oekom

oekom verlag, Gesellschaft für ökologische Kommunikation mbH,
Waltherstrasse 29, 80337 München, Germany

Layout and Typesetting: Reihs Satzstudio, Lohmar, Germany

Published by
Wuppertal Institute for Climate, Environment and Energy

Knowledge as transformative energy

On linking models and experiments in the energy transition in buildings

Authors:
Anja Bierwirth, Karoline Augenstein, Stephan Baur, Johannes Bettin, Johannes Buhl, Jonas Friege, Georg Holtz, Thorben Jensen, Jan Kaselofsky, Christa Liedtke, Alexandra Palzkill, Mathieu Saurat, Uwe Schneidewind, Sophia Schönborn, Stefan Schweiger, Peter Viebahn, Florin Vondung

Assisted by: Isabel Drissen, Steven März

Graphic design: Stephan Preuß Grafik & Design, Wuppertal

Translated by: Teresa Gehrs, LinguaConnect

Table of contents

1 Introduction 7
1.1 The nature of this book 8
1.2 How to explore transformation 10

2 Basic concepts of research into transformation 13
2.1 System innovations and human-environment systems 14
2.2 Transformation research and transformative research 17
2.3 Transdisciplinarity: how does socially robust knowledge for transformation processes emerge? 19
2.4 Knowledge integration and the role of boundary objects 22
2.5 Forms of knowledge and research approaches along the transition cycle 26

3 The city and the neighbourhood as boundary objects 41
3.1 System analysis using the example of energy refurbishment and energy savings in residential buildings 43
3.2 The energy transition as a target vision: target knowledge for the heating transition 70
3.3 Transformation knowledge: real-world experiments and diffusion . . . 77

4 Models for knowledge integration 87
4.1 Agent-based modelling as a boundary object 96
4.2 Opportunities and limitations of agent-based modelling 112
4.3 Breaking habits – interaction between user experiments and agent-based modelling 120
4.4 Modelling an ecological dilemma: energy versus resources 138

5 **Conclusion / Hypotheses / Summary** 151

6 **Acknowledgements** 155

List of figures 157
Bibliography 158

1

Introduction

1.1 The nature of this book

This book is ostensibly about the energy transition in the building sector. It provides insights into the work conducted during the 'EnerTransRuhr' project. This project, whose full name is 'The German "Energiewende" – Development of an Integrative and Transformative Research Design in the Case of the Energy Transition of the Ruhr Area and North Rhine-Westphalia', was funded by the German Federal Ministry of Education and Research (BMBF) under the 'Environmentally and Socially Compatible Transformation of the Energy System' funding programme. The project, involving the development of strategies for reducing energy consumption in buildings, provided a number of interesting insights into the transformational challenge of the energy transition in buildings, which is the determining factor for the success of the energy transition in Germany as a whole.

Essentially, however, the book is a workshop report from the EnerTransRuhr project, which itself can be seen as a representative project in the field of sustainability and transformation research. As with numerous other sustainability challenges, the energy transition in buildings is a complex transformation task: the energy-saving potential in the building sector depends on a wide range of factors. These factors include the technical characteristics of the building stock, the legal and economic framework conditions that are intended to encourage owners to make their buildings more energy efficient, as well as the behaviour of those who use a building, especially their heating and ventilation habits. This complex interplay of the political framework, the building itself and people's behaviour within its walls means that the topic of the energy transition in buildings, which may appear minor at first sight, is destined to be an important field of application for exploring complex transformation challenges. Researchers also took the opportunity offered by the EnerTransRuhr project to contribute towards advancing integrated and transformative research designs.

The transformation initiated by the energy transition is present in all conceivable systems that humans have created to ensure orderly coexistence. A mind shift towards the more responsible use of energy and the environment, and consequently efficient and sustainable practices, must not only be viewed as a collaborative exercise in the building sector; it requires new forms of participation and integrative moments in research. Taking the example of the energy transition in buildings, this book asks how complex socio-technical transformation processes towards sustainable development can be supported academically. How can we gain a better understanding of the opportunities and obstacles in our path to achieving a world that puts less pressure on resources and the climate? And how can science contribute towards new solutions and ideas leading to change in practice? Such transformative research that leaves the neutral observer position needs appropriate concepts and methods: how can knowledge from different disciplines and from practice be integrated in order to be able to explain and understand complex circumstances and interrelations? What role do complex (agent-based) models and experiments play in this respect? Which mix of methods is required in transformative science in order to actively support the actors in transformation processes?

This book focuses on these questions. The next section provides a brief overview of the basic concepts of transformation research, demonstrating that one of the key challenges involved is making knowledge integration interdisciplinary and transdisciplinary. Boundary objects may play an important role here, acting as a point of origin that gives us a common understanding of the problem (but viewed from different perspectives), and that ensures exchange between different stakeholder groups. In this connection, boundary objects may be specific places, such as cities or neighbourhoods, or abstract scientific models. Both forms have played a central role in the EnerTransRuhr project, and have therefore been chosen as the starting point for the following specific insights into the project and its findings.

1.2 How to explore transformation

In order to meet climate change mitigation targets in the building sector, it will not suffice to support technological innovations alone. One must deal with established structures in cities and neighbourhoods and take into account the relevant circumstances and framework conditions. The political and legal situation is also complicated. The right incentives have to be created, but these may differ considerably in some cases, depending on the stakeholder group and the building stock, and unintended consequences may arise. It is also essential to consider each individual actor's different underlying motives, for example, to leverage the potential created by changing people's heating and ventilation habits.

It becomes apparent from this field of enquiry that it is not easy to determine the contribution to be made by science and research in implementing the energy transition in buildings. The interlinkages in the energy transition in buildings starkly reveal the limitations of investigating these questions solely within academic disciplines when asking which technological innovations are needed, which policy instruments could be useful, which business models have to be developed, and what role is played by actors' behaviour. All these aspects are relevant, but must, above all, be investigated in interaction with each other.

On the whole, the energy transition (not only in the building sector) is both a technological and a socio-cultural transformation challenge. Academic guidance in the energy transition faces various integration challenges as well. To begin with, technological (new production technologies, grids, storage facilities, efficiency technologies) and socio-cultural innovations (new governance patterns, lifestyle adaptations, new use patterns of products and services, new forms of participation, and so on) must be considered in an integrated manner. In this respect, the cultural conditions concerning the energy transition have as yet been studied very little compared to the technological conditions. Yet they are of great importance when it comes to understanding innovation in energy efficiency. In addition, change processes must be analysed in the interaction between different levels of government—in our case, in particular, at the national and municipal level. In the course of developing suitable strategies for the energy transition, potential problem shifts must also be taken into account. In light of the close link between energy and resource issues, it is important to conduct an integrated assessment of the resource impacts of the energy transition from its earliest stages.

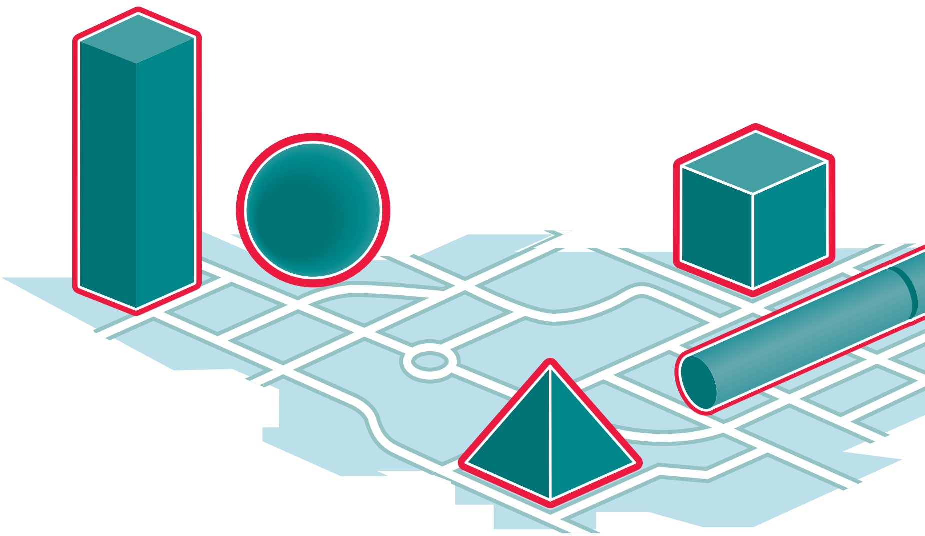
Since research into transformation should not be based on research into transformation processes alone, but should identify specific options for action and initiate change in practice, it is essential to link (inter)disciplinary model-based knowledge (knowledge about the system) with empirically and/or experimentally gained transformation knowledge (knowledge for designing the system) in a transdisciplinary research process. Sustainability-oriented transformation and transition research addresses these fundamental challenges[1].

The underlying basic concepts of this research area are presented in Chapter 2. Building on this, Chapter 3 outlines fundamental methodological approaches towards exploring transformation processes along the 'transition cycle', which describes the ideal-typical phases of transformation processes and shows how relevant system, target and transformation knowledge can be generated. Chapter 4 provides an overview of the specific application of transformation research within the EnerTransRuhr project. Using the example of this project, the chapter shows what an integrated research design in the field of transformation and transformative research might look like, and which specific challenges are most relevant. It demonstrates the possibilities of how knowledge of the different contextual and methodological approaches can be integrated. The possibilities and limitations of modelling as a place of integration are discussed on the basis of the project. The book closes in Chapter 5 with a number of conclusions and thoughts about the further development and application of transformative research designs.

1 For an overview, refer to Markard et al. 2012; van den Bergh et al. 2011; Göpel 2016.

2

Basic concepts of research into transformation



The progression of environmental risks and climate change[2] clearly show that minor reforms are of no use. On the contrary, according to the German Advisory Council on Global Change (WBGU), a 'Great Transformation' (WBGU 2011) is required in order to embark upon a path towards sustainable development. The special challenge involved here is to shape the ongoing and constantly accelerating transformation process of the economy, society and the environment so that it is steered in a sustainable direction. In recent years, several key terms and concepts have evolved that help us the understand such comprehensive socio-technical transformation processes. These terms and concepts will be described in greater detail below.

2.1 System innovations and human-environment systems

Cities and neighbourhoods are what is known as 'human-environment systems' (Scholz 2011). Within these systems, infrastructure, technological systems and human activities act on and interact with ecological systems with considerable repercussions and feedback. Innovations are required to change such systems to give them a positive ecological impact. Purely technological innovations rarely suffice to achieve this goal. In fact, there needs to be what is referred to as 'system innovations', i.e. a combination of technological, social and institutional innovations.

One look at the diversity of these challenges and issues is enough to show that a purely technological understanding of innovation is not sufficient. Today, the central bottleneck is often no longer caused by a lack of technological innovations. Instead, the search for new business models, funding schemes and organisation models, for intelligent forms of cooperation between partners from different fields, and for suitable means of political participation prove to be much more important. Nowadays, sustainability solutions call for system innovations in which technical, economic and institutional elements are closely interwoven so as to pave the

2 See, for example, Rockström et al. 2009; IPCC 2014.

way for the transition from existing orders of the system to a more sustainable development path (Schneidewind 2011).

The term 'system innovation' describes fundamental changes that go far beyond technological innovations and change whole socio-technical systems or human-environment systems in terms of their institutions, values, organisational structures and infrastructures. In this respect, system innovations refer to whole societal subsystems that fulfil fundamental basic functions such as the supply of energy, mobility, food and housing. It involves describing the combination of technological and social innovations and their embeddedness in social structures and infrastructures. Related to this, it is important to understand that it is more than superficial interaction or a loose combination of new technologies and altered behaviour patterns. How, then, can a system innovation be defined? Reflecting the work of researchers such as Abernathy and Clark (1985), Christensen (1997) and Utterback (1994), Geels (2004, p. 19 f.) describes three aspects of a system innovation.

The starting point is initially a technological innovation that replaces an established technology or acts as its substitute. The second step involves co-evolutionary processes: the new technology interacts with its social environment. This then leads to social and institutional innovations, such as changes in use patterns, new business models, changed market and industrial structures and new policy instruments. These co-evolutionary processes result in the third (crucial) aspect of a system innovation, which is the emergence of a 'new functionality' of the relevant socio-technical system as a whole. In other words, although the system concerned continues to fulfil its original function, it does so in a qualitatively and often radically different way. There is thus more to it than new technologies or optimised contexts of application and adapted system configurations—a system innovation involves fundamental shifts in meaning (for example, from car traffic to mobility) and the application of new quality criteria to a system and its functioning (such as the energy efficiency standard as a criterion for the quality of a building). A system innovation therefore means a real paradigm shift that leads to a fundamentally new system architecture via altered functioning logics.

In sustainability-oriented system innovation research, the emphasis is on altered system configurations and new functionalities such that induce positive social-ecological effects. The central potential of system innovations for sustainable development lies in the processes of socio-technical co-evolution: technological innovations as well as individual institutional, policy or civil society initiatives may all provide a decisive impetus for change. Since these initiatives always interact with other elements of a socio-technical system, the possibility exists that dynamics and processes relate to each other and mutually reinforce each other. Particularly in cities and individual neighbourhoods, such interactions become possible due to spatial densification: cities and neighbourhoods can also be defined as socio-technical human-environment systems that are characterised by interaction between topographic and technical (infra)structures and the actions of stakeholders. For this reason, the energy transition in buildings is, of course, faced with the challenge of having to develop complex solutions in the sense of system innovations—and yet, in positive terms, this provides the opportunity for the mutually reinforcing positive effects and dynamic interactions of a system innovation process. In this respect, both technological innovations and social catalysts for change can be enablers of comprehensive change. In order to achieve robust change processes, it is above all important to take into account the tacit knowledge of those people affected and involved locally. The actual implementation of a system innovation can only succeed if it is accepted and propagated by the relevant users. For science, this means that research geared to a sustainable transformation must take into account not only the knowledge of the different academic disciplines, but also the practical knowledge and experience of non-academic partners.

2.2 Transformation research and transformative research

As the WBGU has noted, research plays a central role in the implementation of transformation processes: 'The transformation is a societal search process that should be supported by experts. In collaboration with politics, the economy, and society, research and education are tasked with developing visions for a low-carbon society, exploring different development paths, and developing sustainable technological and social innovations' (WBGU 2011, p. 21). In the WBGU report, a differentiation is made between transformation research and transformative research:

In *transformation research*, the emphasis is on exploring transition processes in order to investigate the factors and relations in transformation processes, and to critically reflect on them. 'One particular challenge for transformation research is the interaction of social, natural and engineering sciences in order to understand the interaction between society, the Earth system, and technological development' (WBGU 2011, p. 22).

In research, different disciplinary approaches play a role in representing the different dimensions of a comprehensive societal transition. Transition has a technological dimension in many areas, particularly in the energy transition: here, questions arise as to whether and how the restructuring of a system is possible and which individual technologies are needed in the process. This quickly leads to pressing issues from the economic side: how can the transformation be financed, and which economic and market mechanisms are needed? In the case of the energy transition, the Renewable Energy Sources Act (EEG) and feed-in payments were developed, for example; financial incentives, such as subsidy programmes and tax relief, also play an important role in the building sector. This dimension is closely linked to the institutional dimension, the political framework and issues concerning the regulation and management of transformation processes. Besides creating financial incentives, policies can also make use of many other instruments. In the area of the energy transition in buildings, these range from classic control mechanisms, such as urban land use planning, to the provision of information. Finally, the energy transition is a

Figure 1: **Transformative literacy**

good example of the fact that a cultural dimension is also essential for the understanding of contemporary transformation challenges—even if they appear 'minor' at first sight. Without a change in both individual and societal handling of the topic of energy and how we use it, the transformation will not be achieved.

The aim of transformation research, as outlined and called for by the WBGU, is to gain an integrated perspective of all these dimensions that are relevant to transformation processes. Such a perspective can also be described as an ability, referred to as 'transformative literacy' (see Figure 1, Schneidewind 2013a; b) that modern science and society should gain in order to be able to adequately meet the current challenges. In this respect, transformative literacy should also empower stakeholders to act. Completely new challenges and tasks come into being here for science, which the WBGU describes under the term 'transformative research'.

Transformative research is 'research that actively advances the transformation. Transformative research supports transformation processes with specific innovations in the relevant sectors. ... Transformative research therefore encompasses a spectrum that reaches from purely discipline-based to system-based research' (WBGU 2011, p. 22). Here, the WBGU makes it clear that transformative research 'include[s] economic and social diffusion processes and the possibility of their acceleration, and demands, at least in part, a systemic perspective and inter- and cross-disciplinary methods, including stakeholder participation' (WBGU 2011, p. 343).

By differentiating between transformation and transformative research, the WBGU takes up the idea of transdisciplinary approaches, elaborated 20 years ago, which is explained in further detail below.

2.3 Transdisciplinarity: how does socially robust knowledge for transformation processes emerge?

Transdisciplinarity is a key concept in the exploration of transformation processes, and describes a new form of knowledge production (as compared with classic science and basic research), which is oriented to social problems and which searches for solutions and acts as a catalyst for real change by drawing on the different discipline-based knowledge bases and the practical experience and knowledge of various non-academic stakeholder groups. This new form of knowledge production is especially necessary where complex, life-world problems are involved—such as the energy transition (in buildings), with its typically multi-level technological, economic, institutional and cultural dimensions. The basic idea of a transdisciplinary approach is that a solution for these complex problems initially consists of identifying the scale of the complexity of the problem in the first place—namely in the interaction between the different scientific and practical dimensions of the problem and the various perceptions of the problem from different perspectives. In the second step, the different knowledge that may contribute towards finding a solution (abstract, case-specific, scientific, as well as practical and experience-based) must then be considered in an integrated manner and translated into specific strategies and practices that contribute to a 'good', sustainable solution (Pohl & Hirsch Hadorn 2007, p. 20). In this respect, transdisciplinary approaches are not to be understood as an alternative or a counter-programme to 'normal' science and research, but as a science-based approach to the solution of 'non-scientific', i.e. real-world problems. As succinctly summed up by Scholz, it is about 'disciplined interdisciplinarity in transdisciplinary processes' (Scholz 2011, XVII). Disciplinary knowledge bases are to feed into interdisciplinary exchange and the whole thing should then be embedded in a transdisciplinary process that also includes non-academic perspectives.

Socially robust knowledge is to be generated in this process. This is a kind of knowledge that is not only expandable in academic discourse, but that also provides guidance to the stakeholders involved in transformation processes. Three fundamental characteristics of socially robust knowledge are decisive to achieve this. First, in this context, 'robust' means 'valid', i.e. it must be valid and reliable knowledge. However, this type of validity cannot be tested in the lab or under controlled conditions; it is about the real-world conditions that must withstand the influences of policy, the economy and culture, and their interactions within a social context. Second, socially robust knowledge mainly arises where an extended group of academics and expert ordinary citizens are involved so that different forms of knowledge can be linked to each other, such as classic scientific knowledge, practical experience and other technical expertise. Third, socially robust knowledge is also characterised by the fact that it is repeatedly tested, expanded and modified in a recursive process—and is not created in a linear process by scientific experts, as in the classic understanding of science, and passed on to laypersons to be put into practice (Nowotny 2003, p. 155; Nowotny et al. 2001). Here, too, it is not a matter of abolishing 'normal' science and replacing it with something else, but of new connections and the embeddedness of science in society from an enlightened perspective of responsibility of science towards society as a whole. Socially robust knowledge is also a science-based concept and remains academically expandable, in the specific isolated case, namely through case-specific discipline-based references and methodological standards in knowledge production. At the same time, however, it is necessary that society has the ability to adopt this knowledge; socially robust knowledge also contributes to solving real-world existing problems in practice and offers orientation. Here, 'orientation' should be understood in normative terms, in the sense of ensuring to the greatest extent possible that sustainable development goes in the ‘right’ direction, for example in the development of technological innovations and their often undesirable secondary effects (for example, in the case of nuclear power or genetically modified food). It therefore becomes clear that socially robust knowledge is not knowledge that ‘functions’ practically or is economically exploitable. Socially robust knowledge should rather contribute towards greater capacity for reflection in science and in society in general by helping to establish clarity on the (unintended) consequences of technologies, products or policy instruments more easily and quickly. As a result, reflexivity becomes a key factor in transformation and transformative research, because it is only possible to deal adequately with complex sustainability challenges by ensuring recursive learning processes in academia and society.

The inclusion of practitioner actors in knowledge production called for here has been debated recently under the terms ‘co-design’ and ‘co-production’ (Cornell et al. 2013; Mauser et al. 2013). In the global research programme ‘Future Earth’, these principles of transdisciplinary knowledge production are being drawn on and further developed in a bid to meet global sustainability challenges. Scientists and practitioner actors should therefore ideally work together in the co-design and co-production of knowledge, while taking on different roles and responsibilities. Defining research questions and developing research programmes should be done jointly by academic and non-academic stakeholders, just as the preparation and dissemination of the results should be undertaken jointly, while researchers are responsible for the actual research, the scientific methodologies and knowledge production (co-design). In a more enhanced variant, practice partners would also be directly and proactively involved in this process of knowledge generation (co-production) (Future Earth 2013, p. 21 ff.).

2.4 Knowledge integration and the role of boundary objects

The great challenge of transdisciplinary approaches therefore lies in *knowledge integration*: how can the various findings from different academic disciplines and from practice be connected to each other, contributing to the solution of a multi-dimensional, complex problem? This general issue of sustainability and transformation research is also at the core of the EnerTransRuhr project, and was examined in detail by means of innovative project designs and the integration of methods for the example of the energy transition in buildings (see Chapter 3).

In (ideal-typical) transdisciplinary research processes, knowledge integration takes place at various places and at different points in time. First of all, there must be an understanding of the actual problem to be considered and resolved. The perception of the actual core of the problem generally differs, depending on the perspective of the researchers in different disciplines, and varies in particular among researchers and the practitioner stakeholders concerned. The example of the energy transition in buildings also shows that the perspectives of social scientists, natural scientists, engineers, the municipality, landlords, homeowners and residents differ markedly in some cases. If a common understanding is achieved within a specific research project and the participants manage to develop a description of the problem that is shared by all those involved, then the next stage must involve integrating the discipline-based scientific knowledge with other knowledge as a response to secondary questions in the research project. The final step involves integrating the knowledge with regard to the specific results and their practical implementation (Bergmann et al. 2010; Jahn 2008).

'Boundary objects' (Star & Griesemer 1989) may serve as an important communication device for knowledge integration. Boundary objects are objects 'that enable different actors and disciplines to refer to a common point for the coordination of their knowledge bases' (Schneidewind & Scheck 2013, p. 240). This can either be a specific, physical point of reference, such as a city or a neighbourhood with a joint emission reduction target, or a more abstract object, such as a joint narrative that links different perspectives in a simple story. A scientific model or a jointly developed scenario can also serve as boundary objects that bring together these different perspectives. In the EnerTransRuhr project, agent-based models were developed for this purpose into which the results of the different scientific investigations were incorporated with the aim of creating a joint (model) language and developing models as a joint point of reference (for more information, see Chapter 4). For an overview of other methodologies and tools concerning knowledge integration, see Bergmann et al. 2010.

In addition to the models as instrumental and rather abstract boundary objects, the cities and neighbourhoods that participated as the area of examination and experimentation were the spatial boundary objects in the EnerTransRuhr project. The cities of Oberhausen, Dortmund and Bottrop from the Ruhr Area participated in the project as practice partners. The project focused on the inner city neighbourhoods of Alt-Oberhausen and Lirich, Dortmund-Hörde and the project area of the InnovationCity Ruhr in the model city of Bottrop[3]. As the integrative moment, these locales are where diverse approaches come together in the form of activities and processes at different levels, with joint or divergent convictions and, ultimately, with different methodological and thematic approaches in the project context. They help to bring together complex conditions, processes or individual actors. Thanks to the specific spatial reference, it was possible to relate the different substantive and methodological approaches of the projects to each other. The specific localisation clearly brought to light the wealth of activities and the complexity of processes at different levels (in this case, with regard to the energy refurbishment of buildings) and their interactions with the different relevant actors (from homeowners to tenants, from the municipality to politically engaged citizens) which, in turn, incorporate various mentalities and motivations.

3 For more information about the model city of Bottrop, see http://www.icruhr.de/index.php?id=3

The neighbourhood as a boundary object

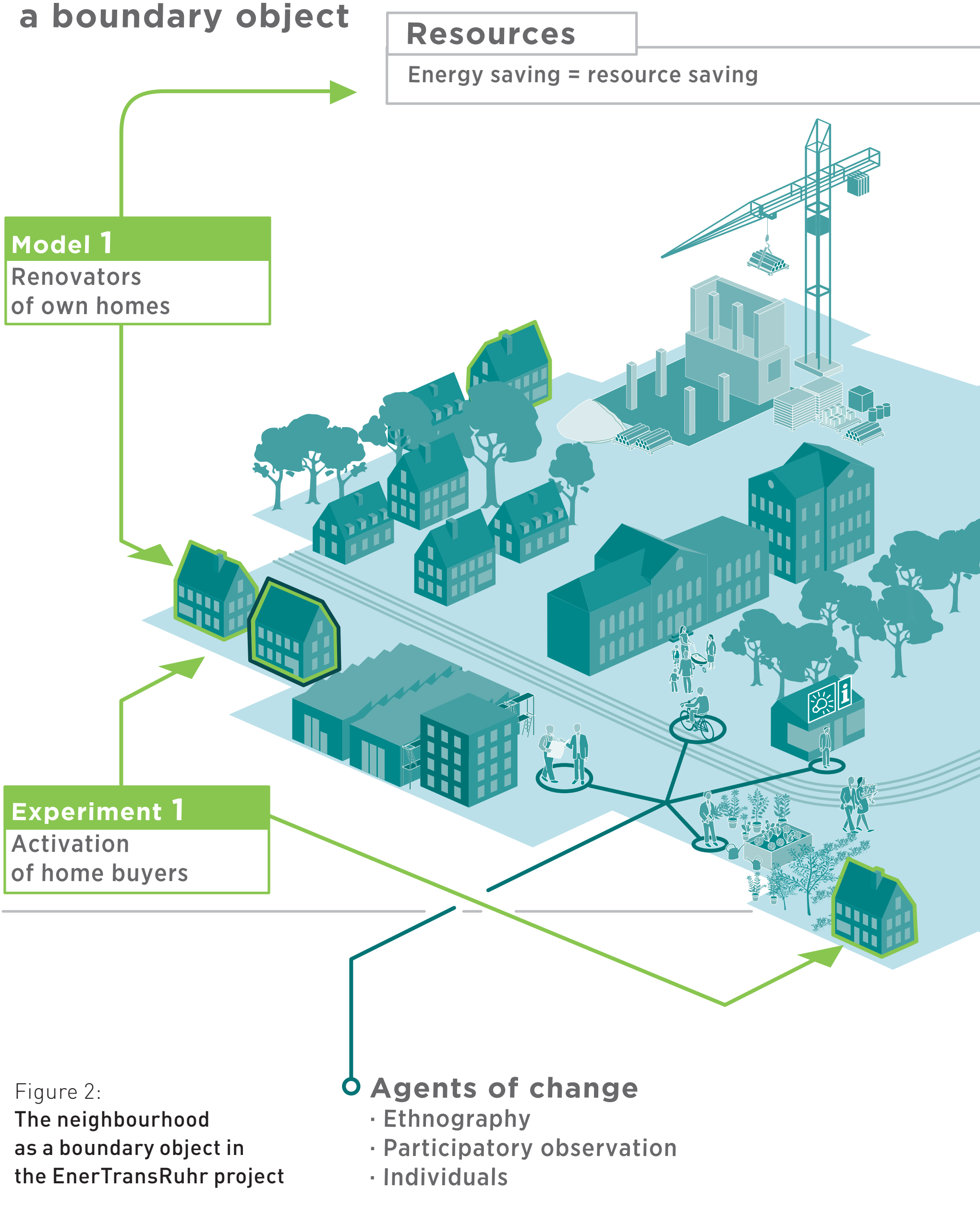
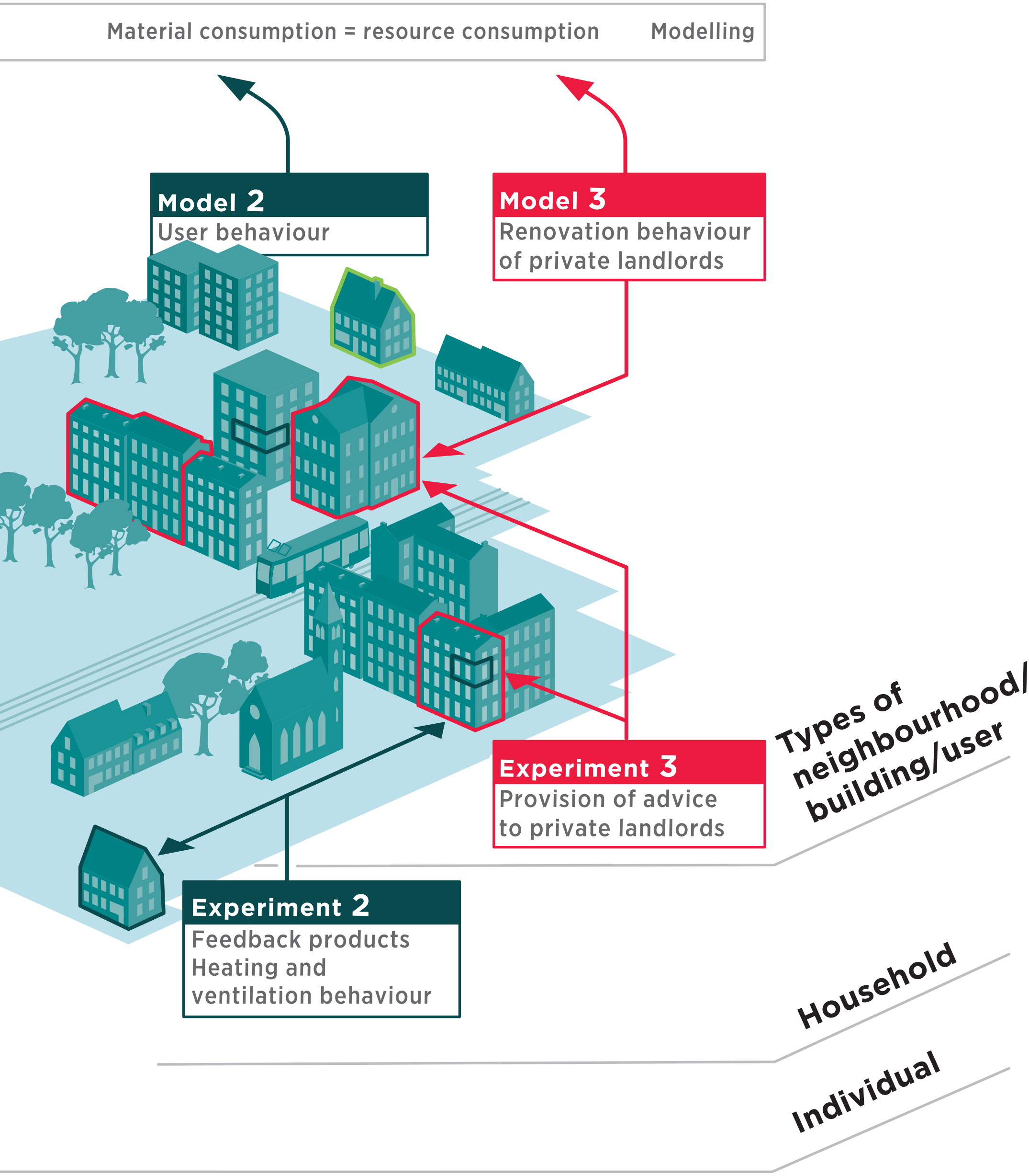


Figure 2:
The neighbourhood as a boundary object in the EnerTransRuhr project


Material consumption = resource consumption
Modelling
Model 2
User behaviour
Model 3
Renovation behaviour
of private landlords
Experiment 3
Provision of advice
to private landlords
Experiment 2
Feedback products
Heating and
ventilation behaviour
Types of
neighbourhood/
building/user
Household
Individual

2.5 Forms of knowledge and research approaches along the transition cycle

How, then, can research for a transition to a more sustainable system be successfully implemented in specific research projects, such as in the area of the energy transition in buildings?

For initial orientation and structuring purposes, it is important to differentiate between three forms of knowledge: system knowledge, target knowledge and transformation knowledge. In this respect, system knowledge refers to the basic understanding of a problem area, the relevant facts for evaluating the circumstances and the causal relationships in human-environment systems. Target knowledge describes the future understanding of desirable system conditions from a sustainability perspective and an assessment of room for manoeuvre and opportunities for action. In order to bridge the gap between the current state of a system and the intended future vision, transformation knowledge of the specific means and ways of how to achieve the developed vision, based on a current understanding of the problem, is required as a third aspect (Jahn 2008, p. 26).

