*Source: International Business times*

# Residential energy savings on a tight schedule

## An ex-ante hybrid bottom-up approach to evaluate contributions of energy efficiency and conservation measures to enhance short-term energy security

Supervisor UU: Dr. Machteld van den Broek
Supervisors Ecofys: Prof. Dr. Kornelis Blok, Katja Dinges
Student number: 3496805
S.Scheffer1@students.uu.nl
ECTS: 30
Climate-KIC label
GEO4-2510 Master's thesis Energy Science Utrecht University

Sacha Scheffer

S.Scheffer1@students.uu.nl

**Abstract**

Short-term energy security (STES) regarding natural gas and electricity has become a high priority on the EU energy agenda. Residential short-term energy efficiency and conservation measures (STEECMs) could have a significant contribution to improve STES. A limited amount of research has attempted to quantify impact of STEECMs on STES. Therefore, this study attempts to quantify contributions of STEECMs to STES by setting up of a detailed ex-ante bottom-up STEECM model. An extensive literature overview is conducted to develop such a model. With Germany as case-study, a detailed reference case is setup with technical, economic and utilization parameters to describe micro-scale characteristics of five energy end-use services (EEUSs). A list of 39 STEECMs is developed extended with additional technical, economic and socio-behavioral parameters to illustrate micro-scale and macro-scale EEC barriers, short-term energy efficiency and conservation potentials (STEECPs), investment costs and energy costs savings. Characteristics of STEECMs can be connected to four dimensions of STES, namely availability, accessibility, affordability and acceptability. Realistic survey data, timescale and disruption severity scenarios and three policy intervention scenarios are developed to simulate realistic energy- or costs savings and lists of favorable STEECMs with regard to a certain STES dimension. Technically, natural gas space heating (SH) STEECMs have the highest micro-scale and macro-scale theoretical STEECP and electricity has no clearly preferred EEUS to realize energy savings. Economically, most energy costs can be saved by space heating- and lighting STEECMs, but affordability is inhibited by long payback periods for renovation and technology replacement. Utilization behavior STEECMs have the lowest implementation difficulty, while renovation and technology replacement have the lowest impact on comfort level. Favorable STEECMs with the highest realistic STEECP could save up to 23% of German residential final electricity and natural gas use, but there is some uncertainty on sufficient stocks and professional installers. Favorable STEECMs in a small disruption scenario are dominated by electricity measures with limited technical contribution (8-13%). A severe disruption scenario favors more SH and domestic hot water (DHW) with a combined STEECP of 15-37% of residential final natural gas and electricity use. An informational and awareness campaign strongly improves a small disruption scenario (11%), but has less impact on severe disruption scenarios (33%). Price signals improve the affordability and subsidy schemes make technology replacement more common in the list of favorable STEECMs to contribute to STES.

# Table of Contents

**List of abbreviations**

DHW: Domestic Hot Water

EC: Energy Conservation

ECM: Energy Conservation Measure

EE: Energy Efficiency

EEM: Energy Efficiency Measure

EEC: Energy Efficiency and Conservation

EECM: Energy Efficiency and Conservation Measure

EECP: Energy Efficiency and Conservation Potential

EEM: Energy Efficiency Measure

EEUS: Energy End-Use Service

ES: Energy Security

ESP: Energy Savings Potential

EU: European Union

hh: Household

IEA: International Energy Agency

MFH: Multi-Family House

NEEAP: National Energy Efficiency Action Plans

R&D: Research and Development

SFH: Single-Family House

SH: Space Heating

STEECM: Short-term Energy Efficiency and Conservation Measure

STEECP: Short-term Energy Efficiency and Conservation Potential

STES: Short-term Energy Security

VoLL: Value of Load Lost

# 1. Introduction

## 1.1. Context

*Energy security* (ES) has been an important aspect of European energy policies for decades, since most of its systems and welfare depend on it. No large energy supply disruptions have occurred since the oil crises of the 1970s' and the European Union (EU) wants to ensure this will stay so in the future (European Commission, 2014a). Attention to energy security in Europe increased significantly in 2006 and 2009, because of short disruptions in gas supply from Russia (European Commission, 2014). Recent conflicts in Eastern Europe and the Middle-East, and increasing attention towards climate change have emphasized the importance of having comprehensive strategies and policies to ensure energy security within the EU. Despite several achievements, such as a semi-completed internal energy market, improved gas and electricity infrastructure and attempts to diversify energy supply, the EU remains vulnerable to changes in external energy input (Ibid.). Currently, the EU imports 53% of the energy it uses, of which oil and gas have the largest deficit, followed by coal and other solid fuels. Energy imports currently total somewhere around 400 billion Euros per year (Ibid.). Furthermore, global energy demand is expected to grow substantially, which puts even more pressure on secure energy supply to Europe (Pasqiuer, 2011; European Commission, 2014a). Hence, in 2014 the European Commission issued several communications to address energy security (ES) in a more comprehensive way, with a more specific focus on natural gas and electricity (European Commission, 2014a; European Commission, 2014b). Also, ES is closely related to climate change, due to transitioning energy systems and increased occurrence of extreme weather events that threaten power plants and infrastructure (Jewell et al., 2014).

ES is highly context dependent, which has led to a multitude of approaches and definitions of ES as a concept. Recent ES literature attempts to structure ES as concept by figuring out its dimensions and gathering various approaches to measure and quantify ES (Kruyt et al., 2009; IEA, 2011; Ang et al., 2015; Narula & Reddy, 2015). One of the most used definitions originates from the International Energy Agency (IEA): 'energy security is the uninterrupted availability of energy sources at an affordable price' (IEA, 2007). Energy security can be looked upon from several (time) scales, types and sources. Firstly, ES can be divided into various geographical scales, from global to local. Furthermore, ES can be applied on a short time-scale or a long-time scale (IEA, 2007). Short-term energy security (STES) concerns mostly mitigation of disruptions that occur due to natural (e.g. droughts) or political (for example trade conflict) events, while long-term ES generally considers depletion of resources and environmental concerns that eventually lead to alterations of the energy system (Kruyt et al., 2009; IEA, 2011). A similar, but slightly different distinction is that energy security can be divided in two general types: security of supply (e.g. fuel availability) and security of capacity (e.g. available power plants and infrastructure) (IEA, 2005; Pasqiuer, 2011). Capacity shortages moreover regard energy shortages during certain periods of time during the day, such as peak hours in the evening. Supply shortage covers energy shortages (or shortfalls) that are constant for a certain amount of time. Hence, both types cover different dynamics. Next to this, there is a significant difference between electricity, natural gas and oil regarding ES. These energy sources have varying import percentages, deliver different services and operate on different markets with various risks and benefits. Hence, ES is a concept, which should be carefully defined to prevent misconceptions. Short-term energy supply security for electricity and natural gas is one of the main concerns with regard European ES (European Commission, 2014a).

Furthermore, it is widely acknowledged that *energy efficiency* (EE) leads to energy savings, which could contribute to increasing ES (Fleiter et al., 2012; Haydt et al., 2013; European Commission, 2014b; Ang et al., 2015). Similar to ES, *energy efficiency and conservation* (EEC) literature contains a variety of definitions, dimensions and approaches, without a clear consensus which term refers to what (Schlomann, 2014). In this study, *conservation* is related to reduced energy consumption with reduced output of a certain energy end-use service and *efficiency* is stated as reduced energy consumption with the same output of a certain *energy end-use service* (EEUS) (Vidmar, 2010). An energy end-use service is the desired output of a service, which is provided to a user with a certain service that requires energy as input, such as lighting or hot water. Each end-use sector (residential, tertiary, industry and transport) has its own set of EEUSs'. *Energy savings* is the combined outcome of EEC compared to a certain reference case. EEC can be realized from a supply- or a demand-side perspective. Supply-side covers more efficient power plants and infrastructure, while demand-side discusses energy use due to consumption during the execution of EEUSs. Demand-side EEC can be seen as an important element to averse energy shortages (ESMAP, 2010). When energy consumption of energy-demanding actors (e.g. households) decreases, the share of non-domestic supply can also decrease. In principle, this makes a certain geographical region less vulnerable to energy supply disruptions and other ES issues (Bettgenhauser et al., 2014; Petersdorff et al., 2014; European Commission, 2014a).

EE improvement and EC efforts are generally regarded as a steady but slow processes that deliver results over a time frame of five to ten years and more. However, threats to ES can emerge quite rapidly, from both a supply side and from a capacity side. Hence, action is often needed on a much shorter timeframe, e.g. next month, next winter, or within a few years. Examples of energy shortfalls can be found in almost every region in the world, from South-Africa to India to Alaska etc. (Pasqiuer, 2011). Researching STES requires a different approach than conventional EEC improvement strategies or policies. Specifically on the energy demand side, there could be more options than conventional EE progress between 0% and 2% for buildings, insulation equipment, appliances etc. Examples of alternative EEC improvements are increased rate of implementation of energy efficiency measures (EEMs), quick demand reduction (EC) in emergency situations with energy conservation measures (ECMs), measures that increase flexibility with respect to different energy carriers and application of equipment or operations that are less dependent on continuous external supply. These demand-side energy savings options are referred to as *short-term energy efficiency and conservation measures* (STEECMs). 'Short-term' refers to the amount of time it takes for a measure to have an impact, not to the actual duration of a potential measure. Also, 'measures' influence EEUSs, for example the replacement of inefficient lighting as a measure to reduce lighting energy use. The execution of these STEECMs contains a certain energy savings potential, which is referred to as the *short-term energy efficiency and conservation potential* (STEECP).

A limited amount of literature has focused on the combination of ES and EEC on the short-term timeframe. IEA (2005a), Pasqiuer (2011), ESMAP (2010) and IEA (2005b) have a descriptive and historical approach on energy shortfalls. Lists of possible STEECMs are given, but in most cases only in a descriptive way. Pasqiuer (2011) assesses for example the situation during a disruption of hydro electricity supply in 2008 in Jeneau, Alaska, which led to a 25% reduction of electricity demand in a less than a month. However, the contributions of specific measures to this reduction are not specified in the report. A follow-up study by Leighty & Meier (2011) describes more specific allocations of energy savings based on data from the blackout in Jeneau in 2008, which indicates that it is possible to quantify demand-side STEECMs in an energy shortfall situation.

ESMAP (2010) includes lists of demand-side tools and STEECMs to improve STES with some quantification for Latin-American countries, such as possible energy savings and costs of light bulb replacement. However, a comprehensive quantitative overview and the quantification of more specific measures regarding STEEC and STES is underdeveloped.

One of the few available studies that attempts to comprehensively quantify STEECMs of a specific region from an ex-ante bottom-up perspective is De Groote (2005). His study confirms that most EE studies focus on mid- or long-term projections and the report states that achievable targets on the short-term are not a scientific, but a policy issue. The research concentrates on reachable *very large efficiency carriers* and *extremely cheap negawatt plants*, such as relighting the service sector and adjusting motors, pumps and ventilators in industry. Hence, a lot of STEECMs are left out to focus on energy savings measures with a high energy savings potential. His report delivers a useful structure that suggests that research on STEECMs is possible. However, the description of his method is relatively short, so certain assumptions are difficult to assess and generalize. In the report, most STEECPs of STEECMs are described as 50% of the yearly electricity or heating loss or consumption of a technology or an EEUS in general. This approach limits the detail level of realistic quantification of possible short-term energy savings.

Also, regions that have experienced serious STES issues have published energy emergency plans that contain information on EEC from various perspectives, for example DoE (2013) and Longoria et al. (2014). However, quantified lists of specific STEECMs are not included in their studies.

At the same time, extensive ex-ante bottom-up studies have been conducted that have quantified energy efficiency and conservation potentials (EEPs) for specific EEUSs with a focus on longer timescales from various perspectives (technical, economic, behavioral), such as Eichhammer et al. (2009), Elsland et al. (2013) and Giraudet et al. (2012). Most of these studies present results on a timeframe of 5 years or more and solely focus on efficiency and not on conservation. On a sectorial scale, studies such as Palmer et al. (2012) and Bürger (2010) offer extensive lists of EECMs with substantial energy savings potentials. However, a specific timeframe when these energy savings could be achieved and the connection of EECMs with ES is not included.

## 1.2. Research question

EECMs could contribute to energy supply security for natural gas and electricity, but most existing literature does not focus on STEECPs, and possible EECMs have limitedly been quantified on the short-term time-scale from an ex-ante bottom-up perspective, especially for ad-hoc STEECMs when energy shortages are faced. Therefore, there is a lack of understanding of the contributions that each of these STEECMs can deliver to STES and what the costs and efforts are to adopt them. Hence, the following research question arises:

<u>How can short-term demand-side energy efficiency and conservation measures contribute to short-term energy supply security?</u>

To answer this research question, different STEECMs are analyzed in a systematic way how they can contribute to improving energy supply security. The analysis is as much as possible quantitative. Therefore, firstly a literature study is done how to develop detailed database and a hybrid ex-ante bottom-up STEECM model that is able to evaluate the potential contribution of STEECMs to STES.

## 1.3. Scope

The main end-use sectors are residential, tertiary, industry, transport and agriculture (Schlomann, 2014). Each sector has its own set of dynamics, which makes it unfavorable to create a generalized model to link EEC to ES. The residential and industry sector have the highest contribution to electricity and natural gas usage, of which the residential sector has the most relevant literature and data available to discuss STEEC and STES. Therefore, the scope of this research is narrowed down to the residential sector. The energy carriers that are covered are natural gas and electricity.

The application of 'short-term' differs in the available literature. For example, Sovacool & Saunders (2014) state that the short-term is less than 2 years, while ESMAP (2010) indicates that short-term is less than six months. In this study, the short-term is defined as less than one year. Although the EU aims for an integrated European energy system, most energy systems and policies are analyzed on a national scale. A large mix of energy policies exists all over Europe, which makes it difficult to conduct a generalized continental study on EEC and ES. Also, energy-related data is not evenly spread and documented in the same way. Germany is the most populated and the largest economy of the EU. Germany has developed extensive plans to realize an energy transition and sees EE as one of the key pillars to realize this shift (Schlomann et al., 2014b). Due to a long history of progressive energy policies, Germany hosts several excellent energy-related institutes, who have gathered a lot of valuable energy-related data (Fraunhofer et al., 2014; Schlomann et al., 2014a; RWI & Forsa, 2013). Statistics on energy consumption and on key activities influencing energy demand is comparatively good compared to other European countries (IEA, 2014 in Schlomann et al., 2014b).

Furthermore, Germany has, apart from brown coal, almost no domestic energy carriers. For example the German gas import dependency is more than 85% and for coal more than 70% (BMWi, 2014). Natural gas and electricity mainly cover the residential, tertiary and industry sectors in Germany. Due to favorable climate policies, Germany already installed a substantial amount of renewable energy capacity, which totals more than 10% of the primary energy supply and 26% of the electricity generation in 2013 (IEA, 2013). Due to variability of wind and solar, renewable energy forms an extra threat to ES. The shift towards renewable energy systems has been depicted as ES risk (Dena, 2010 in Wolf & Wenzel, 2014). Germany also recognizes further climate change risks that threaten ES, which could be overcome by improved EEC (European Commission, 2013). This set of characteristics makes Germany a favorable case-study for this research.

### 1.4. Outline

Chapter 2 discusses existing EEC and ES literature to obtain a conceptual model on linking bottom-up STEECMs and STES. Chapter 3 describes the general method structure, taxonomy structures and analysis framework. Chapter 4 covers the case-study of the German residential sector. Chapter 5 offers an extensive discussion. Chapter 6 concludes the research and portrays further research possibilities.

## 2. Literature overview

Although energy use has been studied for decades, discourses on how energy use can be improved are still incomplete and dispersed (Moezzi & Janda, 2014). Only a limited amount of literature specifically covers STEECMs and STES. Therefore, general EEC and ES literature are assessed as well. Some papers addresses bottom-up EEC classification approaches in general (Eichhammer et al., 2009; Schlomann, 2014; Trianni & Cagno, 2012; Sorrell et al., 2000; Boonekamp, 2006), and some emphasize more specifically on EECMs (Vidmar, 2010; Trianni et al., 2014; Fleiter et al., 2012; Cagno & Trianni, 2014; Palmer et al., 2012). Several insightful papers originate from other sectors than the residential sector, which are included as well. This chapter is divided into three subsections. Section 2.1 elaborates on the classification of EEC by discussing reference cases, energy savings potentials, barriers to EEC, and several characterization of EECMs. Section 2.2 focuses on the description of existing EEC databases, bottom-up models and simulation tools to see what aspects of EEC are gathered and calculated. Section 2.3 gives further insights on ES and the link between EEC and ES. Section 2.4 offers an overview of STEEC and STES policies. Section 0 describes the conceptual model for this study, based on the available literature.

### 2.1. Classification of energy efficiency and conservation

This chapter combines the concepts of energy efficiency and energy conservation to obtain a synchronized terminology to classify both EE and EC for this research. The main emphasis of energy savings literature has been on EE, while EC has received much less attention (Moezzi & Janda, 2014). Bottom-up EE potential studies do not cover the entire spectrum of possibilities and mostly do not include behavior (lifestyle) and societal changes (Moezzi et al., 2009). However, in the last decade, the focus of EEC literature has been shifting towards more EC to assess energy savings potentials (Ibid.). Most articles describe EEC characterization frameworks for a specific sector (e.g. industry or residential), rather than a general approach (e.g. Fleiter et al., 2012 and Cagno & Trianni, 2014). It is assumed that each sector has a similar approach to EE and EC by describing energy-related technical, economic, behavioral and social aspects of a certain scope.

Technical aspects are relates to the energy usage data of certain EEUSs. Economic aspects describe the costs of investments, operation & maintenance and energy costs of energy-related activities. Behavioral aspects can be divided from several perspectives. Yohanis (2012) describes three types of behavior: *utilization behavior* (rate of use, intensity during usage etc.), *maintenance behavior* (state of existing technologies and execution of repairs) and *purchase behavior* (technology replacement decision) (Hitchcock, 1993 in Yohanis, 2012). To prevent misconceptions, these three types of behavior are named per type when behavior is mentioned. Recent literature is critical on current insights how end-use sectors, such as the residential sector, actually consume their energy on a detailed level (e.g. household level) (Wallenborn & Wilhite, 2014; Moezzi & Janda, 2014). These studies call for the inclusion of social aspects next to behavioral aspects in EEC research, which combines behavior of groups of actors. ES literature also illustrates a lot of social influences, which makes the addition of the social dimension in this research very relevant (de Nooij et al., 2007). The classification of social aspects is still in the conceptual phase, so this study groups social and behavioral aspects into socio-behavioral aspects.

