overview (own illustration)

2.2. Research methods

The research is based on three methods: (1) a literature study, (2) qualitative expert interviews and (3) the development of a conceptual model. While the literature study provides the necessary background information about the topic and themes related to it the qualitative interviews provided some additional first-hand in-depth information of certain aspects. The findings from both methods were used for the development of an exemplary model.

2.2.1. Literature study

To provide the necessary context and background this research will use an extensive literature study covering the concepts of climate change, residential energy transition, energy efficiency, data innovation and systems thinking. Major sources were in particular to following literature:

- IEA. (2014). Capturing the Multiple Benefits of Energy Efficiency.
- UN Global Pulse. (2016). Integrating Big Data into the Monitoring and Evaluation of Development Programmes.
- Pentland, A. (2015). Social Physics: How Social Networks Can Make Us Smarter: Penguin Books.
- BMWi. (2015). Energy Efficiency Strategy for Buildings: Methods for achieving a virtually climate-neutral building stock.
- Meadows, D. H., & Wright, D. (2008). Thinking in systems: a primer.

2.2.2. Qualitative interviews

In order to complement the information gathered during the literature study semi-structured qualitative expert interviews were used. This type of interviews tends to be more flexible than structured interviews allowing the researcher to respond to emerging areas of interest and adjust the course of the interview accordingly. In contrast to structured interviewing this leads to richer and more detailed answers. In preparation of the interviews a series of themes and opening-questions were prepared in form of an interview guide which provided a framework for the conversation while offering the flexibility to change the order of the questions (Bryman, 2016; Kothari, 2004). Due to the fact that this research aims to explore the topic beyond the traditional boundaries this method seems to be very useful. Furthermore in qualitative interviewing, interviewees may be interviewed on more than one and sometimes on several occasions (Bryman, 2016). Again this was considered to be very valuable for this research as it offered the chance to explore a topic and then focus on areas of interest as the research progresses.

The analysis of the data gathered during the interviews is carried out according to the six steps of the thematic analysis: (1) read through materials, (2) begin coding, (3) elaborate on codes, (4) evaluate higher-order codes, (5) examine links and connections between concepts and (6) write up insights (Bryman, 2016).

2.2.3. Conceptual model development

A conceptual model is the representation of a real world system made of a composition of concepts which help people to understand and simulate a subject. In the context of this research the findings from the literature study and the expert interviews were used to develop a conceptual model with the aim of to identify and illustrate emerging opportunities as well as challenges of the findings. After the first draft design the model was progressively detailed and improved in a series of iterative steps. This was done as process of participatory co-creation between the researcher and the experts.

2.3. Research process

The process was divided into three parts being (1) the background part that was primarily based on a literature study and which is concerned with providing the necessary context for the research,

(2) the exploration part which is based on both a literature study and expert interviews and which is concerned with exploring the components for an alternative approach and finally (3) integration part which is concerned with the development of an conceptual model by applying the findings of the previous parts.

2.4. Data plan

In order to enhance the reusability of the data this research project will follow the FAIR Guiding Principles (Wilkinson et al., 2016). These guidelines will ensure that the data gathered during the course of this research project will be findable, accessible, interoperable and reusable.

2.5. Ethical consideration

The research was carried out in line with the Human Research Ethics of the Delft University of Technology (TU Delft, n.d.). This includes the careful upfront analysis of the project according to the Ethics Review Checklist for Human Research (TU Delft, 2017) as well as the use of the Informed consent form template for the research with human participants (TU Delft, 2018) as published by the Human Research Ethics Committee (HREC).

2.6. Research output

The aim of this research was to provide an analysis of the challenges that are leading to the lack of information on the actual performance of current interventions. This was done by identifying the underlying factors as well as the wider context and various dynamics in which energy efficiency interventions are embedded. In the next step the research explored the potential application of new data sources (data innovation) to develop a concept for an alternative feedback approach that might provide better evidence and thereby enable more fine-grained interventions, easier follow-up optimisations, the alignment of policy goals and facilitate an overall more effective use of resources.

The findings of this research are hoped to provide a solid starting point for further research in the field by illustrating the opportunities as well as obstacles on the way towards more effective energy retrofit interventions. Ultimately this might not only help to implement more targeted interventions to reduce energy demand and GHG emissions but also help to position energy efficiency interventions as a tool for economic and social development.

2.6.1. Deliverables

The deliverable of this research project was in particular a conceptual monitoring model illustrating the potential of the proposed alternative monitoring approach. The development of the model was based on existing theory gathered during the literature study and additional knowledge gathered during the expert interviews. Based on the elaboration of the findings further research opportunities were identified.

2.6.2. Dissemination and audiences

The output of the research is expected to be an interesting starting point for further research in the field of performance monitoring of complex interventions. This does not only offer interesting opportunities for the various stakeholders involved in the intervention process but also for society as a whole.

2.7. Personal study targets

First and foremost my personal aim for this graduation project was to accumulate a profound understanding of the challenges and obstacles in the process towards a sustainable built environment. I was especially interested in leaving the traditionally boundaries of the buildings sciences and explore those challenges in the wider socio-economic context in which they are embedded. The goal was to develop a more holistic and systemic thinking approach using insights from other disciplines related to the topic of this research.

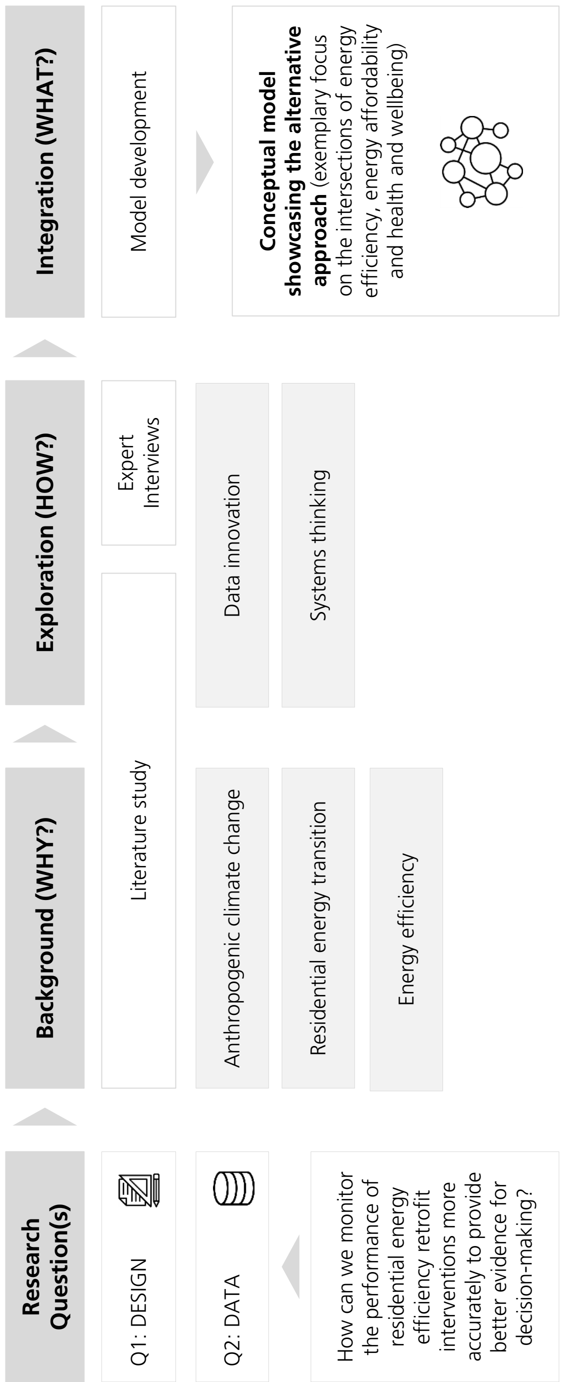

Figure 9: Outline of the research process (own illustration)

Moreover I was very curious to learn more about the potential of new technological developments like innovative data sources and analytical methods and in particular how these could help us to get a more solid understanding of the dynamic processes in the built environment and how these could ultimately enable a more effective management.

I believe that complex challenges like the energy transition in the building sector are not to be solved by every stakeholder working in the boundaries of their own discipline but only by large-scale collaboration. By choosing this graduation project I hope to have laid the foundation for my own contribution to this transformational process.

2.8. Research planning

The research project was carried in the four phases: (1) Preparation, (2) design, (3) evaluation and (4) elaboration. In the following the major tasks of each phase will be introduced briefly:

Preparation phase (CW 26-35)

During the first phase of this project the information needed for the design of the conceptual model was collected. The phase also included main organisational tasks (e.g. interview planning).

Design phase (CW 36-39)

The second phase of the research included the processing and analysis of the collected data and the subsequent design of a first draft model.

Evaluation phase (CW 40-44)

The evaluation phase will start off with a discussion of the conceptual model to generate additional input and identify errors. In the following the proposal will be further developed and improved through a process of co-creation between the researcher and experts.

Elaboration phase (CW 45-48)

The final phase of the research was used for a summary and elaboration on the findings to identify further research opportunities

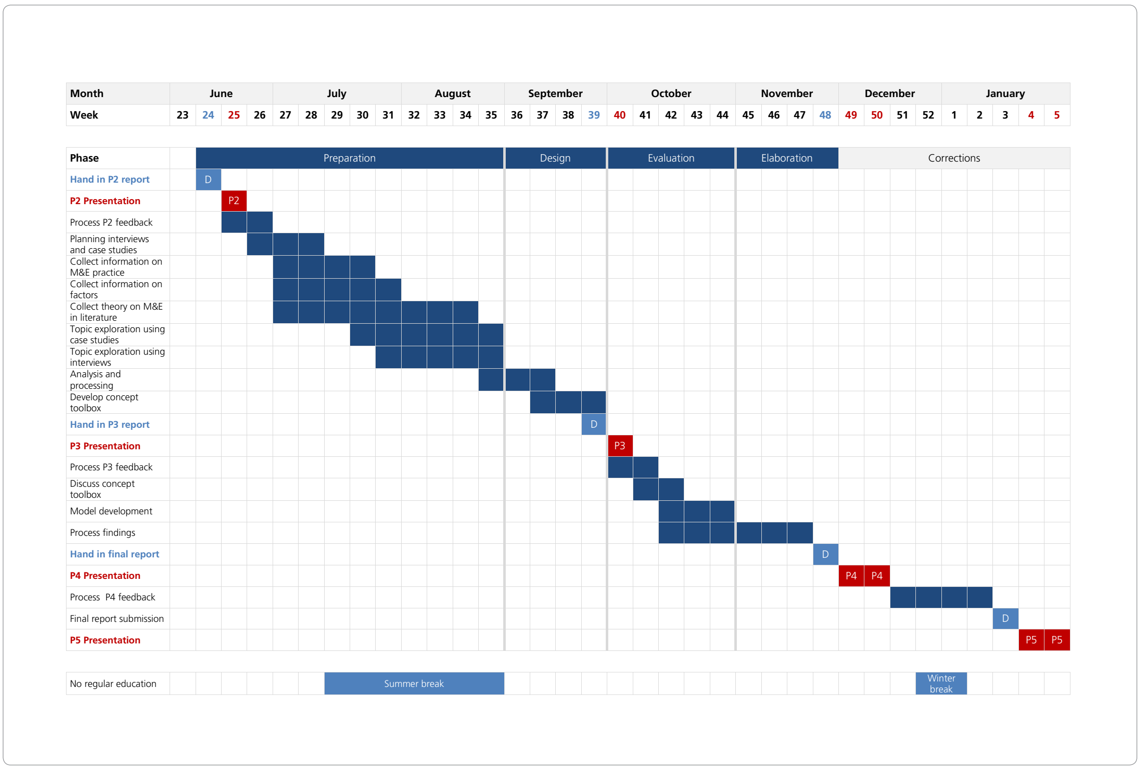

Figure 10: Research tasks and planning overview (own illustration)

3. LITERATURE STUDY

In the following chapter the findings from the literature study of subjects related to the area of interest are introduced. The focus will be put in particular on presenting evidence that illustrates the problems of current energy retrofit interventions but also the on the need to move beyond the technical perspective of energy efficient retrofits to improve their effectiveness and on opportunities that may arise from data innovation.

3.1. Anthropogenic climate change

The rising levels of greenhouse gas (GHG) emissions are widely considered to be the main driver of the anthropogenic climate change. With increasing numbers of extreme weather conditions the devastating consequences of this development became increasingly evident in the last years.

The ongoing rapid urbanization and the growing population combined with our energy intensive lifestyles are most likely to speed up this process of reinforcing developments even more. Most experts agree that only by fundamentally changing the way in which we consume energy this trend could be stopped and the threats from the changing climate at least partially be mitigated.

A major step in acknowledging the problem and creating a global plan and shared commitments towards changing our current energy consumption patterns was made in the Paris Climate Agreement which entered into force on November 4th 2016. The central aim of this agreement is to response to the threat of climate change by keeping the global temperature rise in this century well below 2 degrees Celsius and purse efforts to limit the temperature increase even further to 1.5 degrees Celsius (UNFCCC, n.d.).

The precise GHG reduction targets to achieve this objective differ from country to country. The European Member States (MS) have agreed upon shared targets with specific shares for each sector. According to this planning a major share of the total GHG reduction is to be achieved in the building sector.

3.2. Residential energy transition

In Europe the buildings sector is responsible for about 40% of the final energy consumption and one of the major causes (36%) for the emission of greenhouse gases (EC, 2011b). With a share of about 75% the largest sub-sector is residential housing. The share of residential buildings which is currently being classified as inefficient is again 75. Retrofitting the existing residential housing therefore stock plays a crucial role in achieving the ambitious GHG reduction targets. Considering this critical role in the overall process and the fact that the largest part of the stock will still be standing in 2050 this research will focus especially on the efforts being made to drive the change in the existing residential housing sector.

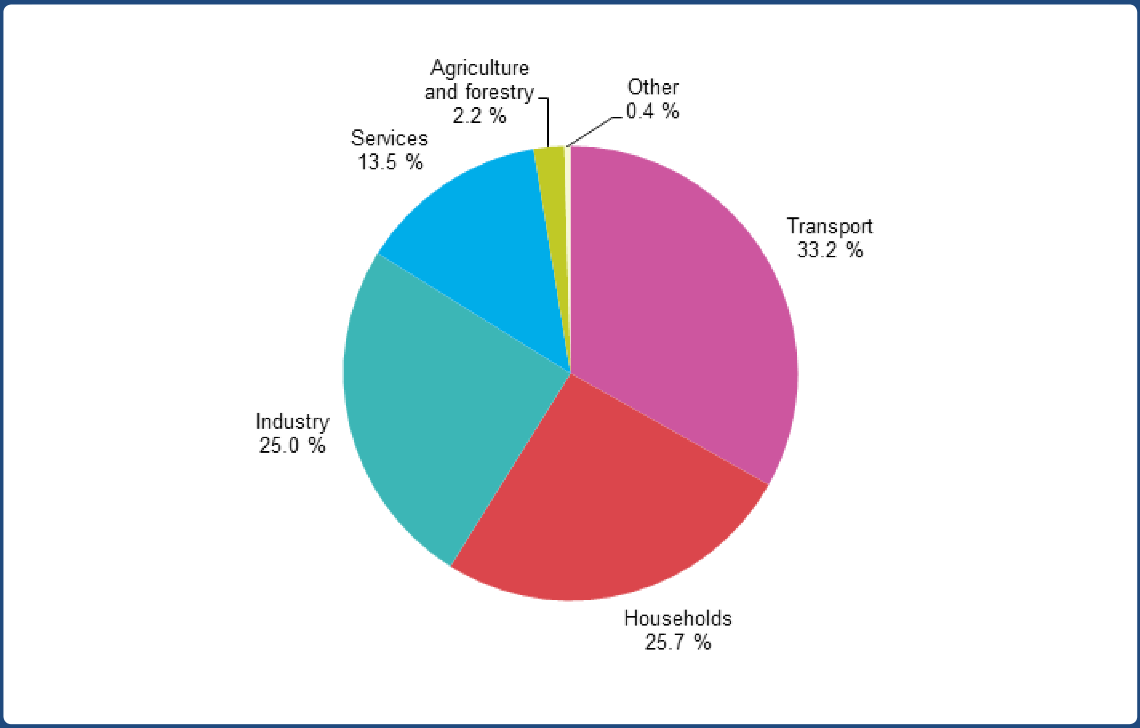

Figure 11: Final energy consumption by sector EU-2018 2016 (https://ec.europa.eu/eurostat/statistics-explained/images/7/73/Final_energy_consumption_by_sector%2C_EU-28%2C_2016_%28%25_of_total%2C_based_on_tonnes_of_oil_equivalent%29.png)

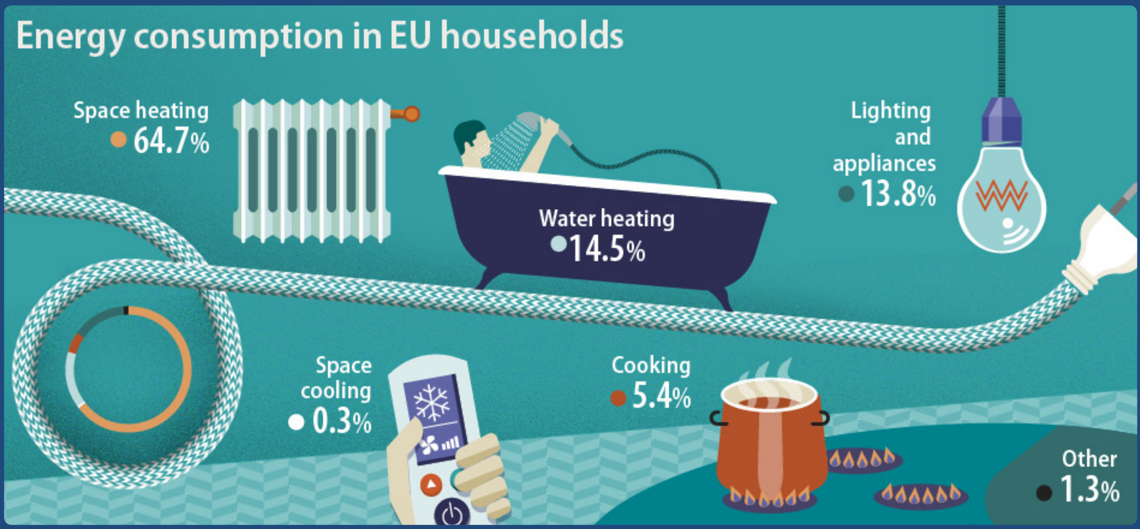

Figure 12: Energy consumption in EU households (https://ec.europa.eu/eurostat/statistics-explained/images/f/fc/Energy2.jpg)