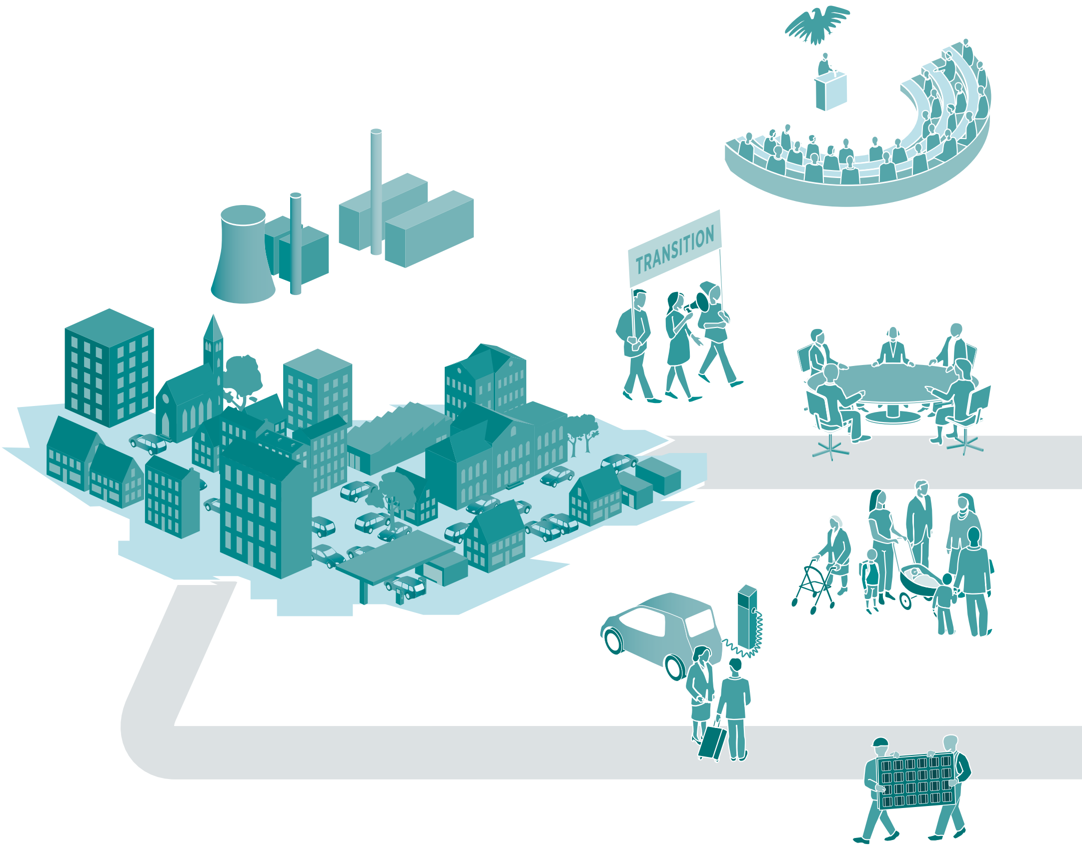
How, then, can these three forms of knowledge and their interaction in the research process be taken into account? It is useful here to take what is referred to as the 'transition cycle' as a point of departure. The transition cycle describes the typical course of transformation processes and the associated forms of knowledge (cf. Wuppertal Institute 2011; with reference to Loorbach 2007 and 2010). The transition cycle describes four phases of a transformation and is therefore a model that illustrates the relevant elements in the practical steering as well as in the academic guidance of transformation processes:

The first phases involves *problem analysis*, based on the systematic structuring and framing of a specific societal problem. During this phase, system knowledge is initially generated as a starting point for the rest of the process. Integrated problem analysis enables all of the researchers and practitioner actors involved to gain a common understanding of the problem, which means they can then identify the possibilities and levers for a change process, as well as the central challenges and the role played by the different actors.

On the basis of such a comprehensive understanding of the problem, the next step that should occur is a *vision development*, meaning that as many of the relevant actors as possible should agree on desirable futures and on the appropriate concepts and strategies for carrying them out. These two steps can be found in the many guiding principles, concepts and studies on sustainable development. The visions of the future may differ greatly, from traditional quantitative and/or qualitative scenarios to multidimensional transformation paths or a transformation agenda negotiated at a transdisciplinary level. In light of this, it is always presumed that vision development represents a common and reflective learning and search process. Since most sustainability challenges are complex, multidimensional problems requiring long-term change, it is virtually impossible to set a precise road map and schedules in advance. The aim of vision development is to define substantive targets and to ensure to the greatest extent possible that development proceeds in the 'right' direction. Although specific technologies, policy instruments and courses of action are by all means to be included in the vision, there is always the need to allow for flexible adaptations to changing conditions and new insights. This, therefore, involves the development of target knowledge, which includes normative value judgments as well as, in particular, the knowledge and wishes of the actors shaping the process.

In order to proceed to the actual implementation of the transformation process, and hence to the generation of specific transformation knowledge, the concept of the transition cycle provides for two further steps: solution strategies should be tested in the form of specific *experiments*. Whereas system analysis assumes a controllable degree of complexity and hence an ability to model the process, reality usually proves to be much more complex. For this reason, there needs to be an 'experimental turn' in transformation research, i.e. a shift towards approaches that enable learning about system behaviour in transformation processes by means of guided or actively catalysed experiments in real laboratories. This takes place on the basis of the aforementioned visions and guiding

Forms of knowledge in transformation research



Describing the system

Understanding complex socio-technical systems as embedded in their environment

Understanding transitions

Understanding and shaping the complexity of social transitions

Figure 3:
Research for transformation requires interaction between system knowledge, target knowledge and transformation knowledge

Transitions to where?

Integrative understanding of an ecological and fair society worth living in

principles; technological innovations, strategies and action concepts are tested as closely to practical reality as possible, involving the relevant actors. As a result, this phase is a central element of the transition cycle and in transformation processes as a whole. For this reason, Section 3.3 provides detailed information about the design of such real-world experiments, including in the area of the energy transition in buildings, and about which principles should be used to plan and implement them.

The experience gained in such specific experiments contribute to *learning and diffusion processes* and help researchers to develop transferable solutions and strategies. Following an up-scaling process, they find their way to the mainstream, helping to find a solution to the problems identified earlier. To effectively disseminate such solutions, the knowledge gained from modelling and experiments must be translated into design heuristics. This involves identifying typical patterns that are promising in a transformation process and that can be transferred to other cases. These can, then, by all means be specific policy instruments or designs of products and services.

The sequence of phases within the transition cycle may vary; for example, conclusions gained from experiments may also lead to visions being adapted. In principle, it is an ideal-typical model that primarily indicates that complex transformation processes take place in recursive learning loops in which experiments play a crucial role (learning-by-doing and doing-by-learning, see Rotmans & Loorbach 2010). Therefore, the transition cycle is a concept that enables transformation research to be linked to transformative research, that focuses on the principles of transdisciplinarity, and that aims to generate socially robust knowledge. As a concept ideal for practical research and a blueprint for research designs, the transition cycle aims to take into account all three forms of knowledge.

The transition cycle also creates a frame of reference for the example of the energy transition in buildings discussed here in order to link together the system knowledge required for this complex transformation challenge (via technical system options, but also social and cultural systems descriptions), target knowledge (for example, via policy objectives in the context of the energy transition) and transformation knowledge (involving the

Figure 4: **The transition cycle (source: based on Loorbach 2010, p. 173)**

knowledge bases of specific actors). For this reason, the various methodological approaches that play a role in the EnerTransRuhr project will be described in further detail below along the phases of the transition cycle and the relevant forms of knowledge in each case.

Problem analysis: generating system knowledge

As described, the generation of system knowledge as a starting point of both transformation and transformative research is about generating factual knowledge of the causal relationships in socio-technical human-environment systems and their interactions. In recent decades, all kinds of techno-economic analysis models have been developed and applied for use in the energy and climate sector to describe the energy transition at different system levels. They either use a bottom-up, top-down or mixed approach. For this reason, they are either target-oriented or technology-ori-

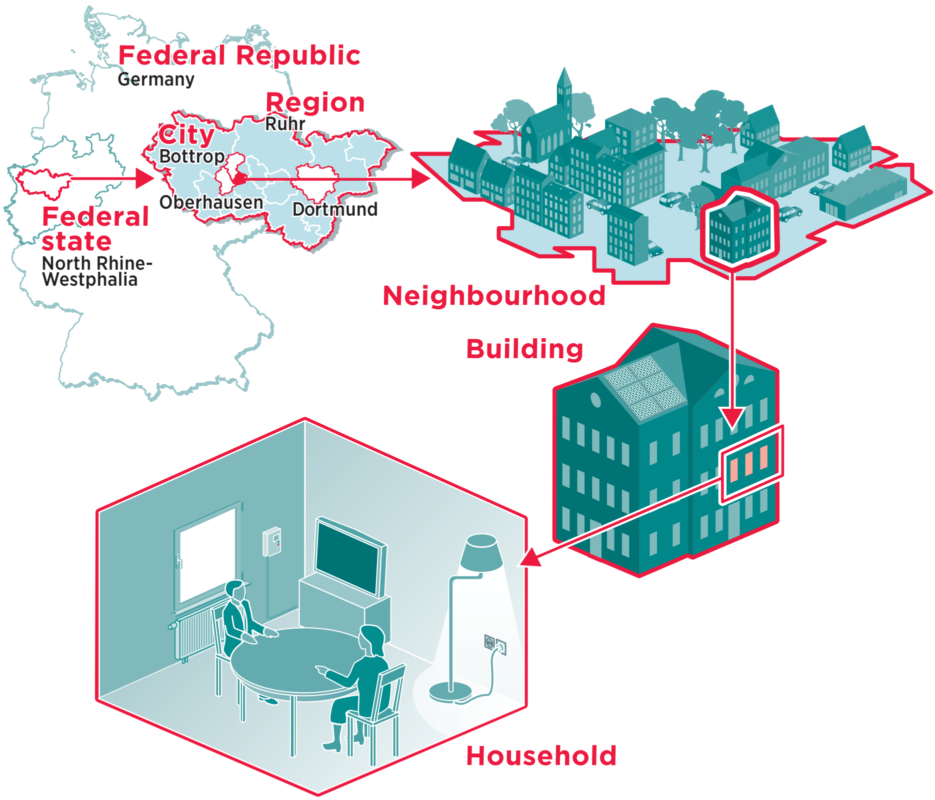


Figure 5: **The energy transition in buildings in the multi-level system**

ented, and are usually created statically, with the exception of electricity generation models (Möst & Fichtner 2009, p. 18). In the case of human-environment systems, however, it is essential to represent actors' behaviour to the greatest extent possible in addition to infrastructures and technologies. The most general way to represent actors' behaviour is to use economic models involving rational behavioural assumptions and market mechanisms. However, the specific fleshing out of the energy transition is influenced by very different stakeholder groups and motivations, which can only be described by economic models with limited success. In reality, social behaviour is often more complex, as demonstrated by the overview of the current challenges in the area of the energy transition in buildings (see Chapter 3).

In the area of residential buildings focusing on the 'heating transition' in the building sector, the socio-technical human-environment system has multiple components: first of all, there are the actual buildings with their components in a more or less decent condition. Then there are the owners who decide, for a variety of reasons, whether to carry out energy refurbishment measures for their building or not. In this respect, landlords can be private individuals or companies, which have very different prerequisites—in terms of personnel and financial resources—for implementing measures. And, finally, there are people living in the building whose behaviour also has a major impact on the actual energy consumption. These residents may be the owners of the building themselves, or they may be households residing there on a rental basis.

These buildings, and the people associated with them, are surrounded by political frameworks and services offered to guide and influence the process of energy refurbishment, such as energy consulting, planning, support and the skilled-trade sector.

Vision development: target knowledge for a sustainable future

Based on a survey of the current situation and its complex systemic interrelationships, the second step involves the normatively motivated, but scientifically processed, development of substantiated visions. Target knowledge of future desirable system conditions, such as in the area of the energy transition in buildings, can be generated in various ways.

In the context of transition research, *scenario analysis* is an important tool for identifying potential future developments, which is followed by an analysis and an assessment. Scenario analysis enables several potential futures to be substantively identified, rather than the prediction of a single probable development. As such, it is a tool for scientific justification in order to define target values for aspects of sustainable development along the lines of the visions in the transition cycle. This applies, for example, with regard to socio-technical innovations and underlying fields of activity (e.g. in the area of energy supply or the demand area of housing). In addition, scenarios are used to obtain a reliable assessment of the future effects of innovative or more developed policy instruments and product-service systems. Other fields of application include analyses of the future need for resources, energy and space.

With regard to the heating transition in the building sector, the targets specified by the German federal government set the direction. In a bid to achieve climate protection and energy transition targets, the German federal government pays considerable attention to the energy refurbishment of buildings, i.e. the installation of thermal insulation and the modernisation of outdated heating systems. According to the energy concept published in 2010 by the Federal Ministry for Economic Affairs and Energy (BMWi), in cooperation with the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), by 2020, the energy requirements for heating should be reduced by 20 per cent compared to 2008 levels (BMWi & BMUB 2010). All buildings should be nearly climate-neutral by the middle of the century. Climate-neutral means that buildings may then only have very low energy needs, and that the remaining energy demand must be covered primarily by renewable energies. Compared to 2008, the energy demand must be reduced by an order of magnitude of 80 per cent. Once this has been achieved, the building sector will make an important contribution to the central goal of cutting all greenhouse gas emissions in Germany by 80 to 95 per cent by 2050 compared to the base year of 1990.

However, it is not clear to what extent such purely quantitative target scenarios will affect the actions of urban-dwelling actors in their decisions such as whether to carry out efficiency measures in the building sector or not. Will these quantitative targets suffice or will they have to be supplemented by a shared qualitative exemplar at the urban or federal state level in order to change the actors' decision behaviour? What requirements must be imposed on such exemplars to be effective? These are important issues in the context of actor-oriented transformation research. Examples of successful 100 per cent renewable energy regions (Ökologisches Wirtschaften 2011) or from the Transition Town movement (Hopkins 2011) are an indicator that shared targets—including of a qualitative nature—can have an impact on actors' behaviour. The connection of abstract quantitative reduction targets to positive visions of future life appear to be particularly important in this case. Such exemplars closely link the technological level of transformation to economic, social and, in particular, cultural dimensions. They often emerge in close participation with key actors from the region or city.

Experiments and diffusion: generating transformation knowledge and learning in real laboratories

Based on an analysis of the challenges of the energy transition in the building sector and with regard to the goals to be achieved, the third—main—step involves generating transformation knowledge that facilitates an actual change process, using specific strategies for action and policy instruments as well as technological and social innovations.

In this respect, the generation of transformation knowledge requires the use of experiments, because human-environment systems are complex systems. In contrast to a complicated system, complex systems cannot be steered according to a causal 'if-then' logic, even if extensive knowledge exists on the different system components. They are marked by a high degree of dynamics, a wide range of interactions within the system, and changing basic conditions. In this way, policy instruments, for example, often fail to achieve the desired effect, or technological innovations are developed that go on to produce unintended consequences. For this reason, it is necessary to have an intermediate step that bridges the discrepancy arising here between problem or system analysis and the target vision:

'For the most part, complex learning processes and comprehensive innovations are not initiated based on the quality of the various crisis diagnoses and cause analyses, but only through the establishment of convincing new orientation offers and action concepts (Wiesenthal, 1995), and the opening up of experimental platforms which allow the familiar to be rearranged into something new (Johnson, 2010)' (WBGU 2011, p. 256).

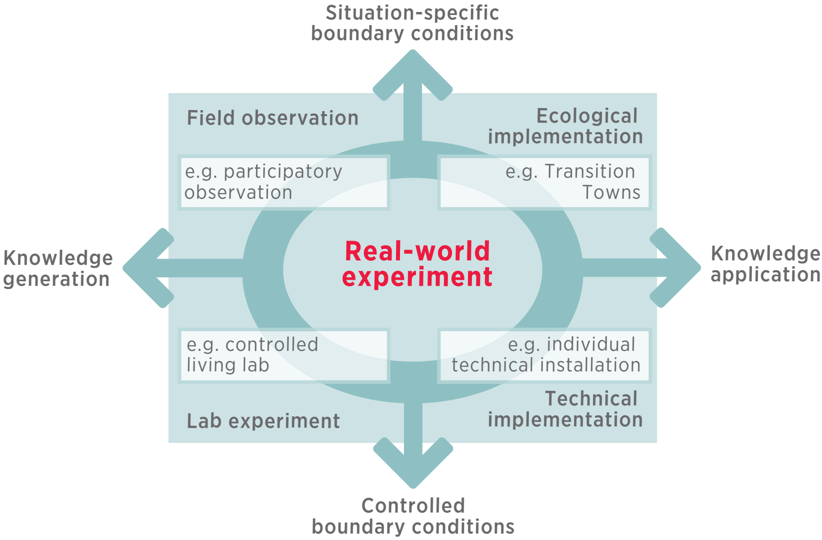


Figure 6: **Classification of real-world experiments in the typology of experimentation (Schneidewind & Scheck 2013, p. 241, based on Groß et al. 2005, p. 19)**

Experimentation with and trying out potential solution options requires a high degree of reflexivity. Since it is virtually impossible in many cases to assess the effects of technological, social or institutional innovations in advance, experimentation with these effects must also be repeatedly verified to determine whether they do in fact help resolve a problem, which unexpected and unintended dynamics emerge, and how lessons can be learned from previous experience.

Consequently, transformation and transformative research also gives research itself a new role if it becomes actively involved in change processes along the lines of an experimental turn. This takes place via established methodological approaches, such as intervention or action research. A new concept that has emerged primarily in the context of sustainability-oriented transformation research is the real-world experiment or research in real-world laboratories. These are research contexts in which researchers from different disciplines and practice partners work together to solve specific problems in the spirit of the co-design and co-production of knowledge. In the process, research not only contributes its discipline-based specialist knowledge, but can also provide infrastructures for experiments and ensure reflexivity in the process along the lines of extended scientific guidance (Schneidewind et al. 2016; Wagner & Grunwald 2015; de Flander et al. 2014).

As understood in the context of sustainability-oriented transformation research, real-world experiments can be designed in very different ways. They may include and address different target groups; they may differ from each other with regard to content and topics; and they may refer to a very specific or a more diffuse geographical area. In the typology of experimentation, Groß et al. (2005) differentiate between whether experiments have been conducted under controlled conditions or in a situation-specific manner and whether they serve the purpose of generating knowledge or applying it (cf. Groß et al. 2005, p. 19).

Using the processes of co-design and co-production, the academic insights gained from problem and system analysis are combined with the expertise of relevant local actors and their know-how. The goal is to develop a design for the experiment that is able to address the previously identified problem[4]. The process finally results in an intervention, a quasi-experiment or a field experiment supported by researchers. The support provided to the experiment can be of an observatory nature, or of an organisational or executory nature. In an experimental process understood in this way, the role of science is therefore an active one in which it is neither possible nor desirable to draw a strict boundary line between the system and the observer[5].

The concept of real-world experiments in sustainability-oriented transformation research is embedded in contextual normativity. Despite differing with regard to the process, target group and topic, it is ultimately always about the same overarching question: to what extent does inter-

4 With regard to criteria for real-world laboratories, see MWK Baden-Württemberg 2013: p. 30.
5 Concerning this, compare also Schneidewind 2014, p. 2.

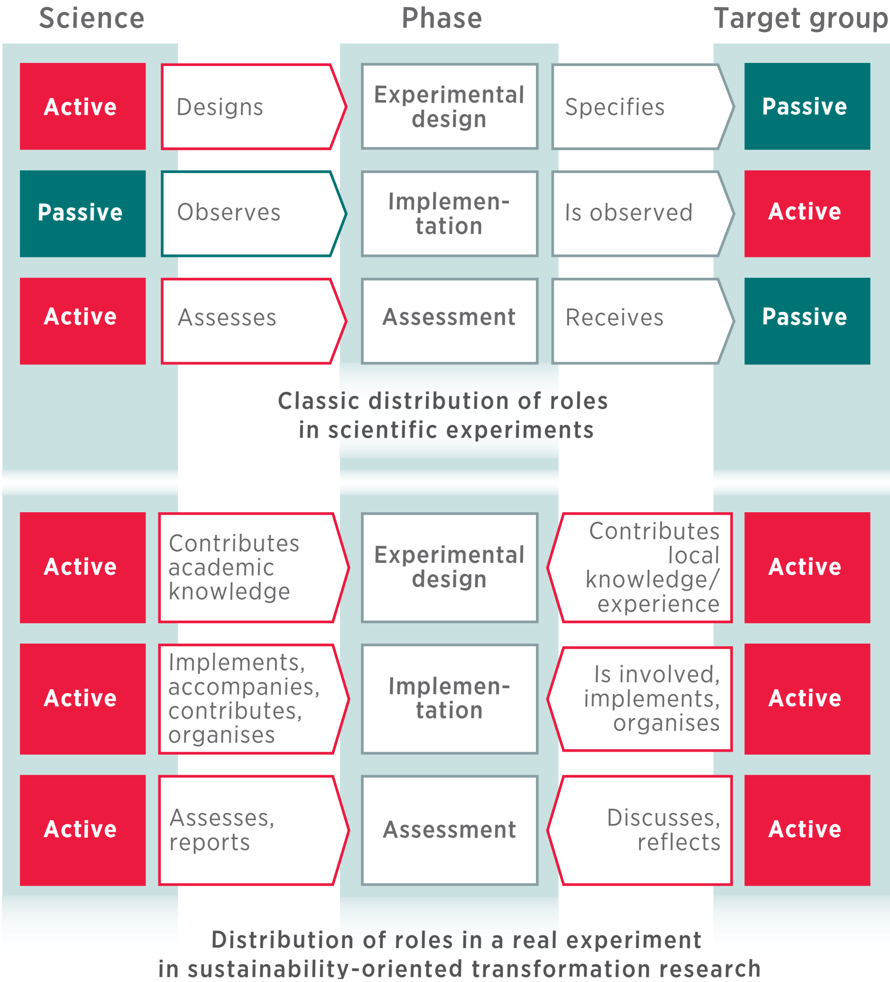


Figure 7: **The role of research in classic and real-world experiments**

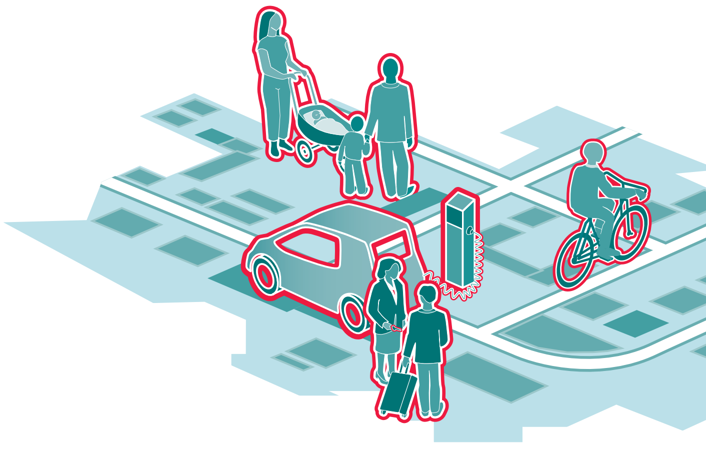
vention in the experiment contribute to a sustainability-oriented transition process?

For this reason, cities and neighbourhoods are ideal as settings for real-world experiments, because the different components of human-environment systems, different areas of need and stakeholder groups actively come together here, meaning that 'developments in society as a whole can be more or less observed in the test tube and findings upscaled to higher levels' (Schneidewind & Scheck 2013, p. 242).

In sum, the aim is always to create socially robust knowledge in the context of a real-world problem and to learn from experiments, simultaneously creating knowledge that can be transferred to other contexts. Moreover, as the final phase of the transition cycle, the point of diffusing transformation knowledge is to translate it into policy instruments, which currently represent the main medium for accelerating the energy transition in buildings. The most recent refurbishment rates demonstrate the need for broader transformation knowledge, in addition to the established policy instruments, in order to successfully achieve the energy transition in buildings. The EnerTransRuhr project takes this as its starting point by combining innovative methods of knowledge integration in an integrated project design. The next chapter gives an overview of this by providing a selection of insights about the approaches adopted for the project and the resulting outcomes.

3

The city and the neighbourhood as boundary objects



Understanding of transformation processes necessitates new comprehensive concepts and methods. The transformation of neighbourhoods and buildings is an excellent field of application. In this chapter, this field therefore represents the thematic reference for presenting and discussing the specific application and shaping of a transformative research design for generating system knowledge, target knowledge and transformation knowledge. This takes place along the four steps described above: problem analysis, vision development, experiments and diffusion. During the first two phases, relevant system knowledge and target knowledge is generated, which in turn creates a scientific basis for the implementation phase involving experiments (interventions) and diffusion processes (models).

Three cities of the Ruhr Area—Oberhausen, Dortmund and Bottrop—served as practice partners and areas of investigation and experimentation in the EnerTransRuhr project. All of the surveys, analyses and experiments conducted within the project took place in these three cities. In terms of content, the investigation focused not only on the decision-making processes of different groups of real estate owners concerning energy refurbishment, but also on the heating and ventilation habits of individual households. The key activities and results generated in the project will be presented below as a specific example of how the concept of transformative science is used. Emphasis is placed on the synthesis of the results, which were generated at different levels (German federation, federal state, city, neighbourhood, household, individual) and using very different methodologies (both quantitative and qualitative) during the project. The common study areas enable the different findings to be aggregated into an overall picture. This way, it is possible to identify interfaces as well as the scope of the different methodologies.

3.1 System analysis using the example of energy refurbishment and energy savings in residential buildings

A system analysis on the topic of the energy transition in buildings is a comprehensive matter if the interaction between policy, structural conditions and possibilities, relevant actor groups and the people who have a stake in the individual building (ownership and use) are to be considered as a whole. It means analysing the interrelations between different policy and spatial levels, between different groups of persons, between individuals, and between different policy issues.

'Only' one part of the energy transition in the building sector is considered by focusing on the topic of the 'energy refurbishment of buildings'—one specific type of energy (heat) and just one of the many different types of buildings (residential buildings). Even then, there is no guarantee of completeness. Each of the areas and topics taken into consideration and analysed involve details and aspects that, taken together, would exceed the scope of this book. The aim of this section is to outline a system analysis based on the understanding of a transformative research design and to identify the key factors and dynamic interactions on the basis of a specific object of investigation (energy refurbishment of residential buildings). In this context, the following individual components of the overall system are described:

- Structural/technical refurbishment potential
- Economic/social refurbishment potential
- Energy saving potential
- Policy instruments
- Ownership structure
- Contexts: people in the city and the neighbourhood.

Structural/technical refurbishment potential

A technical system analysis must be undertaken to identify the structural/technical refurbishment potential. During such an analysis, the researcher considers existing infrastructures, technological solutions, their interdependencies, and the resulting ecological potential.

Taking such a perspective, the next section takes into consideration the existing building stock in Germany and the resulting energy refurbishment potential. The examination is based on the dena Building Report (dena 2015) and the findings generated by the Institut für Wohnen und Umwelt (Institute for Housing and Environment, IWU) with regard to the building typology in Germany (IWU 2010). In addition to containing key data on the energy performance of Germany's buildings, the dena Building Report also considers ownership and tenant structures as well as the framework conditions related to energy efficiency in buildings. The Building Report was first published in 2012, and is updated annually. A building typology enables the building stock to be classified in terms of energy efficiency with the aim of assessing them from an energy perspective and demonstrating typical modernisation options. The current version of the typology also takes into account residential buildings constructed post-2010, which were subject to the new requirements of the Energy Saving Ordinance (EnEV) that came into effect in autumn 2009 (low-energy houses as the standard) (IWU 2015).

Around 70 per cent of all buildings are detached and semi-detached houses. And yet their energy consumption makes up only around 40 per cent of the total energy consumption in the building sector because multiple dwellings and non-residential buildings have a much greater area per building. Around two-thirds of the current building stock were constructed without any requirement to take standards of energy efficiency into account. New buildings in Germany only became subject to minimum requirements concerning energy efficiency when the first Thermal Insulation Ordinance entered into force on 1 November 1977. It is thanks to technical progress and the setting of gradually tighter thermal insulation standards that newly constructed buildings now consume much less energy.

In fact, they consume less than a quarter of the energy required by buildings constructed pre-1978.

According to the most comprehensive survey on the energy performance of the building stock to date, undertaken by the Institut Wohnen und Umwelt, only a small proportion of detached and semi-detached houses in Germany have thermal insulation: whereas almost 80 per cent of all roofs or top floor ceilings are already insulated, only around 40 per cent of outer walls and floors/basement ceilings are insulated, respectively (IWU 2010). Large amounts of heat are unnecessarily lost in particular due to the low percentage of insulated outer walls.

The figures are even worse in the case of multiple dwellings: with this type of building, 70 per cent of roofs and top floor ceilings, 40 per cent of outer walls, and only 30 per cent of floors or basement ceilings are insulated. Double glazing is dominant in the entire building stock. Single glazing is very rare (around four per cent).

Gas is used as the primary energy source for producing heat in around half of all residential buildings in Germany. Approximately 30 per cent use heating oil. The remaining 20 per cent of residential buildings use district heating, biomass, coal or electricity for heating purposes (BMWi & BMUB 2010). A closer look at the distribution of heating systems in new residential buildings reveals that there will be a major shift in the share of energy carriers used for heating in the future: according to the German Association of Energy and Water Industries (BDEW), more than 20 per cent of heating systems are heat pumps, whereas heating oil makes up just less than one per cent (BDEW 2015).

From a structural perspective, therefore, the refurbishment potential in Germany is still far from having reached its full potential. However, there are limitations: listed buildings and façades worth preserving that may not be insulated from the outside. In such cases, the possibilities to undertake interior insulation are limited by structural/physical and design constraints. It is ultimately also a question of whether the residents can do without the area and space that would be lost following interior insulation. Area and space can also limit the possibilities in the case of exterior insulation. A basement ceiling can only be insulated if the room height permits it. Outer walls and ceilings that act as a thoroughfare must continue to have the necessary clearance height and width. There may also be problems if the insulation of an outer wall located at the property line protrudes onto the neighbouring property or into public space, such as onto the pavement. Many federal states have ruled that such an 'overstepping of boundaries' must be tolerated in the case of energy refurbishment if they cause little or no interference with the adjacent property. However, there are limits to the duty of tolerance. In 2011, Beuth University of Applied Sciences and the Institute for Energy and Environmental Research (ifeu) estimated that these technical and legal restrictions made up five per cent of the heating energy demand of the entire building stock in Germany. In the study's three scenarios, involving different rates and depths of refurbishment, the proportion of heat losses due to insulation restrictions will increase to between 17 and 28 per cent of the heating energy demand by 2050 (Beuth Hochschule, ifeu 2012, p. 141).

Economic/social refurbishment potential

That is all that needs to be said at present about the 'constructed' part of the human-environment system of residential buildings that can be refurbished. However, a purely technical system analysis is insufficient for gaining an understanding of the potential for transformation in the building sector. It must be complemented by social and economic aspects. In the building sector, decisions and considerations for or against energy-efficiency refurbishment measures can be differentiated according to ownership and use structures.

The majority of dwellings in Germany are not used by the owner, but are rented out for residential purposes. Thanks to the 2011 Census in Germany, comparatively up-to-date information can be provided on this matter (Statistische Ämter des Bundes und der Länder 2015). For Germany as a whole, almost 43 per cent of dwellings are used by the owner, and some 52 per cent are rented out. The remaining share of dwellings are either empty or are used as holiday apartments. If urban spaces are considered, this difference increases even further. In German cities, i.e. places with more than 100,000 inhabitants, 71 per cent of dwellings are rented out for residential purposes. Only 25 per cent of dwellings are used by the owner. The Ruhr Area, which served as the area of investigation for the project and was therefore the basis for preparing this book, had a relatively high home ownership rate for a conurbation, at 32 per cent. The proportion of rented dwellings is 64 per cent.

Approximately 80 per cent of owner-occupiers' residential units are detached and semi-detached houses, only 20 per cent are located in multiple dwellings. The opposite applies in the case of rented dwellings. Consequently, the energy refurbishment of the building stock is more or less equally in the hands of landlords and owner-occupiers. These two groups differ considerably in part in terms of their motivation to undertake energy refurbishment measures. There are also very different decision-making processes within these two groups. Municipal housing companies may pursue different considerations to those from the private sector, which in turn differ to those of private landlords. The question of 'Is it worth while?' is far more than a purely economic consideration. In addition to the theoretical potential of structural/physical and technological energy efficiency, therefore, there is also an individual, economically and socially driven refurbishment potential, which will be addressed in further detail below.

Still, what do we know about the factors that influence the decision-making process of home and apartment owners and that ultimately lead to the implementation of energy refurbishment measures? And how can the measures be reconciled with residents' behaviour so that efficiency potential also leads to absolute savings?