This subsection describes literature that covers (2.1.1) setting up a reference case, (2.1.2) overview of energy savings potentials, (2.1.3) determining barriers to EEC, (2.1.4) characterization of EECMs and (2.1.5) data preferences and structures.

### 2.1.1. Reference case

A crucial issue of EEC characterization is that it can only be measured indirectly, since EEC is the outcome of using less energy compared to a certain reference (Boonekamp, 2006). Various methods to address energy savings are available, but they all have a similar basis, which is the creation of a reference case and a reference evolution or baseline (Ibid.; Thomas & Schüle, 2009; Schlomann, 2014).

#### *2.1.1.1. Reference case structure*

Reference cases are approached from various perspectives and scales. Table 1 gives an overview of the elements that are involved in the setup of a reference case.

Most elements in Table 1 are linked to each other. The geographical scope determines whether the reference case is set on a micro- or macro-scale. The micro-scale describes specific characteristics of a household or a dwelling with certain types of technologies and utilization behavior. Important macro-scale EECM characteristics indicate the number of actors within a sector (e.g. households), types of technologies, division of types of technologies and the ownership rate of these technologies (Eichhammer et al., 2009). This study assumes that technologies consist of space heating systems, hot water systems, small appliances (e.g. lamps) and large appliances (e.g. refrigerators).

Utilization behavior of an EEUS is mainly characterized in an indirect way, which makes a representative reference case even more complex (Moezzi & Janda, 2014). Moezzi et al. (2009) describes that usage is mostly based on exogenous variables, consisting of relatively fixed assumptions on how certain applications are used. More detailed information could be obtained by finding out the distribution of utilization behavior for each technology within EEUSs (Ibid.). For example, the amount of burning hours per type of lamp per average household or even more detailed per type of household based on income. It can also be beneficial to have a reference case that discusses the output per unit service, such as lumen per watt (Hicks et al., 2015). For example, data could be acquired on the minimum amount of service that is necessitated for a typical household. For example, most households have more lamps in their home than is needed to light the room sufficiently (Yohanis, 2012). These specific insights can make assumptions on energy- or energy costs impact opportunities of STEECMs more realistic.

*Table 1 Different elements of a reference case with corresponding descriptions. Sources: see column 3.*

| Reference case structure | | |
|---|---|---|
| **Element** | **Description/example** | **Source(s)** |
| **1. Starting point in time** | Every reference case needs to have a starting point somewhere in time, which mostly is a specific year. | (Schlomann, 2014) |
| **2. Geographical scope** | The geographical scope can be very small (specific dwelling), but also very large (entire EU). The geographical scope has a large influence on the type and detail level of the analysis. | (IEA, 2014) |
| **3. Energy End-use Services (EEUSs)** | The setup of a reference requires the determination of which EEUSs are relevant for the study. This can be approached on a sectorial or inter-sectorial level. For example, general lighting use or residential space heating. | (Swan & Ugursal. 2009; Thomas & Schüle, 2009) |
| **4. Specification of reference buildings and technologies** | The types of buildings and technologies that are representative for the EEUSs for the geographical scope and the starting point. For example, different types of lamps or various types of residential dwellings. | (Swan & Ugursal. 2009).; (Ballarini et al. 2014) |
| **5. Stock of reference buildings and technologies** | The translation of the specified technologies and buildings to represent the stock of the geographical scope of a study. For instance, the stock of refrigerators based on energy labels. The detail level varies a lot between different researches. | (Boonekamp, 2006; Kavgic et al., 2010) |
| **6. Utilization patterns of reference buildings and technologies** | The way a certain building or technology is operated (frequency, intensity etc.). For example, the daily amount of hours when a lamp is used. | (Kavgic et al., 2010) (Hitchcock, 1993) |
| **7. Reference evolution** | This term also known as a hypothetical development of EE, which depends on several assumptions on the market development and behavior changes (e.g. business-as-usual developments). For example, the yearly replacement rate of washing machines under stable policy conditions. | (Boonekamp, 2006; Thomas & Schüle, 2009; Schlomann, 2014) |

Furthermore, most EEC studies have developed an extensive methodology to describe a reference evolution (Thomas & Schüle, 2009; Kavgic et al., 2010). For example, Eichhammer et al. (2009) approaches the reference evolution by creating a specific scenario called the 'autonomous progress scenario', which describes the reference evolution. This scenario is specified per EEUS, which encompasses many assumptions. The short-term timeframe requires a briefer approach with fewer assumptions compared to their study.

An important aspect of energy use in the residential sector is not entirely covered by the different EEUSs and simultaneously applies to several EEUSs, namely buildings. It depends on the type, age and configuration of a particular building how much energy is consumed for space heating, space cooling, lighting and partially domestic hot water (Ballarini et al., 2014). Attention towards buildings has increased and methodologies have been developed to use reference buildings to calculate energy savings potentials, such as Ballarini et al. (2014) and Blom et al. (2011). The reference buildings are quite often limited to a few types, for example single-family house (SFH) and multifamily house (MFH) (BMWi, 2013).

### 2.1.2. Energy savings potentials

A variety of energy savings potentials are described in EEC literature. Firstly, different types of energy savings potentials are described. Then, further insights on a possible STEECP are given.

#### *2.1.1.1. Types of energy savings potentials*

Table 2 shows a list of various energy savings potentials and how they are described in the available literature.

*Table 2 Literature overview of different types of energy savings potentials. Sources: see column 3.*

| Energy savings potentials | | |
|---|---|---|
| **Type** | **Description/example** | **Source(s)** |
| **1. Theoretical limit** | The theoretical potential is constrained by physical laws. | (Schlomann, 2014) |
| **2. Technical potential** | The theoretical potential assumes the adoption of solely the best available technologies (BAT) with a certain implementation rate (focus on EE). | (Schlomann, 2014; Eichhammer et al. 2009) |
| **3. Economic potential** | The economic potential is limited by cost-effectiveness with regard to the entire society. It assumes that choices are made that give the highest economic benefit for a given scope (focus on EE). | (Schlomann, 2014; Eichhammer et al. 2009) |
| **4. Profitable potential** | The profitable potential focuses on the best possible economical decision based on the individual opportunities, so not necessarily for the society (focus on EE). | (Schlomann, 2014; Eichhammer et al. 2009) |
| **5. Near-economic or Market potential** | The market potential assumes that choices are made with the existence of barriers, such as bounded rationality (Focus on EE). | (Schlomann, 2014) |
| **6. Autonomous potential** | The autonomous potential is derived from a business-as-usual (no additional policy developments) situation. | (Schlomann, 2014) |
| **7. Frozen efficiency** | Frozen efficiency assumes that the EE of given technologies remains equal over the investigated period of time. | (Schlomann, 2014) |
| **8. Behavioral potential** | The behavioral potential focuses on utilization behavior, i.e. how much better an EEUS can be utilized. This potential combines EE with EC from an individual perspective. (EE+EC). | (Moezzi et al. 2009) |
| **9. Social potential** | The social potential goes one step beyond the behavioral potential. It tries to assess how energy can be optimally | (Moezzi & Janda, 2014) |

| | | |
|---|---|---|
| | utilized from a social organizational perspective, so how a group of people would save energy. | |
| **10. The Bürger (2010) theoretical potential** | Bürger (2010) relates the theoretical potential to the full adoption of BAT combined with altered behavior, which leads to a potential that is lower than the theoretical limit, but exceeds the technical potential. (EE+EC). | (Bürger, 2010) |

Table 2 shows that most studies have applied energy savings potentials with a focus on EE or EC, but several recent publications show that more integrated energy savings potentials are possible as well. The large amount of different energy savings potentials makes comparison between EEC studies a challenge. Also, energy savings potentials are frequently presented in the form of policy scenarios, such as the low- and high policy intensity scenarios of Elsland et al. (2013). These types are left out in this analysis.

The application of a diffusion rate is one of the complicating factors of energy savings potentials (Schlomann, 2014). For example, the technical potential assumes a maximum diffusion of BAT. However, this does not mean that every existing technology is instantly transformed into BAT. Most scenarios take the lifetime of appliances, investment cycles (e.g. 10% of the refrigerator stock is replaced each year) and gradual technology improvement into account when applying new technologies (Schlomann, 2014). Detailed insights in the specific methodologies of these potentials are important to take into account when comparing them. Although less relevant for the short-term, a more realistic energy savings potential is also dependent on the development of certain drivers, such as number of households or destruction and construction rates, which could be independent of EE (Schlomann, 2014).

Figure 1 gives a useful graphical representation of the different conventional energy savings potentials due to EE diffusion that develops over time. The near-economic potential is equal to the market-potential. The applied baseline is the *frozen efficiency*, but autonomous potentials are also frequently applied in EEC studies.

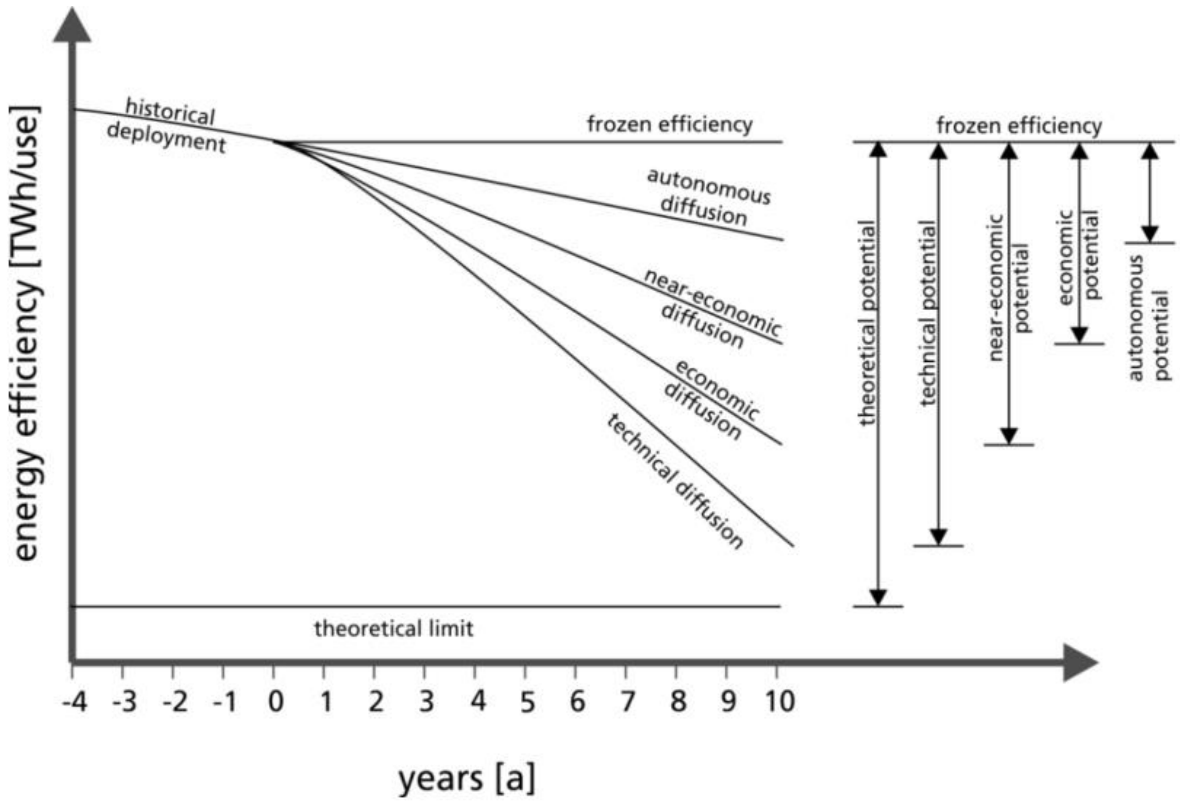


*Figure 1 Visual overview of time development of several types of diffusion of EE with corresponding savings potentials. Source: (Schlomann, 2014).*

Potentials 8-10 from Table 1 are described in more detail, because they offer additional insights to combine EE and EC. The omission of utilization behavior change of EEUSs could significantly underestimate the actual energy savings potential (Moezzi & Janda, 2014). The push of recent literature for better dimensioning and applying combinations of efficiency and conservation lead to the creation of more energy savings potentials, namely the *behavioral potential* and the *social potential* (Moezzi & Janda, 2014; Janda & Moezzi, 2013).

The *behavioral potential* is an important step to shift the focus from EE towards EEC. A lot of research has been done on the behavioral side of energy use and most of these studies have been applied to the residential sector (Delmas et al. 2013 in Janda & Moezzi 2013). These behavioral studies assume that a lot of energy is wasted by individual behavior. Altering individual behavior by policies and interventions, such as informing and educating individuals, a behavioral potential could be reached (Janda & Moezzi, 2013). The *behavioral potential* underlines that human actions are the reason that energy is used, not just by technologies being there (Ibid.). However, Janda & Moezzi (2013) and Moezzi & Janda (2014) criticize the existing behavior-oriented methodologies for assuming blueprint behavior for each individuals and unrealistic assumptions why people would save energy, which seems to be too different from reality that moreover encompasses group behavior. The *social potential* is adopting and utilizing energy in an optimal way at the level of social organizations, which takes creativity and social desires of people into account (Moezzi & Janda, 2014). The *social potential* tries to extend beyond individual behavior and attempts to assess group behavior, culture etc. as well (Ibid.). The *social potential* recognizes that altering utilization behavioral patterns is the most challenging aspect of energy savings and the corresponding assessment. However, creating the right social context could lead to substantially improved opportunities to save energy (Ibid.).

Another interesting approach that was mentioned above is the '*Burger (2010) theoretical potential*' (Bürger, 2010). His study discusses a specific static theoretical potential that covers technology replacement and utilization behavioral aspects for household electricity use in Germany. The *Burger (2010) theoretical potential* goes beyond other approaches considering full adoption of technologies and alteration of utilization behavior. With a calculated combined residential energy savings potential of 60% compared to recent electricity consumption, opportunities are much higher than other energy savings potential studies. His approach assumes that replacement occurs at once, without taking the time dimension into account. Nevertheless, Bürgers' (2010) combined approach towards technical and behavioral EECMs is an interesting starting point for setting up a STEECP in this study.

Thus, the existing list of energy savings potentials has been evolving, which makes comparison difficult. However, it also leaves room to develop new potentials for other specific purposes, such as a STEECP.

#### *2.1.1.2. Short-term energy efficiency and conservation potential*

A limited amount of literature has determined a STEECP (De Groote, 2005; Palmer et al., 2012). Moezzi et al. (2009) states that the energy savings potential during an energy shortage could be seen as a separate category with its own dynamics. Historical data indicates that during energy shortfalls, such as the California energy crisis in 2001 or Alaska in 2008, utilization behavioral changes were the main cause of energy demand reduction (up to 70% of the achieved energy savings) (Moezzi et al. 2009; Leighty & Meier, 2011). Table 3 displays historical realized energy savings during energy shortfalls, which could be used as comparison to setup a STEECP. Realized energy savings are between 5-40%, of which a majority is located in the 10-20% range. De Groote (2005) is actually the only study that names it a 'short-term energy efficiency potential', but the description of the short-term potential is fairly brief.

*Table 3 Realized energy savings during historical energy shortfalls in various geographical regions. Source: see column 4.*

| Historical data on realized energy savings during energy shortfalls | Duration of shortfall | Realized energy savings | Source |
|---|---|---|---|
| **Location and year** | **Weeks** | **%** | |
| Japan (2011) | 52+ | 15% | Pasquier, 2011 |
| Juneau, Alaska (2008) | 6 | 25-40% | Pasquier, 2011 |
| New Zealand (2008) | 104 | 20% | Pasquier, 2011 |
| Chili (2007/2008) | 52 | 10% | ESMAP, 2010 |
| Tokyo (2003) | 12 | 5% | ESMAP, 2010 |
| Brazil (2001) | 40 | 20% | IEA, 2005 |
| Ontario (2003) | 2 | 17% | IEA, 2005 |
| California (2001) | 36 | 14% | IEA, 2005 |
| Norway (2002) | 32 | 8% | IEA, 2005 |
| New Zealand (2001) | 12 | 10% | IEA, 2005 |

### 2.1.3. Barriers to EEC

Theoretical, technical and economic potentials have relatively well-defined limitations. Unfortunately, the determination of a market potential and a STEECP is much more complex. Predicted diffusion of EECMs in the real world is lower than most bottom-up energy models predict (Fleiter et al., 2012). This overestimation could be caused by a too generalized approach towards adoption behavior of EECMs (Ibid.). More characteristics might be necessary to obtain a realistic adoption potential of EECMs. Their paper gives no specific definition of 'adoption', but it is assumed that adoption describes the extent to which a certain EECM is implemented and utilized.

A commonly used term in energy savings literature is the '*energy efficiency gap*', which can be seen as the unused potential of cost-effective EE investment opportunities (Koopmans & Te Velde, 2001). The cause of this EE gap is attributed to the existence of a variety of barriers (Ibid.; Chai & Yeo., 2012; Stieß & Dunkelberg, 2013; Croucher, 2011).

Chai & Yeo (2012) conducted a literature review on EEC barriers described in articles between 2000 and 2010. This has been summarized to a list of 16 key barriers to energy savings, which can be subdivided into six main categories:

1. Economic market failures
2. Economic non-market failures
3. Behavioral
4. Institutional
5. Organizational
6. Physical constraints (Chai & Yeo., 2012; Sorrell et al. 2000)

*Economic market failures* are linked to the malfunctioning of the market. Originally, economists recognized economic market failures as the main barrier for the EE gap. Examples are information issues, unpriced energy costs and unwanted research and development (R&D) spillover effects (new ideas get picked-up by competitors) (Gillingham et al., 2009 in Chai & Yeo., 2012). These three barriers can be split-up in even smaller barriers, which goes beyond the scope of this study. Furthermore, issues arise that conservation behavior is constrained by the fact that economic consequences of using energy are not presented in real-time, which decreases the likelihood of taking action to reduce energy use (Croucher, 2011).