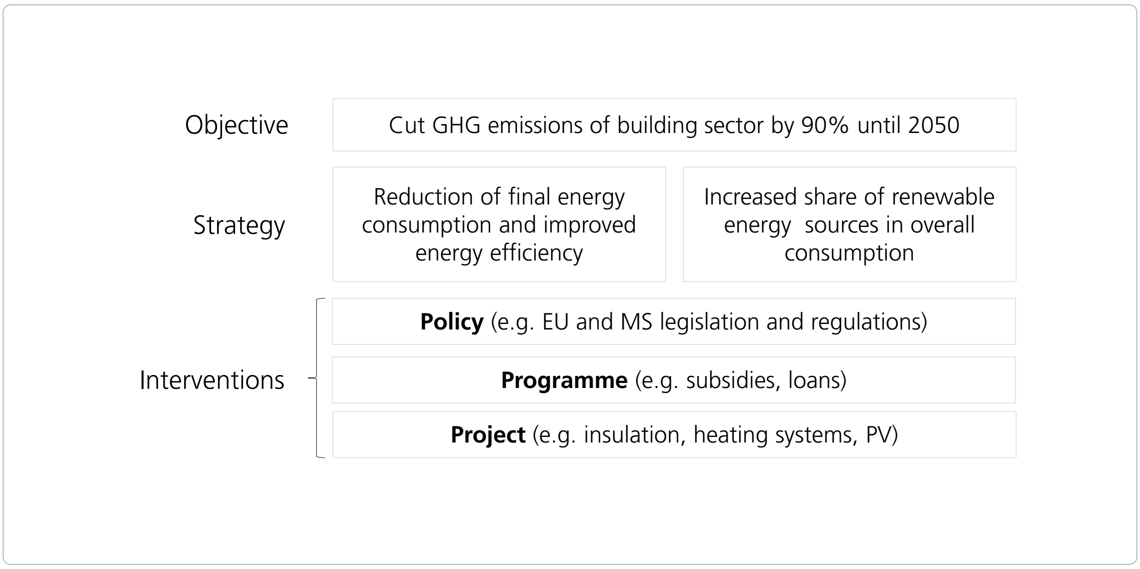

Figure 13: Residential energy transition in the European Union (own illustration)

3.2.1. Objectives, targets and goals

In order to enforce the commitments made and drive the energy transition in the building sector a variety of different interventions has been implemented both on European and MS level. They can be divided by three levels that range from the rather broad policy-level to the more specific program-level and after all to the individual project-level. While the policy-level defines the core objectives and major targets and is implemented using a variety of different measures (e.g. legislation, subsidy and regulation) on the European and MS level the program-level includes European, national, regional and municipal programs which typically again contain multiple components on their own. The individual project which is usually only concerned with a very limited number of components is located on the lowest level. The term intervention is used to cover all three of these levels. In the following the most important interventions on European and MS level as well as signs of lacking performance and weaknesses in their feedback approach will be introduced.

3.2.2. European context

The strategy in which the European Union aims to transpose the commitments of the Paris Climate Agreement is outlined in the European Energy Roadmap 2050. The central objective of this strategy is the reduction of GHG emissions in the EU by 80-95% (compared to 1990 levels) by the year 2050 while increasing the sustainability, competitiveness and security of supply. Intermediate targets are to be achieved in 2030 (40%) and 2040 (60%) (EC, 2011b).

The analysis comes to four major conclusions: (1) the decarbonisation of the energy system is both technically and economically feasible, (2) increasing the share of renewable energy sources and using energy more efficiently are crucial to achieve the goals, (3) early investments cost less and avoid more costly changes in the future and (4) a shared European approach is expected to result in lower costs and more secure energy supplies (EC, 2011a, 2011b, 2011c).

In order to achieve this ambitious goal all major sectors need to contribute according to their technological and economic potential. Being one of the main drivers for GHG emissions the building sector plays a central role in this transformational process. According to the plan emissions from buildings need to be almost completely (90%) cut by 2050. The reduction is to be achieved by a combination of (1) increasing the share of renewables and thereby substituting fossil fuels in heating, cooling and cooking and (2) the reduction of the primary energy demand and improved energy efficiency (EC, 2011b).

The two main legislative instruments in the EU to promote improvements of energy performance in buildings are the Energy Performance of Buildings Directive (EPBD)[1] and the Energy Efficiency Directive (EED)[2]. Since its first introduction in 2002 these two directives set the overall objectives and boundaries while at the same time leaving flexibility for each MS to transpose these into individual national instruments. In 2010 the EPBD[3] was updated in order to put a stronger focus on nearly zero-energy standards for all new buildings.

An impact evaluation of the EPBD published by the European Commission in 2016 came to the conclusion that even though there have been significant improvements regarding the energy efficiency of new buildings, there remains a very large cost-effective saving potential in the transformation of the existing building stock which is currently only proceeding at a relatively slow pace (EC, 2016b).

These findings are supported by the impact assessment of the EED in 2017 which showed that following the implementation of the EPBD and as a result of more energy efficient appliances and improvements in the buildings stock, the final energy consumption in the residential sector dropped by 11% from 309Mtoe in 2005 to 275Mtoe in 2015. However the Commission also acknowledged that the warmer winters during this period also reduced heating needs and thereby partially offset the positive activity effect which was driven by an increase in floor area for heating and gross disposable income (EC, 2017a). This is an important side note when it comes to accurately measuring the performance of an intervention. After all they conclude that for reaching the ambitious reduction targets additional efforts need to be made, especially regarding the large cost-effective potential represented by the existing building stock (EC, 2017a). According to the Commission there is yet a lack of strong market signals that could stimulate large scale renovations and that there is a need for improving the national implementation of the Directive (EC, 2016b). Under 'business as usual' a significant part of this potential will not be realised (EC, 2016b). This is supported by an analysis of the International Energy Agency (IEA) that pointed out that under existing policies, two-thirds of the economically viable energy efficiency potential, across all sectors will remain unrealised. After all the assessment indicates that the implemented targets for all new buildings have ensured a 'future-proof' vision for the sector however the same level of ambition is missing for existing buildings (EU, 2016). According to the analysis of the European Commission 'increasing the rate, quality and effectiveness of building renovation remains the biggest challenge for the coming decades'. (EU, 2016).

In response to these developments the European Commission just recently published its Clean Energy For All Europeans package (EC, 2016a) which includes among others also a proposal for a revised EPBD (EU, 2016). In June 2017 the EU Council agreed upon the proposal (EC, 2017b). In April 2018 the European Parliament gave its final approval to the revised directive (EC, 2018a). The aim of the update is to promote energy efficiency in buildings and integrate and substantially strengthen building renovation strategies with the long term goal of decarbonising the European building stock (EC, 2017b, 2018a). After the final implementation of the revision it will be up

1 Directive 2002/91/EC

2 Directive 2012/27/EU

3 Directive 2010/31/EU

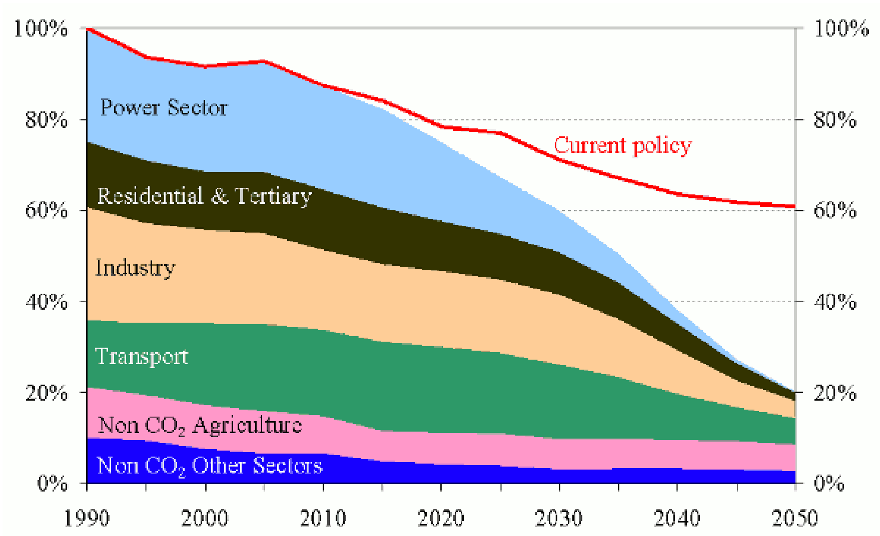

Figure 14: EU GHG emissions towards an 80% domestic reduction (100% =1990) (https://ec.europa.eu/clima/sites/clima/files/strategies/2050/images/targets.png)

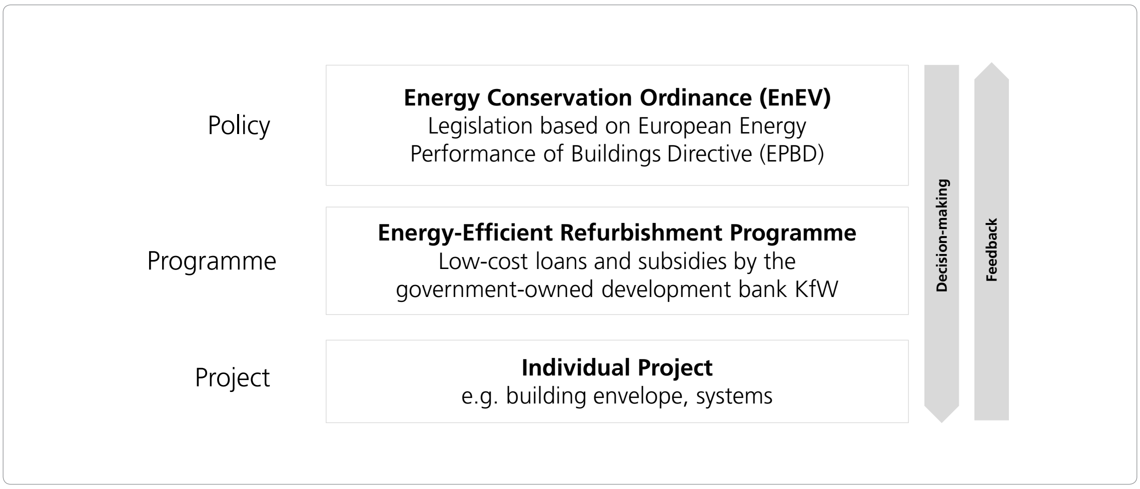

Figure 15: Exemplary selection of national interventions in German (own illustration)

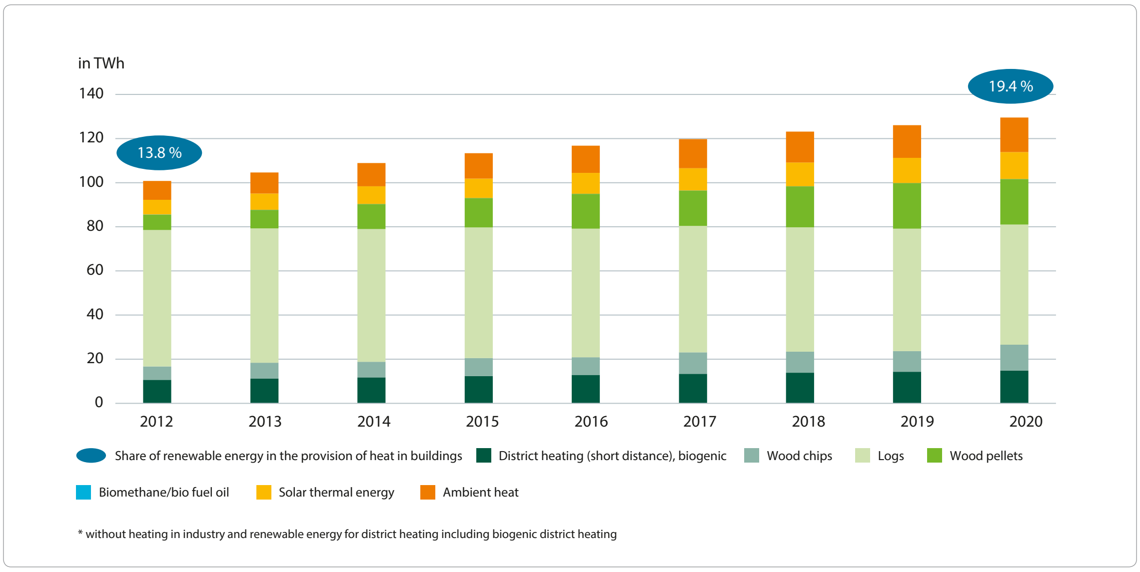

Figure 16: Share of renewable energy in the provision of heat in buildings (BMWi, 2015)

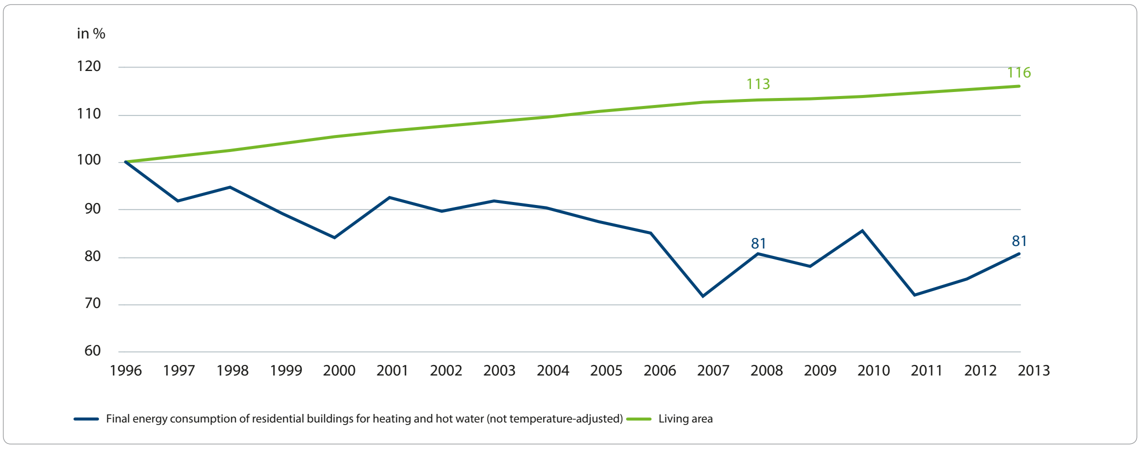

Figure 17: Development of living space and energy consumption for heating (BMWi, 2015)

to each member state to design and implement national policies and programmes that can deliver the ambitious goals.

In the following the example of the Federal Republic of Germany will be used to illustrate how these European objectives have been transposed into German national interventions.

3.2.3. German national policies and programmes

The German equivalent of the European Energy Roadmap 2050 is the German Climate Action Plan 2050 (German: Klimaschutzplan 2050). Just as the European policy this document outlines the measures for each sector by which Germany aims to achieve its GHG emissions reductions by the year 2050. According to his plan the German building sector will be nearly carbon-neutral by the year 2050 while the remaining energy needs will be met through renewable energy sources. This central objective (reducing the primary energy demand while increasing the share of renewable energy sources) corresponds with the European strategy.

The legislative measures to achieve this goal are based on the Energy Conservation Ordinance (German: Energieeinspaarverordnung EnEV), the Energy Conservation Act (German: Energie-Einspaar-Gesetz EnEG) and the Renewable Energies Heat Act (German: Erneuerbare-Energien-Wärmegesetz EEWärmG). The Energy Conservation Act (EnEG) is based on European directives and provides the legal framework to promote the energy transition in the building sector. The Energy Conservation Ordinance (EnEV) on the other hand sets the energy performance requirements for new buildings and existing building in the case of a major renovation. It first came into force in 2002 and was amended in 2007 transposing the European Energy Performance of Buildings Directive (EPBD) into national law. The Renewable Energies Heat Act (EEWärmG) makes the use of renewable energy sources in new buildings and when carrying out major renovations in public sector buildings obligatory.

Next to the legislative measures the German government invests heavily into programmes to improve the energy performance of buildings and support the transition of heating, cooling and electricity supply towards renewable energy sources. These programmes are organized trough the government-owned development bank KfW (German: Kreditanstalt für Wiederaufbau) and provide low cost loans and direct subsidies for specific measures. Whereas the energy-efficient construction program (German: Energieeffizient Bauen) provides incentives for the construction of new buildings the energy-efficient refurbishment program (German: Energieeffizient Sanieren) provides incentives for a variety of different measures that improve the energy performance of existing buildings.