The decision-making process of owner-occupiers and landlords can be roughly divided into two main elements. First and foremost is an event that causes the owner to consider whether to undertake refurbishment measures. Subsequently, a decision is taken about the type and scope of the measures.

Owner-occupiers

In order to understand the action and transformation logic behind these decisions, one must take a closer look at the motivations of different stakeholder groups, in this case 'owner-occupiers', 'communities of owners', 'landlords' and 'tenants'. In the context of the transformative project design, understanding the motivations and decision-making processes enables a translation to (agent-based) models, which then allow the interaction between a large number of individual decision-makers and their dynamics to be considered together (see Chapter 4). In addition, it was also the foundation for identifying target groups in the real-world experiments (see Section 3.3). Events that induce homeowners to consider possibly undertaking refurbishment measures are, primarily, the purchase of an old house and inheritance of the family home, routine maintenance, a conversion, or an extension being added to the building (Stieß et al. 2010). These events are predominantly linked to the execution of measures that do not result in an improvement in the energy efficiency of the building. Examples include renovating the façade or cladding the roof. Since energy refurbishment measures are mainly combined with such measures, the aforementioned events often trigger the implementation of energy refurbishment measures. This is mainly because a multitude of obstacles that the exclusive implementation of energy refurbishment measures brings with it are diminished or even dismantled by combining them with refurbishment measures that had already been planned or become necessary.

Arguments regarding the cost effectiveness of energy refurbishment measures are often mentioned in this context. For example, it usually pays to enhance the energy efficiency of a building in the majority of cases, due to the energy costs saved during the service life of the building. And, indeed, it is easier to present the cost effectiveness of energy refurbishment measures if the costs that would be incurred in any case can be deleted from the calculation. Examples of such costs include those incurred for erecting the scaffolding needed to renew the roof or the façade.

However, the influence of non-economic factors should not be neglected either. Based on the principle of the foot-in-the-door technique, any previous decision to undertake refurbishment measures has a positive impact on the decision to additionally install thermal insulation. Combining measures can also considerably reduce the perceived expenditure of time and other inconvenience associated with the installation of thermal insulation. If the events mentioned had systematically also been used to carry out energy refurbishment measures, then we would already have an energy refurbishment rate of almost two per cent (IWU 2010).

Thus the excellent opportunity of combining the installation of thermal insulation with refurbishment measures arising in any case does not suffice in many cases for homeowners to decide in its favour. Friege & Chappin (2014) demonstrate that the current mix of policy instruments does little to change this situation. Too much attention is paid to the economic dimension of thermal insulation (Friege & Chappin 2014). And yet surveys demonstrate the important role played by non-economic factors in the decision of homeowners as to whether or not to have energy refurbishment undertaken for their buildings. For example, a survey conducted by Stieß et al. (2010) revealed that homeowners view energy refurbishment less as an investment decision than as a strategic consumer decision (see also Section 3.2 on target knowledge at the individual level). In addition, the socio-economic situation, stage of life, and structural requirements only have a small impact on the type of refurbishment decision. The results of the survey show that attitudinal factors (motivations, barriers and attitudes) have the greatest impact on the refurbishment decision (Stieß et al. 2010).

In the information age, it is virtually impossible to undertake a pre-selection of the sources of information used by homeowners for opinion-forming. Studies such as that by McMichael and Shipworth (2013) conclude that, above all, interaction in social networks influences information flows and validates or denies information (McMichael & Shipworth 2013). However, homeowners are rarely experts in the area of energy refurbishment. Coupled with the complexity of the topic, this had led to the emergence of a whole string of myths that are disseminated via social networks or in the media, and that could discourage homeowners from deciding in favour of thermal insulation measures.

A special case of ownership: communities of owners

Communities of owners in multiple dwellings represent a special case with regard to the implementation of energy refurbishment measures undertaken to the owner-occupied property. According to the German Condominium Act (WEG) passed in 2007, an energy refurbishment is a 'modernisation repair'. As such, only a simple majority of the condominium owners is required to implement such measures. According to the new law, therefore, the investment objective of a whole housing community can no longer be blocked by a single condominium owner.

Nevertheless, special obstacles exist in the case of communities of owners. The roof, outer walls and basement ceilings are subject to common ownership, and the community must agree on measures to boost their efficiency. Since, however, owners' meetings are generally held rather infrequently, decision-making processes take much longer than in the case of owner-occupied homes: depending on the number of residential units, a lot of people must be informed before a decision can be taken. For the committee or property management, this means procuring, preparing and forwarding information, obtaining tenders and, finally, putting the measure to the vote. This is compounded by the fact that some measures are beneficial to individual parties, but must be financed by them all, which could mean that they may be more difficult to enforce. For example, only the top dwellings will benefit from roof insulation, whereas only the ground floor will benefit from insulating the basement ceiling.

Another point is the question of financing. Under certain circumstances, even individual measures may go beyond the scope of a community of owners' reserve for renewals and replacements. In this case, additional financing may take place via a special payment which, however, may constitute an excessive burden on low-income households. The alternative option of securing a loan to finance the measure remains difficult for communities of owners to this day. The problem was that credit institutions usually required every individual owner to bear joint and several liability, i.e. each individual was responsible for the whole amount of the loan. This way, the banks protected themselves against the possibility of individual parties being unable to pay for their share of the loan. However, this meant a certain financial risk on the part of the individual household, which not all households are likely to be willing to bear in a community. Only in recent years have a number of federal states decided to secure loans for communities of owners with guarantees in a bid to increase refurbishment activities in the area of multiple dwellings. Some banks have also developed special loan products specifically for communities of owners. However, such products are the exception to the rule.

Landlords: the decision-making process and (personal) decision factors

If the ambitious targets of an energy transition in the building sector are to be achieved, building owners who rent out their property must also make their buildings more energy-efficient. First of all, the question arises as to whether the findings discussed in the previous section can be transferred to building owners who rent out their property. Unfortunately, this question must be answered with 'no'. A closer look at the above-mentioned elements of the decision-making process, i.e. an event leading to thoughts about an energy refurbishment and the actual decision-making process, reveals considerable differences to homeowners. Not unlike the case of the homeowner, a change of user (in this case, therefore, the tenant) is a good opportunity that is often used to consider modernising the residential unit. However, a large proportion of rented residential units are in multiple dwellings. For this reason, it will only rarely be the case that all residential units experience a change of tenants or are empty at the same time—and if that is indeed the case, then the building owner ought to realise of his own accord that action must be taken to improve the property. The much more frequent case of just one or a few residential units experiencing a change of tenants while the other apartments in the building continue to be used by the previous tenant implies that there will only rarely be a specific event that gives rise to a comprehensive refurbishment. In many cases, therefore, extensive energy refurbishment measures must be carried out while the majority of the residential units continue to be occupied. Compared to simple maintenance work (such as painting the façades), extensive energy refurbishment measures usually impose considerable and protracted restrictions on the residents in the building—especially dirt and noise. Although Section 555d of the German Civil Code (BGB) states that a tenant must tolerate modernisation measures, the coordination effort required by the landlord and the possible resentment felt by tenants constitute an obstacle. This obstacle is one of the reasons why the events prompting landlords to contemplate energy refurbishment measures are rarer and less clear.

A landlord's decision-making process also differs considerably to that of an owner-occupier. In the case of a building owner who rents out his property, therefore, the decision in favour of energy refurbishment measures may already not be a strategic consumer decision because he does not occupy the energy refurbished building or residential unit himself[6]. The costs of the energy expended for supplying space heating count as running costs and must therefore be paid by the tenant. As such, tenants benefit directly from the reduced energy consumption and costs achieved through the energy refurbishment measures. However, measures to improve the energy efficiency of the building constitute changes to the rental property. This means that building owners must bear the costs of these improvements. This discrepancy between the payer and the beneficiary is discussed in detail in the academic literature under terms such as the user/investor dilemma or the tenant/landlord dilemma, without a panacea having yet been found (Neitzel et al. 2011).

In addition to the Energy Saving Ordinance (EnEV), which is applicable to all residential buildings irrespective of the type of use, and the support of energy efficiency refurbishment measures by the KfW, which building owners who rent out their property may also utilise, tenancy laws are the most important instrument used by the political sector to attempt to offer landlords incentives to undertake energy refurbishment measures. This choice is a direct consequence of the tenant/landlord dilemma. After

6 This disregards cases where the building owner uses one apartment and rents out other residential units in the building.

all, there should be a way for building owners who rent out their property to have some kind of return on their investment. And since this can primarily be achieved by increasing the rent, legislators have granted landlords such a possibility. For example, Section 559 BGB permits the landlord to increase the rent by 11 per cent of the costs spent on modernising the dwelling if they have led to the sustainable saving of energy. It must be noted in this regard, however, that only modernisation costs may be allocated. Any maintenance costs must be deducted from the overall costs of an investment. In this regard, the proportion of maintenance costs is assessed on a case-by-case basis. Neitzel et al. (2011) discuss the modernisation costs as a proportion of the whole amount invested in detail. In this regard, the proportion of the apportionable costs depends strongly on the type of measure implemented and is over 90 per cent in the case of installing insulation to façades, intermediate floors and basement ceilings, whereas much lower values (40 to 50 per cent) can be found in the case of replacing windows and heating systems. In the event of a complete energy modernisation covering all of the aforementioned measures, around 60 per cent of the modernisation costs would be apportionable. Nevertheless, we initially want to continue assuming at this point that tenancy laws offer a good incentive for energy refurbishment measures. After all, the investments made can be refinanced within a period of around ten years. On closer inspection, however, a much more complex picture emerges in which the incentives for individual landlords are not so clear.

In his decision-making process, the landlord will usually not only consider permissibility under tenancy laws, but will also reflect on the economic impact of his decision. In this context, the following two questions mainly arise: will I be in a better position if my dwelling is refurbished than if it is not refurbished? Will the market enable me to get the rent I desire (and require for refinancing)? These two questions can only be answered if numerous variables are considered—the future development of which is likewise relevant for decision-making, adding to the uncertainty and complexity. In addition, the development of these variables is highly dependent on the behaviour of third parties. These factors will be explained in the next section.

Landlords: external framework conditions related to the refurbishment decision

The question of whether a landlord will be better off economically, or at least not worse off, following an energy refurbishment is closely connected to how the rentability of his dwelling can be assessed based on the given market conditions. First of all, two extreme cases can be considered which, related to the total number of dwellings, ought to occur comparatively rarely. The first case concerns landlords who are faced with the challenge of being virtually unable to rent their dwellings. This is usually a result of a combination of outdated accommodation and a low demand for housing. The landlord then has the option of having the building extensively modernised, which is usually expensive, or having the building dismantled (at the cost of ensuring traffic safety and demolishing the building). Such cases, which are mainly observed in rapidly shrinking regions of Germany, are a particular challenge and politicians continue to search for effective instruments to counter this phenomenon (Schiffers 2009). The other extreme case occurs in housing markets featuring a rapidly growing demand for housing. In this case, modernisation projects can be used to appeal to a different rental segment following the modernisation. Consequently, these refurbishment projects are not merely for the sake of improving energy efficiency, but are also linked to raising the quality of the accommodation. This phenomenon is often discussed within the context of luxury refurbishment and gentrification (Knight 2016). In both cases, the demand for rental apartments is a central framework condition for the landlord's decision. This decision will be largely determined by the number of households and the demand for housing, which in turn are the result of a variety of economic and social developments. In particular, these include income development, trends regarding the composition of the population in terms of numbers and age structure (demographic change) and the shaping of professional arrangements and individual lifestyles. There is a tendency towards smaller average household sizes and therefore a larger number of households due to aspects such as increasing divorce rates, a larger number of long-distance relationships as a consequence of career flexibility, and the weakening of traditional family structures and residential models due to the wish for greater independence and self-realisation, made possible by higher incomes. Moreover, tenants' comfort needs also change as they get older, resulting in a shift towards a demand for high-quality dwellings for elderly people. Consequently, decisions by landlords based exclusively on considerations of profitability must always be considered in the context of socio-demographic developments and their characteristics in the relevant local rental markets. Distinguishing from the above-mentioned extreme cases, we wish to concentrate below on the decision-making processes of landlords who are not facing the difficult choice of whether to modernise or write off their property, and who do not want to use the modernisation process to access a different market segment.

We therefore now have the case in which a landlord wishes to modernise his residential building (from an energy perspective), but who is not in a situation where the residential building is unused and who does not intend to rent out all dwellings to new tenants at a higher rate after the refurbishment. His economic incentives will then depend on the situation of the rental housing market. In order to comprehend all this, one must first consider which possibilities landlords have to increase the rent. One possibility is to agree on a stepped rent (Section 557a BGB) or an indexed rent (Section 557b BGB). In the first case, the rent is increased annually or even less frequently based on a contractually agreed scheme. In the second case, the annual increase of the rent is usually based on the increase in the price index determined by the Federal Statistical Office. If stepped rent has been agreed on, it is not possible to apportion modernisation costs in accordance with Section 559 BGB, whereas this possibility is open to landlords who opt for indexed rent. Another option, and the one that is most frequently used[7], is to increase the rent to the local reference rent in accordance with Section 558 BGB. The local reference rent is determined in a rental table for the relevant regional and substantive sub-

7 Cischinsky et al. (2015) determined for tenancy agreements with private owners of dwellings that a stepped or indexed rent was agreed on in only ten per cent of cases.

markets. A rent can be increased to the local reference rent at 15-month intervals. The law also provides for a cap on rent increases, meaning that the rent may not increase by more than 20 per cent within the space of three years.

It soon becomes clear from this why the (economic) incentives for energy refurbishment measures in tight rental housing markets with a considerable increase in the local reference rent are low. Carrying out energy-efficiency modernisation permits the landlord to increase the rent by 11 per cent of the modernisation costs—but in this case, however, the landlord must in fact also bear costs. In contrast, landlords who do not have any modernisation measures undertaken can regularly increase the rent without having to incur considerable costs, in the event of an increase in the local reference rent. If the increase in the local reference rent reaches a value that corresponds to 11 per cent of the modernisation costs incurred before the end of the payback period (i.e. within around a decade), the landlord who has undertaken refurbishment measures cannot expect to achieve the full amortisation of his investment and he will have to bear some of the costs himself. A significant increase in the local reference rent is not unlikely, particularly in tight rental markets. Since, however, the expectation formation with regard to the increase in the local reference rent is subject to significant uncertainties for every market participant and is dependent on many exogenous factors (yet to be discussed), given that the residential building is rentable, the decision to invest in extensive energy modernisation measures is not only improbable in the case of risk-averse landlords.

A different situation arises in cities with a relaxed rental housing market: even though landlords can only expect a small increase in the local reference rent, they are still uncertain whether they will be able to refinance the investment made. A relaxed rental housing market is characterised by comparatively high vacancy rates and a slight increase in the rent level. In this case, then, the landlord will wonder whether he will be able to enforce the rent increase on the market. Will the present tenants accept the increase in the basic rent or can new tenants be expected to be found in spite of the increase in the basic rent?

Going back to the tenant/landlord dilemma, the question can be asked in this context as to whether the tenants have an economic interest[8] in the energy modernisation of their dwelling. They would have an economic interest if the energy modernisation of their residential building reduced their housing costs (i.e. the sum of the basic rent and running costs): do the energy costs saved by the energy modernisation suffice to compensate for the increase in the basic rent? Unfortunately, it is not easy to answer this question because the costs of energy modernisation measures vary considerably from case to case, and the energy costs are also determined by user behaviour. There is also a high degree of variation in the estimates and empirical surveys of average refurbishment costs—which is understandable, considering the large variance in the (energy) status of existing buildings. Nevertheless, on the basis of recent studies, it can be estimated that, given the current level of energy prices, an energy modernisation would signify an increase in housing costs for the tenants (insofar as the landlord takes full advantage of the scope for rent increases stipulated in Section 559 BGB). Neitzel et al. (2011) calculate a potential increase in the basic rent of €2.08 to €2.70 per square metre per month for an exemplary modernisation project for a 1950s building, depending on the desired standard of energy efficiency. Given current energy prices, however, the decrease in energy costs is only €0.88 to €1.30[9] per square metre. In a similar fashion, on the basis of empirical data for Berlin, Hentschel and Hopfenmüller (2014) determine a median increase in the basic rent of €1.55 per square metre per month following energy modernisation measures. In the cases where relevant data existed, these costs were offset by a maximum energy cost saving of only €0.50. On the basis of model calculations for the case of full refurbishments, Pfnür and Müller (2013) even determine an increase in housing costs of €2.10 to €2.60 per square metre per month. But even under the more moderate assumption that there would be

8 The numerous co-benefits of an energy modernisation (such as better living conditions) are initially disregarded here.

9 These values are yielded when the difference between the energy demand before and after the refurbishment is used for the calculation. If the difference between the average energy consumption before the refurbishment and the energy demand after the refurbishment is used in the calculation, the energy cost saving decreases to between €0.27 and €0.70 per square metre per month.

an average increase in housing costs for tenants of €1.00 per square metre per month in the case of energy modernisation measures and a complete allocation of modernisation costs, it becomes clear that tenants will only benefit financially from an energy modernisation in specific cases. As long as there is no significant increase in energy costs—which could be supported politically, for example, by introducing a carbon dioxide tax—the allocation of the costs of an energy modernisation will often be a distribution of burdens.

When considering landlords' decision-making processes, it must also be taken into account that building owners who rent out their property are not a homogenous group. Private individuals with a portfolio containing only a few residential units operate on the rental housing market alongside large, listed commercial housing companies. The information contained in the 2011 Census only enables a statement to be made with regard to the total number of dwellings, i.e. including those used by the owner (Statistische Ämter des Bundes und der Länder 2015). For Germany as a whole, around 80 per cent of dwellings are owned by private individuals or communities of owners. Housing associations, municipal and private sector housing companies each own just over five per cent. In cities, which have a lower home ownership rate, only 67 per cent of dwellings are owned by private individuals and communities of owners. Housing associations and municipal housing companies each own over 8 per cent of dwellings in cities, private sector housing companies own just under 11 per cent. Housing companies from the private sector play a comparatively large role in the Ruhr Area, where they own almost 14 per cent of all dwellings. These differences become important when the assumption is made that the decision-making processes of private landlords differ from those of municipal and private sector housing companies. For instance, it is plausible to assume that some private landlords (especially if they are also resident in the rented house) are much more emotionally attached to their property than commercial companies, where the management decides on the further development of a residential property based on economic considerations. It can be assumed that this factor will also be reflected in decision-making for or against energy modernisation measures.

There is a further need for research on these differences in the decision-making processes of building owners who rent out their property, so that they can be defined precisely. Leaving that matter aside, it should be noted that the energy transition in the area of rented residential buildings represents a major transformation challenge. As discussed in this section, there has so far been little incentive for landlords to undertake energy modernisation measures. New approaches and policy instruments are required to change these incentives so that these challenges can be met while ensuring the fair distribution of benefits and encumbrances.

BOX 1

External wall insulation – 'Not in a million years'

Hildegard is 85 years of age, and has been living in her 9-party multiple dwelling in the city centre for more than 50 years. The house, now managed by her daughter, was to provide for her and her husband, who has since passed away, in their old age. It was home to the family of three children for several decades.

Since Hildegard had and continues to have a close relationship with her tenants, and since she considers long-term tenancies to be more important than maximum returns, they regularly invested in the house. The windows, bathrooms and the stairwell were renovated step by step, and currently meet the standards required by the demand for rented accommodation. The roof is insulated and the house is connected to the district heating. However, there is one thing that Hildegard never considered all those years—having the outer façade insulated. This was not for reasons of economy. In fact, Hildegard was wary of the risk that her tenants would ventilate the 'plastic-wrapped' house incorrectly, resulting in mould.

BOX 2

The energy efficiency paradox

Ömer is a 50-year-old who, several years ago, inherited a multiple dwelling from his parents who came to Germany from Turkey as guest workers in the 1960s. Neither he nor his parents had contemplated energy efficiency for a long time. Recently, however, he received a voucher from the municipal utilities inviting him to take part in a free thermography campaign. Ömer was surprised by the results. The former exterior corridor of the house leading to the inner courtyard, which was converted into conservatories in the 1980s, showed up navy blue, a sign that the dwellings had little heat loss. The same happened with the windows facing the road, even though they had been installed way back in the mid-1970s. The representative from the municipal utilities assumes that Ömer's parents had high-quality windows with a high sound insulation standard installed back then. He concluded that there was no acute need for action. This assessment was confirmed by the Energy Performance Certificate issued subsequently. With a heating energy consumption of around 110 kWh/m^2 (including hot water), the building is less efficient than a new construction, but nevertheless considerably better than the average—despite not having consciously invested in energy efficiency in recent years.

Potential for energy savings

In order to round out the complex picture of the energy transition in buildings, however, not only the theoretical potential for energy measures to boost the efficiency of the building stock as a whole must be considered, but also the predictable reduction in the energy demand of individual buildings, the economic and individual decision-making processes of the people who decide whether or not refurbishment measures shall be carried out, as well as the actual energy consumed by residents. Both factors can differ greatly from one dwelling to another, for example, due to the composition of the household and the necessary care work associated with it, personal circumstances, habits and behavioural routines: a family with two small children where the parents spend a lot of time working at home will usually need more energy in the home than a single person engaged in gainful activity outside the home.

There may be many reasons why less energy is saved than the calculated values. In this context, a direct rebound effect occurs when the energy costs saved by installing thermal insulation are directly invested in increasing the indoor temperature. According to Sorrell (2010), the average direct rebound effects in the area of space heating are between 10 and 30 per cent. Indirect rebound effects, i.e. reinvesting the monetary budget saved in another demand area, are very difficult to calculate, but can even lead to backfire effects (Buhl et al. 2015). With space heating, however, the indirect rebound effects or compensation are lower in terms of resource consumption. If the money saved from reducing the room temperature is reinvested, between 29 per cent (Buhl 2014) and 59 per cent (Buhl 2016) of the savings are offset in resource consumption. The main reason for this is the relatively high resource intensity in the area of housing. If money is saved, it is likely that the majority of savings will be used in relatively resource-light areas. It is therefore worth while striving to make savings in relatively resource-intensive areas such as housing in spite of, or rather because of, the occurrence of rebound effects.

Besides rebound effects, so-called prebound effects may also occur. It could be the case, for instance, that the actual energy consumption prior to the refurbishment is less than the calculated energy demand, further reducing the energy saving potential of refurbishment measures (Sunniak-Blank et al. 2012). Individual ventilation habits (shock ventilation versus tilt ventilation) can result in considerable differences between the calculated energy demand and actual energy consumption. Finally, quality assurance deficiencies before, during and after the refurbishment can also be the reason for the lack of success in saving energy (co2online 2015).

In connection with economic efficiency calculations for energy refurbishments, the significance of deviations between calculated energy demand values and measured energy consumption values is repeatedly debated, which constitutes a major element of uncertainty. This can only be grasped by considering the factors that determine heating energy consumption in a dwelling or residential building. These factors are primarily the energy performance of the building and user behaviour. In the case of multiple dwellings, the position of the dwelling in the building also exerts an influence on energy consumption for space heating that should not be underestimated (Keimeyer et al. 2016). The energy performance of the building can primarily be changed by undertaking an energy refurbishment, i.e. by installing additional insulation, replacing windows and doors, and other small-scale measures. It is absolutely impossible to change the position of an apartment in a multiple dwelling. The third option is to induce a change in user behaviour. But how does user behaviour influence energy consumption, and what effect does user behaviour have on the amount of energy consumed? The first factor is the amount of time household members spend in the dwelling, and the length of time spent away from it. Energy consumption is usually higher if the owner or tenant is present in the dwelling—and if this is not the case, then it would be all the more urgent to change the user behaviour or to set the heating system differently.

The second factor is the desired room temperature that should be achieved by heating the dwelling. The rule of thumb often heard is that a reduction in the room temperature by 1 degree Celsius signifies an energy saving of 6 per cent (co2online 2017). The third factor is residents' ventilation habits. Compared to long-term or even permanent tilt ventilation, brief shock ventilation leads to much less energy consumption involving a higher air exchange rate. Political action can be taken to influence the last two factors. Transformation knowledge to be developed should therefore define how residents can be motivated to select a lower room temperature (this does not apply to households that already use low temperatures, see Box 8). In addition, interventions should be identified that improve ventilation habits in such a way that they minimise additional energy consumption. Yet the question is: how high is the savings potential that can be achieved in this case?

The literature provides a wide range of figures on the actual amount of potential savings that can be generated by changing user behaviour. Some authors state that a five to seven factor difference can be achieved concerning heating energy consumption in similar buildings with a comparable heating system (Liedtke et al. 2014). Other studies are much more sceptical as to the savings potential that can be achieved by changing ventilation habits—also because many households tend to ventilate their dwellings too little rather than too much. Based on a comparison between calculated energy demand values and determined energy consumption values, one investigation concludes that a changed user behaviour can have a maximum savings potential of 20 per cent (Keimeyer et al. 2016). This assessment is also consistent with a current meta-analysis of studies that investigate the effect of feedback on household energy consumption. According to this meta-analysis, the feedback measures investigated achieved an average reduction in energy consumption of 8 to 12 per cent—although many studies were admittedly included that only explored the influence of a feedback on electricity consumption (Karli et al. 2015). It can be concluded that many studies agree that user behaviour has a considerable impact on energy consumption—even though the figures were wide-ranging, if only on account of their research designs and object of investigation in estimating the exact dimension of this impact. This was particularly the case concerning the amount of energy that could be saved by changing user behaviour (see also, and in greater detail, Section 4.3).

Ultimately, the question of how much energy was actually saved due to which measure—whether due to the energy refurbishment of the building shell or building technology or due to altered heating and ventilation habits—is not only dependent on the next heating bill. In order to gain a definitive picture, it must be viewed in the entire life cycle in connection with the resources used for the measure and the energy required for extraction, production, transportation and disposal. It is now accepted that energy savings and reductions of greenhouse gas emissions in the use phase are several times higher than the production energy and emissions (for example, Rodrigues and Freire 2016; Mazor et al. 2011; Schmidt et al. 2004). The question as to which energy refurbishment measures result in which resource implications and to what extent the problem is shifted from energy consumption to resource consumption remains largely undetermined. It is not apparent which interactions will ultimately arise; they often depend to a great extent on the design of the process chains considered. Relevant life cycle analyses have addressed this issue using a variety of resource efficiency indicators and have so far come to the conclusion that insulation strategies can make a significant contribution to material efficiency (Becker 2014; Soukup et al. 2012).

Policy instruments for the energy transition in buildings

A policy system analysis must now be conducted in order to identify which adjustments can be made within the heating transition in the building sector. A combination of different policy instruments seeks to speed up the energy transformation of the building stock. In Germany, there are three main types of instruments to do this at present: regulatory provisions, government support programmes and the provision of information. Understanding how they interact is essential in order to be able to identify further potential.

At the highest political level, EU requirements are binding for Germany. The 'Energy Performance of Buildings Directive' (EPBD) of 2010 and the 'Energy Efficiency Directive' (EED) of 2012 constitute the major regulatory frameworks governing the reduction of energy demand in buildings at the EU level. These directives give rise to central instruments and targets, also for Germany, such as the introduction of the energy performance certificate, the requirement that new buildings must meet the standards of a nearly zero-energy building by 2020, and that minimum standards must be met in the case of extensive renovations. Added to this is the requirement to develop an action plan for increasing energy efficiency[10].

At the federal level, the central regulatory instrument is the Energy Saving Ordinance (EnEV). In 2002, the EnEV replaced the Thermal Insulation and Heating Systems Order that had been applicable up till then, and has since regulated the requirements applying to the energy performance of buildings. The current version of the EnEV has been in force since 1 May 2014. If changes are made to external building elements in any case,

10 See https://ec.europa.eu/energy/sites/ener/files/documents/2014_neeap_en_germany.pdf (accessed on 15 May 2016).

the EnEV states that certain limit values must be met for thermal transmittance values (U-values). In addition, in the event of a change in ownership, the new owner has a mandatory retrofitting obligation: boilers installed before 1 October 1978 must be replaced, and hot water pipes and the top floor ceiling must be insulated. The biggest problem of the EnEV is its enforcement: in many cases, energy refurbishment measures are not carried out in spite of the obligation to do so (Diefenbach et al. 2005). There is a lack of checks and penalties, which is why the EnEV is often called the 'toothless tiger', an instrument that is unable to develop its impact in the present implementation.

The 'Energy-efficient refurbishment' promotional programme of the KfW Group is the most important financial instrument for speeding up the energy transformation of the building stock in Germany. On request, the programme enables homeowners to obtain soft loans as well as grants for refurbishment measures that improve energy efficiency in buildings. Both single measures and complete refurbishments that go beyond the standard required by the EnEV are eligible for funding. The amount of the grant is based on the efficiency class achieved by the building following the energy refurbishment measures. So far, the promotional programme has mainly reached well-informed and highly motivated refurbishers (Albrecht 2010). In addition, municipalities can obtain funding from the KfW to develop integrated neighbourhood concepts that identify technical and economic possibilities for saving energy within the neighbourhood. A Refurbishment Manager can be requested for the relevant neighbourhood to ensure the implementation of concepts.

These programmes are supplemented at federal state level[11], in some places at the regional level[12], by municipalities[13] or municipal companies, primarily municipal utilities (EnergieAgentur.NRW GmbH 2012). These instruments are framed by various approaches to convince homeowners

11 For example, in North Rhine-Westphalia [http://www.nrwbank.de/de/Landingpages/gebaeudesanierung.html; 15 May 2106]

12 For example, in the Hannover region [https://www.proklima-hannover.de/privat/modernisierung; accessed on 15 May 2016]

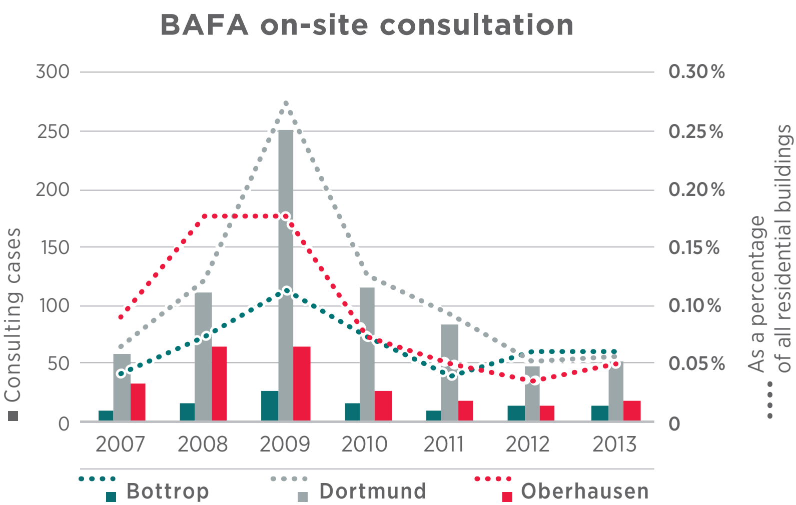
13 For example, in Düsseldorf [https://www.duesseldorf.de/saga/foerderung/; 15 May 2016]

of the advantages of energy refurbishment measures (information tools). These include local and stationary energy consulting services, advice provided by the skilled-trade sector, information portals on the internet, TV and in the press, and the use of energy performance certificates and heating bills to raise awareness of the savings potential. These framework conditions and services principally apply nationwide. But how much of this information reaches those who are supposed to implement and utilise it?

A glance at current energy refurbishment activities shows that the instruments used up till now do not yet achieve the desired effect. Measures to boost the energy efficiency of the building stock have only proceeded slowly. The IWU believes that the energy refurbishment rate is less than 1 per cent altogether (IWU 2010). This means that, mathematically speaking, around one in one hundred buildings are fully insulated each year, whereby roofs and top floor ceilings are insulated more frequently than outer walls. The lowest insulation rate can be found in floors and basement ceilings. Windows are replaced at a rate of slightly over 1 per cent (IWU 2010). In purely arithmetical terms, the energy refurbishment rate must at least be doubled in order to achieve the savings targets.

The number of energy consultations provided, an important instrument for increasing the quality and implementation of measures (see Schüle, Bierwirth, Madry 2011), is still below the refurbishment rate. An assessment of consulting cases in the three cities investigated in the EnerTrans-Ruhr project—Oberhausen, Dortmund and Bottrop—reveals that advisory services offered by the Consumer Association and private energy consulting companies funded via the Federal Office for Economic Affairs and Export Control (BAFA) are used for 0.05 to 0.1 per cent of all residential buildings each year. Even if the services offered by municipal utilities, the skilled-trade sector and private energy consulting companies are not considered here, it can be assumed that consultancy services are not utilised in all of the places where refurbishment potential exists or where refurbishments are undertaken[14]. A field test conducted by co2online reaches the

14 One exception to this is the project area of the InnovationCity Ruhr Bottrop, in which an extensive on-site consultancy initiative was implemented.