*Economic non-market failures* are more related to low priority of energy issues, access to capital and risk perceptions of actors (Chai & Yeo., 2012). This is confirmed by for example Leiserowitz et al. (2008), who describe that economic aspects are an important restriction for taking EECMs.

Stieß & Dunkelberg (2013) further conceptualize both types of economic barriers in the form of decision-making by describing constraints of two types of resources: (1) available knowledge, origin of information and social networks, and (2) salary, available capital or conducting refurbishment yourself. These two resources give concrete indications for operationalization to measure economic EEC barriers.

*Behavioral* barriers are summarized by Chai & Yeo (2012) as 'resistance to behavior change', which is still is an unclear definition. Also, irrationality or bounded rationality is named as a barrier of human behavior (Ek & Söderholm, 2010). More papers have studied behavioral barriers in the last 5-10 years, without a clear focus on defining the behavioral barriers to EEC (Moezzi et al., 2009; Gottwalt et al., 2011; Janda & Moezzi, 2013; Brown & Cole, 2009; Moezzi & Janda, 2014). So far, behavioral and societal change, which would be expected when energy shortages arise, has not been included in detail (Moezzi et al., 2009). Stieß & Dunkelberg (2013) describe two types of attitudes towards EE, which are (1) attitudes concerning the outcome of a certain refurbishment, such as aesthetics, comfort etc. and (2) attitude during the implementation, for example skill in refurbishment and unpleasant tasks.

*Institutional barriers* cover the quality of the legislation and enforcement from a government perspective. Certain regulations limit the types of technology replacement or renovation that are allowed (Stieß & Dunkelberg, 2013). *Organizational barriers* are related to the internal organization of energy related activities within companies, such as 'lack of energy related policies'. The residential sector does not have many energy-related policies that try to restrict EEC, so it is assumed that institutional and organizational barriers do not have a big influence. *Physical constraints* take applicability of technologies into account, for example buildings that are heated by district heat are limited in their ability to switch their heating system (Chai & Yeo, 2012).

Despite of the large amount of available literature, there seems to be no concise approach on the classification and the level of importance of each barrier yet (Chai & Yeo., 2012). Also, there is a lack of knowledge on the interactions between these barriers and whether overcoming these barriers will actually lead to the adoption of EECMs (Ibid.).

### 2.1.4. Characterizing energy efficiency and conservation measures

Energy savings potentials are connected to a certain reference case, but to realize energy savings, EECMs need to be adopted, which are restricted by certain EEC barriers. Available literature discusses characterization of the three main aspects of EEC (technical, economic, and socio-behavioral) of EEC. Multiple configurations to divide EECMs are possible. There is a grey area between EE and EC, which sometimes makes it confusing to see where a certain measure belongs to (Vidmar, 2010). Most technology replacement measures can be seen as EE, except if replacement leads to reduced EEUS output, such as using a fan instead of an air conditioner. Maintenance behavior measures are mostly EE, but in some cases emergency maintenance is related to EC, such as lowering the output of the water circulation pump. Utilization behavioral measures are moreover related to EC, but some can be considered as EE, such as turning off the lights when someone leaves a room. Another distinction that has been described by Bürger (2010) indicates a grey area of measures that require small investments, such as lighting sensors. This research assumes EECMs are divided into (1) renovation, (2) technology replacement, (3) maintenance behavior and (4) utilization behavior. Furthermore, a distinction is made between micro-scale and macro-scale characteristics of EECMs.

#### 2.1.4.1. Micro-scale EECM characteristics

Micro-scale EECM characteristics describe technical, economic, socio-behavioral characteristics of an EECM per actor within a sector (e.g. a household in the residential sector). Depending on the detail level, technical aspects require several exogenous variables, such as lifetime, operation- and standby power & hours or specific consumption per certain amount of time (Eichhammer et al., 2009).

Eichhammer et al. (2009) offers a clear method how to structure technical aspects of EECMs per EEUSs, which can be seen in Figure 2. This figure shows that EEUSs have internal variations per type (e.g. refrigerator and refrigerator with freezing compartment), size (e.g. 150 liter refrigerator or 200 liter refrigerator) and label (e.g. A-label energy use of 200 kWh and 240 kWh). The average yearly energy use of a certain appliance part of EEUS X in year Y is given. Specification of new technologies is given as well. Utilization behavior aspects are not presented, but could be added to each type of technology.

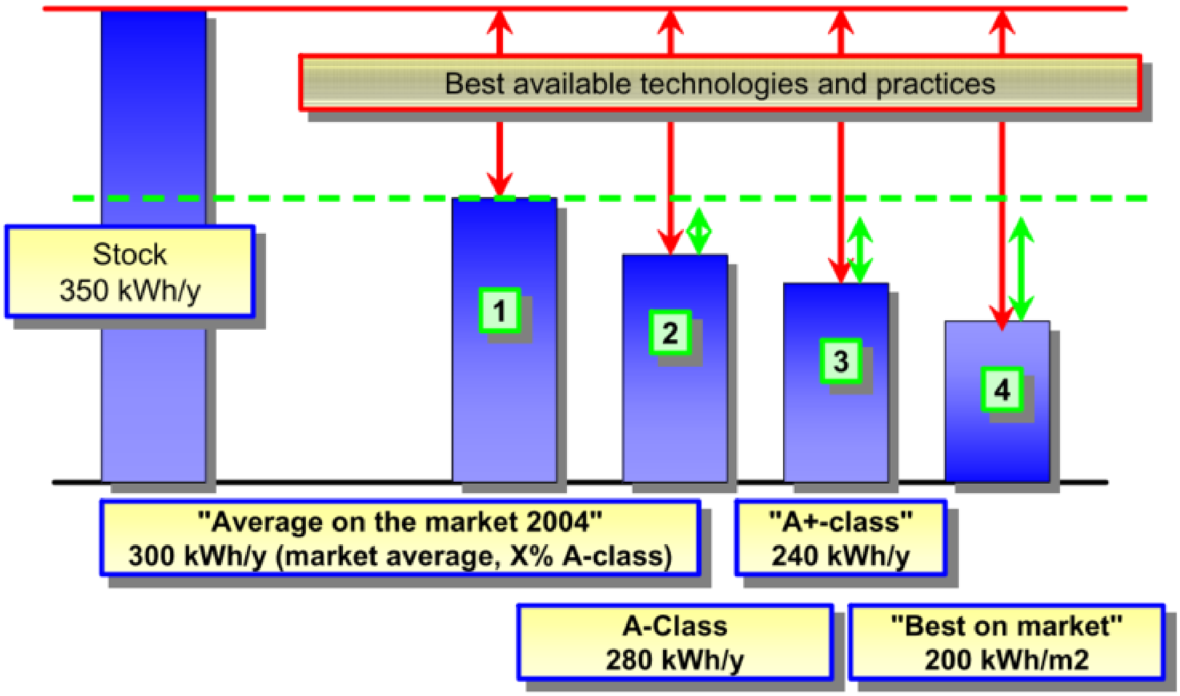


*Figure 2 Structure of a reference case of a specific end-use and replacement opportunities. Source: Eichhammer et al., (2009)*

Also, economic aspects of these options could be added in the form of investment costs, operation & maintenance costs and saved electricity costs (Eichhammer et al., 2009).

Furthermore, recent research advocates for further quantification of EEC barriers that characterize EECMs, who add to general technical and economic characteristics (Fleiter et al., 2012; Moezzi et al., 2009; Giraudet et al., 2012; Trianni et al., 2014). The choice of EECM characteristics is dependent on the scope and goal of the study. At this moment, outcomes of energy savings studies are often different from reality, which indicates the requirement of alternative calculation and assessment methods (Trianni et al., 2014). Fleiter et al. (2012) offer a useful guideline how to choose appropriate characteristics for a specific research on EECMs. The characteristics of STEECMs should be chosen based on:

- Relevance
- Applicability
- Specificity
- Independence
- Distinctness (Ibid.)

These five items assist in the setup of a list with relevant EECM characteristics. Similar to the reference case, EECMs are classified per EEUS (e.g. space heating, lighting etc.) or per system (building type, heating system etc.), which only describes the target area of improvement (Fleiter et al., 2012). The detail level can be increased by assigning multiple types of EECMs per EEUS. Table 4 gives an overview of extended methods of EECM characterization found in the available literature.

*Table 4 Literature overview on various EECM characterization schemes with extended taxonomies. Source: see column 1.*

| Extended EECM characterization schemes | | |
|---|---|---|
| **Source** | Main EECM characterization dimensions | Description |
| Fleiter et al. (2012) | 1. Relative advantage (financial aspects)<br>- Internal rate of return<br>- Payback period<br>- Initial expenditure<br>- Non-energy benefits<br>2. Technical context<br>- Distance to core process<br>- Type of modification<br>- Scope of impact<br>- Lifetime<br>3. Informational context<br>- Transaction costs<br>- Knowledge for planning and implementation<br>- Diffusion progress<br>- Sectorial applicability | Their study focuses on the industry sector. Existing literature has been assessed on EEMs, adoption behavior and barriers in the industry sector, which is translated into a classification method that uses EEM characteristics that can be valued in a semi-quantitative way. Each of these three categories consists of four subcategories. These subcategories have been parameterized on a 2-4 level scale, which describes the development from a low to a high adoption rate. For example, transaction costs are divided into low, medium and high and distance to core process is divided into close and distant. |

| | | |
|---|---|---|
| Trianni et al. (2014) | 1. Economic attributes<br>- Payback time<br>- Implementation costs<br>2. Energy attributes<br>- Resource stream<br>- Amount of saved energy<br>3. Environmental attributes<br>- Emission reduction<br>- Waste reduction<br>4. Production-related attributes<br>- Productivity<br>- Operation and maintenance<br>- Working environment<br>5. Implementation-related attributes<br>- Saving strategy<br>- Activity type<br>- Ease of implementation<br>- Likelihood of success<br>- Corporate involvement<br>- Distance to core processes<br>- Check-up frequency<br>6. Interaction-related attributes<br>- Indirect effects | Their study also focuses on the industry sector. Each of these categories contains 2-7 subcategories, which also are parameterized on a semi-quantitative scale, such as low to high, or close or distant etc. This characterization is tested on several cross-cutting technologies that show positive signs of applicability. The framework is applied to a variety of industrial EECMs, but no specific weights are given, since these are context dependent on the preferences of the decision maker. This approach differs from Fleiter et al. (2012) by distinguishing efficiency from conservation. This differentiation can be found back in the form of implementation related attributes. |
| Ek & Söderholm (2010) | Transaction costs (a perception of how much effort is required based on time or inconvenience)<br>- Legal<br>- Administrative<br>- Information gathering<br>- Searching for suppliers<br>- Completing market transactions | Ek & Söderholm (2010) approach the characterization of residential EEMs in an economic way by differentiating between transaction costs that describe inconveniences and direct costs in the form of investments in replacing applications. Benefits can also be expressed financially by saved energy costs and improved usage conditions. Their study also recommends that when transaction costs are used to analyze EEMs, the bounded rationality barrier should be clearly taken into account. For example, habitual routines and vague estimations during decision making processes. Their research emphasizes on the role of information and conduct surveys on the willingness to invest or execute in EECMs on a 1-5 scale. |

| | | |
|---|---|---|
| Moezzi et al. (2009) | - Distribution of usage<br>- Price elasticity<br>- Magnitude of the '*rebound effect*'<br>- Manual compared to automated operations<br>- Measure effectiveness and persistence<br>- Awareness and willingness | Moezzi et al. (2009) indicates that more realistic energy savings estimations could be developed by generating more in depth knowledge on the five presented aspects. Their study also refers to a study done by Marbek Resource Consultants (2007), that extensively covers residential energy use and the impact of appliance saturation, lifestyle and behavioral changes by conducting surveys and analyzing sustainability plans. |

Table 4 displays that on a micro scale, several EECM characterization approaches are possible with different levels of detail. Trianni et al. (2014) and Fleiter et al. (2012) have the most developed frameworks, while the other two are more indicative. However, care should be taken how these parameters are specifically operationalized, since they are focused on the industry sector. Furthermore, Stieß & Dunkelberg (2013) do not describe an EECM characterization framework, but their refurbishment decision model, influenced by limitations in attitudes, resources and regulations could be translated into concrete parameters (see section 2.1.3). Parameters from Table 4 that describe implementation related effects, utilization behavior and specific economic parameters are discussed in more detail.

**Implementation related effects**

Information is seen as an important aspect to enable EEC to happen (Ek & Söderholm, 2010; Yohanis, 2012; Stieß & Dunkelberg, 2013). However, Yohanis (2012) emphasizes that information is not the only aspect that affects implementation. Fleiter et al. (2012) assumes that the *transaction costs*, *required knowledge for implementation*, *diffusion progress* and *sectorial application* are important in the informational context. Especially the *required knowledge for implementation* could be applied to the residential sector.

Trianni et al. (2014) describes several implementation-related parameters, such as *activity type*. This parameter is operationalized as (1) procedure, (2) optimization, (3) retrofit or (4) new installation. Their study emphasizes that industrial decision-making processes are dependent on the activity type, where more difficulties are expected when new installations are considered instead of technology replacement. Ek & Söderholm (2010) raise the notion that households favor the status quo over alterations, which confirms the usefulness of differentiating between several types of interferences for the residential sector.

Other possible interesting implementation-related effects are *ease of implementation* and *check-up frequency*. *Corporate involvement* and *likelihood of success* Trianni et al. (2014). *Ease of implementation* is how much effort is required to successfully execute an EECM, which does not differ much from the residential sector. *Corporate involvement* and *likelihood of success* have less in common with residential EEC barriers.

**Utilization behavioral effects**

An aspect that influences the easiness of utilizing a certain EEUS after implementing a EECM is the *check-up frequency* (Trianni et al., 2014). Their research makes a distinction between (1) one-time intervention and (2) periodic check. Most technology replacement measures are considered as a one-time intervention over the target timeframe. Periodic checks are for EECMs that need to be checked and maintained to function properly. This issue could be of importance in the residential sector as well.

Furthermore, *Non-energy benefits* could influence the perceived comfort level of an EECM a lot (Fleiter et al., 2012). This parameter actually combines a variety of benefits, such as health, safety, environment etc. Many households include health and safety in their priority to save energy (Yohanis, 2012).

Another interesting aspect that could be analyzed is *willingness* (Ek & Söderholm, 2010; Moezzi et al., 2009). A variety of behavioral studies has been dedicated to find out how and when people change their energy-related behavior. Moezzi et al. (2009) defines willingness as the amount of households that is eligible and willing to adopt a technology, which unfortunately is hard to measure, observe and compare.

**Additional economic effects**

An economic factor that could influence residential STEECM adoption is *initial expenditure*, which is applied to the industry sector by Fleiter et al. (2012). Most households are not very keen on investing in EECMs, which indicates that investments should be kept as low as possible (Yohanis, 2012).

Both Fleiter et al. (2012) and Trianni et al. (2014) use the parameter *payback period* to discuss economic limitations. The residential sector also applies payback period as economic measurement (Wada et al., 2012). Furthermore, research has shown that lower income households prefer to work with higher discount rates than high-income households, which indicates a preference for low initial expenditure (Wada et al., 2012). A majority of the households can be seen as low-income due to asymmetric income distribution, so on average a short payback period is preferred (Schmid & Stein, 2013).

#### 2.1.4.2. Macro-scale EECM characteristics

Macro-scale EECM characteristics have the goal to enable micro-scale EECMs to be translated into a more aggregated energy savings potential. In most cases, macro-scale EECM characteristics have an exogenous character (Moezzi & Janda, 2014). Moezzi & Janda, (2014) describe several types of macro-scale aspects, but do not translate it to EECM characterization. Macro-scale aspects that could be quantified are the potential adoption rates of EECMs, which lead to aggregated energy savings, investment costs and energy costs savings.

The reference case links the micro-scale to the macro-scale by ownership rate of certain technologies and the division of these technologies between the different types of dwellings. Also, EECMs link micro-scale with the macro-scale by knowing the amount of actors (e.g. households) that could adopt a certain EECM (Swan & Ugursal, 2009). The adoption rate can be split up into a theoretical adoption potential and a realistic adoption potential. Palmer et al. (2012) approach the theoretical adoption potential as the full adoption on the micro-level, but only a part of the households could in theory execute a certain EECM. For example, only households with a thermostat can execute the EECM *lower thermostat 1 degrees °C*. The realistic adoption potential has the goal to evaluate which part of the households would realistically take an EECM, which is equal or lower than the theoretical adoption potential (Fleiter et al., 2012). For instance, in case of an energy shortfall, only half of the households with a thermostat is willing to lower its thermostat with 1 degrees °C.

Germany has not encountered a severe blackout in recent history, so there is no national historical data to assess realistic adoption behavior of STEECMs. De Groote (2005) describes that overall most EECMs can be executed in the short-term at least to some extent, which confirms the importance of the realistic adoption potential. De Groote (2005) and Palmer et al. (2012) approach the realistic adoption potential as 50-100% of the theoretical adoption potential, with no ES related explanation. However, historical data from literature that covers other regions could be used or more indirect data on willingness to save energy could be interpreted and converted. Interesting studies that could be used are IEA (2005) and Leighty & Meier (2011), who present surveys performed after energy shortfalls in several regions. These surveys have measured which percentage of the respondents took a certain STEECM during and after an energy shortfall. These papers warn for generalization towards other regions, but for certain EECMs, such as lowering the thermostat temperature, their outcomes give a more realistic indications than just stating '50% or 75% uptake of theoretical potential' from de Groote (2005) or Palmer et al. (2012). However, it should be taken into account that the energy price rose significantly and information campaigns were initiated in the cases where surveys were conducted.

Other papers try to obtain information how EECMs are adopted over time. Marbek Resource Consultants (2007) approaches macro-scale adoption as several development paths or transformation curves. Figure 3 displays three adoption developments: (1) linear, (2) tipping point and (3) S-curve. A big difference on macro-impact could arise depending on which path is followed, especially in shorter timeframes.