Since its implementation ten years ago in both programs together the KfW has supported over 4 million housing units with close to EUR 100 billion in loans or grants to builders and renovators. According to their in-house assessments these interventions have triggered another EUR 260 billion in individual project interventions and thereby secured an average of 320.000 jobs per year in the building industry and regional trades. The measures are expected to reduce GHG emissions by almost 9 million tonnes per year. (KfW, 2017) Other official government assessments state that the current interventions already help to ensure that despite an increase in residential and other usable spaces in Germany the absolute energy consumption in the building sector is declining. This can mainly be referred back to newly built buildings that are mostly able to deliver higher energy efficiencies. Besides that the share of renewable energies to cover the remaining final energy consumption is also increasing. However the assessment also highlights that in order to

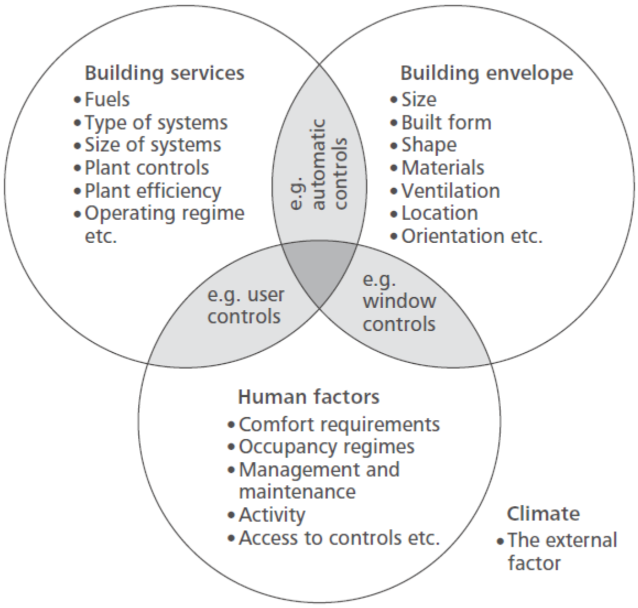

Figure 18: Key factors that influence the energy consumption (CIBSE, 2012)

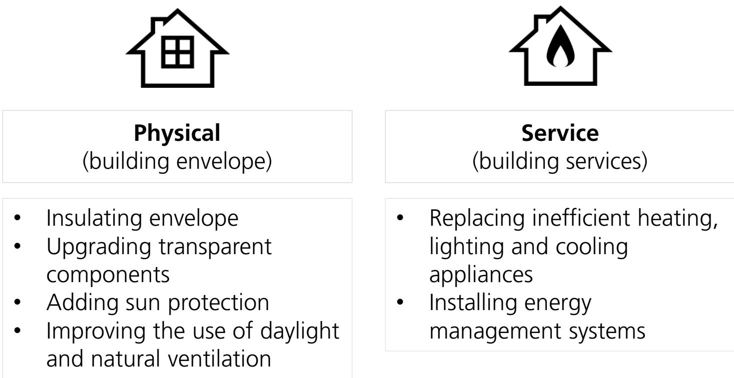

Figure 19: Typical project level interventions (own illustration)

meet the 2050 reduction targets further efforts are necessary especially regarding the existing residential housing stock (BMWi, 2015).

With the European context as well as MS national interventions (policies and programmes) in mind in the following a focus will be put on energy efficiency interventions on the individual project level.

3.2.4. Individual project energy efficiency interventions

Energy efficiency is being defined as the ratio between the total energy input and the useful output. In this sense an energy efficient building is able to provide the internal environment and services with minimum energy use in a cost effective and environmentally sensitive manner. The total energy consumption of a building is the result of the interactions between three components: (1) the building envelope, (2) the building services and (3) the human factor (CIBSE, 2012).

Traditionally the main focus of the building sciences and most EE retrofit interventions lies on the on the physical building-related and services-related aspects (CIBSE, 2012). These include interventions to reduce the primary energy demand through:

- Insulating the building envelope;
- Upgrading transparent components like e.g. windows;
- Improving summer heat protection by adding sun protection devices;
- Uncovering or increasing the storage mass;
- Improving the use of daylight;
- Improving natural ventilation.
- Moreover they include interventions to provide more efficient building services through:
- Replacing inefficient heating appliances;
- Replacing of lighting appliances;
- Replacing of cooling systems;
- Installing management systems.

The third and maybe most important factor influencing the energy consumption of a building is the way in which the building is actually used by its occupants. Interestingly this factor is often not considered carefully enough which has been identified by research as being the main reason for the performance gap between anticipated and actual energy use of a building (Abrahamse & Steg, 2011; D'Oca, Hong, & Langevin, 2018; Fabi, Andersen, Corgnati, & Olesen, 2013). Whereas solely physical factors performance models of a building are already highly sophisticated most have problems to account for the complexity of human behaviour.

3.3. Challenges of current interventions

Yet despite the seemingly positive results of current interventions there is increasingly doubt about their actual performance. In the following are closer look will be taken at the low take-up rate and the so called performance gap. Whereas the former can be observed on the policy and programme-level the latter is best observed on the individual project level.

3.3.1. Low take-up rate

Even though major efforts have already been made on the policy and programme level to stimulate energy retrofits the annual uptake of energy efficiency interventions in Europe remains rather low between 0.8-1.0 percent. However, to reach the 2050 CO_2 reduction goal this level would have to rise above 2.0 percent (Becchio et al., 2016; EC, 2011b).

Even though Germany is often considered a frontrunner for some building policies and instruments, the national renovation rate is just at the level of the European average (around ~1% per year). Out of every three building renovations that are undertaken in Germany, only one implements energy-saving measures (BPIE, 2014).
According to an assessment of the International Energy Agency the reason for the low uptake

can often be referred back to barriers such as information failures, split incentives, subsidised pricing of energy, inadequate pricing of externalities and a shortage of financing. The combination of these factors leads to a deferred and often intangible an abstract perception of energy efficiency interventions in the opinion of private households, investors and policy makers (IEA, 2014).

3.3.2. Performance gap

It has been mentioned before that when studying official assessments and progress reports of current retrofit interventions especially striking is the general data scarcity. Consequently most progress and performance evaluations need to rely heavily on assumptions. Even though the official statics European and MS level draw a rather positive picture of the progress being made in reducing GHG emissions there is a growing number of experts that have doubts about their actual performance. Questionable is in particular the actual energy consumption (respectively GHG emissions) of buildings which often deviates significantly from the anticipated pre-retrofit calculations.

The level on which the so called 'performance gap' can best be observed is the individual project level. The reason for that is the slightly better availability of data as well as the lower complexity compared to the programme or policy level. However it is only logical that errors due to wrong assumptions on the lowest intervention level will subsequently lead to wrong and potentially accumulated errors on the higher programme and policy levels. One of the major factors contributing to the gap seems to be the individual behaviours of the users. (Gram-Hanssen & Georg, 2018; Hong et al., 2017; Steg et al., 2015; van den Brom et al., 2018). In practise this means that simulations often overestimate the energy wasted in pre-retrofit (inefficient) buildings and vice versa underestimate the potential savings in post-retrofit (efficient) buildings. (Gram-Hanssen & Georg, 2018; Hong et al., 2017; Steg et al., 2015; van den Brom et al., 2018)

Due to the fact that today's policy interventions are focussed in particular on the theoretical consumption of a building this leads to rather unwanted results in which the actual post-retrofit consumption of a building is actually higher than before (Galvin, 2014; Winther & Wilhite, 2015). Several researchers have showed that this can partly be explained by the changing behaviour of the user. Whereas current calculations consider the user´s consumption patterns as static, research has shown that the users actually adapt their behaviours to the new situation (Gram-Hanssen, Christensen, & Petersen, 2012; Hansen, Gram-Hanssen, & Knudsen, 2018; Madsen, 2018).

In their 2017 impact assessment of the EED the European Commission acknowledged that changes in behaviour, e.g. switching to bigger appliances and better comfort levels led to an increase in final energy consumption in the residential housing sector (EC, 2017a). After all this does not only undermine the GHG reduction goals but it also means that economic feasibility studies, payback time and savings are most of the time misleading and thereby a bad basis to take decisions. This becomes even more problematic as today´s policy interventions try to convince people to retrofit their houses based on the economic feasibility of the interventions. However, triggering people with false assumptions will most likely not lead to the aimed wide-scale change and might partly explain the low retrofitting rates across Europe. Interestingly several researchers showed that the people that actually undertook retrofitting measures often did not mention economic reasons as their main driver. (Galvin, 2014)

Besides the directly energy-related effects which have just been introduced there are other factors which are not directly related to the energy consumption of a household. Worth mentioning in this context is in particular the so called rebound effect which describes a phenomenon that occurs when savings due to improved energy efficiency lead to the consumption of other GHG intensive goods and services. Instead of a reduction this might in some cases even lead to an increase of emissions (IEA, 2014). This causes the problem that the actual performance of retrofit interventions is often very different from the estimates made during the planning and design stage. Even though in general this knowledge is available already it has yet not been considered carefully enough due to the lack of understanding of the complex interdependencies between the different factors that are involved. However only by enabling decision-makers to fully assess and account for any potential rebound effects it is possible to ensure that targets are realistic and goals are achieved (IEA, 2014).

After having illustrated the challenges and some underlying reasons for the underperformance of current energy efficiency inventions it is reasonable to conclude that one of the major shortcomings is their often narrow perspective with focus on their physical aspects and the often inadequate performance assessment that focus solely on their carbon benefits. In combination these two factors favour ineffective decision-making and resource allocations. With the purpose of broadening the perspective in the following this research will take a closer look at the potential additional effects of energy efficiency interventions.

3.4. Additional effects of energy efficiency

As mentioned before one of the major weaknesses of current energy retrofit practise is its narrow perspective that focussed primarily on technical aspects of an intervention. This leads to a variety of negative phenomena which have been introduced before. However in order to take the most beneficial decision towards achieving a certain goal it is necessary to explore the performance of an intervention within the wider context in which it is embedded and evaluate the different trade-offs. This means that we have to stop viewing energy retrofits as independent

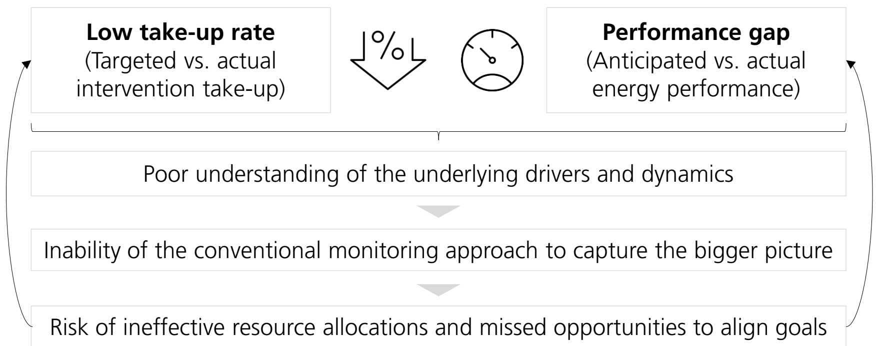

Figure 20: Challenges faced by current interventions (own illustration)

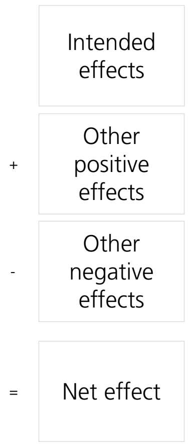

Figure 21: Holistic approach to determine the net effect of energy efficiency interventions (own illustration)

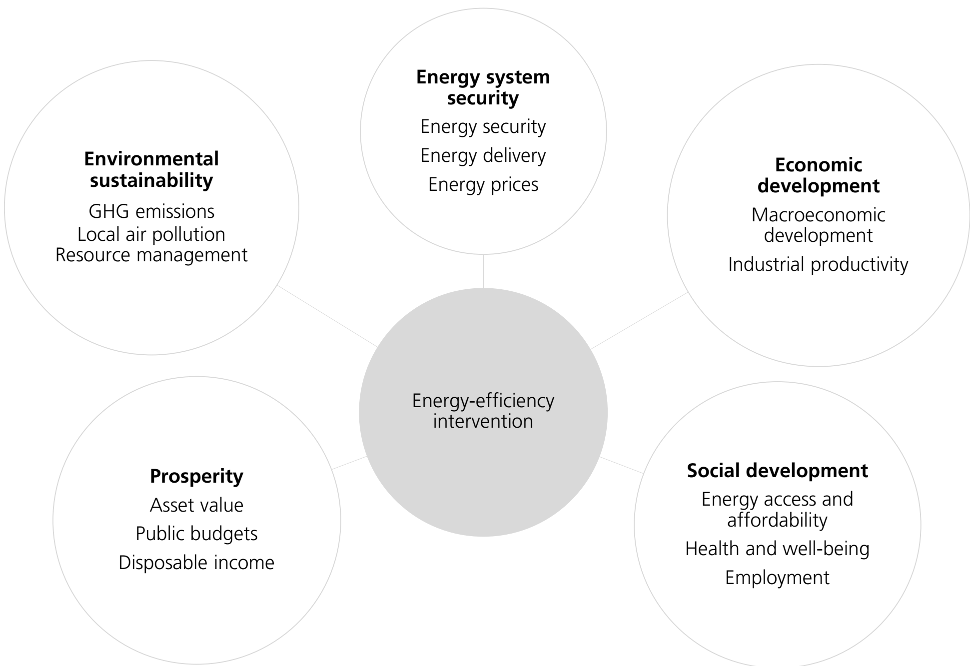

Figure 22: Potential positive effects of energy efficiency interventions (own illustration based on IEA, 2014)

interventions and develop a more holistic view that considers the various dynamics and multiple interdependent factors that influence the performance of an intervention. Only then it will be possible to determine the actual net effect of an intervention and thereby enable effective decision-making and resource allocation.

This is supported by an assessment of the International Energy Agency (IEA) that points that in order to stimulate more retrofit interventions in energy efficiency is necessary to pay more attention to the additional investment opportunities posed by energy efficiency investments (IEA, 2014). This however can only be done when the wider benefits or an intervention (positive and negative) are considered. This is in line with a report published by the Buildings Performance Institute Europe (BPIE) in 2014 which recommends that in order to achieve better results the energy retrofit interventions should factor in the quantifiable wider benefits like economic impact, societal impacts and environmental benefits. So far only energy, carbon and cost savings are considered (BPIE, 2014).

An interesting alternative approach in this direction which was introduced by the IEA aims to extend the reach of energy efficiency beyond the impacts of energy demand reduction and reduced GHG emissions towards its potential in delivering a variety of other benefits to the economy and society (IEA, 2014). According to the IEA attention should be given in particular to the impact and contribution of energy efficiency interventions to the following concepts: (1) Enhancing energy system security, (2) macroeconomic development, (3) social development, (4) environmental sustainability and (5) increased prosperity.

It is important to notice that this list is not exhaustive but only a collection of the most prominent areas that might be influence by energy efficiency interventions. In the following a brief introduction into how these factors might be related is given:

The energy system security is enhanced through improved energy security (demand reduction), improved energy delivery (reduced costs of generation) and reduced energy prices. All of these factors also have relationships with economic and social factors. The macroeconomic development is influenced tough direct and indirect effects across the whole economy (lower energy expenditure, investments in energy efficiency, consumer spending).It also influences the industrial productivity through enhanced production and capacity utilisation. Reduced energy costs are directly related to improved energy access and affordability. Besides that there is a positive correlation with increased health and well-being particularly among vulnerable groups as well as downstream social and economic impacts like for example reduced health spending. Regarding the environmental sustainability aspects there are positive effects in the form of reduced outdoor concentrations of air pollutants as well as improved resource management. Positive effects in the form of increased prosperity are also to be for public budgets through reduced expenditures on energy, increased tax revenues, and reduced unemployment payments. Besides that there are positive effects in the form of increased disposable incomes and asset values. (IEA, 2014)

According to IEA (2014) the broader effects of energy efficiency interventions have yet not been systematically assessed due to a lack of data and the absence of adequate methodologies that are capable to measure these effects. As a result they are not well understood and only considered in decision-making only in a qualitative way, if at all (IEA, 2014).

After all it became clear there are many additional (non-carbon) effects of energy efficiency that have yet not been considered carefully enough. The introduced example however also showed that the increasing numbers of factors raises the complexity significantly. The conventional linear thinking approach (single input – single output) seems no longer adequate. Instead an alternative thinking approach that is required that is capable of capturing and illustrating the complex relationships and trade-offs of the various factors involved. In the following one possible alternative approach that could be helpful to deal with the increasing complexity will be introduced.

3.5. Systems thinking

The predominant underlying concept of the conventional thinking approach is characterized by atomism. This approach assumes that the whole is nothing but the sum of its part. Thus by taking the whole apart and understanding its individual parts and then adding these together one could understand the whole. Given the problems of the current feedback approach to provide accurate information the atomistic approach seems to be adequate when dealing with complicity however not so much when dealing with complexity.

It is important to notice that even though in the general linguistic usage the two terms are often used as synonyms they describe two very different ideas. A complicated problem simply means the existence of a high level of difficulty which is however based on strict rules and a linear process. Once these rules have been identified there is a high certain-ty being able to reproduce a certain outcome. Complex problems in contrast are characterized by a non-linear process based on relationships between multiple components. They are far less predictable and easy to understand.

In contrast to that the concept of holism gives priority to the whole as a necessary framework and thereby denies the atomistic proposition that the whole is nothing but the sum of its parts. In viewing systems as wholes and not taking them apart these can may show synergies and emergent behaviour which is based on the idea that each individual element of a system is being shaped and informed by its relation to the whole (Mobus & Kalton, 2014). The idea of this systems thinking approach is to make sense of the non-linear behaviour of a complex system using stocks, flows, feedback-loops and time delays. Systems can be embedded within bigger systems, which can yet be embedded in other systems (Meadows & Wright, 2008). Given the weaknesses of current feedback approaches to understand the process and dynamic interdependencies with other factors this thinking approach seems to offer interesting opportunities to overcome the limitations of the conventional linear approach.