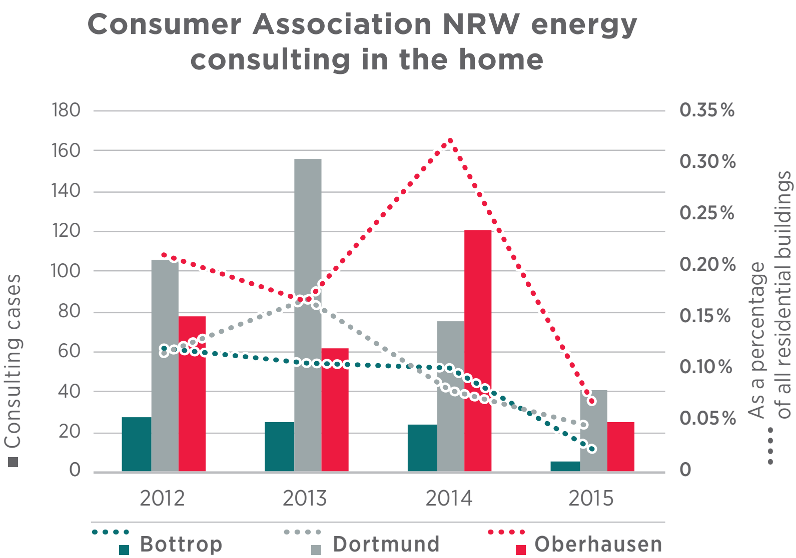


Figure 8: **Consulting cases conducted by the Federal Office for Economic Affairs and Export Control (BAFA) and the Consumer Association NRW in Bottrop, Dortmund and Oberhausen**

same conclusion. This study revealed that energy consulting was used in only one out of three cases in which refurbishment measures were carried out in buildings (co2online 2015).

Contexts: people in the city and the neighbourhood

Besides capturing the technical and political framework, an extensive system analysis also requires an understanding of the relevant stakeholders' actions. And this in turn can only be understood if the contexts in which the stakeholders are integrated are also considered. In this respect, there are individual stakeholders who make a considerable contribution to shaping the context by taking the initiative to launch change projects. The members of this specific stakeholder group are called 'agents of change'. The next section focuses on these agents of change.

If one deals intensely with a topic—such as energy refurbishment, as in this case—it can sometimes happen that one notices with amazement that there are people who pay only little attention to the topic, in spite of all the information, services and news reports about it. The belief that citizens have been comprehensively enlightened in this respect—or at least ought to be, based on all the widespread information available—is due to a certain degree to institutional blindness. In order to understand actors' systems and their motivations with regard to specific decisions, agents of change are therefore a particularly interesting group that has been little explored.

Have you ever carried out energy refurbishment to your home, comprehensively renovated rooms, or experienced modernisations carried out by your landlord? Then you are aware of the fact that, in addition to being a financial burden, such measures also take a lot of time: to obtain the necessary information, to plan, to find and coordinate skilled-trade firms and, not least, to tolerate the inconvenience caused during the refurbishment phase. Consequently, refurbishments are not suitable for everyday life. On the contrary, in fact. The question of 'How can I motivate people to carry out energy refurbishment measures?' can obviously not be answered with information, campaigns and financial incentives alone. In this case, a fundamental understanding of decision-making processes, motivations and, not least, social practices may help to bring about or at least aim to achieve behavioural change. These are usually closely linked to the local situation.

Customary routines must also be abandoned in other areas of extensive transformation and sustainable development, such as in the case of nutrition or mobility. It is therefore worth looking beyond the horizons of energy refurbishment to gain knowledge of the background and structures of new social practices.

In order to understand what motivates people to engage in something and to try out something new, we searched for agents of change in Oberhausen and Bottrop within the EnerTransRuhr project—and found them: people who work directly or indirectly to achieve sustainability. They take innovative action, campaigning for a more sustainable and climate-friendly society. Since these agents are active in different fields and each have their own individual understanding of sustainability or climate targets, we differentiate between implicitly and explicitly sustainability-oriented agents of change. Agents with an explicit sustainability orientation consciously take motivations of sustainability, environmental and climate protection as a basis for their actions, and are often found in social movements such as the environmental movement and anti-nuclear movement (Sommer & Schad 2014). Agents with an implicit sustainability orientation, on the other hand, act in a sustainable manner, but without it being the primary intention of their actions (ibid.). The aim of gaining a profound understanding of such agents and their socio-technical innovations is to help identify similar potentials or obstacles in the area of energy-efficient building refurbishment. Agents of change accelerate conversion processes, substantiating and shaping ongoing socio-technological changes, legislative processes and market development as consumers, social entrepreneurs and investors, citizens' groups, administrators and politicians (see WBGU 2011, p. 257). This means that they break existing routines, offer resistance, establish new routines, put alternatives into practice, and generate new discourse.

Even if their commitment cannot be transferred directly to energy refurbishment and energy-saving behaviour, a lot can be learned from them about the motivations and dissemination mechanisms of new social practices and structures (see Section 3.3).

It became apparent with the agents of change investigated that they were all dependent on spatial references—to the regional economy, to municipal schools or to the neighbourhood in the district—which they specifically used for their commitment. All the same, they have to demonstrate so much flexibility and such great communication skills in this respect that they also always have to fall back on contacts outside these niches or be able to activate them for their 'issue'. As a result, they come across not only proponents, but also have to deal with conflicts of a technical and political nature.

Thus an individual's behaviour causes other people to make similar decisions, leading to the decision in favour of energy refurbishment being replicated in the social network (Friege et al. 2016). This phenomenon can also be described as follows: an individual's actions change the system, which in turn changes the behaviour of individuals.

3.2 The energy transition as a target vision: target knowledge for the heating transition

Target knowledge describes knowledge of desirable target states taking into account existing room for manoeuvre and options for action. It is a compass for transformation processes, as it were. Target knowledge can be dictated by policy or law and can be substantiated scientifically within the meaning of sustainability-oriented transformation. A broad spectrum of different targets is defined in the context of the energy transition, of which the goal of the heating transition in the building sector is a part. These are differentiated by time and sector.

Target knowledge at the national, regional and municipal level

The targets of the German federal government with regard to the energy transition and climate protection are laid down in the Energy Concept 2050 (BMWi, BMU 2010). At the federal state level, North Rhine-Westphalia adopted the Climate Protection Act NRW in January 2013. The aim is for North Rhine-Westphalia to reduce its total greenhouse gas emissions by at least 25 per cent below 1990 levels by 2020 and by at least 80 per cent by 2050 (Landesregierung NRW 2013).

Many cities in Germany have also set themselves energy saving and climate change targets. They share the targets of the German federal government and have signed up to municipal or regional climate action plans; they are members of the Covenant of Mayors, a European network of cities[15] or Climate Alliance[16]; and, within the initiative of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), they are developing the 'Master Plan 100% Climate Protection', a concept that aims to reduce CO_2 emissions by 95 per cent by the year 2050. The cities of Oberhausen and Dortmund have also developed climate action plans containing emission reduction targets. Dortmund aims to reduce its CO_2 emissions by at least 40 per cent below the base year 1990 by 2020. The city is also a member of Climate Alliance, which means that it has undertaken to halve its 1990 emissions level by 2030 and achieve a long-term reduction to a maximum of 2.5 tons of CO_2 per person. Oberhausen is also a member, and has affirmed the Climate Alliance targets in its climate action plan. The city aims to reduce its CO_2 emissions by up to 95 per cent by 2050. Since the start of the project in 2010, the InnovationCity | model city of Bottrop has set itself the goal of halving its emissions in the project area by 2020.

However, the possibilities and requirements for achieving these goals depend on a multitude of overarching trends and development paths in different cities and regions. Examples include economic development, immigration and emigration and, not least, the existing infrastructure and

15 The members of the 'Covenant of Mayors for Climate & Energy' have set themselves the goal of reducing their CO_2 emissions by 20 per cent below 1990 levels by 2020. They present a 'Sustainable Energy Action Plan' (SEAP) and report on progress made in implementing the measures in the 'Monitoring Action Plan'. In 2015, the topic of climate change adaptation was included in the objective of the covenant, as well as the pledge to reduce CO_2 emissions by at least 40 per cent by 2030 (see http://www.covenantofmayors.eu).

16 Klima-Bündnis der europäischen Städte mit indigenen Völkern der Regenwälder e.V. (Climate Alliance) For more information, see http://www.climatealliance.org

technological possibilities. In some cities in the Ruhr Area, for example, where very energy-intensive coking plants and steelworks companies were closed down, CO_2 emissions have in fact fallen considerably since 1990. However, this was not as a result of efforts to combat climate change, but was due to structural change in the economy. At the same time, this change presents these cities with major social and economic challenges, in some cases even to this day. This makes it difficult to implement more extensive climate change measures (see März et al. 2013). Other regions and cities, on the other hand, are experiencing a significant increase in the population. What may be positive for economic development, however, signifies greater energy consumption from a climate protection perspective: in households, traffic and the economy. In order to achieve their climate change targets, growing cities and regions must step up their efforts considerably.

In addition, objectives, strategies and measures can be found in different policy areas at the national, regional and municipal level that hinder each other. Whereas on the one hand, climate change objectives are being set out in the area of mobility, transport development plans may, for example, provide for the expansion of the road infrastructure for car traffic in order to free very busy routes from traffic. The result is that the traffic volume tends to continue to increase, and not a strategic avoidance of car traffic involving a shift to environmentally friendly modes of transport.

Such conflicts of objectives are apparent, for example, in the current political debate about the housing market. In rapidly growing cities, housing is generally scarce, let alone affordable housing. The debate has been exacerbated by the increase in immigration in 2015 and the associated questions of how to accommodate and integrate the refugees. It is estimated that hundreds of thousands of new residential units must be constructed each year in the whole of Germany (BMUB 2016). In order to ensure that this demand is met as economically and swiftly as possible, one of the questions being discussed is whether energy requirements applying to new buildings should be lowered. However, the longevity of buildings does not only mean increased energy consumption during the construction phase, but also throughout its use. The quality of today's design determines energy needs in the building sector for future decades, and hence the ability to meet climate change targets. This clearly shows how decisions taken against the background of contemporary, short-term developments can impact long-term objectives.

Lively exchange between politicians and researchers is required in order to identify such conflicts of objectives, to search for appropriate responses, and to translate them into policies. In this respect, the key question is how multi-issue and cross-cutting structures can be established in policymaking and administration in a bid to bring climate change objectives in line with other environmental policy objectives, social issues and economic aspects or to integrate them into existing concepts, visions and strategies.

Objectives at the individual level

It is appropriate to note, as a preliminary point, that a transformation of the residential building sector to a lower—and hence more sustainable—level of energy demand requires the cooperation of the people who own and use the buildings.

For this reason, the individual actors' visions that govern their actions are also of relevance. In the context of driving transformation to energy-efficient buildings, visions provide information about the desirable states that building owners and users develop with regard to their building. These desired target states may take entirely different forms or—figuratively speaking—may be measured in other units than the politically defined target knowledge. Examples of building owners' desirable target states with regard to their residential building include achieving a high standard of living, preserving the value of the building, having to pay low energy and additional costs and (in the case of building owners who rent out their property) a regular rental income.

Visions can likewise be identified for the users of residential buildings. This group also includes tenants who are the users, but not the owners of a building. Users' desirable target states usually overlap with those of building owners (such as a high standard of living, and low energy and additional costs). For building owners and users alike, it is the case that visions are formed in complex interaction processes and are therefore influenced by other actors' ideas.

But what target visions can building owners and users have with regard to energy refurbishment?

At this point, the case of owner-occupiers shall be considered. What motivates them to make their residential building more energy efficient? What objectives to they specifically pursue? Studies have brought to light new findings in recent years with regard to owner-occupiers' refurbishment decisions and the objectives that owner-occupiers wish to achieve by making their building more energy efficient. According to these findings, the hypothesis about decisions for or against undertaking energy refurbishment measures being taken for purely economic reasons is not tenable (Stieß et al. 2010). It is not very easy for building owners to compare the cost of investment with the expected energy cost saving for individual refurbishment projects, and to calculate the capital value, or have it calculated, according to the textbook. In view of the uncertainties surrounding these calculations, it would also be difficult: it is relatively easy for an energy consultant to determine the reduction in the calculated energy demand depending on the measures carried out. But the influence of user behaviour is hardly likely to be considered in economic efficiency calculations—not least due to a lack of data. And yet evaluations of energy refurbishment measures frequently come across this phenomenon: the calculated reduction in energy consumption is not achieved—which has repercussions on the economic efficiency (summarised in Rosenow & Galvin 2013). If you then also bear in mind that a reliable estimate of the changes in energy prices can only be made by assuming a corridor of different values, it becomes clear that calculating economic efficiency in the case of energy refurbishment measures is a highly complex matter. It is therefore only logical that owner-occupiers orientate themselves towards the objective of 'perceived economic efficiency'.

For a significant section of homeowners, this perceived economic efficiency is already achieved when there is a perceptible reduction in energy costs (Albrecht & Zundel 2010). For economists: the capital value of the refurbishment therefore need not even be greater than zero. It suffices for there to be a positive cash flow after the investment. However, perceived economic efficiency is just one of many factors when it comes to refurbishment decisions. The decision in favour of energy refurbishment is likewise a strategic consumer decision. It increases the quality and value of the building. Depending on the owners' values and attitudes, there may also be a utility connected to the certainty of contributing towards a reduction in environmental impact.

On the other hand, energy refurbishment measures signify greater effort on the part of the owner. Irrespective of the financial costs, the planning, organisation and restrictions experienced during the actual construction process put a strain on owner-occupiers. A decision against refurbishment can therefore also pursue the objective of avoiding such effort.

Nevertheless, refurbishment rates for owner-occupiers' buildings are considerably higher than in the case of buildings offered for rent (Institut der deutschen Wirtschaft Köln 2012). At this point, consideration must therefore be given to which visions guide building owners who rent out their property in their refurbishment decisions.

With regard to owner-occupiers, we have emphasised the importance of non-economic motivations. Since various different suppliers operate on the rental housing market—from small private-sector landlords to housing associations to municipal and private sector housing companies—it can be assumed that they are characterised by different decision-making processes, as a result of their different objectives and motivations (including non-economic motivations). Particularly in the case of small private-sector landlords, it can be assumed that they are more emotionally attached to their property—and in many cases to their tenants, too—meaning that its maintenance and modernisation is not a purely economic decision for them (Odermatt 1997). Housing associations and municipal housing companies could potentially have a greater social remit, predetermined by the cooperative members or partners. Unfortunately, there is little empirical evidence on the decision-making paths of actors in the housing market, highlighting a need for further research. Empirical analysis to date merely provides initial indications: according to the results of a survey, for example, the rent remained constant in more than 40 per cent of refurbishment measures carried out by small private-sector landlords, whereas it stayed the same in 25 per cent of cases with cooperatives and in just 18 per cent of cases with private housing companies (Henger & Voigtländer 2011). There may be various reasons for this. One possible explanation could be the different weighting given to non-economic motivations by the various actors in the housing market. However, a more indepth statistical analysis conducted by the authors determined that the type of enterprise plays only a minor role—and there was even a greater probability that private landlords would increase the rent in one model. This would suggest that the differences described above can be explained by differences between the dwellings, as controlled for in the model, and not by the different motivations.

A consideration of the visions surrounding the energy refurbishment of rented building stock also includes tenants' objectives and motivations. They may potentially benefit several times over from energy refurbishment measures. But are they, then, a driver behind energy refurbishment?

In the first instance, the tenant benefits directly in many cases, particularly from the improvement in the standard of living. However, whether the tenant also benefits financially from the energy refurbishment is another question that, unfortunately, cannot be answered in general. The central question is: in what way do the housing costs to be paid by the tenant change as the sum of the basic rent and running costs? The energy costs, and consequently the running costs, decrease. However, the landlord will often increase the basic rent in order to refinance his investment. Are the energy cost savings sufficiently high to offset or even outweigh the increase in the basic rent? Is it, in other words, possible to carry out a refurbishment where the costs are offset by the energy savings? This is by all means possible in the case of the refurbishment of very poor-quality buildings. However, empirical surveys and model calculations indicate that this is not the normal case (Hentschel & Hopfenmüller 2014). It is therefore improbable that large numbers of tenants will encourage their landlords to step up their refurbishment efforts in the short and medium term, increasing refurbishment rates.

The target states desired by building owners and tenants may be, but need not be, compatible with those that have been politically defined. The politically defined objectives are derived on the basis of scientifically based target knowledge for sustainability-oriented transformation. The standards specified in the EnEV, for example, result from the desired reductions in greenhouse gas emissions and primary energy consumption, taking into account economic boundary conditions. In contrast, the desirable target states of building owners and users are the result of their preferences. The challenge is now to reconcile the divergent visions of politicians and actors in the housing market.

3.3 Transformation knowledge: real-world experiments and diffusion

Transformation knowledge is knowledge of the specific means and ways of how to achieve the developed vision, based on a current understanding of the problem. Transformation knowledge must answer the question of how the desired target state, or the target state necessary from a sustainability perspective, can be achieved: is inducing a change in systemic variables the appropriate way, which in turn would motivate the relevant stakeholders to change their actions in the desired way? Or is it more promising to support a critical mass of individual actors in such a way that they change the entire system to the desired state in a cascade process? Or perhaps the coordinated use of both strategies is required?

Real-world experiments: a reality check for researchers

Experimental interventions conducted within a predefined frame and evaluated accordingly can provide answers to these questions. The compilation of system knowledge and target knowledge as described above is the foundation for developing such an experiment. Scientific analyses alone are not sufficient, however. Particularly with regard to the heating transition in the building sector, the very different starting situations of individual cities and neighbourhoods must be taken into account, as well as the

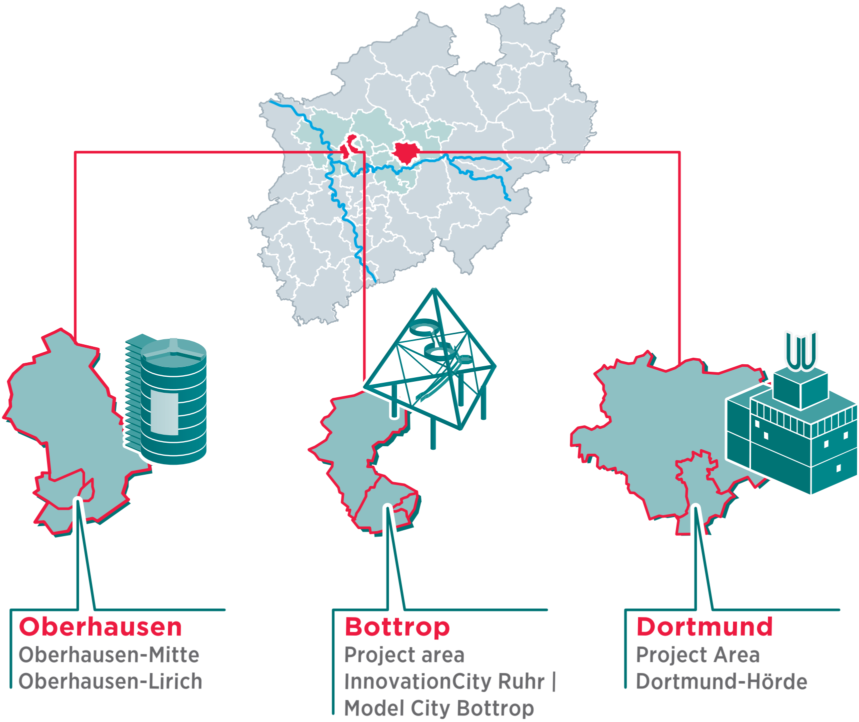


Figure 9: **The area under investigation in the EnerTransRuhr project: the three cities of Oberhausen, Dortmund and Bottrop**

structure of their buildings, their residents, and previously tested interventions. The know-how of local actors is of particular relevance at this point.

In the specific case of the EnerTransRuhr project and the cities of Dortmund, Oberhausen and Bottrop, a series of workshops was held to this end in a bid to develop a consultancy experiment that did not previously exist in this form in any of the three cities. It became apparent at the very first meeting that the smaller and larger interventions with regard to energy consulting that had been tested up till then differed widely. Consequently, the question concerning the target group for which the experiment was to be developed could not be answered universally either. There are institutions that offer energy consulting in all three cities: a branch of the Consumer Association NRW is established in Oberhausen; Dortmund has an Energy Efficiency Service Centre (dlze); and InnovationCity Management GmbH provides advisory services in Bottrop. In addition, some neighbourhoods have district bureaus within the Social City and Urban Restructuring in the Old Federal States programmes. Some of the bureaus have been active for years, and have implemented a whole host of measures. Due to this considerable know-how, it was decided to conduct the experiments in some of these neighbourhoods: in the inner city of Alt-Oberhausen and the adjacent district of Lirich in Oberhausen; the district of Hörde in Dortmund; and the project area of the InnovationCity Ruhr in Bottrop.

Whereas in Bottrop extensive visiting advisory services had already been provided, due to its special situation as a model city, the experience gained by the relevant institutions in Oberhausen and Dortmund enabled small private-sector landlords to be clearly identified as a group that has been addressed—and hence reached—the least in previous campaigns. And yet they make up a high proportion of building owners in the selected neighbourhoods. In Dortmund, a special need was identified to provide information to elderly female owners who rent out their property. In Bottrop, on the other hand, those people who had newly purchased a property in the project area and who had therefore missed the visiting advisory campaign were identified as a target group.

Subsequently, other stakeholders that are relevant for the development and implementation of the experiments were discussed. In accordance with the different target groups, a variety of actors and experts were invited to design and organise the experiment in the workshops that were then held independently in the three cities.

In Oberhausen, for example, a series of events was developed and implemented in order to illustrate to private landlords the synergies between their visions concerning their property and energy refurbishment. As far as content is concerned, then, energy refurbishment was connected to the topics of preserving the value of the building, rentability, accessibility, façade design and financing. In Dortmund, similar topics were discussed during an event, albeit with reference to specific properties in Dortmund-Hörde. In Bottrop, on the other hand, a special flyer was designed and is sent by the city to new owners as soon as the change of ownership is put on record at the city. The flyer informs property owners about the existing advisory services in the InnovationCity project area and the municipal support programme for energy refurbishment measures. In addition, within the project, a real estate company agreed to place the flyer in the information portfolios that it hands out to persons interested in purchasing a property in the project area. In this case, therefore, the special window of opportunity offered by the property acquisition is exploited by energy consulting to encourage a decision to be made in favour of energy refurbishment.

The accompanying evaluation revealed that, in spite of the great deal of effort involved in sending out invitations and activating people, it was only possible to reach a very limited number of people from the target groups in each case. However, those who participated in the programmes stated that they were mainly very satisfied with the offer. The experience gained in the experiment and the results generated were exchanged and discussed at a workshop involving all three cities. However, representatives from the cities, district bureaus and advisory centres reported that the number of persons reached by all means reflected their experience gained in other activating initiatives.

Diffusion and up-scaling

This second part of transformation knowledge refers to the dissemination of experience and knowledge gained from the previous phases. Diffusion asks how greater attention can be drawn to desirable innovations in line with the interests of sustainability-oriented transformation. These innovations reach higher levels via up-scaling processes, and are able to change political or societal framework conditions.

With refurbishment decisions in mind, it is interesting how agents of change motivate others, recruit fellow enthusiasts, and also gain support outside their direct environment. How, then, do agents of change interact with the system surrounding them from the base of their ‘commitment niche’—whereby in this case, the system may be the urban district, local politics, associations, the economy and the rest of urban society? Acting as individual or collective players, agents of change initially establish their innovative ideas in a small social network or build on already established networks that are not opposed to the objectives of the innovations (Leggewie, Reicher, Schmitt, 2016). These committed activists also go in search of the support of individuals whom they may activate from their own circle of friends and acquaintances or those whom they have already experienced in matters concerning voluntary involvement. As a result, they manage, on the one hand, to elude certain systemic restrictions. On the other hand, they find an innovative way of dealing with the given political, economic and social structures, and specifically exploit actors and structures that are favourable to their activities (see David & Schönborn 2014). These include funding opportunities—such as the promotion of energy-efficient construction by KfW—and regional players such as the Emschergenossenschaft. As is the case with refurbishment events, opportunity structures may also play a dominant role for agents of change, who identify and use them, and possibly even combine them creatively in order to be able to press ahead further with their innovations. Others are initially scarcely dependent on interaction with other stakeholders. Equipped with the appropriate financial resources, the entrepreneur Reimann, who was closely associated with his district, initially shaped his niche himself by purchasing the dilapidated, disused orphanage and making it more energy-efficient. In contrast, the activities above and beyond that—setting up an ‘energy nursery’ and collaborating within the urban district—must have required endless interactions with municipal players and structures.

BOX 3

Energy nursery and energy refurbishment in Oberhausen-Osterfeld

The entrepreneur and investor Heinz Reimann and his wife Doris are deeply rooted in their home town and want to preserve the impressions of their region that they had as children. The old orphanage, that had been left to decay for years, was to be demolished to make way for the construction of free-standing owner-occupied dwellings. To Heinz and Doris Reimann, the building gives the area its identity, so they wanted to prevent it from being demolished or left to decay. And so they approached the municipality, purchased the old building, undertook energy refurbishment measures (KfW 70) and sold the 18 newly created dwellings to owner-occupiers. In the course of their travels, the couple had witnessed environmental pollution and the consequences of climate change. As such, they are not only interested in the architectural preservation of their home district, but think on larger scales and time periods. For this reason, they added an energy nursery to the refurbished, car-free site of the former orphanage. The educational concept focuses on nature, the environment and renewable energies—there are solar panels on the roof and some of the toys are solar-powered. Doris Reimann established a friends' association, and the donations received ensure the further development of this form of education. Heinz Reimann embodies the ideal responsible owner of a medium-sized company who not only feels responsible for the growth of his company, but also for keeping an eye on the future of his area, nature and the environment.

Another agent of change who is committed to environmental education in Bottrop's schools must cope with very different external obstacles: she must motivate lots of teachers to become actively involved in the topic voluntarily. The main difficulty is ensuring continuation: projects that depend to a great extent on voluntary involvement need to constantly recruit and (re)motivate their supporters.

BOX 4

Networker for 'Schools of the future' in Bottrop

Nearly 15 years ago, Birgit Offert, a comprehensive school teacher and educationalist at the 'Umweltpädagogische Station Heidhof', collaborated with other committed colleagues to start encouraging schools in Bottrop to develop projects with pupils, and for pupils, that would bring environmental protection and sustainability topics closer to them in practice.

Since then, the teacher has been encouraging local schools to establish new projects again and again, and to enter these projects in the 'Schools of the future' competition for their town. The aim of her commitment: by organising these small and large-scale projects, she wants to give pupils in Bottrop a greater sense of empowerment and social participation. Birgit Offert has since developed the competition into a consistent, active network for environmental education in Bottrop. In addition to contacts to municipal facilities, including the environmental agency and the education authority, the InnovationCity Ruhr initiative launched by business enterprises in the Ruhr Area is also a partner in Birgit Offert's school network. Thanks to her commitment, film projects were created in addition to specially designed models of 'buildings of the future', which the children built using energy-saving elements (such as photovoltaics). Even though energy-efficient building refurbishment does not appear to be very appealing material for school lessons, since their effectiveness is only recognisable in the long term, the teacher can gain something positive from the topic in her innovative educational work with local pupils: most of them live in the InnovationCity refurbishment project area and, thanks to these cooperation projects, can associate the knowledge gained at school with their homes.

Enlightenment, consultancy and continued efforts at persuasion are therefore important elements of diffusion processes. Both social and institutional networks can be harnessed for this purpose by helping refurbishers in many ways to become disseminators.

Within the real-world experiments in the cities of Oberhausen, Bottrop and Dortmund described above, the question was also discussed as to whether and how the experiences and findings can be reutilised. A desire to document the process was expressed, which should give other cities the possibility to conduct such real-world experiments developed in this transdisciplinary way. In addition, the topics and content generated in the series of events in Oberhausen were also used for follow-up events. In Bottrop, the target group was extended. Now, people who purchase a plot of land with the intention of building on it are made aware of the advisory services offered in the InnovationCity in a covering letter. In addition, the City of Oberhausen also expressed an interest in providing newcomers with similar information.

In summary, in relation to transformation knowledge for achieving higher refurbishment rates, it may be useful to extend the portfolio of measures considerably to approaches that address non-economic incentives and barriers, which should therefore be increasingly applied. In spite of all the uncertainties that still exist concerning decision-making paths for or against energy refurbishment measures, it can still be concluded that individual players do not take decisions in isolation. Simply changing economic incentives by providing financial resources is not enough to drive forward the transformation to energy-efficient buildings. So far, politics has given little consideration and made little use of the many variables that influence the decisions of building owners (and hence those who actually decide in favour of driving transformation to energy-efficient buildings). One example of this is the influence of third parties in individual social networks, determined by Friege et al. (2016).

At the same time, it can be stated that, in the area of an altered user behaviour in buildings in the spirit of the objectives of driving transformation to energy-efficient buildings, transformation knowledge is not very advanced or is only rarely applied. The agent-based models developed within the EnerTransRuhr project explore this very question of the diffusion of decisions in favour of refurbishment measures and energy-saving heating and ventilation habits. This aspect is addressed in detail in Section 4.3.

Based on the findings with regard to existing transformation knowledge in the area of energy building refurbishment, the question now arises as to the appropriate strategies for diffusing and up-scaling measures and new use patterns for the successful achievement of the energy transition in buildings. What could such strategies entail? A glance at the studies shows that some assume that user behaviour has a major impact, while assuming a comparatively minor connection between the state of the building and energy consumption. Others determine a high savings potential due to energy refurbishment measures in the building sector. As a result, it can be concluded that it is advisable to pursue a complementary strategy. This means understanding refurbishment and behavioural change as a 'both-and', rather than an 'either-or' phenomenon. This is the natural conclusion if one accepts that it makes sense to implement energy refurbishment measures in the refurbishment cycle and that refurbishment rates will not increase considerably in the short and medium term. But also that the savings potential offered by altered user behaviour is limited. A change in user behaviour then becomes an approach to save energy before the refurbishment, and ensures that the anticipated energy savings are in fact realised after the refurbishment. This offers a great opportunity, particularly if this change in user behaviour can be induced at little cost.

Decisions in policy areas that at first sight have little to do with driving transformation to energy-efficient buildings can also strongly influence individual players' incentives. One important example of such a phenomenon is urban development policy. These examples show that interdisciplinary and cross-sectoral perspectives and approaches must be observed when further developing and deepening the transformation knowledge described.

4

Models for knowledge integration

In the following, we use the term 'model' to mean a simplified representation of a part of reality that defines elements and establishes relationships between them, and in this way works out the key interrelations for an issue and presents them in a structured manner. In the model presented by Friege et al. (2016), for example, homeowners, houses and refurbishment options are the 'elements'. These elements relate to each other in that homeowners take decisions on renovation options, and their implementation changes the state of houses. In addition, homeowners influence each other on account of their decision-making (see Section 4.1). Models are in principle useful tools for transformation research. However, it is not always easy for the modeller to fulfil the promises of modelling. Models can and should perform different things: reduce complexity, work out generalisable patterns, explain emergent phenomena, provide a 'language' for transdisciplinary work, assess future development in an explorative manner, act as a virtual laboratory for 'What would happen if' experiments, to name just a few possibilities. The wish list is accordingly long when it comes to modelling. A guiding principle of all models, however, is that a *model design depends on the purpose of the model* (note the singular use of the work 'purpose'). It is therefore crucial for successful modelling to clarify at an early stage what the purpose of the model is and then to take a clear line. Otherwise there is a risk of lacking in focus and of ending up developing a model that is able to achieve everything, but is of little use. In search of a useful model design, questions must be answered about the purpose of the model, the level of abstraction, and the model complexity.

Purpose of the model

In principle, models can be used for many things. Epstein (2008) lists 16 different purposes of models off the top of his head. For transformation research, Halbe et al. (2015) form three rough clusters of model purposes: first, 'understanding', second, 'case-by-case consultancy', and third, 'supporting stakeholder processes'. In the case of a transformative claim, the focus is generally less on 'understanding' in the sense of analysing certain events retrospectively and deriving explanations for emergent phenomena that are as universally valid as possible. After all, transformative research wants to look ahead and make a contribution to specific changes, rather than 'merely' have academic debates. Transformative research therefore focuses on the purposes (2) 'case-by-case consultancy' and (3) 'supporting stakeholder processes'. How a model must be designed in order to have a transformative effect depends on the setting, i.e. on the addressee of the model and the contribution it is supposed to make. With 'case-by-case consultancy', modelling is problem-driven, and is supposed to develop *scientifically based* recommendations for solving a problem for a specific context and a specific issue. In the process, the knowledge and values of stakeholders are usually taken into account, but they are not involved directly in the modelling process. One example would be developing a strategy for boosting refurbishment rates in the Ruhr Area in the context of a research project. In this case, a solid scientific basis of a model developed for this purpose is essential in order to meet the transformative claim. An inadequately substantiated model would not be taken into consideration as the basis for decision-making.