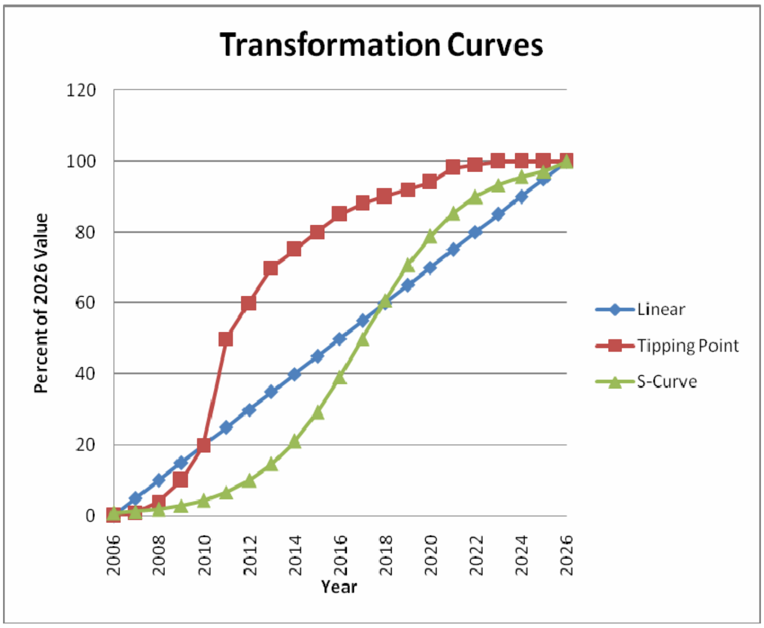


*Figure 3 Different types of transformation curves how energy savings are realized. Source: (Marbek Resource Consultants, 2007)*

Furthermore, Leighty & Meier (2011) discuss that stocks of certain technologies or available technical personnel could potentially limit realistic adoption when technology replacement is maximized. For example, there might not be enough A+++ refrigerators to reach the theoretical replacement or not enough installers to replace old boilers. Their case study of Alaska is a much more remote geographical scope than Germany, but the requirement of very large stocks could still be limited.

### 2.1.5. EEC data configuration

To correctly quantify EEC parameters on both micro-scale (specific EECM per household) and macro-scale (national EECP), reliable data has to be gathered and additional configurations have to be applied. Data that describe micro-scale aspects of a reference case or a list of EECMs differ in time, geographical location and aggregation level (Boonekamp, 2006). Bottom-up parameters encounter difficulties to remain valid and reliable when the aggregation level of utilized data increases. The energy savings potential of a single building can be assessed quite accurate, because its properties can be checked one by one. On a higher aggregation level, such as the entire building stock, there are many types of buildings, systems and appliances with varying properties and stock levels. In order to prevent excessive data requirements or enormous databases, types of buildings and technologies have to be simplified (Moezzi et al., 2009).

Nevertheless, building configurations and technologies involve a lot of input data, which can be seen by the large variety of approaches in the available literature to describe technical, economical and behavioral aspects of EEC (Schlomann, 2014). EEC data that is required for this study is not available in a single source or database. Hence, various data structuring methods are required. It is assumed that reference cases and STEECMs have the same types of data structuring requirements, since they both analyze the same type of aspects (technical, economic etc.). For some EEUSs standardized systems, such as Ecodesign directive, could be used as the starting point of technology replacement data (Kemna, 2014; VHK, 2014).

Several terms have been used to structure data, such as normalization, correction, harmonization, synchronization etc. (Thomas & Schüle, 2009; Schlomann, 2014; IEA, 2007). Schlomann (2014) states that normalization and correction factors have the goal to balance out EEC data to take indirect EE influences or EE policy influences into account. Normalization factors are the same for bottom-up and top-down indicators, while correction factors are not. Although not entirely clear, normalization covers technical related external impacts that are relatively clear defined, such as weather fluctuations and stock levels.

Correction factors are more focused on solving measurement issues between measures, such as free-rider effect and double-counting (Ibid.). Other literature use the term correction factors as normalization factors (Kemna, 2014a; IEA, 2014; Kockat & Rohde, 2012; Kemma et al., 2007; Mata et al., 2013). Varying use of terminology makes it a challenge to distinct both factors. Harmonization is used by Thomas & Schüle (2009) and refers to a model that enables the direct comparison of various calculation methods by using the same accounting unit, consistent basic assumptions and equal level of evaluation effort. Synchronization is used by Moezzi & Janda (2014) and describes the link between certain assumptions with certain concepts, such as linking types of persons with types of energy savings potentials. Most of these publications do not give clear specific definitions of terms to improve data structuring, which makes it difficult to apply them in a proper way. This paper assumes that normalization factors consider external influences regarding a specific data type belonging to a reference EEUS or STEECM. Correction factors apply to correct comparison of STEECMs to a more realistic total. Harmonization is the method to get calculation methods in one line, such as combining micro- and macro scale. The following subsections describe specific normalization, correction and harmonization factors.

#### 2.1.5.1. Normalization factors

Data between different years can be normalized by obtaining insights on external influences. Normalization is linked to setting the reference case at a certain timeframe or geographical scope (Blom et al., 2011). Unfortunately, apart from climate variations, there seems to be a lot of discussion on how to evaluate most factors, especially regarding economic aspects (Schlomann 2014). This uncertainty is often caused by data limitations (Ibid.). Table 5 shows some insights on normalization factors and how they are described.

*Table 5 Literature overview on bottom-up normalization factors. Sources: see column 1.*

| **Bottom-up normalization factors EEC data literature overview** | | |
|---|---|---|
| **Source** | Normalization factors | Description |
| (Schlomann, 2014) | - Temperature variations<br>- Stock variations<br>- Occupancy levels | These three factors differ per year and per geographical scope. Therefore, factors need to be applied to make them comparable. |
| Thomas & Schüle (2009) | Not specifically described. Refer to the Eureopean directive on energy end-use efficiency and energy services (ESD) (Eichhammer et al., 2009) Annex IV(1.2) | Names correction factors for weather, structural effects etc., which conflicts with the temperature variations normalization factor of (Schlomann, 2014). |
| (Blom et al., 2011) | No specific factors mentioned. A lot of normalization factors are technology-specific. | The total environmental footprint is compared with the footprint of a single technology or process. |
| (Greller et al. 2010) | - Climate factors | Energy ratings are translated into universal figures by normalizing for climate factors. |

This table illustrates that there is no clear list of normalization factors and that many of them are referred to other publications.

#### 2.1.5.2. Correction factors

Table 6 gives a literature overview of bottom-up correction factors.

*Table 6 Literature overview on bottom-up correction factors. Sources: see column 1.*

| Bottom-up correction factors EEC data literature overview | | |
|---|---|---|
| **Source** | Correction factors | Description |
| Thomas & Schüle (2009) | - Avoid double counting<br>- Multiplier effects<br>- Free-rider effects | Double counting has the aim to prevent that multiple EECMs within the same EEUS do not directly get added together to calculate an energy savings potential. The multiplier or spill-over effect involves EECMs that are taken without policy or company interventions. This factor is less relevant for impact EECMs. The free-rider effect relates to subjects who take benefits from a supportive action to save energy, while they would have saved energy anyway. Also, this factor is more focused on policy measures. |
| (Giraudet et al. 2012) | - Rebound effect<br>- Learning effect<br>- Information effect<br>- Price effect | These correction factors are different from other sources in this table. Nevertheless, these factors could be useful for setting-up a STEECM model. The rebound effect is described below. Learning effects describe altered energy use or costs due to improved conditions when certain EECMs are increasingly applied. The information effect is based on the presumption that increased information enhances the impact of EECMs. Price effects influence the likely service output, where higher prices decrease demand for services. |
| (Schlomann, 2014) | - Double-counting<br>- Non-compliance<br>- Multiplier effect<br>- Free-rider effect<br>- Direct rebound effect | Double counting occurs due to interaction of EECMs. Non-compliance applies to the part of an EECM that is not fulfilled. The multiplier effect extends the original impact of an EECM. The free-rider effect covers the adoption of EECMs that would have been done without policy interventions. The direct rebound effect influences EEUS due to perceived benefits of EECMs. |

Several of these factors are more related to policy measures than to demand-side EECMs, such as the multiplier effect and the free-rider effect. Double-counting and rebound effects are the most interesting factors for bottom-up STEECM analysis, so a more detailed description can be found below.

**Double-counting**

Double-counting can be approached on several levels. Schlomann (2014) approaches double-counting on a policy level, where energy savings can be related to multiple policies, which overestimates the contribution of separate policies. It depends on the detail level how big the overlap is (Thomas & Schüle, 2009). The combination of utilization behavior and technology replacement creates even more difficulties, since overlap is not 100%, which could be seen as indirect double-counting. For example, it is clear to see that replacing old light bulbs with CFL or with LED leads to double-counting, while replacing lamps and reducing the amount of burning hours only partially overlaps, which leads to overestimation of energy savings potentials.

**Rebound effects**

Rebound effects are considered as altered behavior after certain EECMs have been taken, which in most cases reduces the expected energy savings (Wallenborn, 2014). The rebound effect can be split up into a (1) direct rebound effect, (2) indirect rebound effect and (3) economy-wide rebound effect (Barbu et al., 2013). Direct rebound effects can be linked to specific technologies, while indirect- and economy-wide rebound effects are more difficult to link to specific items.

There is much discussion around the impact of the rebound effect. The rebound effect can be approached from various scales and angles, which makes quantification very challenging (Wallenborn, 2014). Sovacool & Saunders (2014) see rebound effects as a challenge to improve ES with EE without quantifying the issue. Giraudet et al. (2012) tries to quantify rebound effects as a service factor that contributes to economic constraints. A higher EE increases the service factor, because energy costs per unit service decreases. There is a difference between short-term and long-term rebound effects, where short-term considers utilization behavior and long-term covers changes in technology stock (Gillingham et al., 2009). Leighty & Meier (2011) have measured short-term rebound effects by measuring several energy-related aspects, such as thermostat temperature, during- and after an energy shortfall. Their approach on rebound effects differs from Gillingham et al. (2009), because time differences are related to crisis behavior instead of general behavior. However, it is unclear whether the presented outcomes can be generalized to other cases (Leighty & Meier, 2011). Also, many more detailed specifications are described in various sources. For example, rebound effects were found to be different between various groups of people, such as renters and homeowners (Leighty & Meier, 2011; Barbu et al., 2013).

#### 2.1.5.3. Harmonization factors

The origin of available data influences the application possibilities due to varying data collection methods (Thomas & Schüle, 2009). Harmonization factors could contribute to tackle these differences in applied methods. Just like with normalization factors, Thomas & Schüle (2009) refer to a specific ESD Annex IV(1.1), where harmonization is referred to as using calculation methods that make data comparable. They state harmonization should consist of a common structure for documentation of energy savings and calculations that are involved. This structure also includes reference evolutions and correction factors (Ibid.). Harmonization is divided into three levels: (1) European default values, (2) national representative values and (3) program- or participant specific values, with complying data sources, documentation and processing (Ibid.). Depending on the data, different harmonization levels have to be applied for energy savings evaluations (Thomas & Schüle, 2009).

#### 2.1.5.4. Uncertainty

All technical, economic and socio-behavioral outcomes have an error margin. The error propagation theory, as is described in Harvard (2007), indicates that the combined error of multiple estimations is substantially lower than the separate forecasts. This theory could be applied to STEECMs as well. The combined outcome of STEECMs is more reliable compared to outcomes of separate STEECMs. It is not the goal of this study to obtain an exact energy- or energy costs savings potential in PJ, but a magnitude on how much energy can be saved between one month and one year (e.g. 10% in 6 months).

## 2.2. Energy efficiency databases, models and simulation tools

Most conventional databases and models mainly focus on technology replacement, while utilization behavior can have substantial impact on changes in short-term energy use (Kavgic et al., 2010; Moezzi et al., 2009; Ürge-Vorsatz et al., 2009 in Giraudet et al., 2012). Several relevant EEC databases, models and tools are described.

One of the largest available European EE databases is the ODYSSEE-MURE database (Enerdata, 2015). This database is used to monitor and evaluate $CO_2$ emissions and efficiency trends on a yearly basis (ODYSSEE-MURE, 2013). The 'ODYSSEE' part of the database contains thorough techno-economic data on energy, energy related activities and efficiency indicators on the level of all end-use sectors. The 'MURE' part of the database contains information on available EEC policy measures, information on qualitative and quantitative impact evaluations of these policies, as well as a tool to identify and analyze the available policy measures within national energy efficiency action plans (NEEAP's) (Ibid.). Furthermore, MURE contains a simulation tool to model EEC policies and measures from a bottom-up perspective, which is further elaborated in the paragraph below. In most cases, national energy agencies or research institutes deliver the required data.

Enerdata et al. (n.d.) present a bottom-up simulation tool based on the MURE database to assess the NEAAP's and identifies pathways to realize EE in the most efficient way. This tool contains a high level of disaggregation, for example energy savings potentials of refrigerators in households for a certain year can be analyzed. The allocation of an energy savings potential is based on several technology and economic drivers that differ per potential. The applied indicators are focused on technology efficiency, not on behavioral aspects. For example, the energy savings potential of a refrigerator is only given by a technology driver that describes the replacement for a more efficient unit, so behavioral aspects like the energy savings potential of increasing the temperature of the refrigerator is not included. Also, no STEECP is included, which limits the applicability of the model to assess STEEC. The method of the MURE simulation tool is further described in Eichhammer et al. (2009), which contains a wide-ranging disaggregated overview of techno-economic energy efficiency potentials of various EEUSs to evaluate the reachability of Energy Efficiency Directives (EED) initiated by the EU. Their report mentions that solely simulation models with sufficient technical detail like the MURE simulation model have to be used for bottom-up potential calculations. The focus of the report is on trends until 2030, so the STEECP up to a few years is not specifically taken into account.

Haydt (2011) covers a support methodology how NEEAPs can be developed by proposing a hybrid multi-objective model based on a database of EECMs. This model enables the inclusion of multiple objectives of EE policy, so various preferences of decision makers for setting up EE plans can be researched. His dissertation is based on a database of 1598 technical-based and modal-shift EEMs that cover households, services, industry and transport. Of these 1598 measures, 217 contain technical data, but more specific energy savings potentials data are not explicitly taken into account. Haydt (2011) compares his database to the National Residential Efficiency Measures Database set-up by NREL in 2013, which contains standardized retrofit measures in the US on a household level (NREL, 2013). For example the replacement of a central air conditioner of a certain standard with an air conditioner with a better standard. This database does not include EC, which limits the applicability of their database to this research.

Furthermore, the Energy Transition Model (ETM), developed by Quintel, offers an online tool that can simulate a variety of energy development scenarios up to 2030 for several countries on a disaggregated level including energy efficiency adaptations (e.g. different energy labels for household appliances) (Quintel, 2015). Their model also covers multiple behavioral factors. The model does not include STES scenarios, but the tool offers the opportunity to calculate a residential STEECP for most EEUSs. Only the residential sector and buildings are modeled in sufficient detail to encompass both EE and EC.

Kavgic et al. (2010) reviews bottom-up models in the residential sector, which often lack multi-disciplinary approaches. Giraudet et al. (2012) covers an extensive model study for French residential energy savings, which tries to link the micro-scale to the macro-scale by using of heterogeneous parameters, intangible costs, learning behavior, and tradeoffs for renovation etc. Nevertheless, they critique that most of these factors are simplified versions of partially unexplained phenomena and state that issues that arise during the empirical quantification of EEC barriers are currently unresolved (Ibid.).

## 2.3. Connecting STES to STEEC

This subsection discusses additional literature how STES can be linked with STEEC, with a focus on energy supply security. Ang et al. (2015) and Narula & Reddy (2015) are the most recent scientific publications that offer an overview of ES definitions, dimensions and indexes. They state that recent studies have focused on ways to quantify various aspects of ES by setting up new indicator indexes, which also encompass multiple configurations. Especially contributions of specific aspects (e.g. EE, infrastructure, environment etc.) and the development of over time are underdeveloped (Ang et al., 2015). The following subsections give an overview of dimensions that link STEEC and STES and possible operationalization of suitable dimensions.

### 2.3.1. Dimensions of ES

Narula & Reddy (2015) state that EEC is still neglected in most ES studies. Various studies describe the different dimensions of ES (Narula & Reddy, 2015; Ang et al., 2015; Jewell et al., 2014; IEA, 2011; Gracceva & Zeniewski, 2014). Table 7 gives a short literature overview of frequently-used dimensions to ES.

Ang et al. (2015) and Narula & Reddy (2015) depict that EEC is one of the main themes of ES in the last 10 years, although not the most important. This link could make the relationship between STES and STEEC very straightforward. Theoretically, EEC positively influences availability, affordability, acceptability and accessibility, since energy demand is reduced, lowering energy costs and less pollution (Ibid.). IEA (2011) uses more practical dimensions, which are mostly focused on availability and accessibility. Costs and environmental aspects are only implicitly mentioned. Gracceva & Zeniewski (2014) offer dimensions that discuss potential threats to ES, which is focused on the cause and context of an ES issue.