„Managers are not confronted with problems that are independent of each other, but with dynamic situations that consist of complex systems of changing problems that interact with each other. I call such situations messes. Problems are extracted from messes by analysis. Managers do not solve problems, they manage messes.“

Ackoff (1979)

Besides the limitations concerning the design the second major limitations of the conventional feedback approach are the data challenges meaning the inability to collect up-to-date high quality data on the process as well as contextual factors. In this sense data innovation seems to offer interesting new opportunities which are to be explored in the following.

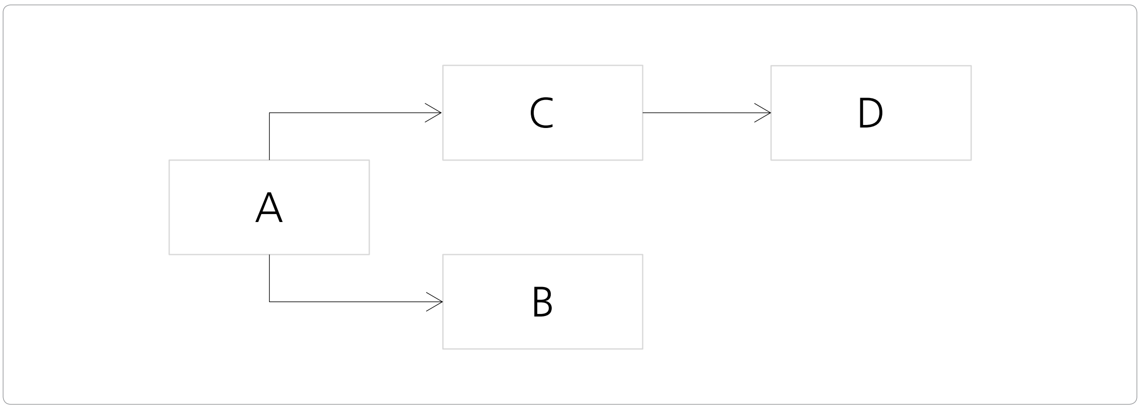

Figure 23: Schematic illustration of a linear approach (own illustration)

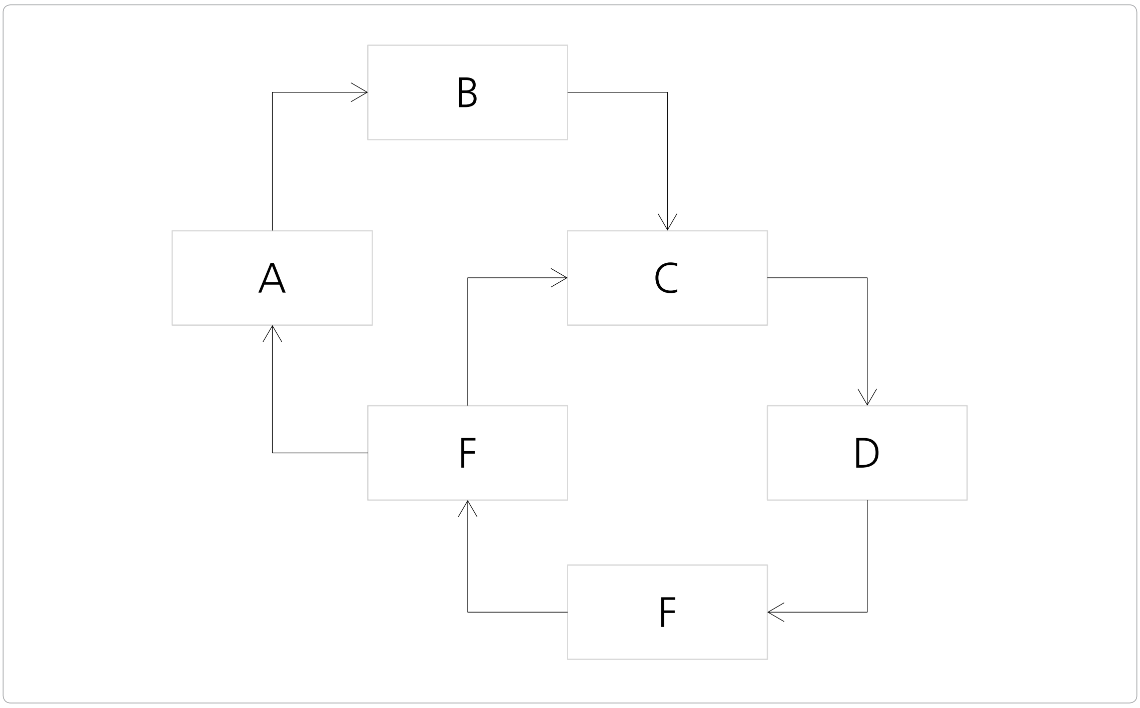

Figure 24: Schematic illustration of a systemic approach with feedback loops (own illustration)

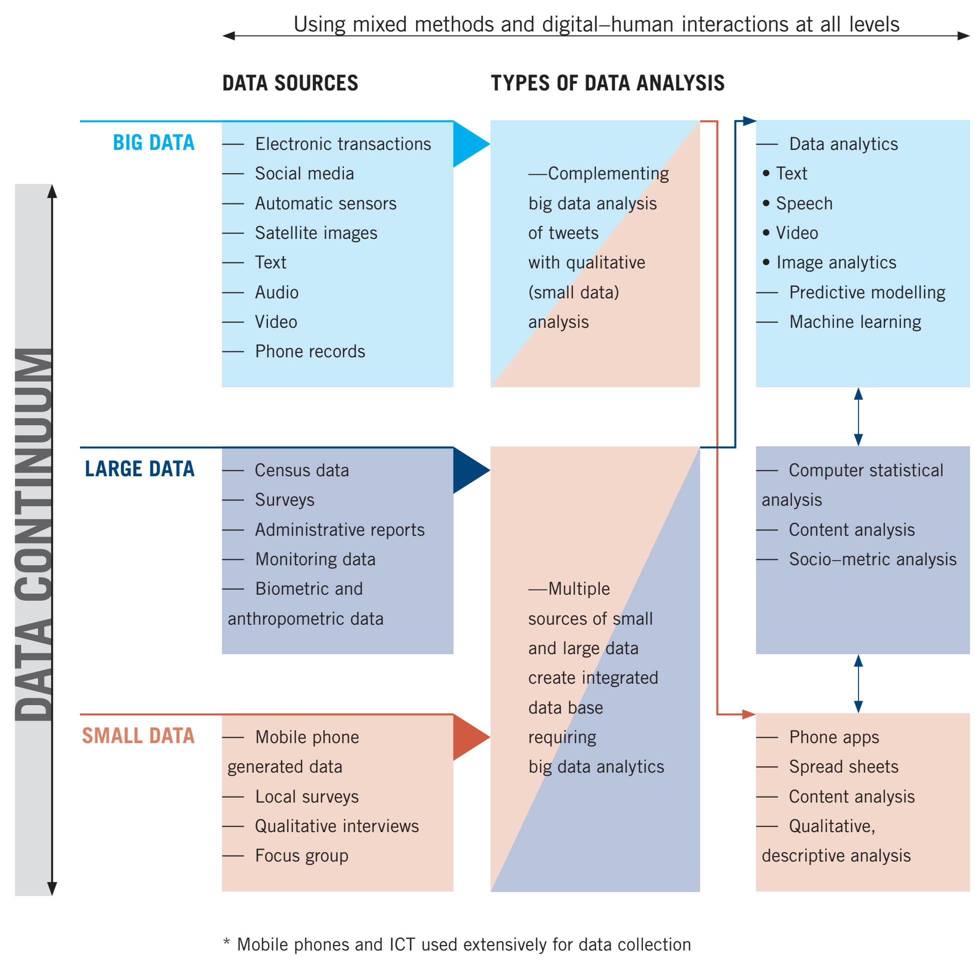

Figure 25: The Data Continuum (UN Global Pulse, 2016b)

3.6. Data innovation

According to a definition by UN Global Pulse (2016a) data innovation describes the use of new or non-traditional data sources and methods (e.g. data derived from social media, web content, transaction data or GPS devices) to gain a more nuanced understanding of an issue. In combination with traditional source of data (e.g. household surveys) these sources can help to provide more complete, timelier and more granular information about an issue and may open opportunities for more cost-effective interventions (UN Global Pulse, 2016a). In the context of this research 'data innovation' is used as an umbrella term for a variety of data sources, collection methods that are the result of the so called big data revolution.

3.6.1. Big data revolution

Today increasing amounts of data are produced about every aspect of our life. Besides that the calculating capacity of modern computer systems is increasing rapidly which suddenly makes the analysis of large data sets possible and economically feasible. The so called big data (BD) revolution describes the on-going explosion in the volume of data, the speed with which data is produced, the number of producers of data, the dissemination of data, and the range of things on which there is data, coming from new technologies such as mobile phones and the 'internet of things' and from other sources, such as qualitative, citizen-generated data and perceptions data (UN, 2014).

Even though there is yet no universally accepted definition for big data many definitions refer to the so called three Vs to characterize big data: Volume, velocity and variety. Volume refers to the size of the data sets that are constantly generated. Velocity refers to the high speed in which the data is generated which provides a continuous steam of information. Variety after all refers to the many different types of data sets that are generated including data sets that are generated intentionally as well as passively generated data in the form of digital traces (Petersson, 2018). In addition to that some other definitions also include the terms variability, veracity and validity (Al Nuaimi, Al Neyadi, Mohamed, & Al-Jaroodi, 2015). Variability refers to the way in which the data continuously changes its meaning. Veracity on the other hand refers to the data being structured and unstructured, uncertain and unprecise. Validity after all refers to the correctness and accuracy of the data (Petersson, 2018). The list of terms could be easily prolonged.

These rather abstract characteristics can be best understood in contrast with traditional data sources and methods. In that sense the so called data continuum as introduced by UN Global Pulse (2016b) provides a solid overview. It divides the data sources into three categories ranging from (1) small data to (2) large data to (3) big data. While traditional data sources like local surveys, interviews and focus groups are to be found in the small data category the innovative non-traditional sources like social media data, financial transactions data as well as automatic sensor data are to be found in the big data category. In between these two extremes is the category of large data which covers national census data, large scale surveys but also administrative reports. Due to the type and quantity of data each category requires different approaches of data analysis. There are however overlaps between all the categories meaning for example that small or large data sources are analysed using big data analytics.

Naturally the seemingly vast opportunities emerging from the data revolution have inspired the imagination of people around the world and seems sometimes to be elevated to be the answer to many of the challenges we are facing today also referred to as 'big data hubris' (Lazer, Kennedy, King, & Vespignani, 2014). However whereas the private sector has already managed to effectively use and thereby gain a competitive advantage from the application of these new technologies they are yet not that popular in the public sector. Thus they still have to proof their true value. According to UN Global Pulse (2016b) potential areas where Big Data may be able to contribute positively to many challenges of current methodologies. Interesting in the context of this research are in particular the following areas of application:

- Improving the understanding of the intervention context which may include among other economic, social, political, cultural, demographic and ecological factors;
- Improving the data collection by providing less cost-intensive and more timely data;
- Monitoring process and behavioural change by providing continuous data about certain phenomena;
- Evaluating complex interventions by collecting data on a larger number of variables and analysing interactions among them.
- To illustrate how data innovation could be used in practise some exemplary projects will be introduced in the following.

3.6.2. Exemplary data innovation projects

When it comes to the actual application of data innovation in practise the number of cases is yet very small. However there are some projects where researchers explored and showed that data innovation could offer indeed new opportunities for the monitoring and evaluation of all kinds of (policy, programme and project) interventions. Three of these which are also interesting in the context of this research will be introduced in the following.

Global Pulse: United Nations

One of the pioneers exploring the use of data innovation for public policy and programme evaluations is the UN Global Pulse team. In the recent years they have tested innovative data sources in a range of different projects (UN Global Pulse, n.d.). Interesting in the context of this research are in particular several projects were social media data was used to measure the public opinion and thereby providing real-time feedback about policy reforms (UN, 2015a, 2015b). According to their analysis todays monitoring and evaluation methodologies are not well suited to deal with the complexity of today's development programmes which most often require the participation of vast numbers of stakeholders and do mostly have impacts far beyond the original intervention (UN Global Pulse, 2016b). In order to measure and evaluate the process and outcomes of these complex developments there is a great demand to develop a framework that is capable of operating in these complex environments. Even though the Global Pulse team put their focus on development programmes, the general thoughts

Figure 26: Selected interesting data innovation projects (own illustration)

on data innovation seem to be also applicable in the context of energy efficiency interventions in particular on the policy and programme level.

Human Dynamics: MIT Media Lab

As mentioned before one of the challenges of today's interventions is the complex nature of human behaviour and behavioural change. With traditional methods it has so far been rather impossible to capture accurate data and understand the full complexity of these processes. However due to the advances in technology it becomes increasingly feasible to gather wide-scale data about social interactions and behaviour. Interesting insights into how data innovation could support this development are provided by the Social Dynamics (SD) research group at MIT´s Media Lab. Their focus lies on exploring innovative data sources to better understand how social networks influence people when they make decisions, transmit information, adopt new technologies, or change behaviours (MIT, n.d.-a). The central component of their data collection process are regular self-phones and mobile sensors like their self-developed 'sociometric badge' that are able to collect data on the individual communication behaviours of people using location sensors, accelerometers, proximity sensors and a microphone (Pentland, 2015). Using these technologies they were able to gather large data sets and provide teams with real-time feedback on their interactions at the workplace (Olguin Olguin et al., 2009).

Another interesting example is self-phone based open-source sensing framework funf that can be installed on any regular self-phone. According to MIT (n.d.-b) self-phones have become a very promising platform for the understanding of social dynamics and influence, because of their pervasiveness, sensing capabilities, and computational power. Installed on the phone funf enables the continuous collection of data on social and behavioural activities (e.g. location, movement, credit card statements, logs of social media activity and daily polling of moods, stresses, sleep etc.) and could help to explain how ideas spread and change within communities (Aharony, Pan, Ip, Khayal, & Pentland, 2011). The central hypothesis of the study is that the spread of new behaviours starts with the individual´s broad exploration of new ideas followed by a more detailed evaluation which finally leads to transforming these into new habits. In the wider societal context these

Figure 27: Sociometric badge (https://cdn.nanalyze.com/uploads/2017/04/Humanyze-Badge.jpg)

new habits are then turned into norms through social learning and social pressure. According to Pentland (2015) this is how social change occurs. Using the devices mentioned before they were able to successfully illustrate these processes. Applying a similar approach in the context of energy-related behavioural change, could allow major insights for decisions-makers. A more detailed description in particular concerning the funf framework is provided in the model development chapter (p.55) of this report. According to MIT (n.d.-b) the greatest obstacles for the use of these new technologies is the lack of data in the public domain as well as the interdisciplinary nature of conducting research with mobile phones. Software engineers and data miners need to work collaboratively alongside researchers from various fields.

Center for Big Data Statistics: Centraal Bureau voor de Statistiek (CBS)

The aim of the Center for Big Data Statistics (CBDS) established by Statistics Netherlands (CBS) the national statistics agency of the Netherlands is to provide a platform for collaboration of national and international parties from government, industry, science and education and to work together on the develop of big data technologies and methods for the production of statistics (CBS, n.d.-a). Besides many other projects they are working for example on new ways of studying the motives behind peoples mobility decisions using innovative data sources such as traffic data and anonymised mobile phone data. In addition to that they used more traditional data sources such as the register of wages, the education register and a register of addresses of utility services (CBS, n.d.-c). Another interesting project is the so called social tension indicator which combines both traditional and non-traditional data sources to measure the sentiment in society. In particular the indicator makes use social media data (opinion and express their feelings on social issues) in combination with in-depth interviews (CBS, n.d.-b). The visualisation of this data shows peaks in the social tensions indicator in the case of unusual events e.g. after the terrorist attacks in Paris.

Other interesting projects

In addition to the given examples data innovation has also a great potential to improve the physical understanding of our built environment. Energy data produced by a smart houses and a

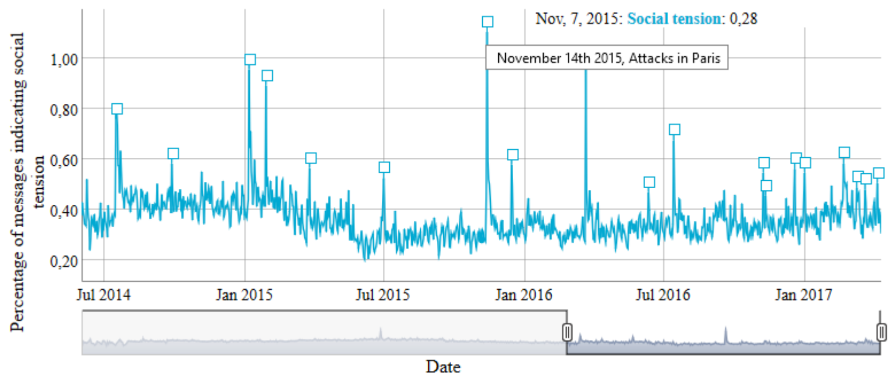

Figure 28: Exemplary event in the social tension indicator (CBS, n.d.-b)

smart urban infrastructure linked with multiple other data sets like for example weather data, building data and socio-economic information could help to better understand the inter-related factors and correlations. Interesting approaches in this direction have been made for example by Buffat, Froemelt, Heeren, Raubal, and Hellweg (2017) who built a model to simulate the building heat demand of a building stock based on comprehensive GIS data including location and building specific solar irradiation and shadowing. Moreover they proposed a GIS-based decision support system for building retrofits which again is based on an extensive GIS dataset an building data as well as climate data (Buffat, Schmid, et al., 2017).