It is a different matter when the purpose of the model is 'supporting stakeholder processes'. In this case, models serve the purpose of detecting the different ways of viewing the problem, background understanding and values, and developing a common understanding of the system in a participatory process. Therefore there may not even be a basic consensus as to what the actual problem is at the outset. Hence there can be no talk of solutions. In such a case, joint modelling with stakeholders offers a transparent and precise language to create understanding. For the purpose of the model, it is often (initially) irrelevant whether the resulting model is ultimately valid in the scientific sense or simply arises from the participants' distorted perception. The model becomes transformative in that those involved talk to each other and elaborate a common view of the problem or the world—or at least clearly state the differences—creating a basis for further solution-oriented debate. The model developed can then, of course, in principle be used to consider 'What would happen if' situations. However, this has to be undertaken with great caution if the model represents the stakeholders' understanding, but is not necessarily valid.

These two observations show that the addressees' faith in the model is central to whether a model can have a transformative effect. In order to enhance trust, the state of the debate and the dominant discourse must certainly also be taken into account, particularly when addressees are familiar with the topic. For example, there is a risk that studies with basic assumptions that do not tie in with the current discourse will not be heard because they are 'filtered out' on the path towards concentrating complex and ambiguous interpretations of reality into a simplified basis for decisions. In addition, it can especially be assumed that such models contribute to a change with an outcome that contains new findings, but that does not completely contradict the previous state of knowledge. In the latter case, the model on which the study was based would no doubt initially be questioned or rejected. At least, as long as it is only an individual study that is not embedded in a more broadly rooted alternative discourse. In order to fulfil the transformative claim by means of scientifically based models within 'case-by-case consultancy', a rule of thumb would therefore be that new insight should of course be generated, without which no change can be initiated, but that the basic assumptions and model results should remain compatible with the debate.

In the case of close collaboration with stakeholders and joint modelling, on the other hand, these stakeholders must primarily have faith in the model. This means that the basic assumptions of the model must reflect their view of the world. If this is not the case, there is a risk that 'uncomfortable' model results can be ascribed to the 'wrong' model structure, and that the results of the model will be dismissed. In this case, then, the dominant scientific and political discourse is not necessarily the yardstick for the basic assumptions of the model, but the view of the world taken by the stakeholders who work directly with the model.

This orientation towards addressees, which is necessary in transformative research, can create a dilemma for researchers: how far can one's own scientific convictions be 'stretched' in order to build trust and to be compatible, raising the transformative potential of the study? When is it uncompromising to represent one's own deviating conviction in the discourse with addressees (perhaps enabling a contribution to be made to an arising alternative discourse)? And when does it make more sense to remain closer to the current debate and to steer the target group in the 'right' direction, even if one is of the opinion that the extent of movement is insufficient? With regard to these deliberations, it is essential to repeatedly strike a balance between the scientific and the transformative claim.

Level of abstraction

A model's level of abstraction is the degree to which a model corresponds to a certain real system that exists. To this effect, a model can be classified as (rather) conceptual or (rather) realistic. Conceptual models investigate typical patterns abstracted from the individual case. For example, a simple model with three rules can explain swarm behaviour without specifically being there in order to determine whether fish or birds are concerned. In contrast, realistic models illustrate a specific system. They capture more details and case-specific knowledge, and therefore offer a more exact representation of a defined system. The more details are considered, however, the more probable it is that the model will deviate from other real-life systems that differ from the modelled system with regard to these very details, meaning that the statements can no longer be transferred readily. In this respect, the differentiation between conceptual and realistic should be understood to be gradual. For transformative research, the question then arises: what is more useful—a generalisable but possibly unrealistic model or a specific but less unrealistic model? What level of abstraction is appropriate for the purpose of the model? Are there any abstractable patterns in the considered case at all that are transferable but remain specific enough to make policy recommendations? What, perhaps, is identical in Bottrop and Dortmund? And which details in case studies, and hence which differences between them, must be taken into account in order to capture the essence of a problem—even if it means that the model results are then no longer transferable?

For modelling in transformative research, the following question especially arises, again and again: 'How can I represent human behaviour?' Assumptions on the behaviour of actors are pivotal to modelling a (potential) transformation. They are also crucial for deciding which measures can effectively support a transformation. The problem here is that nobody knows exactly when and how people behave and make decisions. There are all kinds of theories about this in economics, (social) psychology and sociology, all of which are plausible in some way and yet have their weak spots—Jackson (2005) provides a good overview of the different theories. In addition, different people behave differently in the same situation, and, to make matters even more complicated, even one and the same person may apply different decisions-making strategies in different situations and at different times (Payne & Bettman 2000). As such, it is impossible to achieve a perfectly realistic model of decision behaviour in all its facets and characteristics.

However, no expedient abstraction is apparent either at first sight. The complexity of the circumstances often leads to use being made of the model of the economically rational actor, the 'homo oeconomicus'. This simple model is very much universally applicable and indeed explains in many cases a large part of the variance in the behaviour observed. However, the (justifiable) criticism of this model is very extensive, and the underlying assumptions, such as an optimal amount of information, are dubious, particularly in the areas of investigation in transformation research. People take decisions surrounded by major uncertainties in highly complex and dynamic situations. One example of an acceptable alternative that enables the key differences in the decisions-making strategies of various stakeholder groups to be worked out without creating the need to empirically record every single detail is typing actors and a preferably empirically underpinned selection and adaptation of theoretical models to describe the behaviour of the different types.

Model complexity

By model complexity we mean here how many elements and interactions a model contains and how complex its presentation turns out to be[17]. The model complexity is closely linked to the level of abstraction. The more

17 A differentiation can be made between 'complex' and 'complicated'. Even relatively simple models can create complex, dynamic behaviour that is 'not trivial', but also 'not chaotic'. In this case, however, the term is used rather colloquially.

realistic a model is, the more details are typically also included in the model, increasing its complexity. However, the model complexity does not only depend on the level of abstraction, but also on other factors such as how extensive the model design is. If, for example, a model is to be designed on the development of a city's energy efficiency over time, then it must be decided which of the relevant aspects—from the types of heating systems, district heating networks, cogeneration units, thermal insulation and user behaviour to all kinds of actors such as homeowners, landlords and tenants, energy consultants, municipal utilities and the skilled-trade sector, to sets of regulations such as the EnEV and legally binding land use plans—should be considered in the model and where the system boundary should be drawn. In order to answer this question, the purpose of the model and the addressee of the model must first be clarified. What is the central question to be addressed by the model? Who is expected to work with the model or its results, and must therefore have faith in the model? And how important is it for having faith in the model that the addressee of the model can also relate to the results it produces? A complex model can by all means become a 'black box' in which the connection between assumptions and statements is no longer completely comprehensible to outsiders (and sometimes not even to the modeller). The more complex the model becomes, the more difficult it becomes to comprehensibly explain the results on the basis of the interaction between a few factors. If, then, a stakeholder only accepts conclusions derived from a model if he is able to comprehend them, then there must be an upper limit for the level of model complexity that is expedient in this case.

Even once the purpose of the model and the addressee have been clarified, it is often not easy to draw system boundaries in a highly complex dynamic system. In particular from the standpoint of transformative research, with its interdisciplinary and transdisciplinary approach, rather a lot of factors appear to be potentially relevant. There may by all means be differences of opinion on which factors must be taken into account to resolve a certain problem, and what can be neglected. This is less problematic if the aim of the model is 'merely' to develop a common understanding. In principle, a (conceptual) model can be quite elaborately designed, with the different aspects being related to each other and the relationships being discussed. The maximum model complexity is then largely a question of the time available for the modelling. But if a model is to be used to perform simulations and enable comprehensible conclusions to be drawn on cause-effect relationships, then the model must have a manageable level of complexity. In this case, a justified selection must be made from the many potentially relevant aspects.

Another important aspect when defining the model complexity is data. From the modeller's point of view, there is never sufficient data available in practice. Although this is pretty much the case for any type of model, the situation is exacerbated in transformation research because actors play a central role. In addition to the above-mentioned diversity of theories, there are also challenges involved in describing stakeholders' actions in models on the empirical side. In order to quantify the interrelations in a model, the knowledge required becomes very specific at some point: how many peers in the network must use a transformative product before a household from the hedonist milieu adopts it: one, three or five? With such data requirements, a great deal can surely be achieved using surveys and other methods of empirical social research. However, at the stage of designing the model, consideration must be made of the data that is (expected) to be available. If the model turns out to be largely speculative, there is a risk that the addressees will not trust the results.

However, even if the modeller plans carefully, taking into account the availability of empirical data, some parts of the model will usually still not be (sufficiently) empirically supported. The time and human resources hypothetically required to clarify all questions that may arise are not usually available in transformation research. In the event of any remaining uncertainties, however, a sensitivity analysis helps to differentiate robust conclusions from those dependent on unreliable assumptions. In order to be able to make scientifically proven statements using models, ideally *all* uncertainties in the model design should undergo a sensitivity analysis. In practice, however, this ideal situation, involving not only the variation of individual parameters but also the validation of random parameter combinations and structural variations of the model, will rarely be achieved.

Keeping the model complexity at a low level is conducive to coming as close as possible to the ideal situation because the quantity of unreliable model aspects remains small.

The needle in the haystack: on the design of transformative models

Focusing on the transformative potential of models, a wide range of considerations and dependencies of the model design were discussed in the sections above. Finding the right balance between the different 'dimensions' of modelling is often a balancing act—effectively like finding the needle in the haystack of possible model designs. Modelling guidelines such as by Nikolic et al. (2013) help to structure the search process. There is no 'manual' in the narrow sense. However, guidelines can help modellers to retain sight of the big picture when weighing up all of the different considerations. As a guideline for creating transformative models, a few key points expressed in simple terms may be of use—ideal for cutting out and attaching to the monitor:

- For a model to have a transformative effect, an addressee must trust the model and the results it produces. This must be taken into account when designing the model.
- A model is not an all-in-one product. Particularly in the confusion of transformative research, a model design must pursue *one* clear purpose to ensure the model's usefulness.
- The level of abstraction and the model complexity must be appropriate for the purpose of the model. It is always a balancing act. In case of doubt: 'small is beautiful'.

4.1 Agent-based modelling as a boundary object

Agent-based modelling enables actors, their decisions, interactions and the framework conditions relating to their actions to be simulated (Gilbert & Troitzsch 1999; Heckbert et al. 2010). This type of modelling makes very few implicit assumptions on the system considered, and therefore enables different theories, empirical knowledge and assumptions about the circumstances considered to be integrated (van Dam et al. 2013). It is therefore very well-suited to capturing case-specific knowledge. Agent-based models act as a reminder in two ways: first, the necessary formalisation produces a need for precision, which refines the analysis of the system considered and the central feedback mechanisms; second, the simulation reveals the dynamics and emergent phenomena arising from the complex interactions that remain hidden in the static consideration of codes of conduct and interaction processes. Consequently, agent-based modelling also allows insights into phenomena that are often surprising, but (in retrospect) understandable and comprehensible. In this way, agent-based models foster an assessment of the potential development paths of the system considered, as well as the associated promoting and inhibiting factors and cause-effect relationships, and hence the effectiveness of intervention strategies.

As already noted in the introduction to Chapter 4, models represent an important part of the spectrum of methods relevant for transformation research. In this section, we wish to shed greater light on the various contributions made by models. We believe that models contribute in four main ways, which we will discuss below on the basis of the experience we gained in the EnerTransRuhr project.[18] Models can

- Make the debate objective
- Integrate knowledge from different disciplines in a structured manner
- Derive an overall dynamic from individual factors and developments
- Enable virtual experiments to be conducted to support the policy design.

18 For a more detailed discussion on the contribution made by models to transition research as well as related literature, see Holtz et al. (2015).

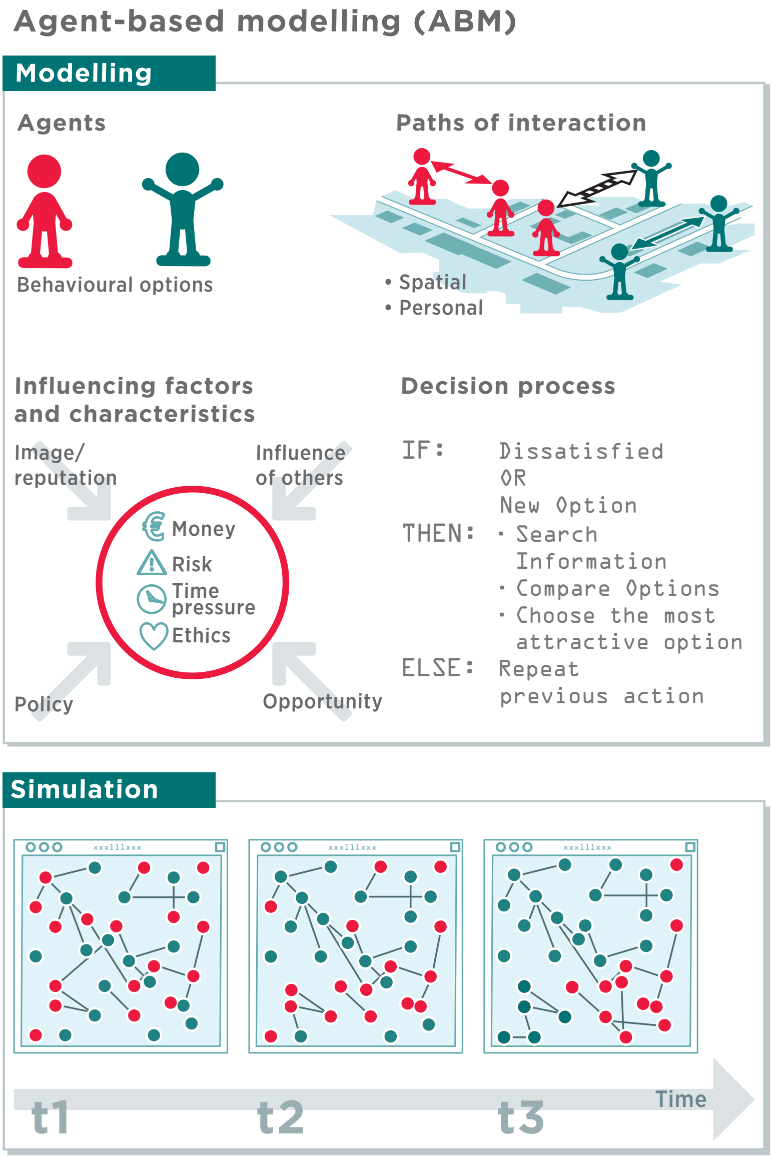


Figure 10: **Agent-based modelling**

Making the debate objective

In the debate on measures for saving energy and emissions in the building sector (including insulation and feedback products), there have mainly been two positions so far. The first assumes that no or only negligible negative trade-offs result from the measures; the second criticises the measures, arguing that they are resource-intensive and cause additional waste streams in the future. So which is correct? Are the energy savings generated by the energy refurbishment of buildings offset by the resources consumed in undertaking these measures, or is this far-fetched? How high are the energy savings and resource consumption, then, both now and in the future? With questions such as these, models help by presenting the 'facts'—or at least by making assumptions transparent and deriving logical conclusions from these assumptions by means of 'calculation'. In this way, models enable a debate to be made objective. Models enable arguments to be backed up with figures, enabling informed discussion of these arguments to take place.

In the EnerTransRuhr project, the 'RessMod' model was developed and used in order to quantify the resources consumed by energy efficiency measures, putting the debate about energy savings and resource consumption on a foundation based on facts. The RessMod model combines the agent-based models by Jensen et al. (2016) and Friege et al. (2016) with the 'HEAT' (Household Energy and Appliances Modelling Tool) model developed at Wuppertal Institute and a material flow model. The agent-based models represent actors' decisions, and the building energy model and the material flow model quantify the energy savings and resource consumption caused by these decisions. This construct offers a virtual test environment in which we are able to quantify and assess the consequences of agents' decisions with regard to refurbishment rates, net energy savings and net resource consumption.

In concrete terms, for example, the agent-based model called 'Eigenheime' (homes) by Friege et al. (2016) provides annual refurbishment decisions differentiated according to types of buildings and building components for every homeowner in a simulated city. For the actual purpose of the model—developing policy recommendations to raise refurbishment rates—it is not necessary or expedient in the actual agent-based model to record extensive information about types of buildings or building components such as the direct material consumption (for example, for insulation or new windows). However, this more specific information is required in order to calculate the net energy and resource effects of the simulated scenarios, and to assess the energy resource dilemma in an informed manner. The HEAT model closes this gap. HEAT enables numerous saving measures on the building side to be modelled in detail with regard to their direct effects on energy efficiency, their direct use of materials, and their costs. In order to ensure a comprehensive consideration of the effects on energy and resources, however, the indirect consumption of resources and energy across the life cycle of the refurbishment measures must also be taken into consideration. This is ultimately performed by the material flow model, which comprises consistent life cycle models of energy refurbishment measures, and the indirect consumption of resources and energy involved in the use of materials identified by the HEAT model. The model package therefore underpins the debate by systematically linking a broad factual basis from the social sciences, physics, engineering and materials engineering, and making it accessible to the debate.

In this respect, the bottom-up approach of our model enables us to consider issues at different levels. A virtual investigation can be conducted not only of the refurbishment behaviour of individual agents ('ant perspective'), but also of the aggregation of all or just some of the agents ('ant colony'). In the first case, research issues such as the net energy and net material characteristics of different refurbishment decisions of individual homeowners can be addressed objectively. In the second case, compliance with statutory or other imposed policy objectives (such as average energy refurbishment rates) can be determined from the sum of individual behaviours (using the same data basis). Based on this information, the energy savings and resource consumption related to different scenarios can be calculated and compared with energy and resource policy targets or simply arguments of a debate. In this respect, the insights gained using the model package are valid within the underlying assumption and parameter boundaries. However, the assumptions and the data corpus of the models can nevertheless be challenged. This is a necessary restriction of the prerogative of interpretation claim for models of all kind, which of course is also relevant for our model package. And yet models can help to drive the debate forward precisely by identifying the key assumptions and facts and deriving the logical consequences of these premises.

Integrating knowledge from different disciplines in a structured manner

As a rule, models are created in the form of mathematical equations or programming code. This necessitates the definition of variables and of logically consistent relationships between these variables (such as in the form of 'if-then' rules). In this connection, the process of creating such a formal model necessitates a higher degree of precision than is usually the case in a description of interrelations in words. People need to 'get to the point' of what is meant. If in the process a model is created involving exchange between different disciplines, the need for precision can lead to deviating meanings of words and concepts as well as implicit assumptions being detected and discussed. In a less formalised exchange, these deviations would remain undiscovered. In addition, the insights generated by specific approaches can be tied in using a model—whose formal language theoretically offers points of reference in all disciplines. The model constitutes a 'bridge', as it were, between the more specific analyses, and offers a systematic representation of the entire knowledge of the system. By integrating the partial analyses, the model enables knowledge gaps and inconsistencies to be identified—for example, if a reference has to be defined for the logical consistency and completeness of the model, but there is not (yet) any knowledge available about it.

Based on the premise that the specific fleshing out of the energy transition is influenced by very different stakeholder groups and motivations, which can only be described adequately to some extent in purely economic models, in particular agent-based models were used in the EnerTransRuhr project to perform a supra-disciplinary, integrated consideration of the energy transition in the building sector. The agent-based model by

Friege et al. (2016) on the energy refurbishment of homes enables aspects such as the decision-relevant characteristics of homeowners to be put into relation to the technical properties of different refurbishment options, the IWU building typology, the current state of refurbishment (or backlog), spatial structures of cities (for example, clustering buildings of a similar age) and policy measures, and to comprehend the energy transition in this way as a socio-technical transition. The development of the model requires exchange and discussion about how these different aspects influence each other and find expression in homeowners' refurbishment decisions. The main aim of the model was not necessarily to structure debate within the project, but primarily to act as a tool for integrating the wide range of knowledge on the topic area, mainly from the literature.

The transdisciplinary and interdisciplinary approach of transformation research offers no a priori perspective of which factors should be considered in a model, but is fundamentally open to insights from all kinds of sources. In order to identify relevant knowledge, the development of the agent-based model on the energy refurbishment of homes therefore went through several steps altogether. During the first telephone interviews conducted, a first impression of homeowners' decisions with regard to the energy refurbishment of their buildings was initially gained. The excerpts of results presented as examples in the three boxes below demonstrate the high degree of heterogeneity and complexity of such decision-making processes, and give an initial indication of factors that play a role in the decision-making process of homeowners.

BOX 5

Roof insulation to stop draughts

Karin is a 34-year-old nursery school teacher who lives in a terraced house that was built in 1949. The loft was converted for her son, in the course of which thermal insulation was also installed. She stated that high energy costs and draughts were the reason for additionally having thermal insulation installed. Her parents-in-law, who own a similar house, advised the family to undertake these measures. Since her son will inherit the house one day, economic feasibility played only a minor role in the decision. All told, it was a very easy decision to take: 'My husband decided that we were going to have insulation installed, and that was that.' They did not think about any funding schemes or support measures. They decided against having exterior insulation installed in the form of clinker brick facing for the façade for financial reasons, because they were already paying off the mortgage for the house and were unwilling to take out another loan. On the whole, Karin is very pleased with the insulation of the roof: 'There are no longer any draughts, it is significantly warmer on the upper floor and our gas bills have decreased.'

BOX 6

Refurbishment for urgent reasons

Heinz is a 69-year-old retired mechanical engineering technician. He and his wife live in a terraced house that was built in 1976. Owing to the breakdown of their heating system and radiators, there was an urgent need for action. Just one week after the heating system failed, the new boiler was installed by a fitter who had been recommended to them. Heinz installed the radiators himself. The new gas condensing boiler consumes less gas, which is already positively noticeable in their heating bills. Ideally, Heinz would prefer not to carry out any further refurbishment measures: 'It's not worth me carrying out any energy measures because I will be unable to redeem this money before the end of my life, meaning that I would have less money now.' Heinz used his current account to pay for the installation of the new heating system; he was overdraw for two months.

BOX 7

Efficiency, energy costs and visual appearance

Hannelore is a 67-year-old retired judge. Her detached house underwent extensive refurbishment measures in 2000: core insulation was applied, windows were replaced, and a new heating system was installed. Her reasons for undertaking the measures were to protect the environment, to reduce the high energy costs, to improve the poor appearance of the windows, and to replace the heating system, which was often defective. Hannelore sought advice from the Consumer Association and the energy agency 'Klimawerk'. A civil engineer friend of hers took thermograms of the building. She took out a loan with KfW Bank to finance the refurbishment measures. Since the economic feasibility of the measures was unimportant to her, she did not undertake an amortisation calculation. Altogether, Hannelore is very pleased with the measures undertaken: 'It's now two degrees Celsius warmer in the house, I now need half as much oil, and the windows look much better then before.' Since then, she has often told others about core insulation because it was relatively unknown in her community. In this way, she has already managed to persuade two of her neighbours to have core insulation installed, too.

The results of the telephone interviews suggest that a refurbishment event is required for energy measures to be carried out (such as a loft conversion, a defective heating system), and that both economic factors (such as borrowing money to have a measure undertaken, the measure is not worth while) and non-economic factors (such as draughts, environmental protection, aesthetics) play a role in the decision. In addition, communication with trustworthy peers is often a key factor in the decision (father-in-law, neighbours). These results already indicate initial interrelations, but are insufficient for deriving decision rules for the model. For this reason, based on the initial insights, in the next step taken by Friege and Chappin (2014) a comprehensive literature analysis was undertaken. One of the conclusions they drew was that the role played by non-economic factors in homeowners' refurbishment decisions has not been taken into account sufficiently in the literature so far, and has therefore also received little consideration in policy measures (Friege & Chappin 2014). Since the majority of energy refurbishment measures pay off, it is hardly possible to explain the low level of homeowners' energy refurbishment activities by purely economic factors (see Chapter 1).

In order to close the explanatory gap shown, modelling should then be used to further explore the role played by non-economic factors and, in particular, the influence of social interaction on the energy refurbishment activities of homeowners. For this purpose, use was made of existing theory on the influence of social interaction on decision-making processes for the model. In the context of virtual experiments, Friege et al. (2016) then used the model to simulate and analyse energy refurbishment activities influenced by social interaction under varying framework conditions.

An online survey of 275 homeowners was then conducted and evaluated in order to further differentiate and empirically underpin the implemented decision behaviour of homeowners with regard to the refurbishment event and the influence of certain socio-demographic and psychological factors on their decision behaviour. The results show that the transfer of ownership is usually the catalyst for the implementation of refurbishment measures. In the decision in favour of or against the implementation of thermal insulation, a differentiation must be made between the different building components (roof/top floor ceiling, outer walls, floor/basement ceiling).

The results of the survey show that the wall insulation behaviour of homeowners can be largely explained on the basis of a few variables. According to this survey, the state of the outer walls, homeowners' attitudes towards thermal insulation and their age are the main factors that influence the decision. It was not possible, based on the data collected, to derive factors that mainly influence the decision to insulate the roof or the basement ceiling. As already to be expected on the basis of the literature analysis (Friege & Chappin 2014), the data shows that the homeowner's disposable income or standard of living has no crucial impact on the decision to insulate. The results indicate that financial reasons are often personally perceived as an obstacle, but that other people with similar financial resources have had insulation installed nonetheless, meaning that there were no differences in the income distribution of those who had insulation installed and those who did not. The results of the survey were subsequently used to calibrate the agent-based model by Friege et al. (2016). In the next step, the adapted model was used to evaluate policy measures aimed at increasing energy refurbishment rates.

Throughout all of these steps of the model development, knowledge from a variety of sources is identified, factors are selected and put into relation, interrelations are refined, and the understanding created is translated into the precise language of programme codes again and again. In so doing, the process of modelling exhibits knowledge gaps, particularly with regard to the role played by non-economic influencing factors. On the one hand, these knowledge gaps presented us with a challenge concerning the specification of the model. On the other hand, however, by revealing knowledge gaps, model development makes a contribution to research, and the simulations performed helped to assess the relevance of different factors and to set priorities for further empirical research. The resulting model now represents a synthesis of a wide range of knowledge. It differs considerably in its structure from the economic logic of refurbishment decisions that dominate the debate, and therefore offers alternative starting points for understanding a backlog of refurbishment work and for policy measures to clear this backlog.

Deriving an overall dynamic from individual factors and developments

Even if individual factors of a system—such as in the model by Friege et al. discussed above, for example, characteristics of homeowners and the impact they have on refurbishment decisions, socio-economic structures in cities, and technical features of refurbishment options—have been understood and placed in relation to each other, the dynamic consequences of the interaction between these individual factors—how does the refurbishment rate develop?—is often not easily discernible. This is simply due to the fact that the human brain is not good at understanding complex systems and their dynamics, as has been proven in a wide range of experimental studies. In this case, models may help which, based on the postulated interaction between individual factors, determine system states at a later point in time (for example, in the following year) and that can also extrapolate system states over long periods by applying this approach iteratively.

In keeping with this logic, the agent-based model by Jensen et al. (2016) was used to investigate the energy saving potential or household behavioural change induced by feedback products on the city scale and with a time horizon up to 2030. The effect of feedback products such as the CO_2 'traffic light' device at the individual household level was investigated by conducting empirical research within the EnerTransRuhr project, and beforehand in the SusLab project (Liedtke et al. 2014). For example, after introducing a CO_2 traffic light device in the households observed, an average 8 per cent saving of heating energy was determined if the intervention was a success. However, merely upscaling these findings to the city level would fall short of the mark. For example, it cannot be assumed that every household installed a CO_2 traffic light at a certain point in time. On the other hand, it can be assumed that behavioural change can also occur without feedback products so that the overall effect is not only dependent on the number of CO_2 traffic light devices installed. In order to assess the potential of feedback products, therefore, not only the effect within individual households must be considered, but also the diffusion of feedback products between households, as well as the effects of (altered) behaviour between households. The model by Jensen et al. creates these relationships, and therefore enables a dynamic analysis to be conducted of the consequences of introducing feedback products at the city level. For the CO_2 traffic light device, the model calculates an (additional) energy saving potential of around 1 per cent up to 2030 at the city level. The main reasons for the difference compared to the 8 per cent observed at the household level are the assumed speed of dissemination of the products, in that a large number of households already practice shock ventilation, as encouraged by the CO_2 traffic light device, meaning that no additional effect can be expected in these households, and the assumption that the practice of shock ventilation would also continue to spread (albeit more slowly) even if the CO_2 traffic light device was not introduced. However, the exact quantification of the savings potential is not the only result of the model experiments. In fact, additional findings on the key mechanisms are of central importance. For instance, although the outlined insights into the low effect at the city level also appear to be comprehensible in the absence of a model, they only become apparent following the integrated consideration of different factors in the model. In addition, the model also contains a differentiation according to individuals' lifestyles and enables statements to be made on which individuals were persuaded to change their behaviour to what relative extent and via which channels. It also enables the effects of socio-economic structures (proportions of lifestyles and their spatial distribution) to be investigated. This forms a basis that can be used to investigate the influence of policy measures.

In the process, the integration of different individual factors from different areas and disciplines and the derivation of the dynamics resulting from this interaction generates an added value compared to purely discipline-based models. However, it also presents challenges, because creative solutions are often required where the interfaces and interrelations beyond the individual areas are not adequately defined or known. However, the model-based implementation of integration is often highly relevant for the resulting model dynamics. The crucial point of agent-based models in this regard are the action models of agents. This is where many factors from the different areas considered often come together, and have to be condensed to a decision taken by actors, such as what type of refurbishment is to be carried out or whether a feedback product is to be used. At the same time, there is no definitively 'correct' action model that modelling can draw on. Various disciplines, from economics and social psychology to sociology, offer a wide range of approaches to explain human behaviour that can be drawn on. This challenge was addressed in different ways in the EnerTransRuhr project. For the model by Jensen et al. (2016), there was virtually no empirical basis for specifying actors' models for the case considered, because transformative products are not yet available on the market and it has not yet been sufficiently explored how actors respond to these particular products. For this reason, use was made of experience gained with comparable products and, following the theory and models from the literature, simple rules of behaviour were defined differentiated into milieus. In addition, the resulting model dynamics were empirically validated using the diffusion pattern of a similar product and typical patterns of diffusion curves, and the model also underwent a detailed sensitivity analysis. A sensitivity analysis enables the robustness of the model against (uncertain) assumptions to be determined, underpinning the explanatory power of the model, as the case may be. One result of the sensitivity analyses of the model by Jensen et al., for example, is that details with regard to the spatial arrangement and clustering of milieus do not significantly influence the dynamics investigated. As long as the main structural aspects of social networks are represented true-to-life, it is not necessary to undertake a detailed empirical survey of the spatial localisation of the milieus. The different milieus as a percentage of the total population, however, are by all means relevant. It is therefore important to collect this type of data in order to be able to assess the process. In contrast, there was rather a lot of particular knowledge on homeowners' decision-making available as a foundation for the model by Friege et al. (2016). As discussed in the previous section, the model provides an added value simply by compiling this knowledge in a structured manner. The resulting model is tailored specifically to the case of energy refurbishment by homeowners. This is in line with the intended purpose, because the refurbishment backlog addressed in the model cannot be explained by more general models—particularly those that take a purely economic perspective. The specifically developed model enabled the wide range of findings from the empirical research to be harnessed. In addition, conclusions could be drawn about the cause of the refurbishment backlog by comparing simulations with the empirically observed overall dynamics.

Another challenge for the model-based derivation of the overall dynamics arises from the fact that transition processes are characterised by co-evolutionary dynamics in different areas—from technological innovations to changes in institutions, actors, behaviour, the economic framework conditions and socio-cultural structures. For longer simulation periods, the question also arises as to which model structures and parameters can be assumed to be constant over which period. In our models, we therefore only simulate for limited periods of 10 or 15 years into the future. These periods are long enough to be relevant for policy recommendations, and yet avoid misunderstandings from the outset with regard to the validity of model statements for the more distant future.

Conducting virtual experiments to support the policy design

Models can be used as 'virtual laboratories' to conduct experiments. As in the laboratory, the boundary conditions of the experiment can be controlled exactly. Beyond the possibilities provided by real-world laboratories, in a virtual laboratory even the 'insides' of a virtual test object can be closely analysed during the experiment using appropriate methods of data collection and assessment. In the model by Friege et al. (2016), for example, as well as being able to observe the aggregated refurbishment rate, one can principally comprehend for every single homeowner in which time step he takes which refurbishment decisions under which conditions. Such a virtual laboratory even enables the researcher to try out things that would be impossible, impractical or unethical in the real world. In addition, once the model has been created, virtual experiments only require a small amount of time and financial resources, which means that a much larger number and range of experiments can be performed compared to the case of real-world experiments.