*Table 7 Literature overview on energy security dimensions. Sources: see column 1.*

| Summary dimensions of energy security | | |
|---|---|---|
| **Source** | Dimensions | Description |
| (Kruyt et al., 2009) | - Availability<br>- Accessibility<br>- Affordability<br>- Acceptability | These four dimensions are also known as the four 'A's'. Availability is linked to physical aspects of energy carriers (is there enough energy available in the geographical area). Accessibility is explained as geopolitical aspects (are suppliers willing to share the amount of resources that you want). Affordability describes the economic issues. Acceptability discusses the environmental and social components. |
| Narula & Reddy (2015) | - Availability (diversity)<br>- Affordability (costs)<br>- Acceptability (environmental concerns)<br>- Accessibility<br>- Efficiency | These dimensions are not explicitly described in the text, but are referred to as the four 'A's' of ES. See the cell above. |
| Ang et al. (2015) | - Various | Ang et al. (2015) gives a meta-overview, which covers too many dimensions to be described in this table. |
| Jewell et al. (2014) | - Various | They describe that there are over 300 indicators and more than 20 different dimensions for ES, which makes the list too long to be included. |
| (IEA, 2011) | - External risk<br>- Domestic risk<br>- External resilience<br>- Domestic resilience | External risks discuss energy imports. Domestic risks apply to internal infrastructure. External resilience covers substitution of suppliers. Domestic resilience relates to responsiveness to impacts on fuel stocks. These factors differ per energy source. |
| (Gracceva & Zeniewski, 2014) | - Location<br>- Temporality<br>- Provenance | Location discusses the place in the supply chain where an issue occurs, from production to end-use. Temporality covers the moment and duration that the energy system is stressed, which alters the available strategies. Provenance is the origin of the energy shortage, which could be internal (own control) or external (more difficult to control). |

### 2.3.2. Operationalization of EEC related ES dimensions

The operationalization of EEC related dimensions of STES is only limitedly described. Ang et al. (2015) describes that EEC leads to enhancement of technologies, systems and practices, which decreases energy use and therefore improves ES.

Another operationalization that is used by Ang et al. (2015) is energy intensity, which can be operationalized per in monetary or in product values. When the energy intensity goes down, ES goes up. This factor is less applicable to the residential sector.

EEC also positively influences the required imports, the affordability of energy and improves the environment by lower emissions from energy production (Sovacool & Saunders, 2014).

The *temporality* dimension is interesting for STEEC, because it acknowledges various opportunities of EECMs to save energy in different timeframes (ESMAP, 2010; Gracceva & Zeniewski, 2014).

Some has to be said about the altered magnitude of impact of EEC barriers on STES related STEECM adoption behavior, since STES risks could overrule certain constraints that would be a significant barrier in a conventional EEC improvement scenario. The fear of no access to energy could lower economic barriers to invest in energy efficient technologies and take conservation measures (Petermann et al., 2011). People are more willing to take unpleasant energy savings measures in case of an STES issue, which eases barrier limits (IEA, 2005a). Ek & Söderholm (2010) also raise the loss-aversion preferences of subjects, which creates an interesting discussion point. Loss-aversion can be applied to the success of adopting an EECM, but when impending energy shortages lie ahead, this potential risk may overrule the EECM-taking aversion.

ESMAP (2010) specifically describes adoption opportunities for several time steps, which limit the possible types of STEECMs (maintenance, technology replacement and utilization behavior), influenced by certain EEC barriers. They assume that within one month, only STEECMs that consider utilization behavior are adopted. Up to six months, also small replacements can be executed. Within one to two years, some bigger EECMs can be accomplished as well (Ibid.).

## 2.4. STEEC and STES policies

This subsection gives a short overview on EEC and ES policies that are relevant for the short-term perspective. Firstly, a short description is given on main EEC policy types. Then, more specific STES policies are discussed and linked to EEC.

### 2.4.1. General EEC policy overview

Schlomann (2014) offers a list of policy instruments that aim to enhance EEC by tackling relevant EEC barriers:

- Favorable regulations (for example, standards for new technologies)
- Economic incentive schemes (subsidies, loan grants etc.)
- Tax regulations
- Planning (urban and infrastructure)
- Education
- Research & development
- Information or communication strategies (awareness, voluntary labelling)

Not all EEC policies can contribute to STEEC (Pasqiuer, 2011). Favorable regulations, planning, education and research & development normally develop over longer periods of time. Economic incentive schemes, tax regulations and information or communication strategies could be useful on a shorter timeframe.

### 2.4.2. STEEC-related STES policies

In case of an impending energy shortfall, several policy instruments could be applied to reduce the STES risk. ESMAP (2010) and Pasqiuer (2011) present lists of concrete policy tools to manage energy shortfalls for all sectors, which can be subdivided into five main themes:

1. Price signals
2. Behavior change
3. Technology replacement
4. Rationing
5. Market mechanisms

**Price signals**

Price signals have the goal to increase residential energy prices to curb demand. The response is often evaluated by looking at the price elasticity, which is the amount of energy reduction when the energy price doubles (Pasqiuer, 2011). For example, Leighty & Meier (2011) show a reasonable price elasticity after the power lines were cut, namely a 25% demand reduction by a price increase of 500% and 12% reduction for a 200% price increase. A prerequisite is that energy prices can be adjusted (Pasqiuer, 2011).

**Behavior change**

Behavior change is converted into information campaigns that have the goal to increase awareness, understanding of specific ES problems and possibly alter norms and attitudes of target subjects (Pasqiuer, 2011). Information campaigns have a relatively short start-up period and can reach a large part of the population through various media (Ürge-Vorsatz et al., 2009). Care should be taken that information is better received when it is contextualized to specific household circumstances, easy to understand and from a trustworthy source (Simcock et al., 2014).

**Technology replacement**

In Pasqiuer (2011), technology replacement is exemplified as an improvement program to facilitate increased replacement rates. Replacement could be increased by e.g. subsidy schemes that favor energy efficient technologies (ESMAP, 2010; Kanellakis et al., 2013). For example, certain German subsidies for heat pumps are rewarded up to a few thousand euros per heat pump (Fraunhofer-ISE, 2014). Rüdenauer & Gensch (2007) have conducted a study on increased replacement of residential technologies. Their study is based on average energy consumption and does not give straightforward answers on the viability of increased replacement. Economically, there is substantial variability and uncertainty in cost data. Environmentally, a refrigerator could be replaced after 5-10 years, which is less than their economic lifetime (Ibid.).

**Rationing**

Rationing is one of the least popular policy interventions, since households are forced to do something that they do not want (Pasqiuer, 2011). There are multiple strategies to enforce rationing: (1) block load shedding, (2) consumption rationing via quotas or entitlements, (3) market-based rationing and (4) incentive or reward schemes (Pasqiuer, 2011). From an economic perspective, it is preferable to ration in an optimal way by differentiating between regions based on social or economic consequences (de Nooij et al., 2009). In short, optimization occurs when the consumers with the lowest value are cut off first, based on the Value of Load Lost (VoLL) (de Nooij et al., 2009; Growitsch et al., 2014; Praktiknjo et al., 2011; Wolf & Wenzel, 2014).

However, this is politically sensitive, since some regions with lower economic output will feel disadvantaged. A remedy for rationing is to improve price-based approaches, which lowers the need for energy restrictions (Ibid.). Applying correct rationing necessitates reliable information on the socio-economic impacts of supply interruptions for a certain region (de Nooij et al., 2009).

**Market mechanisms**

Market mechanisms can facilitate other policy tools, such as *power entitlement trade for rationing schemes* (Pasquier, 2011). Next to this, market mechanisms could be linked to household energy use by altering energy prices according to their old energy consumption. This could incentivize households to consume less energy compared to their former energy use. These market-related mechanisms could substantially influence the affordability of energy (ESMAP, 2010).

## 2.5. Conceptual model

Figure 4 describes the conceptual model, based on the literature overview.

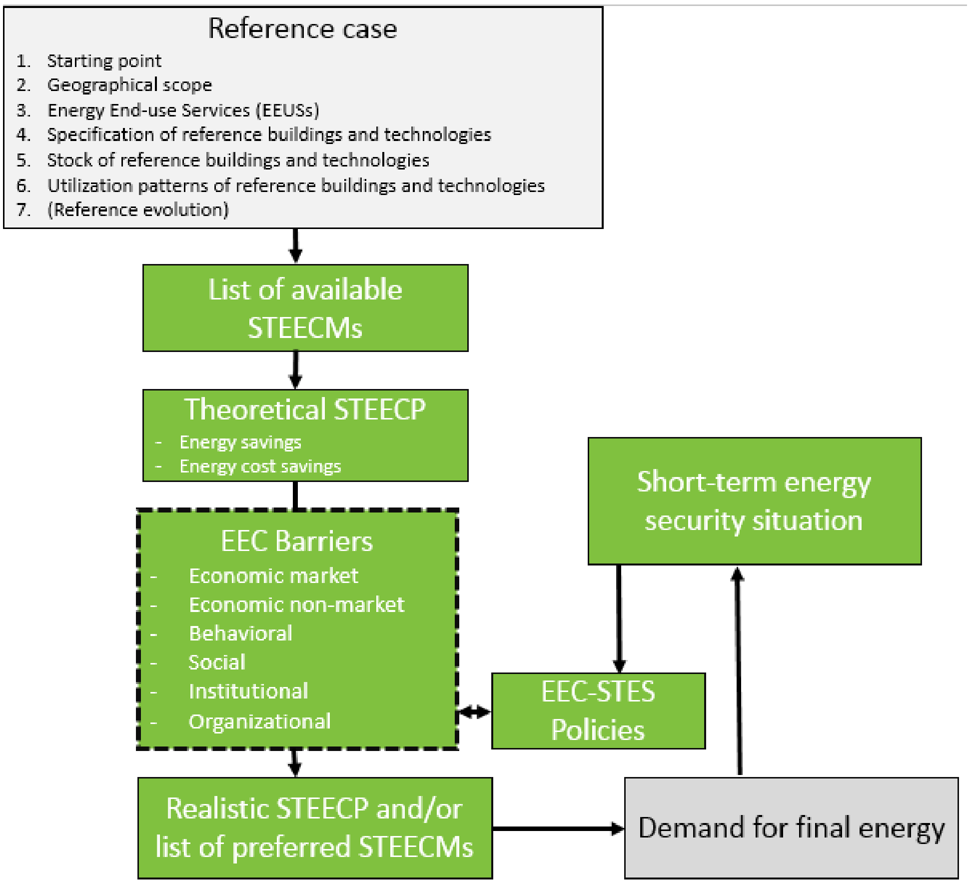


*Figure 4 Literature-based conceptual model on linking EEC and ES from a bottom-up perspective. Based on, among others, Fleiter et al. (2011) and* (Schlomann, 2014).

The conceptual model starts with a *reference case* containing structural aspects that have been described in 2.1.1. A particular *reference case* enables a certain *list of STEECMs* to improve energy use for the target scope. This *list of STEECMs* is described according to technical, economic and socio-behavioral aspects. STEECMs have a *theoretical STEECP*, which can be seen as the maximum amount of energy that can be saved by assuming complete adoption of STEECMs by the amount of the population that is eligible to implement them. The *theoretical STEECP* is similar to the Bürger (2010) theoretical potential, but technology replacement is limited to more specific constraints, which is described in the next chapter.

*EEC Barriers* inhibit proper adoption of STEECMs and which STEECMs are preferred. *EEC Barriers* cover economic mechanisms, behavior change and organizational structures. *EEC policies* aim to impact barriers to achieve improved EEC. An example of an impact of an EEC policy on *EEC barriers* is a subsidy scheme for residential insulation, which reduces the financial risk or initial investment barrier for investors. Also, policies influence preferred STEECMs, because e.g. subsidies make technology replacement relatively more favorable than changes in utilization behavior. Policies are also affected by *EEC barriers*, since the existence of *EEC barriers* is one of the main reasons for the creation of policies (Schlomann, 2014). For instance, Schlomann (2014) indicates that the *profitable potential* is not reached due to e.g. a lack of proper information on STEECMs. This information barrier could lead to the development of an EEC policy that creates an adequate information platform to address STEECMs. EEC policies are also influenced by the STES situation. In case an STES issue occurs, policies are set in place to prevent energy shortages from occurring.

The set of *EEC barriers,* influenced by *EEC policies,* determines the *realistic STEECP* and lists of preferred STEECMs. The *realistic STEECP* is less than the *theoretical STEECP*, more than conventional technical and economic potentials, but with limitations (barriers) of the market potential. Realization of the theoretical or realistic potential of preferred STEECMs leads to a lower *demand for final energy* and thus realized energy savings. Reduced *demand for final energy* increases STES. Next to this, when *demand for final energy* goes down, the *theoretical STEECP* goes down as well, because a part of the STEECP has been achieved. A lower *demand for final energy* positively influences the *STES situation*.

Finally, the *demand for final energy* could also influence the *reference case* as a negative feedback loop. This feedback goes beyond the scope of this research and is left out of the conceptual model.

# 3. Method

This chapter builds on chapter 2 and further operationalizes the conceptual model. This chapter is divided into the STEECM model structure (3.1), data configuration (3.2), development of reference and STEECM taxonomies (3.3) and an analysis and scenario framework (3.4).

## 3.1. Model structure

Haydt (2011) offers a short and clear list of requirements to an energy model. Table 8 displays the eight aspects that need to be considered when setting up a model.

*Table 8 Basic model structure for STEECM contribution to STES, based on Haydt (2011)*

| **Model structure** | |
|---|---|
| **Aspect** | Focus |
| **1. Energy carrier considered** | Natural gas and electricity |
| **2. Model focus** | Impact/appraisal |
| **3. Type of model** | Hybrid bottom-up model (aggregation level is micro and macro) |
| **4. Underlying methodology** | Ex-ante static simulation and scenarios |
| **5. Geographic scale** | National |
| **6. Sectors considered** | Residential |
| **7. Time horizon** | Short (less than one year) |
| **8. Time-steps of energy balance** | None (static) |

Researching the contribution of STEECMs to improve STES focuses on the *impact* of specific STEECMs on final energy demand. A*ppraisal* is included, because lists of preferred STEECMs are incorporated as well.

The type of model is *hybrid bottom-up*, since bottom-up technical, economic and behavioral data on specific STEECMs are included, but some data has to be to be extracted from macro-scale figures. STEECMs are assessed on the highest detail level possible, which is the micro level. However, results are also translated to the macro-scale to evaluate national energy- and energy costs savings.

The underlying methodology consists of two parts. Firstly, a reference case of a certain geographical location considering technical, economic and socio-behavioral aspects. Secondly, a list of STEECMs, based on existing literature and databases, which is connected to the reference case. These STEECMs an extended set of parameters to include short-term benefits and constraints are statically simulated to see which STEECMs and what part of these STEECMs can be adopted within several scenarios. Since these STEECMs have not yet been executed, the type of evaluation is ex-ante (Haydt, 2011; Schlomann, 2014).

IEA (2005a) indicates that advance warnings of energy shortfalls is between one day and twelve months. This makes it suitable to apply a timeframe of less than one year. The time-scale is based on the length of the scenario, because of the static nature of the simulations.

## 3.2. Data configuration

This subsection describes the specific data structuring to fulfill all requirements of an ex-ante hybrid bottom-up STEECM model. Firstly, data types are described. Then, normalization, correction and harmonization factors are pronounced. After this, data preferences are presented.

### 3.2.1. Data types

The detail level of the reference case and STEECM data differs per EEUS. Figure 5 gives an overview of different data levels that are involved in the characterization of the reference case and the calculation of STEECMs. This overview gives further insights into the data types that are needed to conduct a proper impact and appraisal analysis. It is assumed that the more disaggregated parameters are, the more realistic STEECMs can be quantified. Disaggregation does not go further than the energy use and utilization behavior of a specific EEUS, such as the energy use of an average A++ refrigerator and the average behavior of door openings per day.

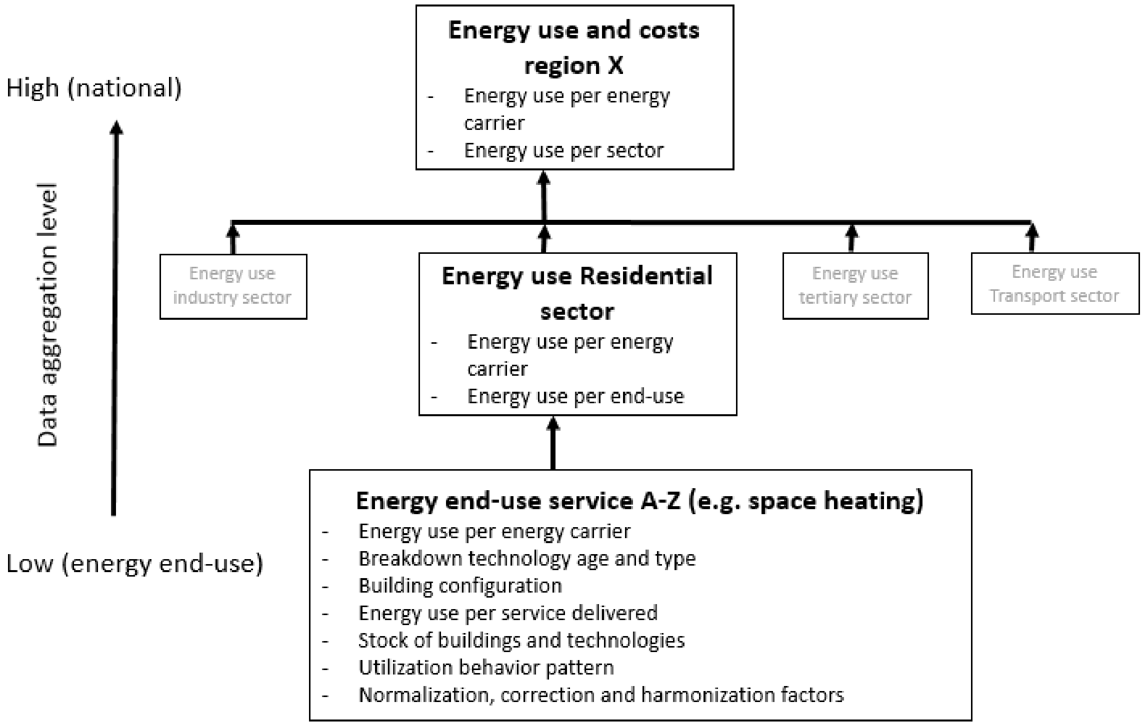


*Figure 5 Structure of reference data for various aggregation levels for a target country in a certain year to enable EECM research. Inspired by (Eichhammer et al., 2009)*

When a publication or a database contains a list of multiple appliance types for each efficiency class (multiple type A-label refrigerators), the average value has been used. If not available, the average value of the most used type in the publication is applied. A benefit of a high detail level is that by knowing these characteristics of the existing stock, the most inefficient refrigerators can be replaced by new ones, instead of replacing the average refrigerator.