3.6.3. Challenges of big data

Despite the seemingly numerous advantages of big data it also gives rise to new challenges and limitations. This is especially important because so far big data solutions are primarily used in commercial applications. For these purposes it is often sufficient to determine for example a consumers search or buying behaviour without the need to ask why a certain relationship exists. However in the context of policy, programme or project assessments the question why relationships exists and how they behave is especially important (UN Global Pulse, 2016b). Besides the omnipresent topics of privacy and security there are some other challenges that need careful consideration when using a big data-driven approach. In the following some are introduced briefly.

Causality

In contrast to the conventional approach which is based on strong causal relationships (direct links between different factors) the big data approach is purely based on correlations between different factors (Petersson, 2018). In practise that means that two factors might look like they have some kind of relationship whereas this correlation might actually only exists by mere chance or as Taleb (2007) put it 'correlation does not imply causality'. The notion that robust correlations are sufficient to satisfy most informational given by some researchers might be true in the context of commercial applications but not in the context of policy (programme or project) interventions were the question of how and why certain relationships exist are highly important.

Theory

Closely linked to the questions of correlation vs. causality is the role of theory in a big data-driven approach. Whereas some experts argue that the volume of the data alone in combination with the right analysis techniques can produce insightful knowledge free of any theory others argue that data alone has no (evaluative) value without active analysis, interpretation and sense making through human engagement which necessarily requires some element of theory (Petersson, 2018).

Privacy

The great value of big data is that it can provide insights into who we are and what we want. This offers vast new opportunities and makes the data immensely valuable for both private and public actors. While most of these new opportunities are used with good intentions there is also a risk of abusing the data and thereby put people at risk. The disclosure by former NSA contractor Edward Snowden of massive phone and internet surveillance through government agencies is just one of the examples that show why finding solutions that ensure personal privacy and freedom while as the same time enabling the use of the data for research purposes is critical (Pentland, 2015).

Accessibility

Unfortunately today most data remains in silos of private companies and is therefore largely not available of public purposes. This includes in particular the vast majority of private data in the

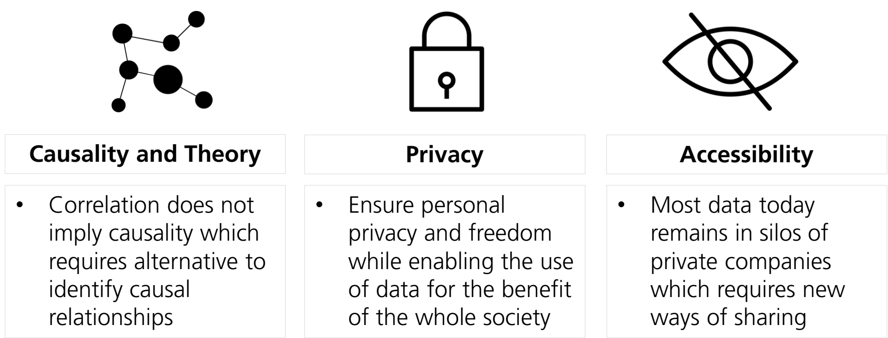

Figure 29: Major challenges faced by big data solutions (own illustration)

form of location patterns, financial transactions as well as phone and internet communications (Pentland, 2015; Petersson, 2018).

After all it became clear that even though the opportunities emerging from data innovation are vast there are also some obstacles that need to be considered and carefully evaluated. In this sense the exemplary challenges that have been introduced are not intended to dismiss the great potential of using innovative data sources but to enable the careful management of possible pitfalls.

3.7. Findings

Considering once again the fact that our population and therewith our urban infrastructure is about the double within the next thirty years and that GHG emissions and climate change is about to accelerate, there is a great urgency in getting things on the right track to prevent more severe consequences. The decisions taken today will determine if people will be locked into their current resource intensive lifestyles or if they enable and stimulate people to change.

Being one of the major causes of GHG emissions the building sector plays a crucial role for the success of the energy transition. In order to identify trigger points and design effective interventions it is necessary to have a solid understanding and information on the factors and various dynamics that are influenced by energy efficiency interventions. It was shown that the conventional thinking approach is inadequate to provide this kind of information in particular due to its narrow focus and challenges to collect data. The consequences are a low take-up rate of energy efficiency interventions and phenomena like the described performance gap.

The literature study showed that in order to overcome these challenges an alternative approach based on a combination of (1) a more holistic systemic thinking and (2) data innovation could offer interesting opportunities.

(1) The underlying idea of the more holistic approach is that by capturing other non-carbon (e.g. socioeconomic) factors that are influenced by energy efficiency interventions it becomes possible to determine their actual net effect. Having this information does not only enable the identification of ineffective interventions but it can also raise the attractiveness of certain interventions (e.g. as an investment opportunity) and thereby stimulate a higher take-up. Due to the complex relationships and interdependencies between the different factors the conventional linear thinking approach was considered to no longer be adequate. Instead a system thinking approach was suggested and introduced that may help to determine trade-offs between the different factors and enable an overall better understanding of their dynamics.

(2) In addition to that it was shown that innovative data sources and collection methods emerging from recent technological developments may help to overcome the general lack of accurate and timely data. In particular it was shown that social media data may help to provide direct feedback for decision-makers on the policy and programme level whereas data collection through mobile sensors and self-phones may allow interesting new insights into human behaviour and many contextual factors in particular on the project level. Moreover it was shown that opportunities may arise in particular from the combination of conventional and non-conventional into mixed methods approaches. Besides the seemingly vast opportunities of data innovation it was also shown that these technologies give rise to new challenges in particular regarding the questions of causality, data privacy, data accessibility and the role of theory.

4. EXPERT INTERVIEWS

In the following chapter the interviewee selection as well as the underlying process of the qualitative interviews and the main findings of the conversations are introduced and discussed.

4.1. Interviewees

In order to gain some first-hand information on the topic expert interviews seemed to be the most suitable solution. Due to the exploratory nature of this research the aim was to involve experts with different views and area of expertise. Out of the twelve applicable organisations that were contacted during the preparation of this research five responded positively and agreed to participate in the research project. The final selection includes both experts from non-government organisations and academia with different perspectives and knowledge ranging from energy efficiency and data innovation to policy-making and evaluation. In particular the selection included two experts from the International Energy Agency (IEA), an expert from the Centraal Bureau voor de Statistiek (CBS), an expert from the University of Maastricht and an expert from the Buildings Performance Institute Europe (BPIE). To ensure the anonymity of the interviewees their names have been substituted with abbreviations (Interviewee A-E).

4.2. Interview process and themes

The interviews were carried out in form of individual qualitative and semi-structured interviews via telephone or Skype. In preparation of the interviews each expert was contacted separately via email to schedule a date for the interview and provide an interview guide including a brief summary of the research and the themes of interest. Due to the complexity of the topic and to speed up the interviews this was considered to be adequate to enable the interviewees to make some upfront preparations.

4.3. Summary of the interviews

The actual interview was structured along three four main themes (1) the conventional thinking approach, (2) complexity-responsive thinking approach, (3) innovative data sources and collection methods and (4) holistic thinking on energy efficiency. In addition to that a more general opening question was posed to start off the conversation. During the interviews the four introduced themes provided the broad boundaries of the conversations while leaving the flexibility for further adjustments during the course of the interview. In the following the main findings of the interviews are presented in a summarized and anonymized form.

4.3.1. Evaluation of the conventional thinking approach

The general need for increasingly up-to-date, more frequent and spatially disaggregated information can be observed in many policy fields and is connected to changing societal needs and the

Organization	Abbreviation	Comment
International Energy Agency	Interviewee A Interviewee B	Individual interviews with two experts from the International Energy Agency (IEA) with focus on the multiple effects of energy efficiency interventions
Statistics Netherlands	Interviewee C	Individual interview with an expert from the Central Bureau voor de Statistiek (CBS) with focus on data innovation
Maastricht University	Interviewee D	Individual interview with an expert from the University of Maastricht (UM) with focus on policy evaluation and data innovation
BPIE	Interviewee E	Individual interview with an expert from the Buildings Performance Institute Europe (BPIE) with focus on energy efficiency policy-making in the EU

Table 1: Overview of selected experts interviewees (own illustration)

various large scale developments of today. Conventional methods like surveys which have so far been adequate to provide the necessary information a national level are not able to deliver this kind of information.

This is not only the fact because the method is more than 100 years old and rather weak in isolation because what people say is not necessarily what people do but also because they are not able to deliver granular and timely data on a continuous basis. For this reason the emergence of data innovation has the potential to improve and sometimes maybe revolutionize common knowledge about certain phenomena.

When looking energy efficiency specifically the underlying reason for the low take-up rate of retrofit interventions is referred back to their mostly discouraging high upfront costs and seemingly long payback periods. Problematic in this context is in particular that most calculations have a rather narrow focus which is only concerned about the carbon benefits of these interventions. Other additional benefits are undervalued or simply neglected. Considering these non-carbon benefits in the calculations will make individual interventions look much more attractive and will thereby help to increase the take-up rate and increase the effectiveness of these interventions. Moreover it is important to make the effects of energy efficiency interventions less abstract by shifting the focus of these interventions from their technical facts to the service that they provide.

However in order to account for their additional benefits it is necessary to have good data and a solid understanding of the process. The data available today is mostly poor in quality and rather fragmented. It is therefore necessary to reconsider the conventional approach and look for alternatives. In this search process for new more accurate solutions of data collection it is important to always keep the overall goal in mind because one might lose track when things get to complex. Sometimes less complex solutions might actually be more adequate and helpful because even a highly sophisticated solution will always remain simplified versions of the real world.

4.3.2. Complexity-responsive thinking

The general tendency to think that complex problems necessary require complex solutions can be observed across research domains and is at least questionable. Focussing instead on crucial

factors and thereby reducing the complexity of certain solutions might actually lead to better outcomes than highly sophisticate and seemingly holistic but thereby also error-prone solutions.
Certainly it can be stated that with increasing numbers of factors, feedback loops and interdependencies the attempt to provide a holistic perspective on energy efficiency interventions can get messy very fast. To keep things manageable it is therefore highly important to set priorities and start by looking at specific sub systems like e.g. the interactions between health and wellbeing and energy efficiency or the intersections with the economy. At a later stage one might link these sub systems with each other to explore how they interact. It is important to notice that the research on this field is still at a very early stage but is likely to offer interesting new insights on a variety of different topics.

After all it is important that even though there is a need to broaden our perspective on energy efficiency interventions and understand linkages and relationships between different factors the increasingly complexification of solutions needs to be watched carefully. Interesting examples in this direction were for example introduced by Gerd Gigerenzer in his studies on simple heuristics as an alternative to the overall desire of people to have more accurate knowledge on complex questions.

4.3.3. Innovative data sources and collection methods

First of all it needs to be acknowledged that the enthusiasm in which data innovation is stylised to be the answer to every question is clearly unrealistic. There are however of course some interesting aspects were these new technologies could add extra depth to conventional methods. One of these aspects is e.g. the way in which the data is collected. Whereas in most conventional approaches like e.g. surveys the data collection takes place consciously many innovative data collection methods take place on a rather unconscious level. Research indicates that this could lead to more accurate results because on a conscious level people tend to not be completely honest or adapt their behaviour.

Data sources like smartphone apps offer possibilities to access and track people's behaviour and thereby get a better idea of their changing habits in relation to policy decisions. Moreover the decreasing prices for technology like e.g. smart sensors make data collection solutions much more affordable. Low-cost solutions for indoor environmental monitoring like for example small single-board computers (e.g. Raspberry Pi) equipped with sensors are just one of the many examples. The positive effects of the additional information on the behaviour of people can already be observed where smart meters for electricity and gas are installed which provide feedback on consumption patterns and thereby enable optimizations. When this information would also be permanently available on e.g. our health and wellbeing parameters it is most likely that this would have positive optimization and learning effects as well. Due to the fact that data is generated on many different levels and by different stakeholders and the fact that data ownership is yet only poorly organized by law one of the major obstacles for the use of innovative data sources is data accessibility. It is therefore critical to find practical solutions that ensure data transparency, protection and security and help to identify common grounds between different stakeholders on which data can be exchanged for the mutual benefit.

After all it is important to notice that the emergence of new data sources and methods does not make conventional methods obsolete. In fact they do have different strength and weaknesses. This is especially important when thinking about how different data sets are linked. Whereas for conventional methods are often linked on the individual object level but confronted with only a limited amount of data, innovative methods have to deal with the opposite phenomenon. Here data is available in very large quantities yet linking this data on the individual object level is rather complicated (see e.g. social media data). This does not only show that it is not critical to find new solutions to link different types of data sets with each other it also shows that instead of replacing existing methods the new methods will rather help to supplement and overcome the limitations of conventional methods.

4.3.4. Holistic energy efficiency thinking

The conventional single input single output thinking is very predictable yet it is not how it things work in reality. This is especially important in areas like the climate change and energy transition. Due to their dynamic interdependencies interventions in these areas can never be viewed in isolation but need to consider their wider context. An interesting example is e.g. the Beyond GDP movement which aims to study societal developments not only based on economic but also environmental and social aspects. By looking at these developments not in isolation but as an integrated holistic perspective it is possible to get a much more accurate picture of society.

When it comes to energy efficiency interventions it is also important to broaden the view and move beyond the carbon and demand reduction perspective. Viewing the technical factors of these interventions in isolation can never be realistic because at the same time there are a vast amount of human factors involved that have a great influence on their outcomes.

The selection of the additional factors is however highly dependent on the perspective and priorities of the individual stakeholder. From a societal perspective jobs, health, carbon emissions and economic growth should definitely be part of the equation. The prioritization of each factor as part of the decision-making is however again highly dependent on the stakeholder and the related political interests. After all a true holistic perspective is something that is probably not realistically achievable because every solution always remains a simplification of the real world and is based on a prior subjective decisions. However an understanding that is close enough might most of the times be actually good enough.

4.4. Findings

After all the five expert interviews provided some interesting additional first-hand insights into the limitations of conventional rather simplistic approaches as well as potential of more holistic approaches that might help to provide a better understanding of energy-efficient retrofit interventions. In particular the experts pointed out the following:

- There is an increasing need for more frequent and spatially disaggregated information across different policy fields
- Conventional methods like e.g. surveys are not able to provide this kind of information
- The simplistic perspective on energy efficiency interventions focussing on technical aspects in isolation leads to misleading information
- More accurate information requires a broader thinking approach and better data
- The increasing levels of complexity needs to watched carefully when developing alternative to ensure that they remain adequate
- Innovative data sources and collection methods have the potential to supplement conventional approaches but give rise to new challenges that need to be explored carefully

5. MODEL DEVELOPMENT

In the following chapter the information gathered during the literature study and the expert interviews was used to develop a conceptual model based on a combination of systems thinking and data innovation. The aim of the model is to provide a tangible application of this approach and thereby help to identify and illustrate emerging opportunities as well as challenges. After all these findings aim to provide the basis for further more detailed research on the topic.

5.1. Design and development process

The design and development process was carried out in three steps: The first conceptual design was made based on the findings and observations of the literature study and expert interviews. This was followed by a subsequent iterative development phase in which the model was gradually improved and finally validated in collaboration with the experts.

5.2. Conceptual model approach

As mentioned before the underlying idea of the model was that by having a more holistic view on the process of energy efficiency interventions it will be easier for decision-makers to identify unintended consequences (positive and negative) and thereby enable the alignment of objectives and increase the performance of an intervention. In contrast to the conventional approach that is based on a linear understanding of the process and mostly limited to GHG and energy demand reductions the aim of the proposed alternative approach is to provide a better understanding of the process as a part of a complex system that illustrates the interdependencies and dynamics between the various factors that are involved. The selection of the factors followed the recommendation of the International Energy Agency (IEA, 2014).

It is important to notice that even though the list of factors is more comprehensive than the conventional view on energy efficiency improvements it is still a selective view of the real world and does therefore not claim to be exhaustive. Moreover it is to be noticed that in practise the selection and prioritisation and weight of factors

Figure 30: Conceptual model design and development process (own illustration)

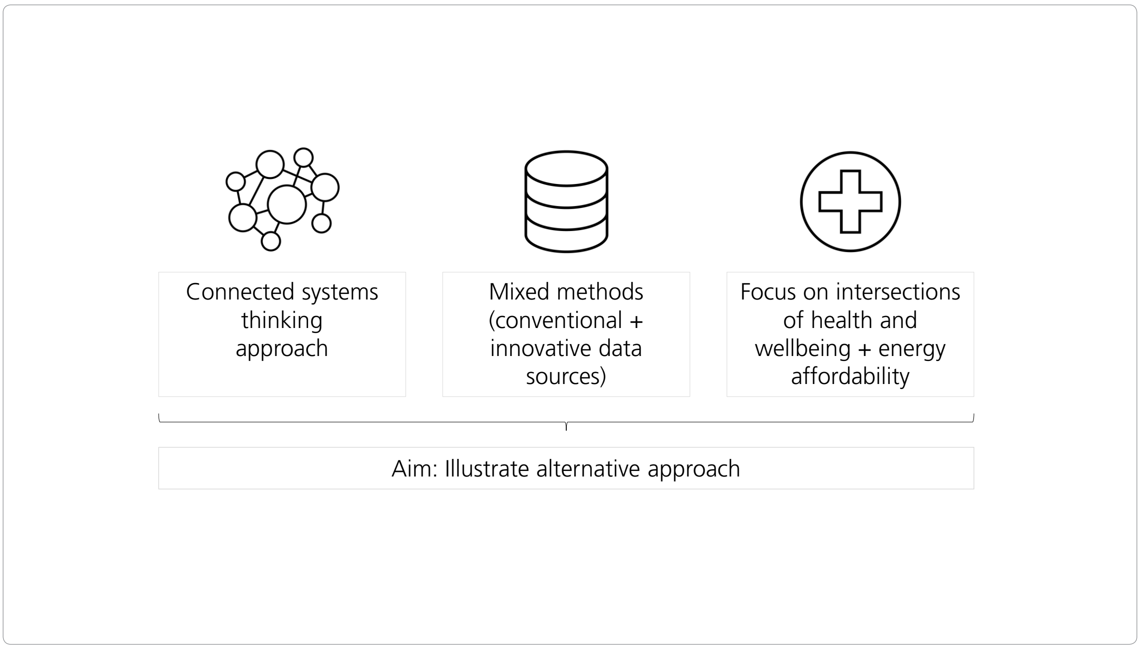

Figure 31: Model concept (own illustration)

will be dependant from the specific interest and perspective of each stakeholder.