One special use of virtual laboratories is conducting experiments to develop suitable policy measures. In the virtual laboratory, different policy measures can be investigated for different assumptions about current initial conditions and future context developments, as well as their impacts, so as to identify the most effective, efficient or robust measures, for example. In this context, it should be noted that policy measures are usually tested for the future and one can therefore (theoretically) never be certain that all of the factors that will be relevant in the future situation have been considered in the model. Hence any prediction of a future situation will be uncertain and the transferability of the results to the real world cannot be guaranteed, even if the model was validated using historical data. Nevertheless, virtual experiments are at least able to identify behavioural patterns that are activated by certain measures, increasing our understanding of the system and considerably narrowing down the range of potential measures before more complex field test or real-world experiments are performed to validate and specify the measures.

In the EnerTransRuhr project, the model by Jensen et al. (2016) on the diffusion of feedback products and behavioural changes induced by them (see above) was used as a virtual laboratory to investigate different measures for introducing CO_2 traffic light devices in the City of Bottrop and their effects on energy savings generated by the increased use of shock ventilation. The measures investigated included 1) the free distribution of such products, 2) conveying knowledge about these products and drawing attention to them, 3) the lending of products, and 4) the targeted mobilisation of opinion leaders; whereby the first two measures were investigated differentiated according to different lifestyles. The model results suggest that the lending of CO_2 traffic light devices may strongly support the diffusion of shock ventilation[19]. Other promising measures include the issue of devices to opinion leaders or to individuals characterised by a high social status and modern values, who have a particularly strong effect as disseminators. In contrast, increasing the knowledge—and awareness—of the CO_2 traffic light device among households with a lower social status, for example, has virtually no impact because these individuals orientate their decisions more closely to their environment, and increased awareness does not lead to the use of the CO_2 traffic light device as long as they are not already being used by a sufficiently large number of other households.

Using the empirically calibrated model by Friege (2016), simulations were made of the effect of policy measures aimed at increasing homeowners' energy refurbishment activities. Owing to data availability, the model

19 However, the model results are based on the assumption that CO_2 traffic light devices are returned after a period of three months and lent out to other households, and that the household learns how to practise shock ventilation and is in principle able to practise it in the future. However, there is a further need for research, particularly with regard to the 'relapse rate' following the return of the CO_2 traffic light device.

is limited to simulating homeowners' decisions concerning whether or not to insulate the outer walls. It investigates the impact that intensified consultation has compared to obliging homeowners to refurbish the building at the time of the purchase. Since, according to the survey, economic factors only play a minor role in the decision to insulate, or no role at all, it was not possible to represent the potential effect of financial support in the model.

The effect of consultancy was represented in the model via a positive effect on homeowners' attitudes towards thermal insulation. Since attitudes influence the decision to have wall insulation installed, the advisory approach leads to an—admittedly small—increase in insulating activities among homeowners in the model of 7 per cent at the most (from 1.4 per cent to 1.5 per cent of outer walls). In this respect, a consulting drive is preferable over a long-term consulting campaign.

Mandatory refurbishment measures in the context of a house purchase are currently limited to replacing old boilers, and insulating top floor ceilings, roofs and heat distribution pipes in rooms that are not heated[20]. There are no discussions at present about any further obligation to refurbish existing buildings. If this issue is raised, attitudes are often shown to be hostile to the perceived dictation. However, linking the obligation to the window of opportunity of the transfer of ownership also has its advantages: in this way, the knowledge of any refurbishment measures that may have to be undertaken can be included in the decision to purchase the house beforehand. As a consequence, the market value of houses without wall insulation is expected to decrease (roughly in line with the cost of installing wall insulation). Since transfers of ownership are registered at the land registry office, it is also easy to check whether the obligation to refurnish has been met.

It would be virtually impossible to test such a regulatory measure in a real-world experiment. In this case, the connection to the virtual experiment of the agent-based model offers an extended testing ground. Encour-

20 Whether a building has to be refurbished depends on the age or energy performance of the building. The statements refer to the current version of the EnEV 2014.

aged by the survey results, the important window of opportunity of the transfer of ownership in the model was linked to the obligatory installation of thermal insulation at the time of acquiring the property, depending on the age and state of the outer walls. Based on the simulation results, the activity of insulating the outer walls increases considerably in the event of an obligation to do so: by almost 60 per cent, taking into account the condition of the outer walls and the number of transfers of ownership (from 1.4 per cent to 2.2 per cent of walls). Altogether, the energy refurbishment rate would then increase by 40 per cent[21]. Although this does not yet equate to the desired doubling of the energy refurbishment rate, which currently stands at around just 1 per cent, it would be a big step in this direction.

It usually takes a long time to negotiate and implement policy measures. And the measures do not always lead to the desired outcome, or unexpected accompanying phenomena occur over time. In the model, on the other hand, successes and consequences can be tested in fast motion, as it were. Different variants of individual measures can also be evaluated, in order to support the most efficient design possible. In addition, measures that are unlikely to be introduced can be modelled if their impact assessment is of interest for other reasons. But it goes without saying that there are also limits to the explanatory power of models.

4.2 Opportunities and limitations of agent-based modelling

Hannah Arendt equates 'taking action' to adding one's own thread to a fabric that has been created by others (Arendt 1981, p. 174). Both 'reflexive transformation research' (Dickel 2013, p. 17) and innovation research seek and investigate this joint between the individual and the system, and explore how social innovation emerges and spreads. The focus is on innovative social practices that emerge due to civic commitment, for example,

21 The energy refurbishment rate comprises the number of thermal insulations carried out in roofs/top floor ceilings (30 per cent), outer walls (55 per cent) and floors/basement ceilings (15 per cent) (IWU 2010).

and that initially spread at the local level. These innovations, usually of a social nature, are devised and established by agents of change. They contribute to the success of the energy transition by breaking existing routines and identifying specific alternative courses of action in everyday life. Due to their social proximity, they are recognised as being trustworthy and credible interaction partners (Mautz et al. 2008, p. 68).

Research into such complex social processes can only be conducted via interdisciplinary cooperation. Qualitative and quantitative research methods should be integrated in order to reliably answer questions concerning under which conditions this innovative commitment emerges, which societal effective force may come out of civic commitment, and which obstacles active players come up against (Leggewie 2012, p. 12). In the study design we selected, qualitative interviews and participatory observation[22] lead to the formulation of reliable hypotheses that are then checked to see whether they can fit into agent-based models as if-then relationships. If this proves practicable, scenarios can then be modelled. These models are intended to illustrate and assess (model) responses to changes in constellations of stakeholders or systemic factors. However, not all observations and data are equally suitable for agent-based modelling. Unique individual cases and events such as the specific mental disposition of an agent of change can only be modelled with little precision. Modelling is more appropriate for probable responses to certain characteristics of the innovative acting stakeholder, such as in the agent's network. The more spontaneity and creativity are important criteria for the stakeholder's actions, the more error-prone the model will be. The question therefore arises as to which aspects of the individual case observed in qualitative studies can be disregarded and analysed using (quantitative) agent-based models with regard to their effects in the system. We will consider this question in the present section using the example of agents of change. This will involve considering the different key characteristics of agents.

---

22 The results of the ethnographical research on this project can be found in the book: Leggewie, C; Reicher, C; Schmitt, L (Eds.) (2016): Geschichten einer Region. AgentInnen des Wandels für ein nachhaltiges Ruhrgebiet. Dortmund.

Implicit and explicit innovative practices in the model

Experience from fieldwork has shown that the differentiation between implicit and explicit agents of change is not just a heuristic differentiation, but has a strong influence on the scaling potential of its influence. This differentiation is therefore a characteristic that must be considered if one wishes to understand the role played by an agent of change in the overall system.

Implicit agents of change—as they are understood in connection with sustainability-oriented transformation—primarily pursue other goals than that of ecological sustainability. They may be intentions that are inherent to the individual—such as pursuit of gain, the fulfilment of an aim in life or a career goal, or the accumulation of symbolic capital within one's neighbourhood. For example, ecological sustainability occurs as a positive external effect of integration measures for asylum-seekers. The 'project' undertaken by the implicit agent of change then becomes more strongly compatible with individuals and groups of persons who are not (yet) interested in the topic of sustainability or who even feel put off by this motivation to act for ideological, aesthetic or emotivist reasons (Stevenson 1975, p. 139 ff.). In cases in which agents of change implicitly present new sustainability-oriented practices, the visibility of the innovation potentially increases due to the possibly wider target group (Rogers 2003, p. 258 f.).

In contrast, explicit agents of change have a powerful influence on sustainability-oriented groups of persons because they exude authenticity due to the congruence of motivation and action. They are perceived as persons who act virtuously. For this reason, their innovative idea is especially compatible with people who have similar or identical sustainability goals. Rogers proposes that compatibility is a factor that can be used to measure the probability of innovations being adopted (Rogers 2003, p. 241 ff.). Compatibility is a gauge for the reconciliation of the innovation with previous experiences, standards, values and needs. Explicit agents of change find it easier than implicit agents of change to disseminate their new practice among ‘potential adopters’ (Rogers 2003, p. 233) because, although they must communicate persuasively with regard to the innovation (Rogers 2003, p. 174 f.), they no longer need to substantiate or justify their action themselves.

Implicit and explicit are opposites which, first, do not occur empirically in the respective extreme position and, second, are not noticed by the acting individuals—at least when they first become established. But it can be assumed that the establishment and diffusion of the agent’s innovative idea has a greater chance of success if the agent acts ‘implicitly’ and therefore offers a projection surface for different charges of significance by potential emulators.

The differentiation between implicit and explicit agents of change can be represented directly using social networks. On the basis of empirical observations, implicit agents’ success appears to be based on their special role in the social network and their impact within it.

From the standpoint of research on social networks, an implicit agent of change is particularly good at diffusing innovations by acting as a ‘broker’ between social groups. Such a broker mediates between groups, making it easier to mutually transfer knowledge and innovations. An explicit agent of change appears to tend to (socially) address a smaller circle of persons within a city. Due to the direct link to an explicit goal (and the relevant values), these agents will tend to address a more homogeneous group of people who also tend to maintain social contacts in other circles similar to theirs, even without the agent. In contrast, an implicit agent of change potentially has more diverse, i.e. heterogeneous, social contacts due to the possible variety of commitment priorities. In all probability, these typically extend to different social groups (Burt 1992). The broker’s stronger influence can also be seen in practical examples of agent-based modelling (Katona et al. 2011). Such modelling enables an agent’s additional mechanisms of influence to be identified: for example, although an agent exerts a very strong social influence if he has a broker role, this can diminish as his number of social contacts increases. This could be due to the fact that an increase in contacts results in them becoming weaker, meaning that individual agents then tend to exert less social influence.

The observed difference in powers of persuasion between implicit and explicit agents of change can also be attributed in part to reactance: 'Merely by virtue of the fact that a certain behaviour is promoted from the outside, this very behaviour becomes less attractive' (Schwarz 2007, p. 414). According to this approach, then, reactance can inhibit agents' powers of persuasion. Explicit agents of change in particular run the risk of invoking reactance owing to their clear position, but may, in contrast, result in an even better reception among like-minded people. In innovation research, people's spontaneous and partly active resistance to an innovation can be subsumed under the role of 'resistance leader' (Kiesling et al. 2010). Such leaders have a particularly negative attitude towards an innovation, and are able to considerably impede its dissemination success. One example of research is the effect this resistance has on product acceptance (Moldovan & Goldenberg 2004). In this way, consumers' response to advertising campaigns, for example, can be modelled—dependent on the timing of these campaigns. One outcome of such modelling is, for example, that mere advertising for an innovation (that is, before it has reached a certain diffusion rate) can create resistance, which can ultimately impede the diffusion of the innovation. In contrast, activating agents of change that have a positive attitude towards an innovation in combination with widespread advertising for an innovation may achieve a better diffusion of innovation.

The ability to model failure

When investigating agents of change, one does not always come across constantly successful innovative commitment—agents of change may also experience failure. Resources are required to ensure the consistent continuation of their commitment. In this case, resources are not necessarily of a financial nature, but primarily psychological and social resources, and time management.

One agent of change who was accompanied within the fieldwork encountered understanding on the part of his employer for his non-work activities. In other cases, however, we observed an acute overtaxation in the reconciliation of involvement with professional and family life, as well as an excessive amount of tasks within the involvement, which led to the agent giving up his commitment. External expectations increase almost in proportion to the resource expenditure for the commitment—up to the point that the commitment is perceived as a substrate for governmental action, like a removal of responsibility from society, the state and politicians (Nullmeier 2006, p. 176). The project is then often no longer able, through verbal appreciation alone, to evoke sufficient response[23] in order to maintain the commitment. And yet response is an important psychological resource that is necessary with regard to the motivation of implicit and explicit agents of change for maintaining commitment that is not motivated by monetary factors. But if other services are requested or broached that differ to those intended by the committed actor, then his motivation will even decrease if these are rewarded symbolically. The individual influence factors are therefore upper load limits and sufficient positive response.

To what extent can such obstacles be integrated in a model?

Such individually varying factors can be modelled in principle. In the process, however, special consideration must be given to the distinct differences between agents of change.

Overtaxation is quantifiable to some extent. The key to this is, for example, generalisable limits on the active working hours available per day. If a limit is exceeded on a long-term basis, the likelihood of acute overtaxation will increase accordingly. Although acute overtaxation is virtually impossible to predict in individual cases, general patterns can nevertheless be determined (Soares et al. 2007), which can be used accordingly in a simulation model as if-then rules.

Although confirmation through response can in fact be modelled, it is exceptionally difficult to determine in individual cases. Just like the activity of a real agent of change is dependent on positive response, the activity of a modelled agent could likewise be made dependent on it. It

23 Within the meaning of Hartmut Rosa as a world and self-relation in Rosa 2016.

would be possible to express this dependence in the model as a function of response. Response, in turn, can be operationalised as the number of people in the agent's environment who adopt his innovation. The requirement, however, would be the ability to determine this dependence empirically beforehand.

These two examples show that influencing factors on agents' actions can be modelled in principle, but that the exact data situation and representation in the model may present difficulties. It therefore appears expedient to, first, base modelling closely on direct empirical observations. Second, such a model uncertainty can lead to a simulation model being applied for explorative reasons rather than for predictive purposes: instead of performing concrete estimates with the model, the consequence of assumptions should be investigated (Brugnach & Pahl-Wostl 2008).

The emergence of agents of change in the model

Citizens become agents of change under certain circumstances; it is not purely coincidental. This is also the case with regard to their commitment. If, then, a researcher would like to incorporate the emergence of these special actors in an agent-based model, these conditions of their emergence must be well known. From which of their life situations do their innovative ideas occur? What are their motivations, or to which problematic situations is the innovation a response? Which constellations of a social network facilitate this phenomenon? With an implicit agent of change, orientation to sustainability, for instance, is not a primary motivation.

The findings from the fieldwork are ultimately unable to name a point in time and a singular reason for the emergence of innovative commitment. What remained were individual isolated cases in which biographical coincidences also played a role, which should not be underestimated. The picture is diffuse. It cannot be said that the motivations invariably come from global contexts and that people began to be active from a determinable greater wealth of information about the hazard potential of a scarcity of resources or climate change. The driving forces mentioned by committed individuals included not only their own good life in a neighbourhood community, but also involvement in achieving more abstract goals within an entire region. No universally valid statements can be made about the conditions of the emergence of agents of change. These can only be described in qualitative terms for the relevant case under investigation.

How can such a phenomenon be integrated in an agent-based model?

Although it is possible in any case to cause agents of change to emerge in a model, this emergence must be made to depend on explicit conditions. Ultimately, in an agent-based model, the emergence of an agent of change must be defined as a specific if-then rule. If empirical insights are lacking during the definition of this rule, then this may well occur at the expense of the realism of the model.

An alternative source of modelling to empiricism would then be tested theories. In the context of the diffusion of innovations, this is the theory of Rogers (2003), for example. The concept of the agent of change is similar to that of the opinion leader in Rogers. Opinion leaders are characterised by being above-average with regard to the following properties: *external communication, accessibility, socio-economic status* and *innovativeness*. In this respect, these properties can be used, for example, as factors that make it more probable that a person will emerge as an agent of change. With this approach, modelling would probably be limited to having a random number of agents of change emerge in a population. Which persons these would tend to be could then indeed be modelled (qualitatively) in accordance with diffusion-theoretical approaches (such as by Rogers). However, it would clearly be uncertain how many agents—and exactly which ones—would be active as agents of change for how long. In other words, although it is technically possible to model the emergence of agents of change, fundamental uncertainty surrounds this procedure.

It is important to only interpret such an abstract, relatively unreliable model in the frame in which it is valid. An agent-based model that is only able to represent the emergence of agents of change unreliably should of course not be used for forecasting such an emergence or for predicting the frequency and duration of their activity. The emergence of possible opposite initiatives is virtually impossible to represent with an empirical basis either. However, it may nevertheless be very useful in order to be able to make other statements or to limit probabilities: assuming a certain number of agents of change would become active, a model would be able to estimate what effects their activity would tend to have. This effect can ultimately depend on the properties of opinion leaders (based on Rogers' theory) that can be modelled and the empirical findings on implicit and explicit agents of change.

Altogether, therefore, the more individual these persons' behaviour is, the more difficult it is to transfer agents of change to the agent-based model. Nevertheless, the interaction between qualitative, ethnologically oriented methodology and agent-based modelling proved to be extremely fruitful. Valid data can be collected simply by conducting participatory observation, interviews based on relationships of trust (Girtler 2002, p. 147 ff.) and a survey of the respective agent's environment. The discussions with the social environment validate the agent's statements or reveal contradictions. This data, collected using open and qualitative methods, can be included qualitatively to a large extent in agent-based models. In the project, we specifically undertook this by testing policy scenarios that use the influence of agents of change in the simulation model.

4.3 Breaking habits – interaction between user experiments and agent-based modelling

'Prediction is very difficult, especially if it's about the future'—although this citation (usually ascribed to Nils Bohr) has already been heavily used in the past, it still describes the central research question facing transformation science. On the one hand, it is clear that behavioural change, particularly in the area of energy in buildings, can make an important contribution to the future achievement of climate objectives. Energy-saving behaviour can reduce building energy consumption by up to 30 per cent, and is possibly the most cost-effective saving option that does not cause too many rebound effects (Wood & Newborough 2003). On the other hand, it does not appear to be clear from the start how this behaviour will be developed in future under one policy or another—or which policy measures are best suited for promoting energy-saving behaviour. However, the examples in the previous sections show how important and useful scenario statements about the future can be. For example, the prediction whether environmentally friendly heating behaviour will spread within a society of its own accord or whether it would be better to intensively promote measures addressing this behaviour can be highly relevant for policy, even today.

How to predict intervention effects

We are specifically interested, for example, in whether a 'classic' feedback device is more suited than a 'transformational product' (Hassenzahl & Laschke 2014) to change heating behaviour (i.e. heating and ventilation). Whereas the former mainly offers information about the effects of one's action (such as changing the room temperature or energy consumption) in specific situations, the latter creates 'friction'. In other words, it specifically attempts to 'break' habits, exerting a much greater influence on an individual's free choice. In addition, it provides information—albeit related much more specifically to a certain situation (such as ventilation)—and it attempts to make the more sustainable option for action attractive using emotional motivational elements and psychological basic needs (such as proximity). Whereas a simple feedback device displays the current temperature and the air quality in the living space, including the associated energy consumption, it would be more difficult to create a conceivable transformational product such as opening the window by 'friction' if the CO_2 value, i.e. the air quality, was still displayed as 'green' or if the heating was not switched off beforehand.

A growing number of publications now readily dare to make such predictions by measuring the effect of interventions in energy-saving behaviour as a simple difference in randomised experiments (Osbaldiston 2013). But is social life truly so simple to be able to accurately predict a similar future development in whole societies using effects produced in a number of people in a number of households, almost under laboratory conditions?[24]

The following question arises: how valuable is the approach of merely conducting empirical observation when policy interventions are to be designed? What added value do complex agent-based models have in this context? And would they not have to be examined more closely beyond the propagation of the modelled technologies, including their specific effect, i.e. the energy and resource saving potential?

We wish to explore these questions by investigating in greater detail the interaction between empirical experiments on behavioural change and agent-based modelling, to be precise, using the example of the effects of different experimental interventions on individual psychological variables related to different people. The measured results generated from the user experiment are incorporated into the model for estimating altered heating behaviour, which represents the diffusion of the products and the altered behaviour in the group of modelled agents. Integrating user experiments (real-world field experiments in a few households) into a model (a hypothetical virtual experiment in many households) enables us to discuss how empirical experiments benefit from virtual experiments, and vice versa. Although specific challenges of integration become apparent at some points, interfaces are also identified at which real-world experiments (empiricism) and virtual experiments (the simulation model) are complementary.

How empirical experiments benefit from virtual experiments – theories as a requirement for universally valid experiments

Let us assume that a simple randomised laboratory experiment came to the conclusion that simple feedback has a stronger effect. We would communicate to policymakers a simple probability of behavioural change as a recommendation for action. But what if only students took part in the experiment, students whose need for autonomy is so great that they per-

24 This question is particularly legitimate if the criticism by Angus Deaton, the 2015 winner of the Nobel Prize for Economics, concerning the supposed methodological superiority of experimental designs is taken seriously (Deaton 2009).

ceived the transformational product to be too restrictive—but in reality the majority of the population had in fact changed their behaviour? In order to overcome the problem described above, experiments must first be conducted involving a representative sample. But still one would be faced with a problem that the cited experimental literature is often unable to overcome: the simple empirical observation of experimental effects it is still far from producing a prediction for the future.

In the absence of clear, monocausal correlations, which define social life, a relative prediction—i.e. a probability statement—can be considered as the best possible statement concerning future developments. Within the history of science, it has become established convention to derive such statements from statistical models of causal interrelations between variables—i.e. from a (quantitative) model. In this case, the most important assumption for the predictive or forecasting powers is that there are such good observations (from the past), in principle at least, that the future can be predicted from them to a large extent. And yet how do we know that the sample was in fact representative—with regard to the characteristics that are crucial for the magnitude of the effect? Moreover, how sure can we be that a mere coincidental detail of the experimental design did not cause the effects (or a detail that was not considered in the experiment) and that exactly the opposite will occur in reality? If we assume that interrelations observed in the past will also have some explanatory power for the future too, we must first postulate a theory about these interrelations in order to know the circumstances under which similar observations can be expected in the future.

An agent-based model makes theories empirically verifiable

An agent-based model embodies such theories. It models very specific theoretical assumptions that can be tested empirically—in this case about the mechanisms of human behaviour and about the behavioural patterns of different interventions. Summarised briefly, we define behaviour as the combination of actions from different motivations at the individual level, which differ from person to person. These include the social norm, rational values and psychological basic needs and emotions. In certain situations, then, specific combinations of these individual characteristics come to light and generate behavioural patterns, one of which is habit. In contrast, we understand interventions to be the targeted external changing of either these characteristics or the benefit that agents gain from certain courses of action according to their characteristics. Feedback on air quality in the room, such as in the form of a CO_2 traffic light device, could make the 'shock ventilation' option more attractive in the specific situation of 'ventilation' if the user prefers to keep the traffic light on green.

In concrete terms, such psychologically more detailed theories were used to add parts to the model by Jensen et al. (2015) that enable different effects of different combinations of interventions on different agents to be modelled. How and why do people change their behaviour? This mainly occurs on the basis of the 'consumat' model (Jager et al. 2000): agents gain a certain utility from a certain behavioural option according to their psychological characteristics. As long as this advantage remains above a threshold in a certain behavioural option, they will repeat this option again and again. Based on an optimisation algorithm, agents only then actively decide (again) if they fall below the threshold. They are therefore 'captured' in repeat or habit mode, even if their attitudes towards the repeated behaviour (slowly) change. Interventions such as the transformational product are not only able to change preferences (causing them perhaps to fall below the threshold for the first time in a long while), they are also able to 'force' agents directly into certain action modes by making repetition 'more difficult' and demanding an active decision.

Combining different theories in such an agent-based model therefore delivers very specific predictions that can be verified in reality—namely far beyond a simple experimentally measured difference between the control group and the test group. We want to monitor the best way to change people's behaviour. On the one hand, one can simply disturb behaviour such as by reducing room temperature if it is too high. Then again, one could draw on emotions and norms to bring comfortable temperatures closer to energy-saving heating. In this case, agents want to consciously change their behaviour, but are not forced to do so. For example, the model predicts that habits will not change even there is a great motivation for an alternative behaviour unless a different cognitive schema is activated—that is to say, a conscious decision as opposed to subconscious repetition. It can also be assumed that transformational products are particularly suitable for simultaneously changing the mode of behaviour in favour of a conscious decision. The agent-based model describes all of these interrelations in quantitative terms. By estimating the relevant parameters and the associated error terms, statements can be made about which properties households would have and which particular interventions have a particularly good or poor effect. Many more general hypotheses can be tested—beyond the laboratory situation.

In other words, in contrast to a mere experiment, a model may be capable of combining the theory with empiricism such that the complexity of transformation processes is taken into account to the greatest extent possible. Concerning the contribution a feedback product makes to achieving climate and resource targets, for instance, it is of no small importance whether this will have a much smaller effect if it continues to be disseminated, because all those who were about to change their behaviour have already been reached. In this case, theories help us to include the corresponding control variables in the explanation of the measurement results, contradicting the specific assumption that this feedback product is 'better' than another intervention.

Achieving more efficient empirical analysis through model-based approaches

In addition, agent-based modelling enables empirical work to concentrate on certain crucial patterns. For instance, the model developed predicts structurally (independently of the relevant parameter values) that the intensity with which the respective intervention is forced from the repetition heuristics to the decision heuristics will be the key property of interventions ('sensitivity' of the behavioural variable). However, it also points out that this intensity may be at odds with agents' needs for autonomy. It might therefore be that an intervention then completely destroys existent motivations in favour of new behaviour. The model therefore enables us to understand better which interaction, which intensification and which conflicts arise between the intervention in behaviour and the self-motivated change in behaviour. Does an external intervention make a behavioural change easier or is it counter-productive? This is then dominant for the design of the experiment or its groups, which should preferably cover the maximum possible variance of these intervention variables in particular—so that precisely such hypotheses can be examined in a valid way. In this way, focusing on the calibration of a specific model also enables the experimental design to be shaped more efficiently because, in the best possible case, the very variables that are necessary to make a convincing prediction will indeed be measured.

Systems of equations versus agent-based models

And yet where does the added value of such a complex agent-based model lie compared with a simpler system of equations? For example, a simple equation could describe a linear relationship between behavioural change and the social norm. The higher the social norm and the more urgently friends and family members suggest a change in behaviour, the sooner one's own behaviour will change. The behavioural patterns behind an experiment could be described in exactly the same way. There would be a lot less uncertainty in the formulation of the model and, by the same token, it may be possible to empirically justify a simpler approach because far fewer variables would have to be measured.

Agent-based models can be regarded as particularly expedient in the area of transformation science because they have the possibility to explain the complexity of social life within the model, rather than having to accept them as being externally given variables at any given point in time (i.e. constant): it is of elementary importance to transformation, for example, that the characteristics of individuals that are crucial for their behaviour do in fact change—such as by way of policy interventions. What is more, it is probable that agents will not only respond very differently to interventions, but that behaviour will spread among agents in different ways—for example, as a social norm within individual networks that are structured very differently. What interventions do people talk about? Which intervention encourages not only the user of feedback products to change his behaviour, but also his friends and acquaintances to change theirs, too? Agent-based models represent a particularly profound attempt to fruitfully combine 'understanding' the complexity of social life with 'explaining' it by means of theories and models, in order to ultimately be able to estimate the effects of policy measures. One (single) system of equations, as used often in empirical social and economic research, would have great difficulty representing such dynamics that differ from agent to agent.

How models benefit from empirical experiments

Empiricism can, then, benefit from modelling. Conversely, it was also possible to support modelling decisions empirically. Of course, adapting the model to data follows the assumption that 'science is but an image of the truth' (Bacon 1620). Such a method, therefore, does not question whether, but which type of empirical foundation the best possible 'image' or reality requires so that the scenarios it delivers can serve as an appropriate basis for policy interventions. However, many agent-based models can only generate meaningful patterns for very limited intervals of the individual variables, particularly if they represent the diversity of social characteristics that are relevant for energy and resource consumption. To what extent can heating behaviour, then, be explained better if complex models are additionally adapted to reality? We will discuss this below on the basis of our example of heating habits, which will first be explained briefly.

Modelling habit

The ability to model habit is particularly interesting for our agent-based model of heating behaviour. A central aspect of habits is that they occur automatically in specific situations. As portrayed in the model by the threshold, people can be 'captured' in their habits, which they in fact (rationally) no longer even support. One way in which to explain this is that, in the same situation, the same behaviour is repeated that was perceived to be satisfactory, particularly with regard to our basic needs, spontaneous reflexes and, not least, emotions. The more frequently, then, a behaviour is repeated, the more these more unconscious motivations play a role compared to more conscious values systems, for instance. The current option for action is therefore charged with utility. On the one hand, this makes it more difficult to break the automatism, i.e. overcome the threshold. On the other hand, however, this additional utility would also continue to exist in the case of a conscious decision to break the habit—alternative courses of action then appear to be less beneficial simply due to the constant repetition of the current behaviour.

As such, habits also have effects on agents and their (psychological) characteristics. People retrospectively adapt their value system to their behaviour ('dissonance reduction'; Festinger 1954). It could, for instance, be the case that, simply due to a quite strong intervention ('windows may no longer be tilted open'), repeated shock ventilation would at some point result in the agents' attitude approaching the threshold so that environmentally friendly behaviour also ultimately continues to exist without the intervention[25]. This is particularly important because the intervention encourages learning, as it were, and helps to develop a behaviour that ultimately no longer requires the intervention. Its aim is to make itself superfluous. With a view to a resource-conserving change in heating practices, this is a very valuable consideration.

Adapting agent-based models to data

Such a theory could now be modelled at different levels of abstraction and complexity. The simplest model is a mere comparison of effects without any consideration of the underlying mechanisms, i.e. without in fact being able to explain the observed changes. In addition, one could define a single function for all habit processes; their usefulness would increase in line with the increase in the number of repetitions of the same behavioural option. A reduction of possible influences of certain interventions from the start would also be conceivable: in this way, one could already theoreti-

25 For a good overview of the psychological mechanisms behind habits, see Verplanken and Wood (2006).

cally exclude 'classic' feedback via 'rational' information having an effect at all. However, this shows that such purely theoretical formulations are subject to a certain arbitrariness: in principle, a model is also able to reproduce a certain behaviour (by chance), even if the underlying assumptions do not accurately describe reality. The prediction could be accurate at this moment in time, but could be thrown into disarray the very next day due to all kinds of underlying effects that then appear to be random[26].

In contrast, in the first step towards greater empirical foundation it is possible to adapt an agent-based model to empirical patterns by means of 'pattern-oriented modelling' (Grimm et al. 2005). The parameter values and model structure of an agent-based model can be varied, whereby tests are performed to check whether a certain (observed) behaviour is produced by the model. In certain respects, therefore, pattern-oriented modelling connects the generalised data from empirical experiments to an inverse calibration of models. This method helps, then, to find abstract model rules that can explain the observed reality.

To ensure that not just any agent-based model can do justice to this indirect calibration, it is important to reproduce the 'occurrence' of several empirical patterns at the same time. If only one type of observation were used, potentially numerous models would be capable of reproducing this target value. If, for example, this parameter was a certain percentage of users of a product five years after its commercial launch, then almost any diffusion model would be suitable for reproducing these patterns by way of parameter variation. In addition to the percentage of users, therefore, the grounds for adoption (influence from social contacts or merely information), the degree pf satisfaction with a new product, or the length of product usage, for instance, could also be recorded empirically and used as patterns. Only this quantity of patterns would truly 'filter' which models could constitute potential explanations of reality. Models with too

---

26 In this case, reference is made to 'overfitting'. In simple randomised experiments (without underlying models), we do not observe systematic patterns of the error terms that point to such problems of unobserved heterogeneity or endogeneity in a regression, i.e. in a simple system of equations. As a result, unobserved third variables are described which actually appear to be responsible for the effect and can reverse the causality, i.e. the direction of the effect.

restrictive degrees of freedom (i.e. too simple explanations) would then no longer be accepted as potential explanations. Conversely, overly complex models could be rejected because they are unable to reproduce all of the necessary patterns. The by all means complex agent-based model constructed for our case of heating and ventilation is initially sufficiently general that different combinations of parameter values could result in the same behaviour pattern. A change in behaviour, for example, could be due to a shift within the conscious decision, or to the threshold between repetition and decision mode being exceeded. Exceeding the threshold, on the other hand, could be a result of a low threshold or of the agent's characteristics which are closer to the threshold.