Buildings are split up into SFH and MFH, so it is not be necessary to describe all insulation parameters for each separate building type. STEECMs that discuss specific renovations go beyond the scope of this model.

Quite detailed data is required in order to give a realistic overview of energy use in EEUS. Where possible, utilization behavior data proposed by Moezzi et al. (2009) (see 2.1.4.1) is extracted from various literature sources.

### 3.2.2. Normalization, correction and harmonization approach

A bottom-up STEECM model requires factors to normalize data for the right scope of analysis. The extent of normalization depends on the origin of the data. Table 9 displays the main normalization and correction factors that are applied in the model.

*Table 9 Description of normalization and correction factors that are applied in the hybrid bottom-up STEECM model.*

| Normalization and correction factors STEECM database | |
|---|---|
| **Factor** | Specification |
| **1. Climate variations** | Climate data is extracted from databases, scientific publications or weather forecasting agencies, such as the ODYSSEE database (Enerdata, 2015). |
| **2. Energy use normalization** | If technology data on a certain EEUS originates from another year than 2013, data is corrected according to average EE development per EEUS of the ODYSSEE database from 2007-2012. It is assumed that reference utilization behavior for each EEUS remains constant during the investigated period. |
| **3. GDP deflator** | Monetary data changes every year due to dynamic aspect of economic systems. Investment costs of STEECMs could originate from a different year than the base year. Therefore, GDP deflators are required. GDP deflators are based on EconomyWatch (2015). |
| **4. Rebound factors** | Rebound factors have different dynamics in an energy shortfall situation, where rebounds occur after a (possible) energy shortfall and much less during the adoption. Only direct rebound effects that target specific technologies that bring direct improvements are included, such as replacement of HL lamps for LED lamps. |
| **5. Double-counting factors** | Only direct double-counting is included. For example, in case replacing HL with LED and replacing HL with CFL are preferred, only the highest is included in the table. |
| **6. Learning and price elasticity** | A certain EECM could be more expensive when a few people do it, while the price goes down when more people adopt the EECM, because of learning effects (Fleiter et al., 2011). These two aspects are not included as a quantitative factor, because the uncertainty is too high. |

Technology-specific normalization is documented and discussed per case.

**Harmonization of micro- and macro scale data**

A common issue that arises in data structuring is that the combined micro-scale bottom-up data translated to the national macro-scale is different from the available aggregated data from other data sources. Each data source has its own set of assumptions, measurement methods and references. This research assumes that there are three types of approaches to harmonize the usage of various micro- and macro scale data approaches.

The first approach is to apply the bottom-up data that has been acquired and extending this directly to a higher aggregation level (following the arrows up in Figure 5) to calculate energy savings potentials for a given region. For example, the average yearly energy use of A-G label refrigerators and the national stock levels per label are known, the macro-level energy use can be calculated by bottom-up multiplying the energy use with the stock.

The second approach translates all bottom-up data in percentages that a certain STEECM impacts the energy use of an EEUS. These percentages are then multiplied by the energy use of the aggregation level that is needed for further analysis. For example, the STEECM 'reduce lighting levels' is based on bottom-up data from source X, which describes a certain reduction potential per household compared to a reference case belonging to that source. This number is translated to a percentage. Then, this percentage is applied to national average energy use of lighting, originating from source Y, which leads to harmonized micro- and macro-scale impact. This macro-scale absolute energy savings potential is different from the multiplication of the absolute energy savings from source X multiplied by the amount of households to obtain aggregated data.

The third approach is a hybrid form, where data from both sides is not complete enough to obtain a decent harmonization. For example, there is no data available on the average micro-scale energy use of a specific type of residential heating system in the residential building stock, but there is data available on the average micro-scale energy use of a non-refurbished specific type of heating system in the residential building stock and there is data available on micro-scale energy use of new heating systems energy use. If there is data on the amount of non-renovated buildings, then the renovation energy savings potential of this space heating system could be calculated bottom-up. However, the total residential heating energy use needs to be extracted from top-down figures, because there is no average residential space heating energy use to enable a bottom-up calculation to obtain national residential SH energy use.

These approaches are preferred in the order that they are presented above. If absolute data is not available to realize this approach, percentages are applied. If both are insufficient, a hybrid form is used.

### 3.2.3. Data preferences

Besides the content of available data, the type of source where data comes from could influence the reliability of presented figures. The source of each reference configuration is carefully documented to enhance the traceability of the applied data.

There are many types of sources that describe possible STEECMs:

- Scientific publications
- Reports from research and governmental institutions
- Corporate reports
- Internet publications by various sources

In this research, the following general preferences are applied to enhance the validity of the data (in preference order):

1. Papers and reports that publish technical, economic, socio-behavioral data on EEUSs after 2009 are favored over older publications
2. Data from scientific papers are favored over other types of publications
3. Complete bottom-up technology and utilization micro-scale data are favored over more aggregated data that has to be recalculated to value STEECMs

Also, standardized systems, such as Ecodesign, are used as guidelines for some EEUSs, such as refrigeration & washing. When a source indicates that the BAT of a certain EEUS has energy savings that are significantly better than the Ecodesign requirements, the source with the most efficient BAT is used.

Only a limited amount of EEUSs and STEECMs are included to enable detailed figures. The reference case indicates which EEUSs have the highest final energy use, but this does not necessarily mean these EEUSs have the highest energy savings potential. Enerdata et al. (n.d.), Bürger (2010) and Pehnt et al. (2009) are used as preliminary search to find out which EEUSs contain the highest conventional energy savings potential for the German residential sector.

## 3.3. Taxonomies to assess residential STEECMs

In order to compare and model contributions of STEECMs to STES, two taxonomies have been developed: (3.3.1) a reference case taxonomy and (3.3.2) an extended taxonomy of technical, economical, and socio-behavioral STEECM parameters. Most parameters have already been ideated by existing literature and some parameters is new. This is clearly indicated in the provided tables.

### 3.3.1. Reference taxonomy

Many assumptions are required to setup a transparent reference case for the residential sector. Table 10 gives descriptions per element to create a reference case that is relevant for ex-ante residential hybrid bottom-up STEECM research.

*Table 10 General description of the residential reference case structure for the hybrid bottom-up STEECM model.*

| **Residential reference case structure** | |
|---|---|
| **Element** | Description |
| **1. Starting point in time** | 2013 is taken as base year. |
| **2. Geographical scope** | The micro-scale is on the household level. The macro-scale is on the national level. |
| **3. Energy End-use Services (EEUSs)** | The energy end-use services in the residential sector are presented in Table 11 |
| **4. Specification of reference buildings and technologies** | The types of buildings and technologies that are representative for the EEUSs for the geographical scope and the starting point. For example, different types of lamps or various types of residential dwellings. These are described in section 4.1. |
| **5. Stock of reference buildings and technologies** | The translation of the specified technologies and buildings to represent the stock of the geographical scope of a study. For instance, the stock of refrigerators based on energy labels. |
| **6. Utilization patterns of reference buildings and technologies** | The way a certain building or technology is operated (frequency, intensity etc.). For example, the daily amount of hours that a lamp is used. |
| **7. Reference evolution** | The reference evolution is approached as frozen efficiency. It is assumed that all the energy that has been saved compared to a reference point in time counts in the possible aversion of energy shortfalls. Other types of reference evolutions for the short-term timeframe brings more complications than valuable insights, because outcomes are statically compared. |

The reference case for the residential sector is split-up into several types of technologies and buildings that cover the different EEUSs. There are slight differences within existing literature on how EEUSs are categorized. Table 11 displays the defined EEUSs.

| Residential energy end-use services |
|---|
| Space heating |
| Space cooling |
| Domestic hot water |
| Cooking |
| Lighting |
| Washing & drying |
| Freezing and refrigeration |
| Other appliances |

*Table 11 Types of EEUSs for residential sector.*

The first four residential EEUSs have to be differentiated to the type of energy carrier, while the latter five all use electricity. Not each EEUS is included in the final model to save time to focus on the EEUSs with the highest energy savings potentials. *Space cooling*, *cooking* and *other appliances* are left out.

Table 12 presents the various reference case parameters required for an ex-ante hybrid bottom-up model.

*Table 12 Reference case parameters for the residential sector for the micro-scale. Source: see column 4.*

| STEEC reference case taxo**nomy** | | | |
|---|---|---|---|
| Parameters | Units | Description | Source |
| Source | | The paper/report/database where the data comes from. | - |
| Sector | Residential/Service/Industry | The sector of the reference case. | Various |
| Scope | Regional/National/Continental | Region where the original data refers to. | Various |
| Energy End-use Service | | The end-use service within the sector where the reference case refers to. | Various |
| Technology | | The type of technology that is used in the EEUS. An EEUS can have a single type of technology (e.g. washing machines) or several types (e.g. different types of lamps). | Various |
| Year | | Year of the original data. | Various |
| Energy carrier | 1 Natural gas/2 Electricity | The energy carrier of the reference technology or building. | (Braungardt et al. 2014) |

| | | | |
|---|---|---|---|
| Energy carrier 2 | 1 Natural gas/2 Electricity | In case multiple fuels are used. | (Braungardt et al. 2014) |
| Operation Power | W | The amount of power that a certain technology uses while in operation. | Elsland et al. 2013 |
| Stand-by power | W | The amount of power that a certain technology uses while in stand-by mode. | Elsland et al. 2013 |
| Operation hours | h/y | The amount of hours that a certain technology is being operated. | Elsland et al. 2013 |
| Stand-by hours | h/y | The amount of hours that a certain technology is in stand-by mode. | Elsland et al. 2013 |
| Specific consumption per cycle | kWh/cycle | The amount of energy that is used for an average cycle. This only applies to technologies that work in cycles, such as washing machines. | Elsland et al. 2013 |
| Number of cycles | #cycles/y | The amount of cycles that a technology runs on average per year. | Elsland et al. 2013 |
| Number of units | #/hh | The amount of units per building or per household on average. For example, four LED lamps per dwelling. | Own |
| Relative number of units | %/hh | The relative amount of units per building or per household. | Own |
| Lifetime | yr | The economic lifetime of a certain technology. | Elsland et al. 2013/Haydt, 2011 |
| Efficiency | | Other types of efficiency that cannot be described with the other parameters. For example, energy use per $m^2$. | Haydt 2011 |
| Efficiency unit | | See cell above. | Haydt 2011 |
| Energy use general | kWh/hh/y | The average amount of energy used per household per year for the reference technology or building. | Own |

| | | | |
|---|---|---|---|
| Service output | # of service/unit/year | The average amount of service that is delivered per specified unit per year. | (Braun 2010) |
| Service unit | | Each service differs, so this parameter will indicate the service that belongs to the specific reference technology. For example, Lumen per Watt. | (Braun 2010) |
| Relative service output | # of service/kWh | The amount of service delivered per energy use. | Own |

#### 3.3.1.1. Technical and economic specifications

Not each parameter has to be filled in to obtain the energy use of each EEUS. For instance, the number of cycles only applies to technologies that have energy usage patterns in the form of cycles, such as washing machines.

Macro-scale energy use per EEUSs from BMWi (2014b) and the ODYSSEE database is used as verification whether the aggregation of micro-scale bottom-up data have realistic outcomes. This has not been translated into a specific parameter.

#### 3.3.1.2. Buildings

Buildings are characterized as SFHs and MFHs. Only existing buildings are included, since relatively few buildings are built in the short-term timeframe. In most cases, building references include SH, ventilation and DHW in their characterization. This is taken into account when EEUS data is matched. Heating systems are mostly calculated in $kWh/m^2/y$, so the heating stock is linked to the applied building heating stock. Other important statistics are the amount of stock that has been renovated and the renovation rate, to see how many buildings can be renovated and at what speed.

#### 3.3.1.3. Behavioral specifications

Most applicable figures for utilization behavior are quantified daily usage patterns, but also the amount of hours per year, the amount of showers per week etc. can be used. If data are not available, more aggregated values are used. For each EEUS, it is indicated which approach was applied.

### 3.3.2. STEECM taxonomy

A taxonomy to assess STEECMs consists of a list of parameters that can measure impact of STEECMs compared to a reference case taking EEC barriers into account to obtain a STEECP.

EEC barriers are included by operationalizing additional parameters. The descriptions is split up into general parameters, a socio-behavioral perspective (implementation and utilization), a technical perspective and an economic perspective. Table 13 gives a detailed description of the parameters that are used in this STEECM taxonomy and literature where it is based on.

*Table 13 Taxonomy of technical, economical and socio-behavioral parameters to assess STEECMs. Sources: See column 3.*

| STEECM taxonomy | | |
|---|---|---|
| **Parameter** | Description | Source |
| **Measure** | Description of energy savings option, specified as much as possible, depending on the availability of detailed information. | - |
| **Source** | This parameter describes the main source where the measure has been described or quantified. | - |
| **Sector** | One of the three sectors: residential, tertiary and industry. In this study only residential. | Haydt, 2011 |
| **Energy end-use service (EEUS)** | The end-use service that creates demand for energy. This differs per sector. For example residential space heating, hot water, lighting etc. | Haydt, 2011 |
| **Description of reference** | This parameter gives further description on the comparison configuration of the STEECM. Some STEECMs focus on the average energy use of the EEUS, such as lowering the thermostat. Others focus more on specific parts of an EEUS, such as replacement of HL for LED. | Own |
| **Type of measure** | This parameter describes whether a STEECM is regarded as EE or as EC. In order to have a clear distinction, the EE and EC definitions that are defined in the introduction will be applied. | Trianni et al. 2014 |
| **Activity type** | The activity type is divided into utilization behavior, maintenance behavior, technology replacement and renovation. New installations are not included due to the high uncertainty and the short timescale.<br><br>This research uses different terms than Trianni et al. (2014), but the idea is similar. Utilization behavior is a non-replacement or retrofit action that alters usage of an EEUS, which decreases energy use, but also decreases other output. This is the same as behavioral EC, for example lowering the thermostat 1 degrees °C. Maintenance behavior refers to non-replacement or retrofit actions that alters usage of an EEUS, which decreases energy use, but has equal service output. This is the same as behavioral EE, such as repair leakages in pipes. Technology replacement is the replacement of a certain EEUS or certain parts of it, which improves the energy use. For instance, the replacement of a refrigerator for a more efficient one. Renovation is the revision of the building, which encompasses various handlings, such as insulation of windows and walls. | Trianni et al. 2014 |

| | | |
|---|---|---|
| **Seasonality** | Several EEUSs have a seasonal dependency, such as space heating and lighting. Therefore, a distinction will be made between winter and summer. STEECMs for space heating mostly apply to the winter, while space cooling is only for the summer. Also, lighting uses more energy in the winter compared to the summer due to shorter daylight. | IEA, 2005 |
| **Availability of information** | When people have to increase their EEC by taking STEECMs, information should be available on what STEECMs can be taken and how these STEECMs should be taken. Some EECMs have much more available information, such as new lamps, while other STEECMs have much less information available, for example light sensors. A four-point scale will be applied to measure the availability of information. A lot of new energy efficiency programs have been set up, so it could be possible that for the target geographical scope, information on most STEECMs is easily available. A preliminary search on a search engine on the internet for a certain STEECM can indicate whether detailed information on the investigated STEECM is available on a website on the first search page. The search operation is conducted per STEECM or per EEUS. If a source in the first five links offers micro-scale technical and economic information on the specific measure, the difficulty level will be 1. If information is non-specific or only available on a word or pdf file, the difficulty level will be 2. When no detailed information is available, the difficulty level will be 3. When no clear information can be found on the target measure, the difficulty level will be 4. If only a general advice is given, the difficulty level will go up one point. When the available information targets the specific region, the difficulty level will stay the same, while when the available information describes another scale, such as the European level, the difficulty level will go up 1 point. Paperback brochures will not be taken into account. | Stieß & Dunkelberg (2013) |
| **Knowledge for planning and implementation** | This parameter has been specified for the residential sector. It is important to know who normally could execute a certain STEECM. A distinction is made between personal-general (1), which are STEECMs that nearly anyone can perform, such as lowering the washing temperature, personal-technical (2), which require some technical background to perform, such as replacing a showerhead and a professional (3), which require special equipment or certified installers, such as replacing a boiler. | Fleiter et al. (2012) |
| **Absolute implementation time per household** | It is assumed that the duration of implementing a STEECM affects the likelihood that the measure is taken. A distinction is be made between members of a household or professionals, since household members normally do not want to spend a lot of time on implementing EECMs. Implementation time is defined as the amount of time that | Own |

| | | |
|---|---|---|
| | a household member needs to implement a STEECM, from information gathering until the STEECM has been executed. For example, from gathering information which lamps are currently installed, finding suitable replacement types, buying new lamps and installing them. Many assumptions could be made, so this study assumes that information gathering takes 15-30 minutes and buying equipment or material like insulation foam takes 1-2 hours, changing settings takes 15-30 minutes and retrofit or repair differs per measure, which mostly can be found in online sources. For example, several websites indicate that it takes somewhere around one working day to replace a boiler. For STEECMs that require frequent usage, the first time of implementation is considered the implementation time. | |
| **Absolute implementation time professional** | This parameter is a follow-up of absolute implementation time per household. This parameter describes the amount of time that a professional needs to implement a technology replacement or renovation. For the professional implementation time parameter it is also interesting to assess how many households can actually take an STEECM that requires professional assistance. Unfortunately, data is very limitedly available. | Own |
| **Relative implementation time** | Since there are quite some differences between implementation times of various STEECMs, a non-linear semi-quantitative scale is applied to compare the implementation times. It is assumed that a STEECM that takes less than 15 minutes to be implemented is considered as low (1), STEECMs that take between 15 minutes and 1 hour are considered as medium (2), STEECMs that take between 1 hour and 4 hours is considered as long and everything that takes more than 4 hours is considered as very long (4). | Own |
| **Difficulty to implement measure** | When households have to increase their STEEC by taking STEECMs, information should be available on what measures can be taken, who could execute them and how much time it takes. The *Availability of information, Knowledge for implementation* and *relative implementation time* are combined in an equally weighted multi-criteria parameter called *Difficulty to implement measure*, which is presented as a percentage. Each parameter is quantified in such a way that a higher score represents a higher difficulty to implement the measure. A four point scale will be applied: 0-45% (low), 45-60% (medium), 60-75% (high) and 75-100% (very high). | Own |
| **Additional time needed during usage** | It is assumed that in general households are not occupied with EECMs that influence EEUSs and prefer to spend their time on other activities. Hence, it is interesting to know whether a certain STEECM leads to additional time to obtain a certain amount of service. This constraint is operationalized by this parameter *Additional time during* | Own |