In the context of this research the perspective of the policy-maker was chosen. It was assumed that instead of the selective view of e.g. single household or private companies (which are likely to prioritize personal benefits over societal or environmental benefits) the perspective of the policy-maker initially needs to be as objective as possible to enable decisions that benefit society or the environment as a whole. How this initially objective information is later interpreted, used and adapted in reality to match political interests is not part of this research project and needs be explored in another context.

5.3. Overall system mapping

The design phase started by the mapping all factors in the form of a causal map to develop a qualitative understanding of their relationships and interdependencies. In contrast to the conventional linear thinking of cause and effect the system thinking approach made it possible to illustrate dependencies between multiple factors that are considered to influence each other.

5.4. Subsystem: Health and wellbeing, energy affordability and energy efficiency

Due to the limitations of this research the subsystem health and wellbeing, energy affordability and energy efficiency was selected to be explored in detail and illustrate and better understand the intersections between the different factors. The individual factors were connected by causal links (arrows) that together form feedback loops that indicate how the system changes over time.

5.4.1. Energy affordability

In industrial counties the term "fuel poverty" is used to describe households that from a technical perspective have access to energy but cannot afford adequate levels to meet their basic needs (IEA, 2014). A household is considered to be in energy poverty if more than 10% of its annual income is spent on energy. In the EU it is estimated that more than 50 million households live in energy poverty (EC, n.d.). The cause for energy poverty is usually a combination of low household income, poor housing quality and high costs for energy. This has direct consequences on the household energy consumption patterns and indoor environmental parameters which are

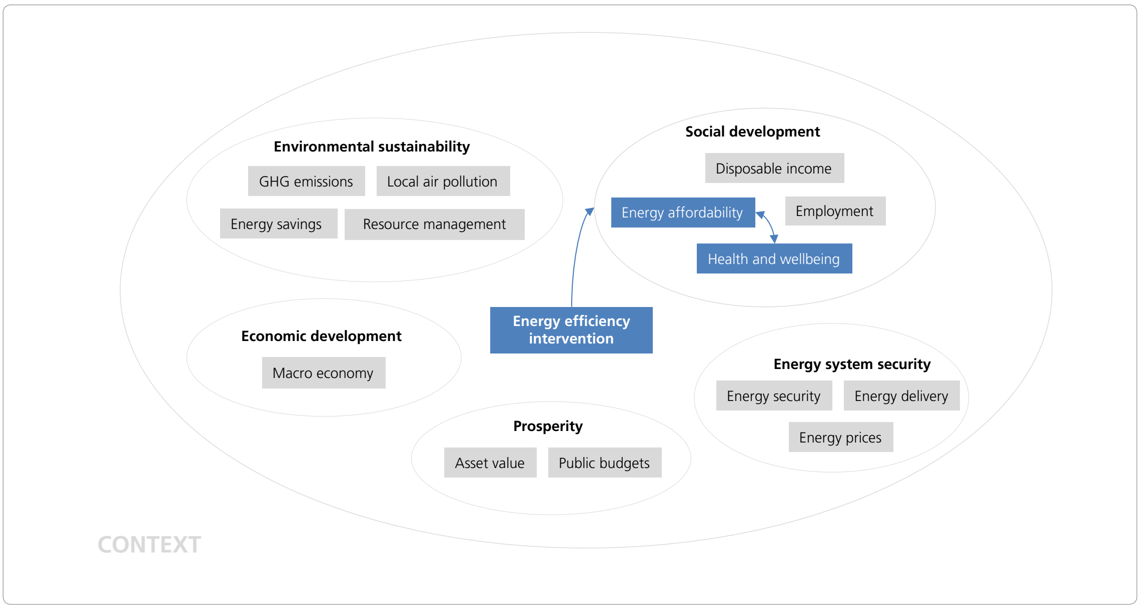

Figure 32: Overall system (own illustration)

themselves strongly associated with sub-optimal physical and mental health conditions. In this sense In energy efficiency interventions that target the cause can in be an interesting alternative to subsidies and fuel grants that target only the symptoms (IEA, 2014, n.d.).

5.4.2. Health and wellbeing

The indoor built environment plays a critical role in our overall well-being because of both the amount of time we spend indoors (~90%) and the ability of buildings to positively or negatively influence our health. According to estimations of the World Health Organization (WHO) air pollution causes about 3 million premature deaths per year (Watts et al., 2018). Energy efficiency interventions targeting air quality are therefore considered to have a significant impact on global health.

This is supported by several research projects that indicate that improving the energy efficiency through insulation, heating and ventilation systems directly affects indoor temperatures, humidity levels, noise levels and air quality. These indicators on the other hand are strongly associated with mental and physical health conditions (Curl & Kearns, 2017; IEA, 2014). The major three key exposure factors related to the indoor environment and considered to have strong correlation with the household health and wellbeing level are (1) thermal quality, (2) air quality and (3) dampness. Thermal quality refers to whether or not the indoor temperature is comfortable and healthy[1]. This includes both the heating in cold conditions as well as cooling in warmer conditions. Air quality refers to the indoor levels of toxins and other gases. Dampness after all refers to the indoor humidity levels which play a crucial role in a range of health conditions such as allergies and respiratory diseases.

The direct and indirect effects these factors have been explored and proved by multiple studies. Strong correlations have been found in particular energy efficiency interventions such improving the thermal quality (insulation, heating-system, ventilation) and positive physical health effects such as reduced vulnerability to illness and improvements to respiratory health (Maidment, Jones, Webb, Hathway, & Gilbertson, 2014). Moreover it was shown that both extreme cold as

1 World Health Organization (WHO) recommends air temperatures between 18-21 degrees Celsius (C°)

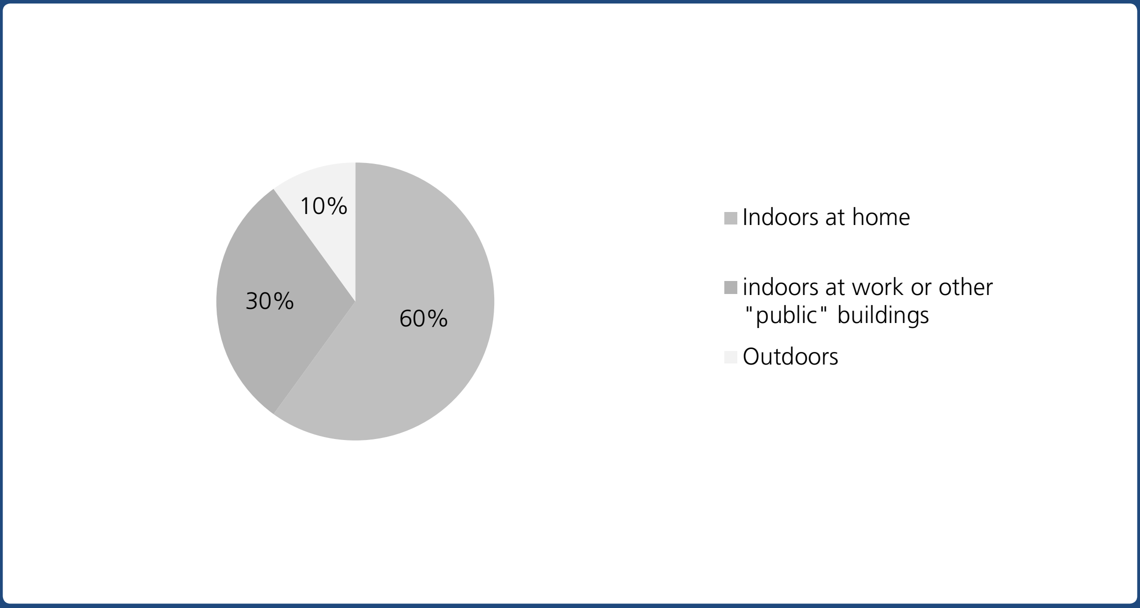

Figure 33: Distribution of time spent indoors vs. outdoors in developed economies (own illustration)

Figure 34: Indoor mould growth after implementing retrofit interventions (https://i.dailymail.co.uk/i/pix/2017/02/23/11/3D91CD0800000578-4252288-image-a-1_1487850461787.jpg)

well as extreme hot temperatures are correlated with excess winter and summer deaths. In this sense implementing retrofitting interventions could help to adapt to these extreme weather conditions and reduce the number of heat or cold related death. In addition to that there is a growing body of knowledge that shows the impact on mental health levels.

Related studies indicate in particular significantly reduced levels of stress, depression and improved levels of wellbeing (Liddell & Morris, 2010). After all there is growing evidence that also suggests correlations with other indirect effects such as reduced public health spending and enhanced cognitive abilities and productivity as well as improved nutrition (IEA, 2014).

It is important to notice that while improving the energy efficiency in a building is generally considered to have a positive impact on the indoor environment there are also possible negative impacts if the interventions are executed poorly. Problematic can be in particular increasing the air-tightness through insulation, sealing and draught-proofing homes without ensuring a good ventilation of the building. This raises the indoor humidity levels and leads to mould growth and a dangerous build-up of indoor air pollutants that promote various negative health conditions (IEA, 2014). The risk of mould growth increases in particular in cases where draughty old windows are replaced by new ones while the ventilation habits of the occupants remain the same. Taking a whole-building approach where the human factor is carefully considered when implementing retrofitting interventions helps to manage the risk and avoid these negative effects.

5.4.3. Indicators and data sources

In the following the relationships and dependencies within this subsystem as well as applicable data sources, collection methods and the stakeholder involved were explored. Especially interesting in the context of this research are the innovative data sources coming from wearable sensors (physiological) and non-wearable sensors (environmental). The functionality of these technologies will be explained in more detail on the following pages.

	Indicator	**Source**	**Stakeholder**
Energy affordability	Energy demand and costs	Smart meter	Private (provider, household)
	Household income	Administrative data (tax statement)	Public
Health and wellbeing	Indoor environmental parameters	Non-wearable indoor ambient sensors	Private (household)
	Morbidity and mortality rate	Administrative data (register)	Private (insurance)
	Health parameters	Wearable physiological sensors	Private (household)
	Psychosocial wellbeing	Mobile phone digital survey	Private (household)
Energy efficiency	Intervention type and costs	Administrative data (report)	Public (programme coordinator)

Table 2: Selection of proposed indicators and data sources (own illustration)

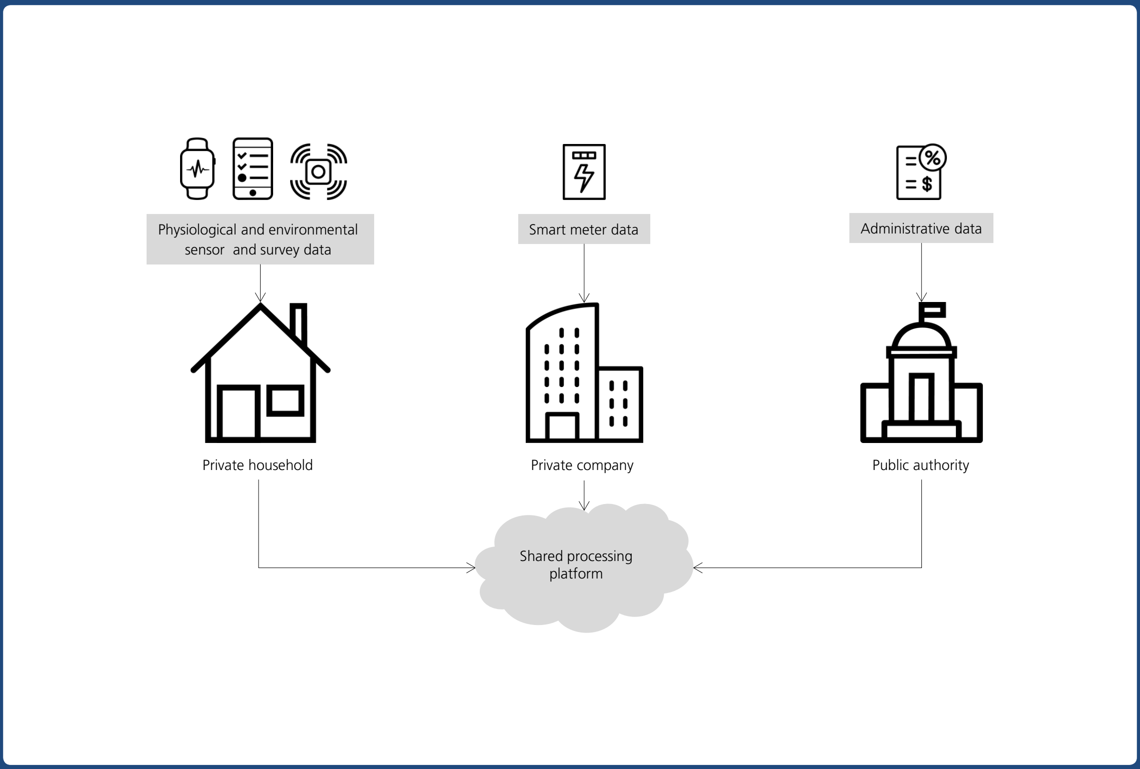

Figure 35: Conceptual data accessibility scheme (own illustration)

5.4.4. Relationships and interactions of model indicators

The conceptual model is structured into three groups with their applicable indicators, data sources and collection methods: (1) Energy affordability, (2) Indoor environment and (3) health and wellbeing. The causal relationships between the different indicators which are based on evidence from literature and expert feedback are illustrated using connecting arrows.

Following the initial energy efficiency improvement the (a) energy demand (green) as well as indoor (b) temperature (red) and (c) ventilation (blue) is altered. A changing final energy demand is likely to lead to downstream effects on energy costs (d), the household disposable income (e) and after all the energy affordability level (f). The actual impact on particular household´s consumption respectively its energy costs is based on the household´s individual income (o). An internal balancing feedback loop between disposable income and energy demand describes a household's changing consumption patterns due to comfort optimizations (e.g. increasing the temperature or heating additional rooms) which are also referred to as rebound effects. The necessary data to measure the mentioned parameters can be collected using smart meters that measure the energy consumption patterns and demand of a household. This data can then be linked to administrative data about the household's income to determine the energy affordability level.

Following the changing affordability level it is likely that this influences the psychosocial wellbeing (g) of a household for example due to health conditions such as stress and depression which could be e.g. triggered by the constant fear of living under strong financial constraints. In addition to that there is a strong link to the household's nutrition (h) which is directly influenced by the household's disposable income and energy affordability.

In addition to that an altered indoor temperature directly influences the thermal comfort (i) and rate of winter mortality and morbidity (j). The great importance of these two factors to the health and wellbeing of a household has been highlighted before. After all the changed ventilation level triggered by the energy efficiency intervention may have a direct impact on the indoor humidity (k) as well as the level of indoor air contaminants (l) which in the following influence the rate of cardiorespiratory health conditions (m). In combination cardiorespiratory conditions, thermal comfort, winter mortality, psychosocial wellbeing and nutrition influence the health and wellbeing level (n) of a household. Close the balancing loop the health and wellbeing level itself is influencing the household income (o) due to changing morbidity and productivity levels as well as the total energy demand (a) of a household due to changes in the times that are spent indoors.

The necessary data to measure the mentioned indoor environmental parameters can be collected using a set of remote sensors while the health and wellbeing related data can be collected using wearable devices (see p.59) as well as digital surveys using smartphones. This data could be enriched with administrative data from health providers and public authorities. Linked with each other these data sets will provide interesting insights into the health and wellbeing level of a specific household. A more detailed description of the data collection technologies that have been introduced and their functionality will be given on the following pages.