As such, the agent-based model outlined here constitutes a further step towards a more detailed adaptation of models to data. After all, in our case, it is possible and expedient to undertake a direct estimate of specific parameter values from the data in addition to structural model decisions (which level of abstraction reproduces the empirical measurements best?). It is therefore a matter of pattern-oriented modelling at the parameter level, and hence frequently direct calibration. An overly complex model could then be rejected if it only explains the overall change in behaviour, but fails at the level of individual function values (such as the increase in habitual use with every repetition). Conversely, we reduce the risk of having too simple model structures by initially being able to reduce very complex functions (for example, thresholds dependent on all agent properties) according to the empirical significance of individual correlations. In this way, the maximum potential volume of experimental data is then used to achieve the best possible prediction of behaviour.

The example of user experiments – the possibilities and limitations of interaction between an experiment and modelling

And yet what is an efficient strategy for empirically underpinning such a model? In the following, we would like to find out exactly which experimental data is required to achieve this. Time series data would actually be necessary to be able to model the effect of feedback products in a structurally correct and realistic manner. After all, even a model of individual behaviour without intervention would theoretically be dependent on being able to observe the same individual with different behaviours. Statistical methods also enable this difference to be calculated from cross-sectional data from surveys up to a certain degree. But if the effects of interventions are now to be measured, this becomes more difficult[27].

Field experiments are ideal for collecting this time series data. They are used to test interventions in households that really exist. In this case, an exact estimation can be made of how quickly an effect occurs, and whether and when certain participants in the study perhaps revert back to earlier behaviour patterns. However, since the development of such prototypes is expensive, particularly at the early stage, and therefore only very small samples can be recruited, field experiments involving new interventions are only possible to a limited extent. In our case, it was possible to develop a feedback prototype and to incorporate it in the field test. The field experiment followed the three-phase design of the Living Lab research based on Liedtke et al. (2015). In the first phase—insight research—12 households in Bottrop and Oberhausen were asked about their heating habits in face-to-face interviews (concerning the results, see Buhl et al. 2016, Baedeker et al. 2016, Liedtke et al. 2014)[28]. The descriptions of those interviewed and the observations made by the interviewers during the insight research formed the basis for the development of the prototype in the second phase (see Figure 11). Using knowledge of the aesthetics of friction (Hassezahl & Laschke 2015), a feedback design was developed from a number of draft concepts that received information from previous investigations. This feedback design combines moti-

27 Even with very large samples one would be able to find a (virtually) exact match to every individual in the control group between which the difference would be measurable. However, this would only apply for the actually measured control variables, meaning that it would never be possible to completely exclude a 'problem of control' concerning the causal analysis (unobserved third variables). In technical terms, the researchers want to control (i.e. to be able to say for sure) which behavioural change would be produced by the experiment, and which were already existent, possibly due to existing behavioural dispositions such as a general openness towards change.

28 The qualitative, in-depth survey was flanked by a statistical analysis of secondary data on the heating practices of the 2012 study on environmental awareness (Rückert-John et al. 2013). This mixed methods research enabled us to quantitatively validate the qualitative findings on motivations and influencing factors for heating behaviour and the significance of heating practices.

vating and intervening elements of a persuasive and frictional, irritating or transformational feedback device (Hassezahl & Laschke 2015). The feedback design provides graphic information about the room temperature and humidity, it interrupts ventilation without reflection that is not expedient when the heating is still switched on, it provides delightful tips about more energy-efficient heating behaviour, nudging the user towards an indoor temperature that seeks negotiation between personal well-being and general energy utility. In theory, the combination of different feedback levels (motivating and strict, general and individual utility) facilitates the most effective behavioural change possible, taking into account people's subjective well-being. The technically complex prototype was tested in the field in households over a period of at least four weeks: the field test involved measuring a one-week baseline, a two-week test phase involving the use of the prototype, and a one-week debriefing phase following the withdrawal of the prototype in order to be able to measure short-term reversion to old heating habits. The room temperature, humidity and ventilation times were measured throughout the experiment. In addition, all of the households were interviewed about their heating behaviour and experience before and during the field test. The field test helps us to check for real (or in-situ) whether new possibilities of intervention actually cause people and households to change their heating and ventilation behaviour. In this way, the design of a field test involving a few participants also enables a user-centred prototype to be developed, facilitating a more effective design of feedback products. After all, Buchanan et al. (2015) demonstrate that user-integrated or carefully designed feedback products enable users to understand their habits and routines better, and to question them.

However, we do not know for sure whether it functions exactly like this in other people, and which other mechanisms could be crucial to behavioural changes. For this reason, we decided to supplement the field experiment involving a few households with a 'survey experiment'. The user experiment therefore combines two experiments—a field experiment and a survey experiment—in a Living Lab design, as illustrated in the figure below.

The online experiment attempts to combine the representative sample and low costs per unit of analysis of a survey with the time series data of

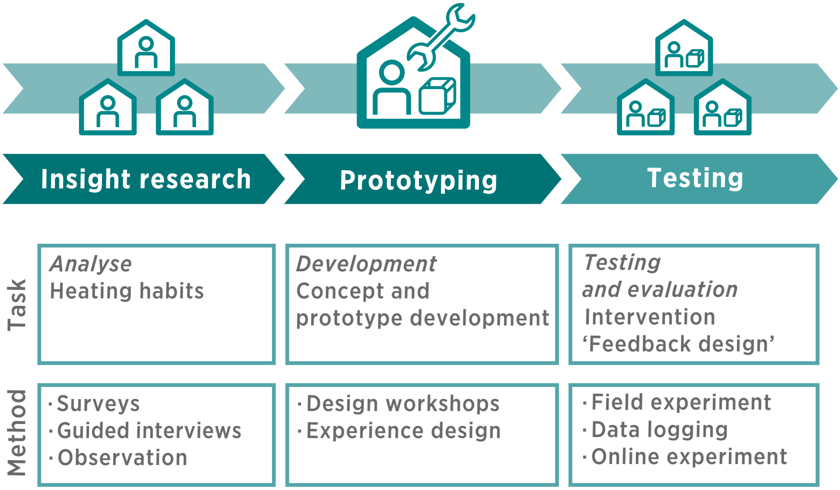


Figure 11: **User experiment in the Living Lab design (Source: Own illustration, based on Liedtke et al. 2015, p. 111)**

an experiment. Several hundred trial participants were chosen randomly from a representative pool of test persons and their participation was recompensed monetarily. The trial participants took part in the online experiment anonymously to ensure that socially desirable response behaviour did not distort the validity of the survey.

The basic idea was to integrate the fundamental levels of intervention (persuasive, frictional, but also mandatory and freely adjustable heating systems as the control) as text vignettes in a randomised survey, and to ask the trial participants about their probable behaviour before and after the intervention. After all, it is only possible to ask in detail about all kinds of control variables (and how they change) about attitudes, the trial participants' personality dispositions and intervention dimensions in a survey experiment. In contrast to the field experiment, however, one must always rely on the subjective information provided by the respondents as to how they would behave. What is more, it involves measuring their hypothetical response to a description in words of an object whose idea is tangible, that stimulates many senses, and that occurs in certain situations. We based this description on our experience in the field experiment, but can never say for sure if, for example, the 'irony' with which the transformational product reflects user behaviour would also have been perceived as such in a real-world situation.

Another difficulty is the fact that, in the survey, all trial participants were questioned twice, i.e. before and after the intervention, within a short space of time. This could easily lead to the first query distorting the later behavioural reaction (referred to as social desirability or priming) or the query concerning behaviour distorting the later answer concerning personality traits. For example, we are interested in how 'activated' the participants are with regard to energy- and resource-saving behaviour. Is it just a matter of overcoming 'bad' habits, or would an entire system of values have to be changed in order to induce a change in behaviour? If, for example, we ask the participants at the start of the survey whether they shop regularly at organic grocery stores, then it could well be the case that the participants then 'get wind of' the desirability at the later query concerning behaviour and answer differently to how they would behave in reality. But if we ask them in reverse, i.e. about their behaviour in response to the description of the intervention, then this should have influenced their perception of behaviour control, for example. If the intention was then to enquire about the basic value of this very control, it would inevitably be distorted.

Important strategies to dispel these concerns wherever possible include involving a control group (the questionnaire also produces a behavioural change in the control group, which can then be subtracted from the actual effect), and asking about certain crucial variables in many different ways so as to exclude random response behaviour. In addition to estimating the individual model parameters and reviewing the subhypotheses and individual theories, a global validation of the behavioural change predicted by the model must also be undertaken.

A further difficulty now arises from the combination of field experiments and virtual experiments alongside all of the advantages outlined: many of the model parameters are highly latent, i.e. 'hidden' constructs in reality. Although it is possible to directly measure the utility that an individual gains from a behaviour, there are competing approaches from all kinds of academic schools concerning this, and uncertainty would surround the measured value in spite of its empirical foundation. It is even more complicated to measure a parameter that is not only 'hidden', but also aggregated in the model: the threshold that decides whether a habit continues or a decision is taken is not even known by the individuals themselves, let alone the researchers. The threshold also combines parts of many different more or less well observed personality dispositions, such as compatibility, i.e. openness and the ability to empathise with other people, or conscientiousness, i.e. an individual's precision or determination, and similar dimensions that can only be measured latently.

Whereas in principle the most important countermeasure here is initially to directly compare different measurement scales for each construct with each other, there is an overall risk of the model becoming unnecessarily complicated, although it is then oriented more closely to measurable constructs. We strive to counter this risk by initially assuming a multitude of necessary parameters, as described, and then attempting to simplify them through statistical analysis. Finally, indirect calibration by means of pattern-oriented modelling can by all means also make a contribution here by reducing uncertainty further within directly measured value ranges—or by producing comparable results using structurally simplified models. However, we hazard the assertion that this multitrack method of adapting the model to the data ultimately leads to the emergence of an agent-based model that will have more to do with (future) reality than 'overly complex' models that have been purely structurally validated on the basis of the result.

Empirical and virtual experiments for a better understanding of behavioural change

A potential win-win situation may arise when agent-based models are able to model general theories on human behaviour or how interventions act at the individual level, with the aim of achieving this with no loss of complexity. The simplification of certain parts of the model, functions or vectors mentioned in the previous section now reveals a more general added value at this point. It entails the possibility to rule out specific and very complex theories with a short reach in favour of much more general theories. In this context, reduction could be grasped as an essence of good theories.

In the first instance, the explanatory power of theories could be weighed against each other empirically. For example, it could be that habits cannot be explained from the complex interaction between individuals' psychological needs, but that what are referred to as 'practices' (in the sense of the same habits) render all other variables insignificant. In addition to heating behaviour, not only a structural model decision would emerge, but also a theoretical added value if it could be shown, for example, that the threshold that enables agents to choose between different modes of behaviour or heuristics is the same from agent to agent and for all different types of motivation. Then one would know from what point, at which level of habit, interventions will be able—or not—to probably reach most people.

For us, therefore, it was particularly interesting with regard to the interventions investigated to determine how interventions can be classified for reasons of simplification and, ultimately, which classification dimension is most effective at changing habits. This could then have a theory-building effect because such a global theory does not yet exist, at least not in the area of habits. The most important intervention dimensions were isolated, one after the other, depending on how strongly or severely the intervention influences behaviour or has a motivating effect on it. Here, too, it may also turn out that individual differences play a minor role. Our user experiment, for example, suggested that the key factors are how the intervention motivates a person to pursue a certain option combined with a particularly drastic intervention (severity) in the occurrence of established repetitive patterns for all individuals. Severe intervention alone can have a counter-productive effect. In this case, sustainability policy could have a completely different design—if, namely, the cost structure was minor information merely at the rational motivation level. Simple effects from randomised experiments could then be fed into considerably simplified models with much more confidence.

Ultimately, irrespective of the accuracy of such hypotheses, an additional 'feedback' loop would be conceivable: the advantages of virtual experiments—such as in the case of a longer time horizon and large samples—could be harnessed. Findings such as on interaction between certain intervention features and their psychological dimensions to become dissipated in very large populations could then enhance the design of new interventions. For example, it could emerge that a lower individual effect would result in a larger overall effect owing to a lower intensity of intervention since social dissipation would then meet the motivations of a majority of the interested population better. However, it already appears obvious that existing interventions are characterised by a certain interaction between variables. Although it would be desirable to construct custom-fit interventions as a result of the virtual experiments, in the user experiment we likewise determined that interaction effects of these variables do not enable such a construction to be made for the time being; the dimensions of intensity and motivation have too different an effect on different people with different personality dispositions (Bettin et al. 2016).

In spite of everything, we will never be able to deny 'fundamental uncertainty' (Keynes 1936). We should never assume that past causal mechanisms can describe the future with adequate precision. In the end, however, the strengths of surveys (representativeness) and field experiments (actual effect) can be combined with virtual experiments so that, in view of the dominant complexity, the best possible predictions can be made on the efficacy of sustainable policy interventions. Such a methodological approach can then claim to understand the world of behavioural change better, also theoretically.

4.4 Modelling an ecological dilemma: energy versus resources

Transformative research seeks to contribute to catalysing specific change processes. In line with the normative content, changes are to occur in the interests of a (more) sustainable society. In the process, however, it could transpire that the development of solutions and technical and social innovations is supported in one area of sustainability, but has negative consequences in another area. This is referred to as problem shifting.

Risk of problem shifting

In order to illustrate this phenomenon, let us take a common example outside the EnerTransRuhr context: a transformation was initiated some time around 2005. Politicians required a minimum content of 'biofuels' (e.g. bioethanol and biodiesel) at filling stations. Benefits were expected to be gained in the economy, in the social areas, and for the environment: agriculture would be able to develop a new sales market, and existing filling stations would be able to remain. Although the combustion of bioethanol and biodiesel causes carbon dioxide emissions, these are compensated by the plants ('renewable raw materials'), which in turn are processed into biofuels. Virtually a zero-sum game, therefore, unlike with the combustion of fossil fuels. If petrol suddenly became 'cleaner', automobile manufacturers would no longer need to work as hard towards designing more economical engines, and we could all continue driving our cars without feeling guilty. Biodiesel and bioethanol have since become billion euro businesses. Apart from that, however, everything else has gone wrong, and the consequences are dramatic.

Not least the growing demand for biodiesel has led to a massive expansion of palm oil plantations, especially in Southeast Asia. This leads to a loss of valuable biodiversity. A large number of animal and plant species are losing their habitats. People, too, are being expelled—sometimes by force—to make space for plantations. The combustion of virgin forests and the processing of peat soils release up to 20 times more greenhouse gases than when fossil-based diesel is used. The problem shift has since been recognised. But the policy-backed development has long taken on a life of its own. Unfortunately, certification systems stating that energy plants may only be grown on existing agricultural areas are not the solution. After all, if energy plants are grown on existing agricultural areas, the agriculture that previously took place there will have to find space elsewhere, resulting in the clearing of forests. A knock-on effect.

There are a number of examples—technical and social innovations for dealing with technology—where a lack of a comprehensive technological impact assessment has led to problem shifting, in spite of having a different intention originally—as in the example above. Reduced to a common denominator, these developments can be described as being 'well conceived, but badly made'.

The heating transition

As described above, the EnerTransRuhr project specifically involved protecting the climate by achieving the energy refurbishment of buildings or by using change-inducing feedback products. For the first case, homeowners' decisions for or against energy refurbishment measures on their houses were modelled (Friege 2016). The second case involved exploring behavioural changes concerning heating and ventilation by means of transformational products (Jensen, Holtz, Chappin 2015; Jensen et al. 2016). In addition, the diffusion of measures, devices and behaviour was modelled in both cases.

BOX 8

Discussions between neighbours

We have already established that people behave differently. What seems normal to one person may seem crazy to someone else, as is also the case with regard to the everyday activities of heating and ventilation.

These lines were written during the winter of 2015/16, which went down in the books as a very mild winter in Germany. One of the authors had not yet turned on the heating in his apartment. Why not? Because the temperature indoors had not yet fallen to below 18 degrees Celsius. 'Pardon?' was the neighbours' reaction, whose apartments are usually kept at a minimum of 20 degrees Celsius. The author's exemplary energy-saving behaviour has not (yet) had any spill-over effect at all. Even the point that evenings could be spent on the sofa watching films cuddling under a blanket failed to convince them. Maybe transformational products could be useful. But then ears pricked up at the mention of the temperature not even falling below 18 degrees Celsius at night, despite not having the heating on. This was due mainly to the brand new triple glazing windows. That was reason enough for some of the neighbours to seriously consider whether they, too, needed new windows.

The author decided to install new windows upon moving in: if it's chaotic anyway, then why not get rid of the old windows that gave inadequate thermal insulation. However, the neighbours have been living in the three-storey multiple dwelling for much longer, and tend to calculate on the basis of a cost-benefit analysis. Also, they like to have it cosy rather than stressful, and prefer to wait for the next major refurbishment so as to kill two birds with one stone. The façade of the building, for example, will have to be refurbished some time over the next decade—provided that no structural damage occurs before then.

Hence this was also another potential systemic problem shift: a current discussion is concerned with the question of whether the measures for saving energy and emissions in the building sector (including insulation and feedback products) would lead to no negative trade-offs or whether more energy would be used to produce the insulating material than can subsequently be saved by the insulation. In addition, it is argued that insulation is resource-intensive and will generate additional waste streams in the future. If no negative trade-offs occur, there is also no risk of problem shifting. But if the other opinion is correct, this could be highly relevant with regard to the heating transition in Germany: the transformation of heating requirements in the building stock. After all, the second case would mean that heating energy, and the resulting emissions, could only be saved in Germany if considerable amounts of energy and resources are consumed in order to produce the insulating materials (possibly in other regions of the world). The problem could then perhaps be shifted geographically and ecologically. Concerning this, the following always applies (it is not a law of nature per se, but almost as good as one): raw materials extracted from nature (irrespective of the kind of materials) that enter human society (the 'anthroposphere') must be returned to nature at some point as waste (not only as solid waste, but also in the form of air or water emissions). Recycling may be a way to keep substances in the anthroposphere for longer, but not for an indefinite period. The problem could, then, also be temporally and ecologically shifted. However, it must be borne in mind that one does not just save oil, gas or electricity, but also the entire raw materials (including energy) along the production chain.

Political relevance

Once again: transformation research must be open to this issue of a potential problem shift. We are presented with the following dilemma: saving energy versus consuming resources and generating waste. Homeowners usually give much less thought to this than to the cost of a measure (motorists are also not usually interested in what percentage of the fuel from the petrol pump is made up of biodiesel, and what effects this has on other places in the world). But politicians and researchers must address these issues. Although Germany has established strong political frameworks in the areas of climate and renewable energies, the country has also started to give resource efficiency and resource conservation a prominent position on the political agenda. The issue of resources is gaining in political importance in Europe and across the world.

The development of Germany's resources policy is taking place in the context of European and international activities focusing on increasing resource efficiency. For example, the flagship initiative on 'Resource efficient Europe' of the Europe 2020 strategy and, building on this, the 'Roadmap to a Resource Efficient Europe' outline the vision of a sustainable Europe up until 2050, causing this vision to gain in impetus and importance. The 'G7 Alliance on Resource Efficiency' was established recently (at the G7 Summit in Elmau in 2015) under Germany's lead. The German

Resource Efficiency Programme 'ProgRess' was adopted at the beginning of 2012, and is currently being updated. During the first stage (ProgRess I), it was implemented with the aim of moving towards the sustainable use and extraction of natural resources. According to this, economic growth should be decoupled to a large extent from the use of natural resources, boosting Germany's innovative drive and competitiveness. The second stage (from 2016 to 2020, ProgRess II) is now just around the corner. The (provisional) central ideas remain unchanged in ProgRess II: linking environmental necessities to economic opportunities and a focus on innovation as well as social responsibility; considering global responsibility as a central orientation of national resources policy; gradually making management and production methods in Germany less dependent on primary raw materials; further developing and expanding closed cycle management; and securing the long-term sustainable use of resources by guiding society towards qualitative growth. In order to further develop the German Resource Efficiency Programme, which also advocates reducing absolute material consumption, design characteristics of successful resource conservation policy were derived from different studies. Setting absolute targets for reducing material consumption, as already exist in the case of climate-changing greenhouse gas emissions, would constitute a major step forward. Last but not least, waste-related concepts such as waste avoidance now also take a prominent position: such as in the European Waste Framework Directive and the German Law on Closed Cycle Management as the top priority of what is referred to as the 'waste hierarchy'.

In a nutshell, the following applies: global material consumption has doubled in the past 30 years, and is likely to double again by 2050, with a world population that is expected to have grown to up to ten billion by then. It is virtually certain that such a level of resource consumption will not be sustainable from an ecological, economic or social perspective. This clearly demonstrates that a major challenge will be to ensure that measures for the energy transition do not put a spanner in the works of the resources transition. And vice versa. In the spirit of transformative research, appropriate findings offer the chance to support or impede change processes. Depending.

Cornerstones of an approach

How, then, can conflicts of objectives, problem shifts and synergies be identified and translated into actions? There is no single uniform procedure. As a rule, modelling is applied that is supposed to develop scientifically based recommendations for the specific context and the specific issue. This essentially means that attention must be paid to details, while not losing sight of the overall picture. In the process, the following two cornerstones must be observed without fail. First, the entire life cycle of energy-saving products, services or measures that use resources must be examined carefully. Only then can it be ensured that problem shifts are considered across geographical and/or temporal boundaries. Second, the dynamics of the problem to be resolved should at least be recognised and, ideally, integrated into the modelling of the system.

The economic, technological, legal and demographic framework conditions surrounding the problem will unavoidably change in the future. If tomorrow's thermal energy (that is saved) and tomorrow's electricity (part of which will contribute towards making energy-efficient products) will generally be produced from other sources, this may have consequences for the general consideration of the energy versus resources dilemma.

Let us now take an example from the EnerTransRuhr project that shows which specific steps the framework outlined in the last paragraph can fulfil. One case from the project involved exploring homeowners' energy refurbishment decisions in the Ruhr Area and the implications they had on energy and resource consumption. The detailed agent-based model by Friege (2016) represents homeowners' behaviour with regard to refurbishment. The model provides annual refurbishment decisions differentiated according to types of buildings and building components for every homeowner (the 'agents') in a simulated city. We are talking here about a virtual world with more than 1,400 residents (the simulated homeowners) who live in 18 different types of houses (detached and terraced houses) that were built in different years. For every house, the owner and the residents can decide each year whether he or she wishes to have one or more from a total of four building components (outer walls, basement ceiling, roof, windows) refurbished to make them more energy efficient (in other words, either having insulation or new windows installed). Occasions for such measures could be, for example, the purchase of the house, or that a new roof had to be installed due to structural damage. A number of input parameters (such as individual homeowners' fundamental attitudes towards insulation) can be varied, enabling different scenarios to be created. This approach enables a detailed consideration (individual refurbishment decisions) to be made, as desired, and creates an overall picture after one aggregation level (average refurbishment rate).

More specifically, let us take a close look at agent #377s8a-0.1. Unravelled, the designation has the following meaning: #377 stands for agent number 377, from the eighth simulation run (s8), in the 'attitude -0.1' scenario, which signifies that, altogether, all of the agents had on average a negative attitude towards energy refurbishment. In the interests of simplification, we shall call agent #377s8a-0.1 the Smiths. The Smiths own a detached house that was built in 1978. From an energy-efficiency perspective, the house is in the following state: the roof and the basement ceiling were insulated a bit between the year of construction and 2007 (which is when our simulation starts). The outer walls and the windows were not touched—from an energy perspective—which is why they yield the same 'insulation performance' in 2007 as in the year of construction. Hence the Smiths are just one household of many in our model. We shall see what the household does with its house over the simulation period.

The agent-based model is just one part of the story. It can stand alone and provide insight into a number of questions, but the energy versus resources dilemma is not one of them. After all, the agent-based model does not collect any data on energy saving and material consumption (for example, for insulation or new windows). And yet these are necessary in order to calculate the net effects of energy and resources. These effects enable us, in turn, to undertake a substantiated assessment of the energy versus resources dilemma for the present case. In a bid to fill this 'gap', the 'HEAT' (Household Energy and Appliances Modelling Tool) model developed by Wuppertal Institute was activated (Soukup, Hanke, Viebahn

2012). HEAT enables numerous saving measures on the building side related to heat to be modelled in detail with regard to their direct effects on energy efficiency (thermal energy saved), their direct use of materials (such as the thickness of insulation), and their costs. Five insulating materials and six energy standards are taken into consideration. Multiplied by the number of agents, building types, building components, insulating materials and energy standards, this yields the number of potential individual cases which, however, can still be extracted (detailed examination) and aggregated (the overall picture).

Let us return to the Smiths. They have not moved house in the meantime. In fact, they have done quite a lot to their house. Namely (remember: this is a simulation, i.e. it is virtual): the outer walls were insulated in 2011, the basement ceiling in 2025, the roof in 2030, and the windows were replaced in 2039 (the simulation ends in 2050). The Smiths reduce their heating demand with every energy refurbishment measure undertaken. At the end of the simulation, it has fallen by almost one half. In other words, at the end of the simulation period, the Smiths would have consumed twice as much heat each year if they had not insulated their house. Over the entire period, around one quarter of the heating energy was saved (annual savings are higher at the end of the period because the effects of the different measures are additive). However, the renovation measures were not obtained free of charge, not only in the financial sense. In fact, the insulating materials for the roof, the outer walls and the basement ceiling, and the new windows total a materials usage of around four tons (on average; the result varies between approximately 2.5 and seven tons, depending on the materials used).

One might think that, with the second module described above and the example given, all of the information required to answer the issue was available: the heating energy saved and the amount of insulating material. And yet one very important aspect is still missing: the life cycle perspective. The heating energy saved would have been produced from some kind of energy source. The energy source itself, its processing, transportation, and so on, can be attributed to the extraction of primary raw materials. The same applies for the insulating materials and energy-efficient windows: resources and energy are required to manufacture them and, later, to dispose of them. In order to ensure a comprehensive consideration of the effects on energy and resources, however, the indirect consumption of resources and energy across the life cycle of the refurbishment measures must, then, be taken into consideration. This is performed by a material flow model, which specifically comprises consistent life cycle models of energy savings and energy renovation measures. It will be possible, just as before, for energy and resources to be compared in individual cases or in their entirety for the whole simulated world.

What does this mean for the Smiths? They used around four tons of insulating materials and window materials to undertake their energy refurbishment measures. If, however, all material consumptions along the life cycle (particularly for production) of the insulating materials and windows are considered, the figure is over 30 tons (an average value that varies between 20 and 55 tons, depending on the material used). The windows bear most of the blame, because they are more difficult to manufacture than insulating boards. And yet: the heating energy saved would have consumed at least 86 tons of material (with an efficient condensing boiler; other heating systems would have yielded even higher values). In the previous step, we attempted to compare apples (energy saving) with pears (material consumption). In this step, we are left only with the pears. And it emerges that the energy refurbishment measures undertaken by the Smiths save more 'pears' than they consume.

So does that answer our question about problem shifting? Not fully. We are interested in a long-term transformation in the building sector. This also means that the dynamics of the system that provides the frame must also be taken into account. We considered different scenarios for the energy transition, such as the official scenario of the German Federal Ministry for the Environment (which approaches 100 per cent renewable energies in 2050: Repenning et al. 2015) and the official scenario of the German Federal Ministry for Economic Affairs and Energy (slightly more conservative: Schlesinger et al. 2014). With such scenarios as these, our agents, buildings, manufactured insulating materials, and saved heat are embedded in a changing system.

But what exactly does this mean for the measures undertaken by the Smiths? In the last step, where we said that four tons of insulating materials and window materials correspond to approximately 30 tons of material when considering the matter along the entire life cycle, we cheated slightly. What we failed to state was the assumption that the insulating materials or windows would be created in our current production system. But that is not the case: the Smiths will have new windows installed in 2039. In this case, the following applies to both the windows and the heat saved: their production will cause different material withdrawals in future compared to today due to a change in processes (which will presumably be more efficient). The relevant question is now: could it be that the energy refurbishment measures undertaken by the Smiths will save fewer pears (i.e. material consumption) than they consume, taking into account the changing system?

Let us take an extreme case in order to assess this. Assuming that Germany's power supply across the entire simulation period is based on 100 per cent renewable energies (which is the goal of the energy transition at the 2050 horizon): the use of raw materials in power generation would decrease sharply. Why is this the case? Because lignite and hard coal currently make up almost half of our power generation and over 90 per cent of its use of raw materials. As a result, the total material consumed during the Smiths' renovation measures would decrease by 20 to 80 per cent because the upstream chains would be free from electricity produced from coal. By the same reasoning, thermal preparation would also benefit from this (albeit to a lesser extent because electricity plays a slightly less important role in the upstream chain). At the end, however, the same result is generated as in the last step: the energy refurbishment measures undertaken by the Smiths ultimately save more material than they consume.

In a nutshell: the integration of three model approaches—the 'agent-based model Eigenheim', HEAT and the material flow model—produces the 'RessMod' resource model, which is inherently consistent. Complemented by energy transition scenarios, this can be used to quantify interactions between refurbishment (use of resources) and heating energy savings (resource savings). In short, we found in our case that energy renovation measures do not consume more resources than they save from the decrease in heat demand. The scale of the effect varies between the individual cases, which means that the aggregated effect may fluctuate, depending on the composition. The Smiths (agent #377s8a-0.1) therefore represent an individual case. In another simulation run or another scenario (such as in which all agents have, on average, a positive attitude towards energy refurbishment), agent number 377 may have acted differently, possibly like his virtual neighbours. The whole net effect (across all agents) on resource consumption is, then, sometimes higher and sometimes lower. All things considered, however, we do not observe any problem shift with regard to material consumption. These results underpin an earlier study undertaken by Wuppertal Institute (Soukup et al. 2012), which had slightly different system boundaries, but an issue that overlapped in parts. The modelling undertaken by Soukup and colleagues revealed that additional expenses for insulating materials in other environmental impact categories are overcompensated by considerable savings made with regard to heating the building.

Transformation research should refer again and again to this or similar ecological dilemmas. However, it is not our intention to declare our procedure described briefly above as a universally valid formula. It is obvious that specific procedures, particularly the modelling involved in each case, need to be rebalanced time and again to suit the specific case.

In any case, the following cornerstones should be borne in mind:

- Those who do not apply a life cycle perspective for analysis purposes is blind in both eyes because solutions implemented at home have environmental implications elsewhere. These can occur before and/or after the implementation of the solution (geographical and temporal problem shift).
- Net effects should be analysed at a minimum of two levels, namely as individual cases and aggregated for a certain number of cases (these may be virtual, as in an agent-based model). The absolute effect from the sum of non-ideal individual cases is what characterises our world and the challenge involved.

- Transformation is a forward-facing timeline. The system in which the analysis takes place changes, and will continue to change. The researcher must be aware of the implications this has for his own model.

Those who consider these points in their analysis will make a contribution to transformation research. But does this already belong to transformative research? One could claim that the publication of such analyses that resolve well-defined ecological dilemmas may have a transformative effect on a wide audience. This results from the hope that people will look in the right drawer, take out the right report, read and understand it, draw conclusions from it, and adapt their behaviour accordingly. Since we know that this is not usually the case, the question still has to be clarified as to how transformative research based on such results can be fleshed out, and which transformative effects can then be expected to occur.

In this case, there is a need for further research to close a loop by transferring back the results of the dilemma analysis to the agents of our model. In concrete terms, this could mean that agents such as the Smiths are given detailed information about the annual and aggregated energy and resource implications of their (possible absence of) refurbishment decisions. But would they (the agents) respond to this? And if so, how? Would they change their refurbishment behaviour? How could one convey the message that insulated houses do not utilise more natural resources, but less? If something along those lines were to succeed, what would be the aggregated effect on refurbishment rates, energy savings and resource consumption? We have created the methodological basis that may help us to answer such questions. However, other transformative projects must be added to this in order to establish a link to the real world (as opposed to the virtual one).

We opened this section with a brief insight into the classic case of problem shifting: biofuels. Could some of the problems described be avoided if more approaches such as that in the EnerTransRuhr project had been pursued before the introduction of bioethanol? The advantage of our approach (linking agent-based models to life cycle analysis, energy models and scenarios) is that it forces us to address matters such as the real reach and the uncertainties surrounding the combined modules. We described briefly that interaction between modelled resourceful agents such as the Smiths and a wide selection of refurbishment cases yield relatively large ranges for the results: on the one hand, resource savings, and on the other, additional resource consumptions. In our model, the two result corridors do not overlap. With regard to biofuels, taking a comparable approach would probably have led to the realisation that the windows of opportunities for the advantages and disadvantages of biofuels overlap tremendously. Such findings create the opportunity for policy conclusions to be drawn accordingly.