| | | |
|---|---|---|
| | *usage*. This aspect mainly regards ECMs, such as air drying takes more time than tumble drying when requiring the service of 'drying'. The more additional time that is required to deliver the same service by applying an STEECM compared to the reference situation, the less likely the STEECM is adopted. The additional time is measured on a three point scale: none, low and high. 'None' requires no extra time. Each measure that requires between 0-5 minutes extra per day gets a 'low' classification, while each measure that takes more than 5 minutes extra per day obtains 'high' score as outcome. | |
| **Check-up frequency** | This parameter is based on Trianni et al. (2014). The more times a STEECM needs to be checked, the lower the chance that the STEECM will be properly utilized. A distinction is made between (1) one-time intervention, (2) periodic check or (3) frequent check. Most replacement STEECMs are considered as a one-time intervention over the target timeframe. Periodic checks are for EECMs that need to be checked less than once per week. Frequent checks are moreover STEECMs that need to be checked all the time, such as switch off unneeded lights. | Trianni et al. 2014 |
| **Non-energy benefits** | *Non-energy benefits* can significantly influence the perception on adoption. Like in Fleiter et al. (2012), this parameter actually combines a variety of benefits, such as health, safety, environment etc. Financial benefits are not taken into account, because other parameters discuss the economic aspects of STEECMs more specifically. Since the list of STEECM parameters is already substantial, this research uses this aspect as a single parameter. A five point scale is used from large to negative. Large benefits can be acquired by improving at least three non-energy benefits, medium for two improvements etc. These benefits can be health, safety, noise, usability (e.g. new washing machine with easier controls), aesthetics and other environmental effects (e.g. less water use). Certain measures, especially for conservation can have negative benefits, such as shorter showers. In some cases, the impact on one of these factors can be severe, which doubles the score, for example air drying instead of tumble dryer will score a -2 for usability. The negative score is, just like Fleiter et al. (2012), limited to one possibility (5), because it is assumed that it does not matter how big the negative influence is once it is negative, comfort is impacted. | Fleiter et al. (2012) |

| | | |
|---|---|---|
| **Impact comfort level** | The *Additional time during usage, Check-up frequency* and *Non-energy benefits* are combined in a multi-criteria parameter called *Impact comfort level*, which is presented as a percentage, just like the *Difficulty to implement measure*. Each parameter is quantified in such a way that a higher score represents a higher difficulty to implement the measure. The scores are divided by the maximum score to obtain the relative importance of each parameter. It is assumed that subjects are more likely to alter their energy utilization patterns when their comfort level is limitedly impacted. STEECMs need to limit their impact on the comfort level as much as possible to be applied. Each of the other parameters will have equal weight influencing the *impact to comfort level*. The parameter itself uses a non-linear four point scale: 0-50% (low), 50-70% (medium), 70-90% (high) and 90-100% (very high). The first 50% is hardly involved, because the multi-criteria with everything on low is already one third. | Own / Stieß & Dunkelberg (2013) |
| **Energy carrier** | Since natural gas and electricity are the target energy carriers, a distinction should be made between (1) natural gas, (2) electricity or (3) other. | Haydt, 2011 |
| **Energy carrier 2** | Some STEECMs use multiple energy carriers | Haydt, 2011 |
| **Energy use frozen** | This parameter describes the amount of energy that would have been used if no alterations were made to the energy use of the reference case where the STEECM is related to. This could be the average use of the EEUS, but also the energy use of a certain type within the EEUS. For example, the energy use of a non-renovated building is higher than the energy use of an average building, so the potential of renovation is compared to this energy use. The unit is kWh/hh/y. | Own |
| **Energy use new** | This parameter indicates the new energy use compared to the *Energy use frozen* (kWh/hh/y). | Own |
| **Energy saved** | The difference between the *Energy use frozen* and *Energy use new* (kWh/hh/y) | Own |
| **Relative energy saved** | The relative amount of energy saved compared to the *Energy use frozen* (%). This could be an EEUS or a specific technology. | Own |
| **Energy saved per average end-use** | The relative amount of energy saved compared to the average EEUS where the STEECM belongs to (%) | Own |
| **Theoretical adoption potential** | The *theoretical adoption potential* (%) is dependent on the physical constraints that exists, for example how many heating systems can be replaced or optimized, since a part has already been executed. | Burger, 2010/Palmer et al., 2012 |

| | | |
|---|---|---|
| **Theoretical short-term energy efficiency and conservation potential** | This potential is a macro-potential, depending on the scale of research. The following formula is applied: $\text{Theoretical STEECP measure X} = \text{STEECP per hh} * \text{Number of hh region Y} * \text{Theoretical Adoption potential region Y}$ | Burger, 2010/Palmer et al., 2012 |
| **Realistic adoption potential** | *Realistic adoption potential* (%) is presented as an independent percentage, where the *theoretical adoption percentage* is the ultimate limit that could be reached. The *realistic adoption potential* is based on findings in existing literature that discuss adoption of EECMs and severity of barriers. | Own/De Groote, 2005/Palmer et al., 2012/Leighty & Meier (2011) |
| **Realistic short-term energy efficiency and conservation potential** | Similar to theoretical STEECP, but with realistic adoption potential, instead of theoretical adoption potential. | Own/De Groote, 2005/Palmer et al., 2012/Leighty & Meier (2011) |
| **Investment costs per hh** | The investment costs in EUR(2013)/hh. | Elsland et al., 2013 |
| **Investment costs total** | The investment costs per household combined with the theoretical uptake potential (EUR). | Own |
| **Energy costs frozen** | This parameter is calculated by multiplying the *energy use frozen* with the energy costs of the energy carrier (EUR/hh/y). Note that this is not for all the households in general, but for the households that conduct a STEECM. Costs are based on residential energy costs. | Various |
| **Energy costs new** | The yearly energy costs that are made after the STEECM has been implemented (EUR/hh/y). | Various |
| **Energy costs saved** | The difference between the *energy costs frozen* and the *energy costs new* (EUR/hh/y). | Various |
| **Energy costs saved total** | The aggregated costs saved by multiplying the amount of households times the adoption percentage times the energy costs saved per hh (EUR). | Various |
| **Payback period** | Based on Fleiter et al. (2012), the *payback period* is from short (less than 1 year), medium (1-5 years), long (5-10 years) to very long (more than 10 years). This will be calculated by the standard payback time formula, dividing the investment by the saving costs. It is assumed that, just like the industry sector, households prefer a short payback time. | Fleiter et al. (2012) |
| **Initial expenditure** | The initial expenditure is not directly linked to a certain investment budget, but this approach is related to the spending capacity of households. It is assumed that most households prefer to keep their spending on EEC improvement as low as possible. Thus, the lower the initial expenditure, the higher the chance that a STEECM is | Fleiter et al. (2012) |

| | | |
|---|---|---|
| | taken. The scale goes from none (less than 5 euros), low (less than 100 euros), to medium (100-1000 euros), to high (1000+ euros). | |

The list of STEECM parameters is quite extensive, but most parameters are grouped to assess micro-scale and macro-scale impacts and facilitate appraisal between STEECMs.

Implementation is linked to the informational context, but the 'ease of implementation' parameter of Trianni et al. (2014) is not sufficient to fully describe implementation constraints for the residential sector. Therefore, the *difficulty to implement measure* parameter is introduced to provide additional insights on implementation issues. One of the aspect that is used to model the difficulty to implement a measure considers the implementation time. This aspect is split up into two parameters: *Absolute implementation time household* and another parameter called *Absolute implementation time professional.* Personal and professional have been split up, because the implementation time of a household member is more important to assess likelihood of implementation than the implementation time for an installer, who executes EEMs for a living.

Adoption of STEECMs requires some additional explanations. Firstly, it is necessary to assess whether an EECM can be executed within the specific timeframe to make it a STEECM. Then, it is valuable to know which part of an STEECM can and will be executed. Literature from chapter 2 indicates that most EECMs can be executed in the short-term at least to some extent. Therefore, the focus of adoption is on the extent of implementation and utilization. The STEECM model assumes that part of the population (macro-scale) (e.g. the number of households or the number of office buildings in region X etc.) completely adopts a certain STEECM (micro-scale). This approach is similar to the methodology used in Palmer et al. (2012).

## 3.4. Analysis and scenario framework

The list of STEECMs is analyzed with various preferences for technical, economic and socio-behavioral aspects. Combining willingness to accept unpleasant implementation and impacts with different types of measures in various timescales enables the creation of lists of preferred STEECMs. The combined insights from ESMAP (2010), Petermann et al. (2011) and Ek & Söderholm (2010) suggest that the more severe the disruption and the longer the timescale, the more opportunities to save energy arise. Further analysis sheds a light on realistic adoption and favored STEECMs under EEC barriers. Finally, several policy interventions improve certain characteristics of STEECMs, which lead to other lists of favorable STEECMs. Most tables are presented with both gas and electricity STEECMs. The standard timescale is one year. Data are presented in tables as a lists of the ten or twenty preferred STEECMs based on the optimization of certain parameters.

### 3.3.1. General analysis

Table 14 shows which parameters have been translated into tables with preferred STEECMs.

*Table 14 General comparison of STEECM parameters to assess technical, economical and socio-behavioral aspects on micro- and macro-scale impact on ES.*

| **General STEECM analysis per aspect** | | | |
|---|---|---|---|
| **Scale** | Technical parameters | Economic parameters | Socio-behavioral parameters |
| **Micro-scale** | (1) Energy savings per household (general and per energy carrier) | (3) Investment costs per household and energy costs saved per household | |
| **Macro-scale** | (2) Theoretical adoption potential and theoretical STEECP | (4) Total investment costs, total energy costs saved and initial investment and payback period | (5) Difficulty to implement measure and impact on comfort level. |

Technical and economic micro-scale tables do not describe renovation STEECMs, since possible energy savings are high, but adoption potentials are low, which makes it hard to read the respective tables. On the macro-scale, renovation STEECMs are included, because despite their low adoption potential, renovation STEECMs could have a significant macro-scale impact. Furthermore, it is not possible to assess combined micro-scale energy savings from Table 24, because different types of households are targeted with technology replacement STEECMs.

### 3.3.2. Realistic short-term potential

The realistic short-term potential is focused on the macro-scale. Some STEECMs are adopted almost up to the theoretical adoption potential, some partially and some not at all. Survey data from Leighty & Meier (2011) on STEECM uptake during an energy shortfall is used as main data source for a realistic adoption potential. If the STEECM is not mentioned, 50% of theoretical adoption potential is applied, similar to other STEECM literature. The realistic short-term potential is optimized for realistic STEECP.

Next to this, further realistic technical limitations are evaluated by comparing implementation time with the amount of technicians in a specific region and the stock of the target appliance to see the potential speed of implementation. Data is gathered on the amount of installers, the amount of hours that they work on average, the installation time and the amount of technologies that need to be replaced. With this data, an estimation is made on macro-scale technology replacement that requires professional help.

### 3.4.1. Timescale and severity of disruption

Several scenarios are related to two dimensions: timescale and severity of disruption. Timescale affect the ability to execute policies and apply certain STEECMs. The severity of the disruption limits the acceptance level of households with respect to *difficulty to implement measure* and *impact on comfort level*. It is assumed that in a situation with an impending energy shortfall, households are more willing to overcome implementation difficulties and sacrifice some of their comfort compared to a non-ES risk situation. Timescale limitations are based on ESMAP (2010). Table 15 gives a structured overview of the scenarios that are analyzed and what restrictions are involved. All tables are optimized for theoretical STEECP, which all are presented on a yearly basis.

*Table 15 Different time and severity of disruption scenarios to simulate STEECP of STEECMs in the German residential sector.*

| **Time and severity of disruption scenarios** | | | |
|---|---|---|---|
| **Timescale**<br>**Severity of energy disruption** | Very short (1 month) | Short (6 months) | Medium (1 year) |
| **Small** | Only EC (utilization behavior)<br>Medium limit for *difficulty to implement measure* and *impact on comfort level* | EC/EE (No renovation or large SH replacement)<br>Medium limit for *difficulty to implement measure* and *impact on comfort level* | All STEECMs possible<br>Medium limit for *difficulty to implement measure* and *impact on comfort level* |
| **Large** | Only EC (utilization behavior)<br>High limit for *difficulty to implement measure* and *impact on comfort level* | EC/EE (No renovation or SH replacement)<br>High limit for *difficulty to implement measure* and *impact on comfort level* | All STEECMs possible<br>High limit for *difficulty to implement measure* and *impact on comfort level* |

### 3.4.2. Policy interventions

Hypothetical STEEC related STES policies alter the magnitude of certain STEECM parameters, which could lead to a different list of preferred STEECMs under particular optimizations. Three policy interventions are operationalized:

1. Awareness and informational campaign
2. Energy price increase
3. Financial support scheme (technology replacement and renovation)

Rationing has been left out, since a possible list of preferred STEECM have the same limits as theoretical energy- or energy costs savings potentials, depending on the optimized parameter. Market mechanisms have been left out, because outcomes of lists of preferred STEECMs do not represent relevant market-related outcomes.

#### *3.4.2.1. Awareness and informational campaigns*

Awareness and informational campaigns increase knowledge of households with regard to STEECMs. This policy intervention scenario lowers the *availability of information* parameter with 1 point with a minimum score of 1. Data is compared with a small disruption scenario, a severe disruption scenario and a severe disruption scenario with only low *initial expenditure* and *payback period*. Results are optimized for theoretical STEECP.

#### *3.4.2.2. Price signal*

The price increase scenario is operationalized by increasing the electricity and natural gas price to similar levels as historical energy shortfalls. Two versions have been setup:

1. One version where a small disruption leads to a 50% price increase.
2. A second version where a sever disruption increases electricity and gas prices with 200%.

Additionally, the *payback period* is limited to short to see if different an alternative lists of STEECMs becomes more economically favorable by optimizing total energy costs saved.

##### 3.4.2.3. Financial support scheme

The financial support scheme policy intervention offers a subsidy to invest in new technologies and building renovation. A variety of support schemes is possible, but to keep the analysis simple, a general subsidy of 50% for technology replacement and renovation is assumed during a severe disruption. The results are optimized for total energy costs saved.

### 3.4.4. Linking STEEC with STES

The link between STEECMs and STES has been approached in a straightforward way. The link between STEECMs and STES is compared for (1) technical aspects (accessibility and availability), (2) financial aspects (affordability) and (3) socio-behavioral aspects (acceptability).

1. STEECMs lower energy use, which directly decreases the requirement for energy carriers. This means that less energy carriers need to be transported and imported, which increases *accessibility* and *availability*.
2. STEECMs lower energy-related costs of EEUSs. When energy costs savings are high, and initial expenditure and payback periods are short and low, *affordability* is increased as well.
3. STEECMs lower energy use, which decreases the production of byproducts from energy generation. Less pollution improves the *acceptability*.

These three characteristics need no further quantification besides the energy savings potentials and energy costs savings per STEECM to explain the link between STEEC and STES and therefore are qualitatively described per outcome table.

# 4. Results

This section presents data that has been acquired for the reference case and the STEECM characterization of the German residential sector. All the results are given as final energy use, unless otherwise indicated.

## 4.1. German residential energy use data and EECMs

Figure 6 - Figure 8 give an aggregated overview on German residential final energy use to get a grasp on the importance of energy carriers and EEUSs. These figures have been based on available literature, because the STEECM database does not represent all EEUSs and energy carriers, so only an incomplete picture could be presented.

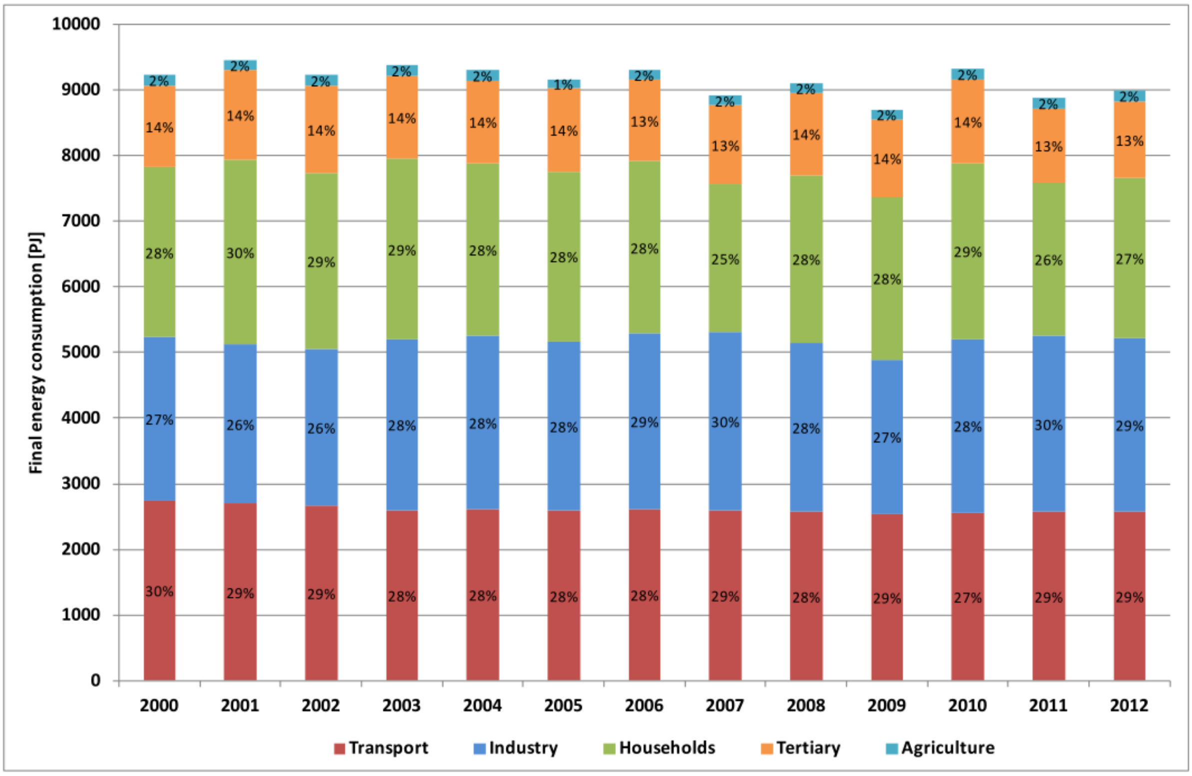


*Figure 6 German final energy consumption by sector. Source:* (Schlomann et al., 2014)

Figure 6 shows that households are responsible for 25-30% of the total final energy consumption. This has been fairly stable over the last ten years.