The boundaries of the subsystem and connections to the wider context in which the system is embedded are indicated by the grey lines and arrows and their corresponding variables such as for example public budgets (<public budgets>), asset value (<asset value>) or employment (<employment>). In order to provide the bigger pic-

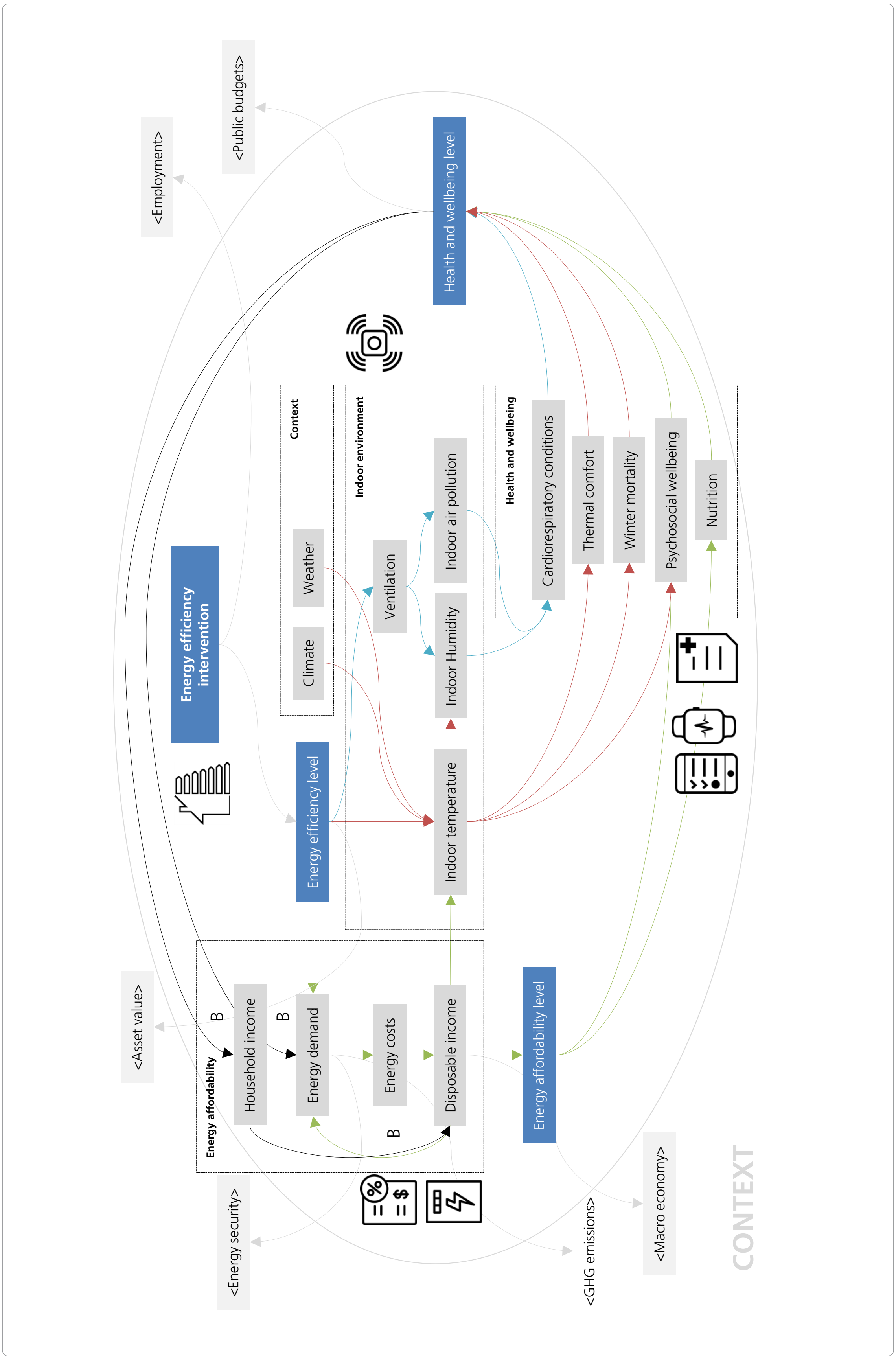

Figure 36: Conceptual model design (own illustration)

ture the relationships to these components outside the sub-system that was introduced need carefully consideration to increase the accuracy of the system while carefully manging its complexity.

5.4.5. Non-wearable sensors

Sensors are the fundamental components for making any environment intelligent (Leung & Mukhopadhyay, 2015). In the proposed model data on the energy consumption could be provided by a so called smart meters whereas data on indoor environmental parameters could be provided by a set of wireless sensors. In the following both solutions will be introduced briefly.

The term smart meter is mostly used in the context of measuring the electricity consumption but can also refer to devices that are used for measuring water or natural gas consumption. In contrast to conventional (non-smart) meters which can only measure the total consumption smart meters can provide much more detail information (e.g. when energy is consumed) which can be used for monitoring or billing purposes by the provider or consumer directly. This information allows consumers to better control their consumption and demand, determine consumption patterns and evaluate opportunities for improving energy efficiency. The information also helps to confirm savings resulting for energy system or building improvements. In addition to the master meter which usually measures the overall consumption of a specific building it is possible to add additional sub-meters in order to understand the way in which energy is consumed in a particular building area. (CIBSE, 2012; Sinopoli, 2010)

Even though indoor environmental monitoring systems which are already existing or currently being developed come in various different forms their central idea is to enable a more effective control of a building by providing feedback on e.g. the indoor air quality and related concentrations of greenhouse gases such as SO2, NO2, CO, CO2 and O2 as well as humidity and temperatures. The sensors are typically installed wireless and can thereby be easily moved within the building (Leung & Mukhopadhyay, 2015). A very basic but interesting example that illustrates the functionality of theses monitoring systems is the low-cost open-source project AirPi[2] which is capable of monitoring the temperature, humidity, air pressure, light levels, UV levels, carbon monoxide (CO) levels and nitrogen dioxide (NO2) levels indoors and outdoors.

Another more sophisticated example for a remote home monitoring system solution for has been introduced by AcuRite. Their system is based on multiple different sensors for indoor room temperatures, humidity and lighting as well as water leak detection sensors and outdoor weather sensors. The sensors can be combined based on the requirements of the user and are installed wireless. The real-time data of the system can easily be accessed and controlled via any regular smartphone. In order to improve and ensure that the indoor environmental parameters stay on a healthy level the system can be configured to alert the user if certain environmental parameters are exceeded leading for example to an increased risk for mould growth. (AcuRite, n.d.)

5.4.6. Wearable sensors and devices

Physiological parameters such as body temperature and heartbeat are essential to monitor the health status of a person. In addition to that the living pattern can provide insights into the well-being of an individual (Leung & Mukhopadhyay, 2015). Popular examples of wearable sensors are for example the Fitbit activity tracker or the Apple Watch that can e.g. measure the heart rate, quality of sleep and other fitness related metrics and provide real-time feedback and analysis via

2 See http://airpi.es/

Figure 37: Electric smart meter (https://upload.wikimedia.org/wikipedia/commons/9/9a/Intelligenter_zaeh-ler-_Smart_meter.jpg)

Figure 38: Indoor environmental home monitoring system (https://www.acurite.com/media/catalog/product/cache/1/thumbnail/600x/17f82f742ffe127f42dca9de82fb58b1/0/1/01167m-alexa-800x800_1.jp)g

a connected smart phone. The trend of tracking personal health data on a daily life basis became known as the quantified-self movement[3] which aims for better self-knowledge through numbers based on grounded and accurate observations.

Another interesting approach to collect data on a continuous basis using any regular smartphone is the open-source sensing framework funf[4]. It was originally developed by the MIT MediaLab as part of an academic research and is in the meanwhile supported and maintained by the Google branch behavio. The key functions of the framework include a set of built in data probes (e.g. GPS, location, accelerometer, call log, running apps, screen on/off state, browser history) as well as a survey system for manual data collection. This enables for example the collection of daily polls concerning moods, stresses, sleep, productivity, socialization and other health-related information. One of the central concerns of the framework is to ensure privacy and protection of any sensitive information (Pentland, 2015). The functionality of the framework was explored and proven with doing a large scale living laboratory study in a residential community (Aharony et al., 2011).

3 See http://quantifiedself.com/about/

4 See http://www.funf.org/about.html

An interesting addition to these tools is the open-source tool mHealth[5] that enables users to integrate, store, process, analyse, visualize and share health related data from various different sources like wearable devices but also desktop and mobile apps.

5.4.7. Conceptual validation

The process of validation aims to demonstrate that the proposed model is a reasonable representation of the actual real world system. Due to the conceptual character of the model and the lack of actual data to test and calibrate the mo-

5 See http://www.openmhealth.org/

Figure 39: Apple watch and Fitbit activity tracker and related smartphone visualization of the data (https://secure.i.telegraph.co.uk/multimedia/archive/03189/ChargeHR2_3189151b.jpg https://support.apple.com/library/content/dam/edam/applecare/images/en_US/applewatch/ios12-iphone-x-watchos5-series4-health-heart-rate.

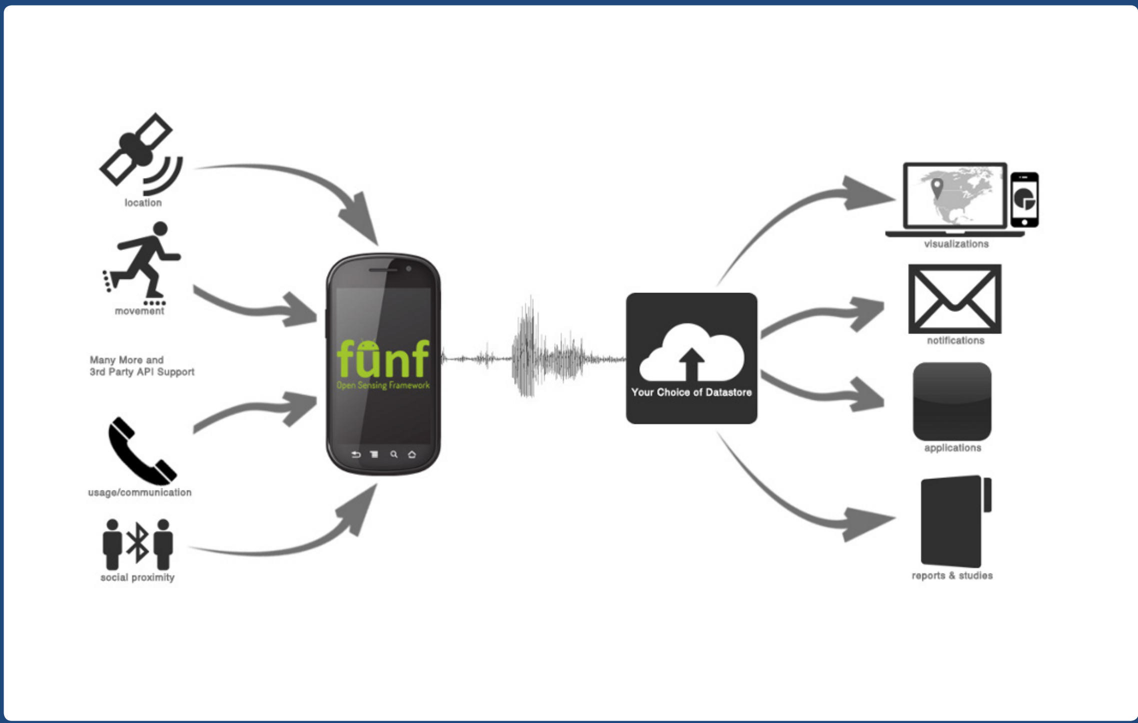

Figure 40: Explanation of the functionality of the funf sensing framework (http://www.funf.org/images/overview.png)

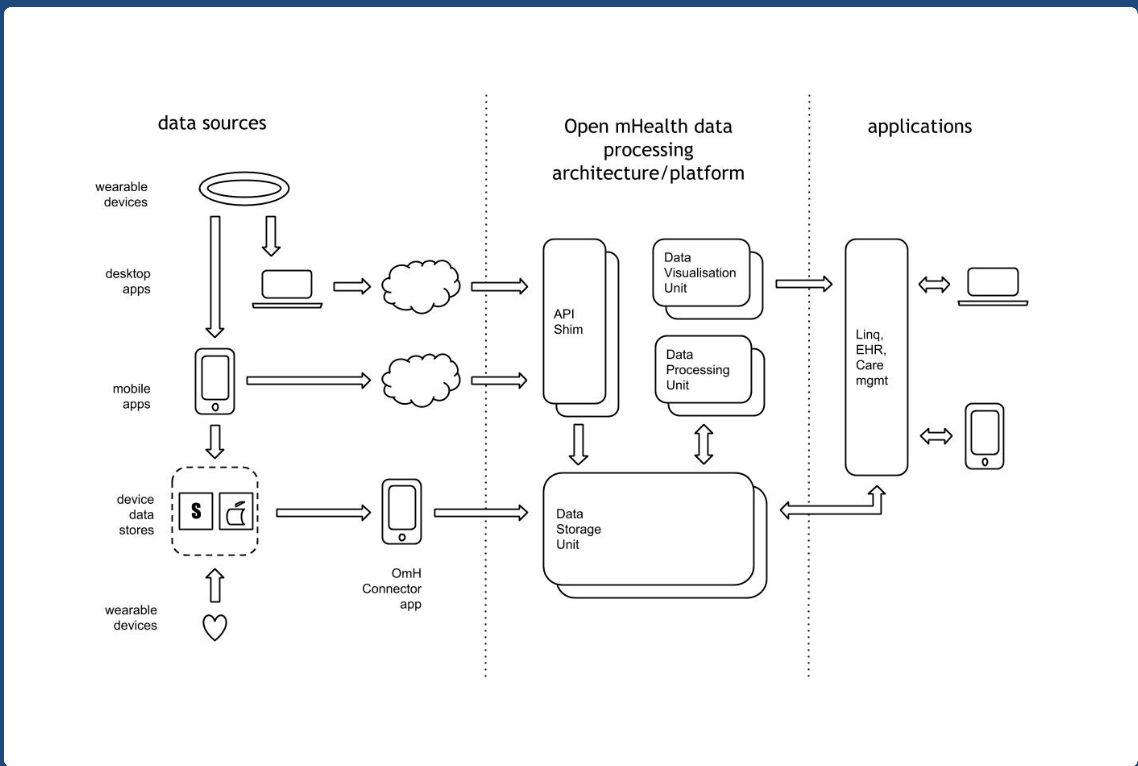

Figure 41: Underlying architecture of the mHealth platform (http://www.openmhealth.org/app/uploads/2015/05/Data-flow-architecture.jpg)

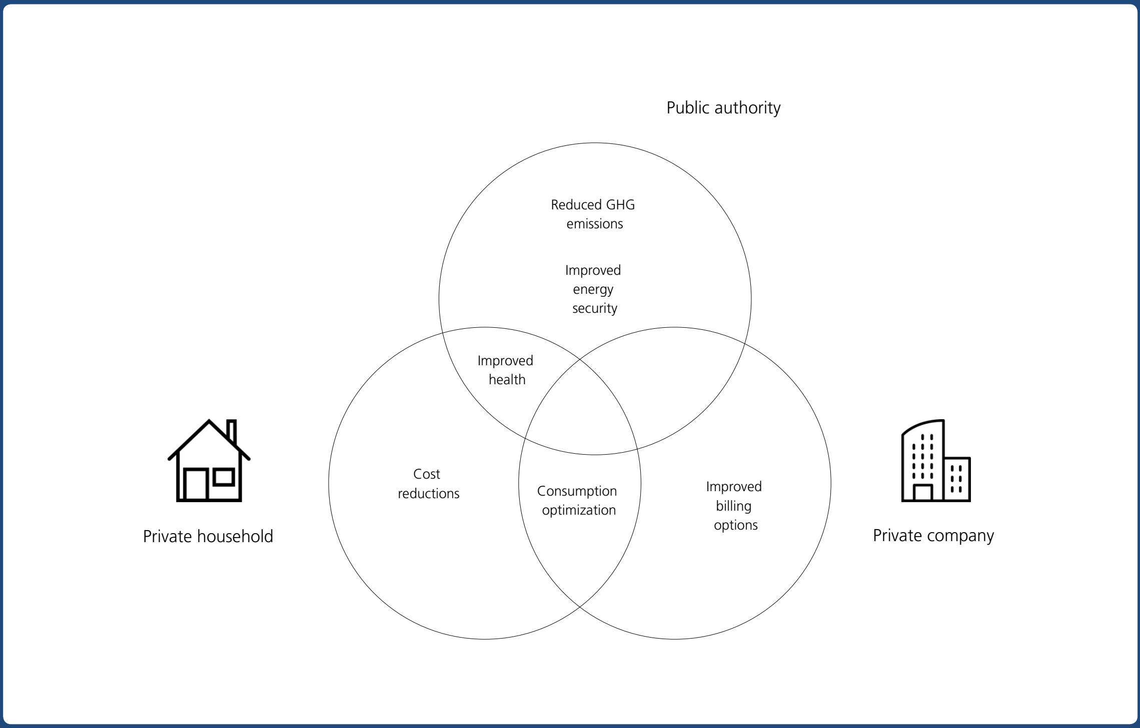

Figure 42: Stakeholder interests VANN diagram (own illustration)

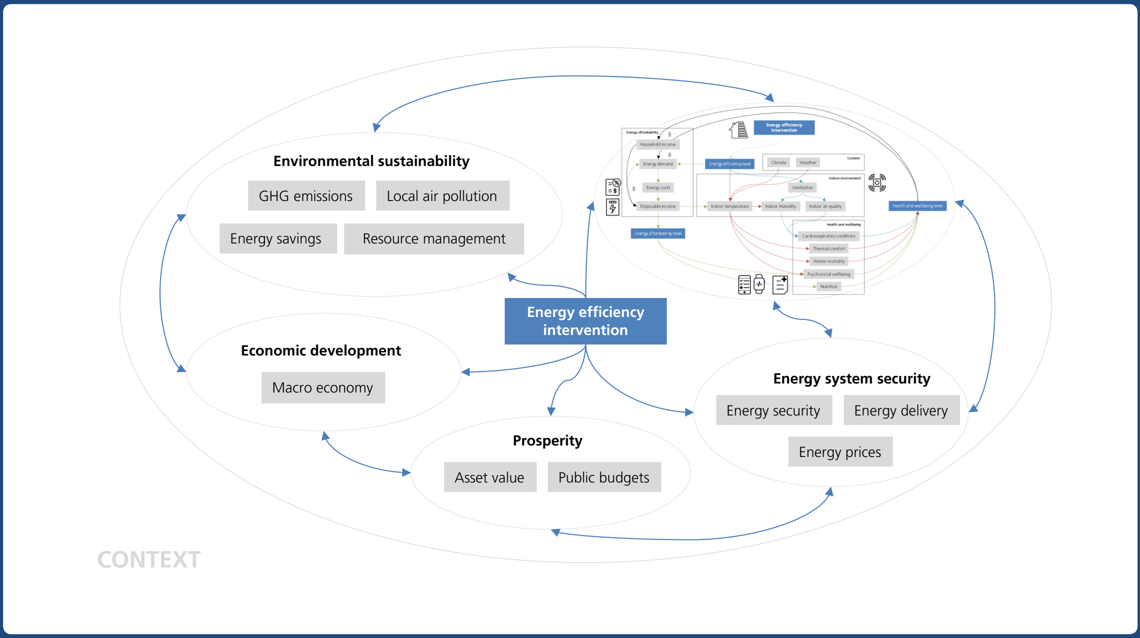

Figure 43: Integration and linkages with the overall system (own illustration)

del the model was validated throughout the development process using the feedback and intuition of the participating experts. The validation process included in particular a careful inspection of:

- the assumptions made regarding the selected system components,
- the structural assumptions (interactions and dependencies between the components) and
- the assumptions made regarding the input and data source

After all final conceptual model is the product of a multiple iterative development steps and it can be concluded that it represents the explored real world system to the best of my knowledge.