5

Conclusion
Hypotheses
Summary

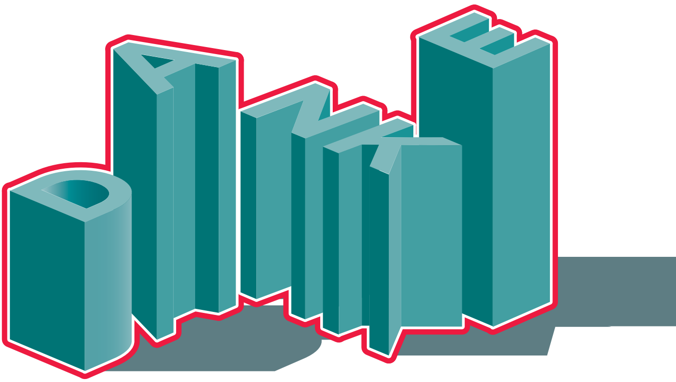
This workshop report about the EnerTransRuhr project clearly shows where the central challenges of transformative science lie in research practice, and how these can be tackled productively. The EnerTransRuhr project is an ideal-typical example of the different modes of science and forms of knowledge that are needed to analyse and successfully implement complex sustainability-oriented transformation processes such as the energy transition in buildings:

- System knowledge about the building stock and infrastructures; political frameworks at the EU, national and local level; economic incentive structures; the typical behaviour patterns of a wide range of stakeholder groups; and, not least, the complex interactions between all these dimensions.
- Target knowledge about sustainable system states that are desirable for the future, not only at the overall system level, but also in the context of the target visions and guiding principles of individual cities and neighbourhoods, as well as with regard to the desires and motivations of individual actors.
- Transformation knowledge about effective strategies, behavioural patterns, innovations and policy instruments that are tested in virtual and real-world experiments, leading to widespread diffusion.

The scientific guidance of transformation processes requires an integrated research design as well as a combination of discipline-based perspectives and methods in order to generate these different forms of knowledge, primarily also outside the academic ivory tower in cooperation with practice partners in their life-world contexts. To achieve this, transformative science falls back on many elements of classic science, but also embeds them in transdisciplinary settings. The EnerTransRuhr project particularly benefited from the connection of virtual experiments and agent-based modelling in combination with policy and user experiments in real-world laboratories. In this way, the interventions tested in the real-world laboratory can be simulated over time and space in the model, enabling knowledge to be gained on the diffusion of technologies, social practices, and decisions for or against energy refurbishment measures. In the process, one must never lose sight of the boundaries of the individual methodologies and the research design as a whole: the EnerTransRuhr project is also unable to reliably predict futures using models—but it helps us to understand the underlying behavioural patterns better. Even if user and policy experiments do not enable any representative statements to be made, they still provide profound insights into 'transformation practice'. Time and again, transformative research offers new insights and starting points for actively designing transformation processes, which have to be further tested and reflected on in experiments. This raises a fundamental question about the role of science in normative-oriented sustainability research: to what extent may and should researchers not only be observers, but also play an active role? Based on the understanding of transformative science, an important contribution can be made to the transformation towards sustainable development, particularly via active intervention in real-world laboratories and reflection using models.

6

Acknowledgements



We would like to thank the German Federal Ministry of Education and Research for supporting the EnerTransRuhr project within the social-ecological 'Transformation of the Energy System'. We are also grateful to the executing agency, the German Aerospace Center (DLR), for the friendly support they provided in their capacity as contact persons.

We would also like to say a special thank-you to the cities of Dortmund, Oberhausen and Bottrop, and their environmental agencies, which were closely involved in the project. In addition, Innovation City Management GmbH, Folkwang University of the Arts, Delft University of Technology, sociodimensions—Institute for Socio-cultural Research, and the Consumer Association NRW were instrumental in the success of the project. The Ministry of Innovation, Science and Research of the Federal State of North Rhine-Westphalia acted as a practice partner, too. We would also like to thank the Federal Office for Economic Affairs and Export Control for supplying us with data.

A number of other institutions and companies also helped to develop and implement experiments in the cities and neighbourhoods that were involved in the project: district bureaus and agencies in Dortmund Hörde, Oberhausen City and Lirich, Oberhausen Advisory Centre of the Consumer Association NRW, the Centre for Environment and Energy of Düsseldorf Chamber of Crafts and Trades, the Energy Efficiency and Climate Protection Service Centre of the City of Dortmund, Haus & Grund, the Dortmund branch of the DHB Netzwerk Haushalt, WohnBund-Beratung NRW, the Institute for Church and Society of the Evangelical Church of Westphalia, and Vivawest Wohnen GmbH.

We would also like to thank the consultants at the different events; the households that participated in the user experiments; and the various agents of change who spent a lot of time with colleagues from the Institute for Advanced Study in the Humanities (KWI).

List of figures

Figure 1:	**Transformative literacy**	Page 18
Figure 2:	**The neighbourhood as a boundary object in the EnerTransRuhr project**	Page 24
Figure 3:	**Research for transformation requires interaction between system knowledge, target knowledge and transformation knowledge**	Page 28
Figure 4:	**The transition cycle**	Page 31
Figure 5:	**The energy transition in buildings in the multi-level system**	Page 32
Figure 6:	**Classification of real-world experiments in the typology of experimentation**	Page 36
Figure 7:	**The role of research in classic and real-world experiments**	Page 38
Figure 8:	**Consulting cases conducted by the Federal Office for Economic Affairs and Export Control (BAFA) and the Consumer Association NRW in Bottrop, Dortmund and Oberhausen**	Page 67
Figure 9:	**The area under investigation in the EnerTransRuhr project: the three cities of Oberhausen, Dortmund and Bottrop**	Page 78
Figure 10:	**Agent-based modelling**	Page 97
Figure 11:	**User experiment in the Living Lab design**	Page 133

Bibliography

Abernathy, W.J.; Clark, K.B. (1985): Innovation: mapping the winds of creative destruction, in: Research Policy 14(1), p. 3–22.

Albrecht, T. (2010): Zum Sanieren Motivieren. Eigenheimbesitzer zielgerichtet für eine energetische Sanierung gewinnen.

Albrecht, T.; Zundel, S. (2010): Gefühlte Wirtschaftlichkeit – Wie Eigenheimbesitzer energetische Sanierungsmaßnahmen ökonomisch beurteilen. [http://www.enef-haus.de/fileadmin/ENEFH/redaktion/PDF/Enef-Haus_Gefuehlte_Wirtschaftlichkeit.pdf; 08.03.2016]

Arendt, H. (1981): Vita Activa oder vom tätigen Leben, München.

Bacon, F. (1620): Novum organum scientiarum. [https://archive.org/details/1762novumorganum00baco; 02.02.2016]

Baedeker, C.; Hasselkuß, M.; Buhl, J. (2016): Actor and network analysis. In: Keyson D., Guerra-Santin, O., Lockton, D. (Eds.). Living Labs – Design and Assessment of Sustainable Living. Springer International, Cham/Switzerland, p. 189–203.

Becker, N. (2014): Ressourceneffizienz der Dämmstoffe im Hochbau. VDI ZRE Publikationen: Kurzanalyse Nr. 7, Berlin.

Bergmann, M. et al. (2010): Methoden transdisziplinärer Forschung. Ein Überblick mit Anwendungsbeispielen, Frankfurt am Main.

Bettin, J.; Buhl, J.; Jensen, T. (2016): Breaking Habits: Modeling Psychological Mechanisms of Interventions for Energy Conservation Behavior. 4th European Conference on Behaviour and Energy Efficiency (BEHAVE), Coimbra, 8–9 September 2016.

Beuth Hochschule für Technik Berlin, Institut für Energie- und Umweltforschung Heidelberg (ifeu) (2012): Technische Restriktionen bei der energetischen Modernisierung von Bestandsgebäuden. Berlin, Heidelberg.

Brugnach, M.; Pahl-Wostl, C. (2008): A broadened view on the role for models in natural resource management: implications for model development, in: Pahl-Wostl, C.; Kabat, P.; Möltgen, J. (Eds.): Adaptive and Integrated Water Management, Berlin, Heidelberg, p. 187–203.

Buchanan, K.; Russo, R.; Anderson, B. (2015): The question of energy reduction: The problem(s) with feedback, in: Energy Policy, 77, p. 89–96.

Buhl, J. (2014): Revisiting Rebound Effects from Material Resource Use: Indications for Germany Considering Social Heterogeneity, in: Resources, 3(1), p. 106–122.

Buhl, J.; Echternacht, L.; van Geibler, J. (2015): Rebound-Effekte. Ursachen, Gegenmaßnahmen und Implikationen für die Living-Lab-Forschung im Arbeitspaket 1 (AP 1.2a) des INNOLAB Projekts, Wuppertal.

Buhl, J. (2016): Rebound-Effekte im Steigerungsspiel. Zeit- und Einkommenseffekte in Deutschland, Baden-Baden.

Buhl, J., et al. (2016). Analysing social milieus and lifestyles – their contribution to a better understanding of heating practices, in: Keyson, D.; Guerra-Santin, O.; Lockton, D. (Eds.). Living Labs – Design and Assessment of Sustainable Living. Springer, Cham/Switzerland, p. 247–257.

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) (2016): Hendricks: Mit Wohnungsbau-Offensive gegen den Wohnungsmangel. [http://www.bmub.bund.de/presse/pressemitteilungen/pm/artikel/hendricks-mit-wohnungsbau-offensive-gegen-den-wohnungsmangel/; 09.05.2016]

Bundesministerium für Wirtschaft und Technologie (BMWi); Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit BMU (2010): Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung, Berlin.

Bundesverband der Energie- und Wasserwirtschaft (BDEW) (2015): Verteilung der Beheizungssysteme im Wohnungsneubau in Deutschland im Jahr 2014. Statistisches Bundesamt. [http://de.statista.com/statistik/daten/studie/37957/umfrage/beheizungssysteme-in-neubauten-im-jahr-2008; 11.01.2016]

Burt, R. (1992): Structural Holes: The Social Structure of Competition, Cambridge.

Catney, P. et al. (2013): Community knowledge networks: an action-orientated approach to energy research. In: Local Environment 18 (4), p. 506–520.

Christensen, C.; Layton M. (1997): The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail, Boston.

Christmann, G. (2011): Soziale Innovationen, Social Entrepreneurs und Raumbezüge, in: Jähnke, P.; Christmann G.; Balgar, K. (Eds.): Social Entrepreneurship. Perspektiven für die Raumentwicklung. Workshop "Social Entrepreneurs in Deutschland – Raumansprüche und Raumwirkungen", Wiesbaden, p. 193–210.

Cischinsky, H. et al. (2015): Privateigentümer von Mietwohnungen in Mehrfamilienhäusern. BBSR-Online-Publikation 02/2015. [http://www.bbsr.bund.de/BBSR/DE/Veroeffentlichungen/BBSROnline/2015/DL_ON022015.pdf; 04.04.2016]

Corsten, M.; Kauppert, M.; Rosa, H. (2008): Quellen bürgerschaftlichen Engagements. Die biographische Entwicklung von Wir-Sinn und fokussierten Motiven, Wiesbaden.

Cornell, S. et al. (2013). Opening up knowledge systems for better responses to global environmental change, in: Environmental Science & Policy, 28, p. 60–70.

Co2online gemeinnützige GmbH (Ed.) (2015): Wirksam Sanieren: Chancen für den Klimaschutz. Feldtest zur energetischen Sanierung von Wohngebäuden, Berlin.

Co2online gemeinnützige GmbH (2017): Richtig heizen leicht gemacht: die 15 besten Tipps zum Heizkosten senken und energieeffizientem Heizen. http://www.co2online.de/energie-sparen/heizenergie-sparen/heizkosten-sparen/richtig-heizen-die-10-besten-tipps/#c27389; 25.01.2017)

Dausien, B.; Kelle, H. (2005): Biographie und kulturelle Praxis. Methodologische Überlegungen zur Verknüpfung von Ethnographie und Biographieforschung, in: Völter, B. et al. (Eds.): Biographieforschung im Diskurs, Wiesbaden, p. 189–212.

David, M.; Schönborn, S. (2014): Offenheit, Beteiligung und Kooperation: 'Governance statt Konflikt' bei der Etablierung von Nachhaltigkeitsinnovationen. [http://www.regierungsforschung.de/dx/public/article.html?id=255; 09.05.2016]

Deaton, A. (2009): Instruments of development: Randomization in the tropics, and the search for the elusive keys to economic development, Cambridge.

de Flander, K. et al. (2014): Resilienz und Reallabore als Schlüsselkonzepte urbaner Transformationsforschung. Zwölf Thesen, in: GAIA, 23(3), p. 284–286.

Deutsche Energie-Agentur (dena) (2015): Der dena-Gebäudereport 2015. Statistiken und Analysen zur Energieeffizienz im Gebäudebestand. Berlin.

Dickel, S. (2013): Transformationsforschung jenseits des Elfenbeinturms. Zur Etablierung einer Transformationswissenschaft, in: Ökologisches Wirtschaften, 2, p. 17–18.

Diefenbach, N. et al. (2005): Beiträge der EnEV und des KfW-CO_2-Gebäudesanierungsprogramms zum Nationalen Klimaschutzprogramm. Darmstadt.

EnergieAgentur.NRW (2012): 57% aller Stadtwerke in NRW haben Förderprogramme für Energieeffizient und Erneuerbare. Förderung von Elektrofahrzeugen auf der Überholspur. [http://www.energieagentur.nrw/foerderung/ea/57-aller-stadtwerke-in-nrw-haben-foerderprogramme-fuer-energieeffizienz-und-erneuerbare-foerderung-von-elektrofahrzeuge-auf-der-ueberholspur; 15.05.2016].

Epstein, J. M. (2008): Why Model?, in: Journal of Artificial Societies and Social Simulation, 11(4).

Festinger, L. (1957): A Theory of Cognitive Dissonance, Stanford.

Fischer, H. (2008): Dokumentation, in: Beer, B. (Ed.): Methoden ethnologischer Feldforschung, Berlin, p. 293–322.

Flander, K. de, et al. (2014): Resilienz und Reallabore als Schlüsselkonzepte urbaner Transformationsforschung. Zwölf Thesen, in: GAIA, 23(3), p. 284–286.

Friege, J.; Chappin, É. J. L (2014): Modelling decisions on energy-efficient renovations: A review, in: Renewable and Sustainable Energy Reviews, 39, p. 196–208.

Friege, J. (2016): Increasing homeowners' insulation activity in Germany: An empirically grounded agent-based model analysis. In: Energy and Buildings, Volume 128, p. 756–771. Elsevier.

Friege, J.; Holtz, G.; Chappin, É. J. L. (2016): Exploring Homeowners' Insulation Activity, in: Journal of Artificial Societies and Social Simulation, 19(1). [http://jasss.soc.surrey.ac.uk/19/1/4.html]

Future Earth (2013): Future Earth Initial Design: Report of the Transition Team, Paris.

Galvin, R.; Sunikka-Blank, M. (2012): Introducing the prebound effect: the gap between performance and actual energy consumption, Building Research & Information, 40:3, p. 260–273

Geels, F.W. (2004): Understanding system innovations: a critical literature review and a conceptual synthesis, in: Elzen, B.; Geels, F. W.; Green, K. (Eds.): System Innovation and the Transition to Sustainability. Theory, Evidence and Policy, Cheltenham.

Geels, F.W.; Schot, J. (2007). Typology of sociotechnical transition pathways, in: Research Policy, 36(3), p. 399–417.

Geels, F.W. (2014): Regime resistance against low-carbon transitions: Introducing politics and power into the multi-level perspective, in: Theory, Culture & Society, 31(5), p. 21–40.

Gilbert, N.G.; Troitzsch, K. (1999): Simulation for the social scientist, Philadelphia.

Girtler, R. (2002): Methoden der Feldforschung, Wien; Köln; Weimar.

Göpel, M. (2016): The Great Mindshift. How a New Economic Paradigm and Sustainability Transformations go Hand in Hand. Springer Verlag, Heidelberg.

Grimm, V. et al. (2005): Pattern-Oriented Modeling of Agent-Based Complex Systems: Lessons from Ecology, in: Science, 310(5750), p. 987–991.

Halbe, J. et al. (2015): Lessons for model use in transition research: A survey and comparison with other research areas, in: Environmental Innovation and Societal Transitions, 15, p. 194–210.

Hassenzahl, M.; Laschke, M. (2014): Pleasurable Troublemakers, in: Walz, S.; Deterding, S. (Eds.): The Gameful World, Cambridge, MA, p. 167–195.

Heckbert, S.; Baynes, T.; Reeson, A. (2010): Agent-based modeling in ecological economics, in: Annals of the New York Academy of Sciences, 1185, p. 39–53.

Henger, R.; Voigtländer, M. (2011): Einflussfaktoren auf die Rentabilität energetischer Sanierungen bei Mietobjekten, in: IW Trends, 38, p. 1–19.

Hentschel, A.; Hopfenmüller, J. (2014): Energetisch modernisieren bei fairen Mieten? [http://www.boell.de/sites/default/files/endf_energetisch_modernisieren_bei_fairen_mieten-web.pdf; 04.04.2016]

Holtz, G. et al. (2015): Prospects of modelling societal transitions – Position paper of an emerging community, in: Environmental Innovation and Societal Transitions, 17, p. 41–58.

Honer, A. (1993): Lebensweltliche Ethnographie. Ein explorativ-interpretativer Forschungsansatz am Beispiel von Heimwerker-Wissen, Konstanz.

Institut der deutschen Wirtschaft Köln (2012): Energetische Sanierung. Quote ohne Aussagekraft. Immobilien-Monitor Nr. 1/2012. [http://www.iwkoeln.de/_storage/asset/69824/storage/master/file/3375615/download/immobilienoekonomik_01_2012.pdf; 08. 03.2016].

Institut Wohnen und Umwelt (IWU) (2010): Datenbasis Gebäudebestand: Datenerhebung zur energetischen Qualität und zu den Modernisierungstrends im deutschen Wohngebäudebestand, Darmstadt.

Intergovernmental Panel on Climate Change (IPCC) (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)]. IPCC, Geneva, Switzerland.

Jackson, T. (2005): Motivating Sustainable Consumption – a review of evidence on consumer behaviour and behavioural change. Surrey, UK.

Jager, W. et al. (2000): Behaviour in commons dilemmas: Homo economicus and Homo psychologicus in an ecological-economic model, in: Ecological Economics, 35(3), p. 357–379.

Jahn, T. (2008): Transdisziplinarität in der Forschungspraxis, in: Bergmann, M.; Schramm, E. (Eds.): Transdisziplinäre Forschung. Integrative Forschungsprozesse verstehen und bewerten. Frankfurt/New York, p. 21–37.

Jensen, T.; Holtz, G.; Chappin, É.J.L. (2015): Agent-based assessment framework for behavior-changing feedback devices: Spreading of devices and heating behavior, in: Technological Forecasting & Social Change, 98, p. 105–119.

Jensen, T. et al. (2016): Energy-efficiency impacts of an air-quality feedback device in residential buildings: An agent-based modeling assessment, in: Energy and Buildings, 116, p. 151–163.

Karlin, B.; Zinger, J.; Ford, B. (2015): The Effects of Feedback on Energy Conservation: A Meta-Analysis, in: Psychological Bulletin, 141(6), p. 1205–1227.

Keimeyer, F. et al. (2016): Informative und transparente Heizkostenabrechnung als Beitrag für den Klimaschutz. Climate Change 01/2016. [http://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/climate_change_01_2016_informative_und_transparente_heizkostenabrechnung_als_beitrag_fuer_den_klimaschutz.pdf; 10.03.2016]

Keynes, J. M. (1936): The General Theory of Employment, Interest and Money, New York, London.

Knight, B. (2016): Offshore investment funds exploit Berlin's housing shortage. [http://www.dw.com/en/offshore-investment-funds-exploit-berlins-housing-shortage/a-19247132; 07.07.2016].

Konferenz der Schweizerischen Wissenschaftlichen Akademien (CASS); Forum für Klima und Global Change – Schweizerische Akademie der Naturwissenschaften (ProClim) (1997): Forschung zu Nachhaltigkeit und Globalem Wandel: Wissenschaftspolitische Visionen der Schweizer Forschenden, Bern.

Landesregierung Nordrhein-Westfalen (2013): Klimaschutzgesetz Nordrhein-Westfalen. [https://recht.nrw.de/lmi/owa/br_text_anzeigen?v_id=10000000000000000574; 19.09.2016].

Leggewie, C. (2012): Wissenschaft muss von den Problemen her denken. Das Prachtschloss Interdisziplinarität, in: Ökologisches Wirtschaften, 4, p. 12.

Leggewie, C.; Reicher, C.; Schmitt, L. (Eds.) (2016): Geschichten einer Region. AgentInnen des Wandels für ein nachhaltiges Ruhrgebiet. Dortmund.

Liedtke, C. et al. (2015): User-integrated innovation in Sustainable LivingLabs: an experimental infrastructure for researching and developing sustainable product service systems, in: Journal of Cleaner Production, 97, p. 106–116.

Liedtke, C., et al. (2014): Addressing consumption patterns through meaning in social practices – findings from a mixed methods analysis of heating practices. 3rd European Conference on Behaviour and Energy Efficiency (BEHAVE), Oxford, 3–4 September 2014.

Lindner, R. (1981): Die Angst des Forschers vor dem Feld. Überlegungen zur teilnehmenden Beobachtung als Interaktionsprozeß. Zeitschrift für Volkskunde, 77, p. 51–66.

Loorbach, D. (2007): Transition Management: New mode of governance for sustainable Development, Utrecht.

Loorbach, D. (2010): Transition Management for Sustainable Development: A Prescriptive, Complexity-Based Governance Framework, in: Governance – An International Journal of Policy, Administration, and Institutions, 23(1), p. 161–183.

Markard, J.; Raven, R.; Truffer, B. (2012): Sustainability transitions: An emerging field of research and its prospects, in: Research Policy, 41(6), p. 955–967.

Mauser, W. et al. (2013): Transdisciplinary global change research: the co-creation of knowledge for sustainability, in: Current Opinion in Environmental Sustainability, 5(3-4), p. 420–431.

Mautz, R.; Byzio, A.; Rosenbaum, W. (2008): Auf dem Weg zur Energiewende. Die Entwicklung der Stromproduktion aus erneuerbaren Energien in Deutschland. Eine Studie aus dem Soziologischen Forschungsinstitut Göttingen (SOFI), Göttingen.

Mazor, M. et al. (2011): Life Cycle Greenhouse Gas Emissions Reduction From Rigid Thermal Insulation Use in Buildings, in: Journal of Industrial Ecology, 15(2), p. 284–299.

McMichael M.; Shipworth, D. (2013): The value of social networks in the diffusion of energy-efficiency innovations in UK households, in: Energy Policy, 53, p. 159–168.

Moldovan, S.; Goldenberg, J. (2004): Cellular automata modeling of resistance to innovations: effects and solutions, in: Technological Forecasting and Social Change, 71(5), p. 425–442.

Münter, A.; Prossek, A. (2011): Handlungsräume und Raumbilder, in: Reicher, C.; Kunzmann, K. R.; Polívka, J.; Roost, F.; Wegener, M. (Eds.) (2011): Schichten einer Region – Kartenstücke zur räumlichen Struktur des Ruhrgebiets, Berlin: Jovis, p. 182–215.

Neitzel, M.; Dylewski C; Pelz, C. (2011): Wege aus dem Vermieter-Mieter-Dilemma. [http://web.gdw.de/uploads/pdf/InWIS-Vermieter-Mieter-Dilemma.pdf; 04.04.2016].

Nowotny, H.; Scott, P.; Gibbons, M. (2001): Re-Thinking Science. Knowledge and the Public in an Age of Uncertainty, Oxford.

Nowotny, H. (2003): Dilemma of expertise. Democratising expertise and socially robust knowledge, in: Science and Public Policy, 30(3), p. 151–156.

Nullmeier, F. (2006): Eigenverantwortung, Gerechtigkeit und Solidarität. Konkurrierende Prinzipien der Konstruktion moderner Wohlfahrtsstaaten? in: WSI Mitteilungen 4/2006, p. 175–180. Hans-Böckler-Stiftung, Düsseldorf.

Odermatt, A. (1997): Eigentümerstrukturen des Wohnungsmarktes: Ein handlungstheoretischer Beitrag zur Erklärung der räumlich-sozialen Wohnstandortverteilung am Fallbeispiel Schweiz, Münster.

Osbaldiston, R. (2013): Synthesizing the Experiments and Theories of Conservation Psychology, in: Sustainability, 5(6), p. 2770–2795.

Payne, J. W.; Bettman, J. R. (2000): Preferential Choice and Adaptive Strategy Use. in: Gigerenzer, G.; Selten, R. (eds.) Bounded Rationality: The Adaptive Toolbox, p. 123–145. MIT Press, Cambridge, MA.

Pfnür, A.; Müller, N. (2013): Prognose der Kosten alternativer Sanierungsfahrpläne und Analyse der finanziellen Belastung für Eigentümer und Mieter bis 2050. [http://www.real-estate.bwl.tu-darmstadt.de/media/bwl9/dateien/arbeitspapiere/Energetische_Gebauudesanierung_in_Deutschland_Teil_2_2.pdf; 04.04.2016]

Polívka, J.; Roost, F. 2011: Kerne, Adern und Ränder, in: Reicher, C.; Kunzmann, K. R.; Polívka, J.; Roost, F.; Wegener, M. (Eds.) (2011): Schichten einer Region – Kartenstücke zur räumlichen Struktur des Ruhrgebiets, Berlin: Jovis, p. 38–79.

Popper, K.R. (1935, [11]2005): Logik der Forschung Springer. Tübingen 2005.

Przyborski, A.; Wohlrab-Sahr, M. (2008): Qualitative Forschung. Ein Arbeitsbuch. Wissenschaftsverlag, Oldenburg.

Repenning, J. et al. (2015): Klimaschutzszenario 2050, 2. Modellierungsrunde. Öko-Institut e.V., Fraunhofer ISI. Studie im Auftrag des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit. Berlin.

Rockström J. et al. (2009): A safe operating space for humanity, in: Nature, 461, p. 472–475.

Rodrigues, C.; Freire, F. (2016): Environmental impact trade-offs in building envelope retrofit strategies, in: The International Journal of Life Cycle Assessment, p. 1–14.

Rogers, E.M. (2003): Diffusion of innovations, New York.

Rosa, H. (2016): Resonanz. Eine Soziologie der Weltbeziehung, Frankfurt am Main.

Rosenow, J.; Galvin, R. (2013) Evaluating the evaluations: Evidence from energy efficiency programmes in Germany and the UK, in: Energy Buildings, 62, p. 450–458.

Rosenthal, G. (1994): Die erzählte Lebensgeschichte als historisch-soziale Realität. Methodologische Implikationen, in: Berliner Geschichtswerkstatt: Alltagskultur, Subjektivität und Geschichte, Münster: Verl. Westfäl. Dampfboot, p. 125–138.

Roth, R. (2009): Handlungsoptionen zur Vitalisierung der Demokratie. Expertise für die Bertelsmann Stiftung. [http://www.b-b-e.de/fileadmin/inhalte/aktuelles/2009/09/nl20_bertelsmann_vitalisierung.pdf; 09.11.2015]

Rotmans, J.; Loorbach, D. (2010): Towards a Better Understanding of Transitions and Their Governance. A Systemic and Reflexive Approach, in: Grin, J.; Rotmans, J.; Schot, J. (Eds.): Transitions to Sustainable Development. New Directions in the Study of Long Term Transformative Change, p. 105–99.

Sackmann, R. (2013): Methoden der Lebenslaufanalyse und Biografieforschung, in: Sackmann, R. (Ed.): Lebenslaufanalyse und Biografieforschung. Eine Einführung, 2nd edition, Wiesbaden: Springer VS, p. 67–88.

Schiffers, B. (2009): Verfügungsrechte im Stadtumbau, Wiesbaden.

Schlesinger, M. et al. (2014): Entwicklung der Energiemärkte – Energiereferenzprognose. Prognos AG, EWI (Energiewirtschaftliches Institut an der Universität zu Köln), GWS (Gesellschaft für Wirtschaftliche Strukturforschung mbH). Projekt Nr. 57/12, Studie im Auftrag des Bundesministeriums für Wirtschaft und Technologie. Basel, Köln, Osnabrück.

Schmidt, A. C. et al. (2004): A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax – Part 2: comparative assessment, in: The International Journal of Life Cycle Assessment, 9(2), p. 122–129.

Schneidewind, U. (2011): "Embedded Technologies" – Plädoyer für ein erweitertes Innovationsverständnis, in: Exzellenz – Das Clustermagazin Nordrhein-Westfalen, 4, p. 14–15.

Schneidewind, U.; Scheck, H. (2012): Die Stadt als "Reallabor" für Systeminnovationen, in: Rückert-John, J. (Ed.): Soziale Innovation und Nachhaltigkeit. Perspektiven sozialen Wandels, Wiesbaden.

Schneidewind, U. (2013a): Transformative Literacy. Rahmen für den wissensbasierten Umgang mit der "Großen Transformation", in: GAIA, 22(2), p. 82–86.

Schneidewind, U. (2013b): Die Zeichen richtig deuten. Auf dem Weg zu einer "transformativen Literacy", in: Politische Ökologie, 133, p. 39–44.

Schneidewind, U. et al. (2016): Von der Stadt zum urbanen Reallabor – eine Einführung am Beispiel des Reallabors Wuppertal, in: Hahne, U.; Kegler, H. (Eds.): Resilienz. Stadt und Region – Reallabore der resilienzorientierten Transformation, Basel.

Scholz, R. (2011): Environmental Literacy in Science and Society. From Knowledge to Decisions. Cambridge University Press, Cambridge, UK.

Schüle, R.; Bierwirth, A.; Madry, T. (2011): Zukunft der Energieberatung in Deutschland. Wüstenrot Stiftung, Ludwigsburg.

Schütze (1983): Biographieforschung und narratives Interview, in: Neue Praxis, 13(3) 1983, 283–293.

Soares, J. J. F.; Grossi, G.; Sundin, Ö. (2007): Burnout among women: associations with demographic/socio-economic, work, life-style and health factors, in: Archives of Women's Mental Health, 10(2), p. 61–71.

Sorrell, S. (2010): Mapping rebound effects from sustainable behaviours: Key Concepts and Literature Review.

Soukup, O.; Hanke, T.; Viebahn, P. (2012): Wärmedämmungs-Strategien im Haushaltssektor und ihr Beitrag zu Materialeffizienz und Emissionsminderung – eine Langfristanalyse bis zum Jahr 2050, in: Zeitschrift für Energiewirtschaft, 36(1), p. 37-50.

Star, S. L.; Griesemer, J. R. (1989): Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39, in: Social Studies of Science, 19(3), p. 387–420.

Statistische Ämter des Bundes und der Länder (Ed.) (2015): Zensus 2011. Gebäude- und Wohnungsbestand in Deutschland. [https://www.zensus2011.de/SharedDocs/Downloads/DE/Publikationen/Aufsaetze_Archiv/2015_12_NI_GWZ_endgueltig.pdf; 01.04.2016]

Stevenson, C. L. (1975): Ethics and Language, New Haven; London.

Stieß, I. et al. (2010): Handlungsmotive, -hemmnisse und Zielgruppen für eine energetische Gebäudesanierung. Ergebnisse einer standardisierten Befragung von Eigenheimsanierern, Frankfurt am Main.

Utterback, J.M. (1994): Mastering the Dynamics of Innovation, Boston.

van Dam, K. H.; Nikolic, I.; Lukszo, Z. (Eds.) (2013): Agent-Based Modelling of Socio-Technical Systems. Dordrecht, Springer Netherlands.

van den Bergh, J.C.J.M.; Truffer, B.; Kallis, G. (2011): Environmental innovation and societal transitions: Introduction and overview, in: Environmental Innovation and Societal Transitions, 1, p. 1–23.

Verplanken, B.; Wood, W. (2006): Interventions to break and create consumer habits, in: Journal of Public Policy & Marketing, 25(1), p. 90–103.

Wagner, F.; Grunwald, A. (2015): Reallabore als Forschungs- und Transformationsinstrument. Die Quadratur des hermeneutischen Zirkels, in: GAIA, 24(1), p. 26–31.

Wissenschaftlicher Beirat der Bundesregierung Globale Umweltfragen (WBGU) (2011): Welt im Wandel. Gesellschaftsvertrag für eine Große Transformation, Hauptgutachten WBGU, Berlin.

Wolff, S. (2000): Wege ins Feld – Varianten und ihre Folgen für die Beteiligten und die Forschung, in: Flick, U.; Kardorff, E.v.; Steinke, I. (Eds.): Qualitative Forschung: Ein Handbuch, Reinbek: Rowohlt , p. 334–349.

Wood, G.; Newborough, M. (2003): Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design, in: Energy Build, 35(8), p. 821–841.

Wuppertal Institut (2011): Transitions towards Sustainability. Rethinking the Wuppertal Institute Research Perspective. Working Paper, Wuppertal.