5.4.8. Stakeholder analysis

In the proposed conceptual model at least three stakeholders need to be involved to get access to the necessary data. These are (1) the private households that collect the health-and well-being and well as indoor environmental data, (2) the private energy provider who collects energy consumption and billing data and (3) the public authority that collects data on the household income. It was mentioned before that data accessibility is considered to be one of the major obstacles that need to be dealt with in the context of many innovative data sources. Identifying shared interest and establishing common grounds for data exchange between the stakeholders involved is therefore essential.

5.4.9. Integration into the overall system

It has been mentioned before that the information through the introduced sub-system gets even more meaningful when it is linked to other sub-systems from related fields such as environmental sustainability, economic development, energy system security and prosperity. Even though this will also never provide a truly holistic picture it does however provide important insights into the interactions of major policy fields and thereby provide information for optimizations that help to increase their effectiveness.

5.5. Taking a look ahead

In contrast to the conventional approach which focusses rather on the individual components and which is therefore likely to produce misleading conclusions and unintended consequences the introduced alternative approach offers interesting new opportunities for a much more dynamic and behaviour-driven policy-making process. This means that in instead of the currently predominant one-time decision-making and one-size-fits all solutions this new approach would allow more fine-grained interventions. In addition to that the individual stakeholders would become partners in the process which is different to the currently predominant top-down structure. In practice this could allow programme coordinators to tailor interventions exactly to the individual project requirements and enable them to grand supports based on actual evidence rather than believe. This would help to ensure that resources are not spread too thinly among a large number of projects but are targeted to those interventions that provide the biggest benefit. On the long run the continuous feedback and optimization supports a learning process that will enable better and more effective decision-making for future projects.

5.6. Findings

The aim of the qualitative conceptual model development was to identify and illustrate emerging opportunities as well as challenges of the proposed systems thinking approach combined with innovative data sources and collection methods. This was done by exploring how the dynamic process of an energy efficiency intervention could be understood as a complex system in contrast to the linear and simplified process of the conventional approach. The causal relationships between the different indicators were based on evidence from research and through personal exchange with the experts involved. For the data collection several innovative methods like wearable and non-wearable sensors to measure physiological and environmental indicators were introduced. The exploration for applicable sources and methods showed that there is a wide range of emerging technologies that offer a vast potential for a better understanding of future interventions.

A major barrier for these developments is the accessibility of the data. Finding answers to ensure the security, privacy, quality and transparency of the data that is collected and enable data exchange for the mutual benefit of the stakeholders involved will be essential for its success. Regarding the systemic thinking approach it can be concluded that is offers in contrast to the conventional linear approach a very promising alternative that can help to better understand and analyse the complex dynamics of an intervention. Due to the conceptual character of the model development the validation of the assumptions made could only be tested based on the knowledge and feedback of the experts that have been involved.

Future research will need to proof the theoretical relationships that have been identified in this first qualitative concept in more detail and finally translate the findings into a quantitative operational model that can be verified and tested in practice.

After all it is important to remember that every model will always remain a simplified representation of the real work. Setting priorities and watching the complexity of future solutions carefully is therefore essential to ensure that they remain adequate.

6. RESEARCH FINDINGS

In the following chapter the research findings are summarized the underlying research question. Besides that recommendations for follow-up research on specific areas of the topic are provided.

6.1. Conclusions

The research started by illustrating the challenges of the anthropogenic climate change and the ambitious GHG reduction targets. Keeping in mind that our population and therewith our urban infrastructure is about the double within the next thirty years there is a great urgency in getting things on the right track to prevent more severe consequences. In that sense the decisions taken today will determine if people will be locked into their current resource intensive lifestyles or if they enable and stimulate people to change. However even though the building sector plays a crucial role in the success of the energy transition process the results of the interventions taken are yet far from optimal. In the following it was shown that the poor understanding of the dynamics of these interventions resulting from a narrow perspective and poor availability of data results in uncertainty that ultimately leads to ineffective decision-making. The consequences are a low take-up rate of energy efficiency interventions and phenomena like the described performance gap between anticipated and actual energy performance. The goal of this research was to explore an alternative approach based on innovative data sources and collection methods that could help to move beyond today´s rather vague and fragmented understanding of residential energy efficiency retrofit interventions towards a more holistic and accurate understanding of their dynamics and effects which could ultimately provide the evidence needed for effective decision-making.

On the basis of this problem the research aimed to answer the following research question: *How can we monitor the performance of residential energy efficiency retrofit interventions more accurately to facilitate more effective decision-making?*

To approach the question two sub-research questions covering (1) the design as well as (2) the data collection aspect of the main question were posed. The goal was to explore solutions that could help to overcome the limitation of the conventional thinking approach.

Q1: Which additional non-carbon factors are influenced and could provide a more holistic understanding of residential energy efficiency retrofit interventions and which alternative thinking approach could help to illustrate the complex relationships and dynamics of these factors?

Q2: Which additional or alternative sources could be used to provide more timely and accurate data on these factors and which methods could be used to collect the data?

In is important to notice once again that the subject is massive and due to the limitations of this research and even though it was explored in a series of steps and under consideration of a vast amount of information this final product is still far from being exhaustive. The findings that are presented in the following should therefore be considered as a first step and basis for further research and are required to be studied in detail before they could be generalized beyond the boundaries of this study.

A1: The underlying idea of the more holistic approach is that by capturing other non-carbon (e.g. socioeconomic) factors that are influenced by energy efficiency interventions it becomes possible to determine their actual net effect. Having this information does not only enable the identification of ineffective interventions but it can also raise the attractiveness of certain interventions (e.g. as an investment opportunity) and thereby stimulate a higher take-up.

The evidence that was presented during the literature study as well as the expert interviews showed that energy efficiency interventions are much more than just a tool for greenhouse gas reductions. In fact the narrow perspective on these interventions and resulting uncertainty is likely to be a major reason for them to remain below their targeted objectives. Broadening the perspective on the other hand would lead to a much more accurate understanding of the effects and thereby allow the identification of trigger points and the alignment of goals. Worth further consideration are in particular the following areas and factors:

- Environmental sustainability (e.g. energy savings, GHG emissions, resource management)
- Social development (e.g. health and well-being, poverty alleviation, employment)
- Economic development (e.g. macroeconomic impacts)
- Prosperity (e.g. asset value, public budgets)
- Energy system security (e.g. energy security, energy prices, energy delivery)

Even though that list does not claim to be exhaustive it does illustrate the wide range of non-carbon factors that are influenced making energy efficiency interventions not only a tool for GHG reductions but also for socioeconomic developments. Based on the individual objectives of the stakeholders the list might be changed and extended and priorities set differently.

Due to the complex relationships and interdependencies between the different factors the conventional linear thinking approach was considered to no longer be adequate. Instead a system thinking approach was suggested and introduced that enables decision-makers to determine trade-offs between the different factors and the wider context and an overall better understanding of their dynamics.

A2: The lack of timely and accurate data was identified as another major obstacle undermining effective decision-making. The evidence presented showed that innovative data sources and collection methods emerging from recent technological developments may help to overcome these obstacles by supplementing conventional methods. In particular it was shown that innovative data collection methods like mobile sensors and self-phones may in particular be helpful in:

- Improving the understanding of the intervention context which may include among other economic, social, political, cultural, demographic and ecological factors;
- Improving the data collection by providing less cost-intensive and more timely data;
- Monitoring process and behavioural change

by providing continuous data about certain phenomena;
- Evaluating complex interventions by collecting data on a larger number of variables and analysing interactions among them.

However even though the seemingly vast opportunities of data innovation it was also shown that these technologies give rise to new challenges in particular regarding the questions of causality, data privacy, data accessibility and the role of theory. This is why opportunities may arise in particular from the combination of conventional and non-conventional into mixed methods approaches and thereby adding additional depth to the findings.

RQ: The application of the proposed alternative approach based on a more holistic perspective and driven by data innovation was tested by developing a conceptual model with special focus on the health and wellbeing aspects of energy efficiency interventions on the project level. The development of the model was based on the findings of the prior literature study and expert interviews and aimed to illustrate challenges and opportunities of the approach.

Concerning the central research question it can be concluded that the introduced alternative approach does offer major advantages over the conventional linear and simplified approach. These advantages are in particular the improved ability to understand and analyse the complex dynamics and trade-offs between different factors. Regarding the data that is necessary innovative collection methods like wearable and non-wearable sensors to measure physiological and environmental indicators as well as personal perception seem to be promising alternatives to conventional methods like surveys or focus groups due to their ability to generate continuous streams of data on many different indicators. Challenging seems to be in particular ensuring the accessibility of the data and findings solutions that ensure the security, privacy, quality and transparency of the data while enabling data exchange for the mutual benefit of the stakeholders.

6.2. Recommendations for further research

The findings of this research were based on an extensive exploration of literature and additional first-hand insights through interviews with experts related to the field. As such the results of this research are considered to be a valuable contribution to the academic body of knowledge by providing a basis on which future research can build on. However due to the limitations of this research such as the time that was as well as the subjective perspective and limited upfront knowledge of the researcher naturally led to findings that need to be explored and ultimately verified by further research. In this sense it could be interesting to organize a direct knowledge exchange (e.g. in form of a focus group) between the involved experts which have so far only be interviewed independently. It is assumed that this would lead to valuable additional insights and also provide the chance to cover the subject more thoroughly and from different perspectives. As a result of this exchange further in-depth exploration of very specific subjects such as e.g. data accessibility, security, privacy etc. could be explored in more detail. Furthermore additional research is needed to test and validate the conceptual thinking approach and the selected data collection methods and sources in practice.

7. REFLECTION

The following chapter reflects upon the research process and used methods as well as the societal, professional and scientific relevance and transferability of the findings. Moreover the relationship between the research project and the graduation studio and master programme is outline.

The connection to the research group

This graduation research project was carried out within the BOLD (Big, Open, Linked Data) Cities graduation laboratory (AR3R010) at the department Management in the Built Environment (MBE). The aim of this graduation lab is to bring together the perspectives of big data, architectural and planning information, smart cities, information technologies, urban area development and governance into demonstrations explaining the potential emerging from these new developments.

By exploring and illustrating the opportunities and challenges of data innovation and developing a conceptual alternative that is capable to provide a more holistic understanding of the complex process of EE interventions and thereby act as a supportive tool towards a climate-neutral built environment this research follows the central idea of the BOLD research group.

The research approach and methods

Due to the novelty of the subjects related to data innovation an exploratory research type was chosen. This approach proved to be adequate in enabling a gradual approach to the subject and the central research question while leaving flexibility to constantly refine the final product. The process was facilitated by using a multi-method design based on a literature study, qualitative expert interviews and the development of a model. Looking back the selection of these methods still seems to be adequate. There are however improvements that could have been made having the knowledge of today.

These improvements concern in particular the literature study which turned out to be extremely time intensive. The reason for that is the rather limited upfront knowledge and need to get are solid overview of the topic and the context in which it is embedded before even being able to start the actual research. During this preparation phase a vast amount of literature was consumed which after all could only partially be used in the context of this research project. With today's knowledge on the topic this phase could have been organized and focussed more precisely on specific aspects of the topic which would have enabled a more effective use of time.

Regarding the interviewee selection and process finding applicable experts proofed harder than expected. From the twelve organizations that were contacted only five responded positively and agreed to participate in the research.

In the beginning this was considered to be a problem but due to the fact that all conversations lasted between 60-90 minutes and were all very rich in information and thereby required a lot of post processing it might also have helped to keep the project manageable. Another challenge during the interviews was the fact that all interviewees had a very specific focus or perspective. This means for example that whereas one interviewee was very knowledgeable regarding the multiple benefits of energy efficiency another was rather knowledgeable in the field of data innovation. Due to this reason a shared meeting in form of e.g. a focus group in which the interviewees could speak directly to each other might have been an interesting addition to the individual interviews and maybe even more adequate. However due to the limitations of this research this could not be organized within the given timeframe. This experience clearly showed that knowledge from a wide range of different areas is needed for the development of new and innovative monitoring solutions for energy efficiency interventions and can only be successful by collaboration and cross-disciplinary research. After all it can be concluded that the conversations with the experts led to both valuable first hand-information for this research but also and maybe most important to new personal insights and learning experiences.

The idea of the subsequent model development was to apply the findings of the literature study and expert interviews to a specific aspect and thereby enable a more in-depth exploration and provide an illustrative example of the challenges and opportunities of the alternative approach. The development phase was planned as an iterative process in which the model is gradually improved based on feedback of the experts. Due to the limited timeframe of this research it was however necessary to reduce the number of feedback rounds. Looking back and with the knowledge of today this phase could also be improved to ensure a more effective use of time. After all it was clear beforehand that this graduation project would be very explorative and without a very clear idea of the end product. This was also supported also by the structure of the BOLD Cities graduation lab which offered me a lot of freedom to develop the subject by myself and dive into topics that I am interested. At the same time this freedom required a lot of energy in order to stay on track and not to get lost in the vast amount of information which was sometimes overwhelming. Despite the obviously many new insights on the topic itself this open process was a valuable exercise for me in structuring and gradually approaching an unknown topic.

Relationship between the project and the social, professional and scientific context

Mitigating the consequences of the anthropogenic climate change remains one of the most challenging problems faced by humanity. The devastating consequences of the changing climate are hard to deny and so it the urgency to change our current energy consumption patterns. In the globally adopted GHG reduction plans the built environment plays a crucial role. In theory the combination of the two central components aimed to drive the energy transition (1) reducing our primary energy demand and (2) increasing the share of renewable energy sounds simple.

Yet in reality evidence on the actual performance of implemented interventions is scare and there are increasing signs that indicate that they are often not able to deliver their ambitious targets. A central weakness and source of uncertainty seems to be the highly simplified approach to assess their process which is unable to deal with the complexity of the invention in a dynamically changing environment. Given the fact that solid information is vital for effective management and thereby to the success of the ambitious GHG reduction goals this exploration of emerging opportunities with the potential to improve our understanding of the process is with no doubt a valuable and relevant addition to the academic body of knowledge.

Potential applications in practice

After all the given information problem that was dealt with in the context of this research concerning the inability of the conventional monitoring approach to capture and understanding the dynamic process and complex relationships of residential EE retrofit interventions can easily transposed to various other challenges humanity is faced with such as climate change or transport. In this sense the findings of this research as well as further research on the subject is likely to also offer valuable insight for other fields of application where decision-makers are faced with challenges characterised by a complex set of factors and poor availability of data.

The personal learning process

For me personally the last months have been a fascinating yet also challenging journey through a vast amount of different topics related to this graduation project of which many have been completely new to me. Looking back I have to admit that I sometimes had a hard time developing the topic of the research from the first idea to the final product. This had on the one hand to do with the topic in general which was in many parts completely new to me but also with my personal ambition to produce actually usable results. At one point during the graduation process I had to realize that in the given timeframe of this project this goal might have been too ambitious especially due to the complexity and the novelty of topic. After all I had to accept that this graduation project will be primarily about my personal learning experience than about the production of actual additional academic knowledge. Even though this might sound negative I am grateful for the opportunity to use the context of my graduation to follow my curiosity for an in-depth exploration for several topics outside the traditional boundaries of the built environment. By doing so I had the chance to develop a much broader understanding of the topic and its context than by staying within the limitations of my own domain. This was especially valuable to me because I believe that complex challenges like e.g. the energy transition in the built environment are not to be solved by people working within the boundaries of their own fields of knowledge but by intensive collaboration that facilitates the exchange of ideas and expertise.

I hope that with this graduation project I could lay the foundation for my own contribution in this transformational process. After all I can say that even though there have been moment in the course towards this final product which have been very challenging, confusing and sometimes even frustrating in the end overcoming these challenges always lead to some new valuable learning experiences or insights. Once again I want to point out that I am very grateful for this unique opportunity.

ACKNOWLEDGEMENTS

At this point I would like to thank my interview partners for their time, ideas, feedback and overall valuable contribution to this research. Moreover I would like thank the EFL Stichting for their generous support of my work. After all I would like to especially thank my mentors Alexander Koutamanis and Andrea Mauri for their great support, guidance during and interesting conversations during this time.

EFL STICHTING

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In deep gratitude for the opportuntiy to learn, grow and share

Humanity is facing large scale environmental challenges emerging from the anthropogenic climate change. Greenhouse gas emissions (GHG) are widely considered to be the main driver of the changing climate. With the built environment currently being accountable for about 40% for our total GHG emissions there is a great urgency to act and change our current consumtion patterns. Whereas new buildings are already mostly able to achieve a high energy efficiency the biggest potential for CO2 reductions lies in retrofitting the existing housing stock. Yet current interventions aimed at retrofitting our built environment often seem to remain below their expectations. Actual solid evidence on their performance is scarce and inaccurate. One reason for the lack of information is seemingly the rather simplified and therfore inadequate approach to generate feedback. In order to provide more accurate evidence and thereby facilitate more effective decision-making this research investigates an alternative approach based on a more holistic thinking and the use of data innovation.