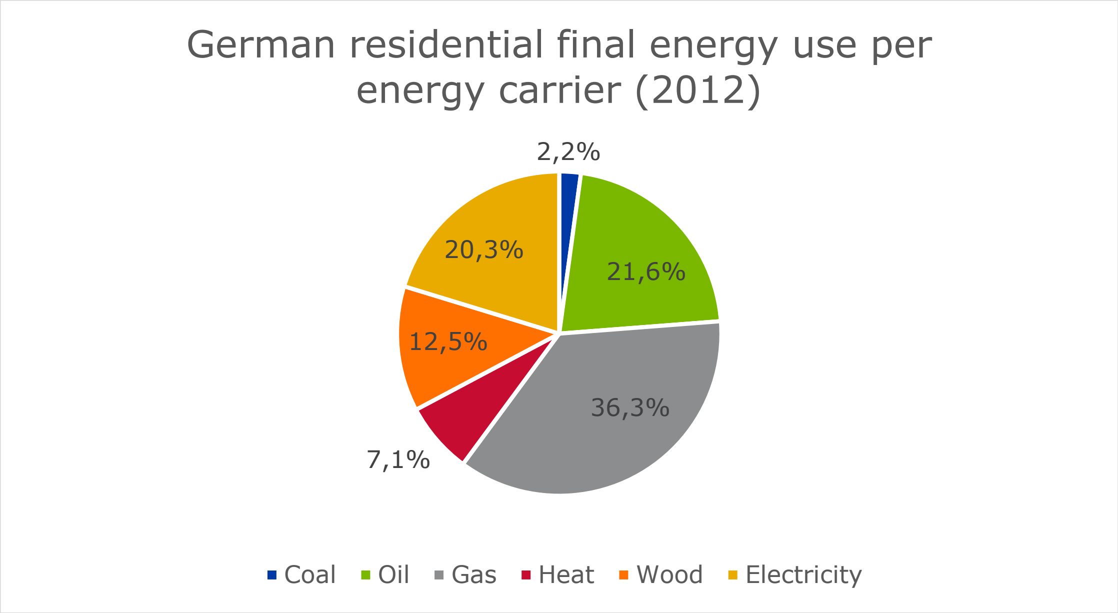


*Figure 7 Breakdown of German residential final energy use per energy carrier. Source: ODYSSEE database.*

Figure 7 shows that gas and electricity cover almost 60% of the German residential final energy use. The average micro-scale German final residential electricity use (3,000-3,500 kWh/hh/y) is significantly lower than total final residential energy use (+-15,000-20,000 kWh/hh/y) (Schleicher, 2011; Bürger, 2009). Combined macro-scale German residential final natural gas and electricity use is +-1450 PJ/y of which gas represents +-1050 PJ and electricity around 400 PJ.

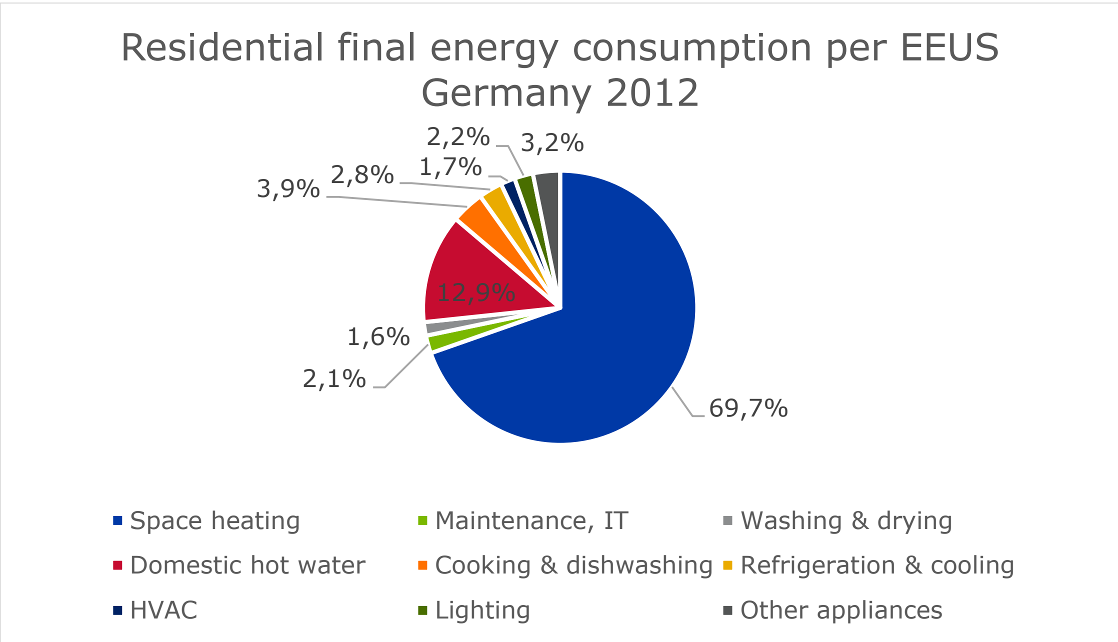


*Figure 8 Breakdown of German residential energy consumption in 2012 per application group. Source: ODYSSEE database.*

Figure 8 illustrates that German residential energy consumption mainly consists of SH, followed by DHW and various electricity related technologies. Space heating energy consumption has been declining with around 2% per year for the last decade, but the share remains high (Ibid.). On the contrary, German residential final electricity demand has been rising between 1990-2010 with 20.9% (Elsland et al., 2013).

#### 4.1.1. General

The development of the ex-ante hybrid bottom-up STEECM model is a considerable part of this research, so outcomes on data gathering are presented as part of the results section as well. Table 16 displays general data that is required to obtain micro- and macro-scale aspects of STEECMs.

*Table 16 Description of general data used in the STEECM model. Sources: see column 2.*

| **Data description general** | | |
|---|---|---|
| **Element** | Data description | Key values |
| **Population data** | Population data originates from Destatis (2013). There are differences with other sources, but the magnitude is similar. There is a lot of detailed population data available, but most figures are not applicable to this model. | +- 40 million households, of which 56% MFH and 44% SFH. |
| **Building stock data** | The total dwelling area originates from Destatis (2013) and Bettgenhäuser (2013). The floor area per dwelling originates from the ODYSSEE database. Bettgenhäuser (2013) also provides non-renovation figures. Current building renovation rates are retrieved from Bettgenhauser & Boermans, (2011) Fraunhofer-ISE (2014). | SFH is on average 115 m² and MFH 68 m². Total area is around 3.67 billion m². Renovation rate is around 1%. |
| **Ownership data** | Ownership data stems from Destatis (2014). | Refrigerator 123%<br>Freezer 57%<br>Washing machine 99%<br>Dryer 41% |
| **Energy price data** | Energy price data is based on (BMWi 2014a). | Natural gas 0.06-0.07 EUR(2013)/kWh<br>Electricity 0.32 EUR(2013)/kWh.<br>Space heating is average of different fuels (0.08 EUR(2013)/kWh) |
| **Efficiency improvement data** | The average improvement between 2007 and 2012 was used from the ODYSSEE database. | Space heating 3.1%<br>DHW -1.5%<br>Lighting -1%<br>Large appliances 1.2% |

MFH bring some calculation issues, because multiple dwellings are found back in one MFH. This is calculated by dividing the amount of MFH households with the amount of MFH buildings, which in Germany is equal to seven dwellings per MFH on average (Destatis, 2013; Bettgenhäuser, 2013).

### 4.1.2. Space heating

SH is by far the largest EEUS in German households, adding up to almost 70% of final energy use (BMWi 2014a). SH is mainly used in the winter season. The average German SH energy use is still significantly above the energy efficiency potential of new buildings (UBA, 2012).

Table 17 shows the different types of SH systems that are available. Only natural gas space heating systems have been included in the list of STEECMs.

*Table 17 Different space heating types in the German residential sector. Source:* (Bettgenhauser & Boermans, 2011)

| Space heating system types |
|---|
| Condensing boiler, gas |
| Condensing boiler, oil |
| Non-condensing boiler, oil |
| Non-condensing boiler, pellets |
| Log wood boiler, firewood |
| Brine-water heat pump, electricity |
| Brine-water heat pump, Gas-absorption |
| Air-water heat pump, electricity |
| Gas CHP, gas |
| Sterling CHP, Pellets |
| District heat, conventional |
| District heat, regenerative |

Table 18 presents the most important data descriptions for SH.

*Table 18 Data specifications of the STEECM database for SH. Sources: See column 2.*

| Data description space heating | | |
|---|---|---|
| **Element** | Data description | Key values |
| **Reference case - Specification of technologies** | The list of technologies is presented in Table 17. Average SH energy use data is collected from (BMWi 2014b). Energy use of non-renovated buildings comes from (Bettgenhäuser, 2013) and (BDH, 2015). This data is weighted for the specific dwelling types per number of SFH and MFH dwellings. | Since the early nineties, the average SH energy use has been going down significantly from +- 200 kWh/m²/y to 140-150 kWh/m²/y.<br>Non-renovated SH energy use is somewhere between 200-300 kWh/m²/y. |
| **Reference case - Stock levels** | The stock is measured in m² per SH type. The average area per SH type is retrieved from internal Ecofys data, presented in Quintel (2015). Total area and area per dwelling type is extracted from Destatis (2013). | +-45% is gas heated, +-3% is electricity heated.<br>Total dwelling area is 3.7 billion m² of which 60% SFH and 40% MFH. |

| | | |
|---|---|---|
| **Reference case - Utilization behavior** | Utilization behavior is specifically described per STEECM. No general description was available. More than 95% of German households have thermostatic radiator valves, which enables temperature control in most situations (Kemma et al., 2007). Some assumptions are inspired by Palmer et al. (2012). A lot of studies illustrate space heating utilization behavior, but not in a way that it can be translated to a general average in Germany. | |
| **Harmonization approach** | Various sources discuss German space heating data on micro- and macro-scale. Section 2.1.5.3 already used SH as example of hybrid data harmonization, since there is not enough data to properly aggregate micro-level data to national data. None of the discovered sources gives a complete picture on average energy use per type, stock levels and utilization behavior. | |
| **STEECM list – New technologies** | Data of new SH systems originate from (BDH, 2015) and (Loga et al., 2015). Not all SH systems and appliances are included as technology replacement, only directly gas-related systems. Costs are derived from internal BMWi (2013) Bettgenhauser & Boermans (2011) and Ecofys data. | +- 80 kWh/m²/y for MFH and 140 kWh/m²/y for SFH for boiler replacement. Costs for boiler 4000 (MFH per hh) or 8000 EUR (2013)/replacement (SFH per hh), renovation around 20000 EUR(2013)/hh |
| **STEECM list – Maintenance and utilization behavior** | As for technical specifications, heating systems consist out of several parts: the generator, the distribution system, the emitters and the overlying controls (Kemma et al., 2007). These aspects can be technically improved, but not many data on specific average maintenance improvements were found. Furthermore, SH utilization behavior has a substantial impact on actual energy use. Palmer et al. (2012) and Schleicher (2011) offer insights on maintenance- and utilization behavior, translated to the German residential sector in 2013. | |
| **STEECP – adoption** | UBA (2012) also indicates that the largest part of German SH systems has not been renovated yet, which shows a big ESP. In 2008, only 12% of the existing natural gas- and oil boilers were up-to-date and almost 600,000 boilers are more than 30 years old, far beyond their economic lifetime (Ibid.). Nevertheless, the amount of non-condensing boilers has been decreasing significantly since the beginning of the 2000s. Theoretical adoption is based on the stock data of SH systems from Ecofys. Renovation data is based on Bettgenhäuser (2013). Utilization behavior STEECMs are linked to specific energy carriers, based on ODYSSEE | 20% (SFH) and 28% (MFH) of total building stock is before 1995 and non-renovated. +- 30% are non-condensing natural gas boilers. Other figures are more specific per STEECM. |

| | | |
|---|---|---|
| | figures. Realistic adoption data is from Leighty & Meier (2011). | 46% of space heating is natural gas. |
| **Other** | - | - |

SH energy use is mostly measured in kWh/m², so it is important to keep track of the various floor areas that are used per building type, per household and on a national scale. To maintain an equal total dwelling area through the model, the area per SH technology is converted to a percentage. The SH energy use per household can be calculated by:

$$HH\ space\ heating\ energy\ use = \sum_{X=1}^{X+1} (\%\ Heating\ system\ X * Efficiency\ Heating\ system\ X * \frac{Total\ dwelling\ area}{Number\ of\ hh})$$

Utilization behavior STEECMs are linked to average SH energy use, which also includes other fuels, such as heating oil and wood pellets, but for simplification SH is linked to natural gas STEECMs as energy carrier.

*Information availability* is different per STEECM, but the relative complexity of SH STEECMs leads to lower information availability. Almost half of the SH STEECMs require certified installers, but there also four SH STEECMs that anyone can execute. The *implementation time* has a big bandwidth, since renovation and boiler replacement require quite some time to be implemented, which makes the *implementation difficulty* quite high for most SH STEECMs. Most measures need no or low additional time during usage. *Check-up frequency* depends on the STEECM. Half the SH STEECMs have high *non-energy benefits* and half of them none or negative, which shows a stark contrast between renovation and utilization behavior.

### 4.1.3. Domestic hot water

Hot water installations are an important source of German residential energy use and significant energy savings can be achieved. Most DHW systems (+-80%) are embedded within SH systems, which significantly influences the flexibility to specifically target DHW (Bettgenhäuser, 2013). Therefore, most DHW STEECMs in this model are focused on energy savings outside of the heating system, such as improved showerheads and taps. Table 19 shows the main data sources that are used for calculating parameters for DHW STEECMs.

*Table 19 Data specifications of the STEECM database for DHW. Sources: See column 2.*

| **Data description domestic hot water** | | |
|---|---|---|
| **Element** | Data description | Key values |
| **Reference case - Specification of technologies** | Energy use of non-renovated DHW systems comes from Bettgenhauser & Boermans (2011). Applied DHW technologies are the same as SH technologies. | Non-renovated DHW systems consume energy similar to 10% of SH energy use (10-30 kWh/m²/y). |

| | | |
|---|---|---|
| **Reference case - Stock levels** | The stock is measured in m² per SH type. The average area per SH type is retrieved from internal Ecofys data, presented in Quintel (2015). Total area and area per dwelling type is extracted from Destatis (2013).<br>More than 75% of DHW systems are embedded in the space heating system, somewhere around 20% is supplied by electrical DHW and 5% is related to natural gas and other forms of water heating (Bettgenhäuser, 2013). | 50-55% is gas heated, +-20% is electricity heated.<br>Dwelling area similar to SH. |
| **Reference case - Utilization behavior** | Energy use per shower originates from HEA (2013). Other DHW utilization behavior from Kemna et al. (2007) and Palmer et al. (2012). | Average 1.35 kWh per shower and 1.4 showers/hh/day |
| **Harmonization approach** | Multiple sources discuss German DHW data on micro- and macro scale. Bettgenhauser & Boermans (2011) and Ecofys data enable bottom-up calculations to obtain average micro-scale DHW energy use. These outcomes are similar to top-down data from BMWi (2014b). | Average DHW use of +-2600 kWh/hh/y. |
| **STEECM list – New technologies** | No specific data on new technologies was useful, due to the strong link with SH. Only specific technology data on aerated showerheads has been used, based on Schleicher (2011) and various internet sources, such as Grunspar (2015). Economic data is described in the same sources. | Aerated showerheads halve shower DHW use with around 50%. |
| **STEECM list – Maintenance and utilization behavior** | Multiple aspects of DHW systems require maintenance. Again, Palmer et al. (2012) and Schleicher (2011) offer insights on maintenance- and utilization behavior, translated to the German residential sector in 2013. | Various figures. From 50 kWh/hh/y (timer on heater) to 623 kWh/hh/y (electric aerated shower head). |
| **STEECP – adoption** | Data originates from same sources as where the technical and economic data from the STEECMs comes from. Realistic adoption from Leighty & Meier (2011). | Various adoption potentials, from 8% (electric showerheads) to 100% (timeswitch). |
| **Other** | - | - |

*Information availability* differs strongly per STEECM. There also is an equal division between the different types of *required knowledge for planning*. Only maintenance in DHW systems requires certified personnel. The *implementation time* is in most cases less than one hour, which improves the *implementation difficulty*. Most STEECMs do not need a lot of additional time during usage. *Check-up frequency* differs per STEECM. Most DHW STEECMs have none or negative *non-energy benefits*, which somewhat tempers the *impact on comfort level.*

### 4.1.4. Lighting

Lighting is described in many publications and the available lighting data makes it relatively easy to obtain a micro-scale overview that can be translated to the macro-scale. Table 20 displays the main data sources that are applied in the STEECM model.

*Table 20 Data specifications of the STEECM database for lighting. Sources: See column 2.*

| Data description lighting | | |
|---|---|---|
| **Element** | Data description | Key values |
| **Reference case - Specification of technologies** | A model that does not describe the German residential lighting use specifically, but that contains detailed data for lighting for the EU-28 is called MELISA (VHK, 2015). This model contains the energy usage per specific type of lamp (CFL, LED etc.), which can be translated to the household level. Lighting technologies are described even more detailed than the five that have been chosen, but this is left out to simplify the analysis. | Distinction between LFL, CFL, HL, GLS and LED. |
| **Reference case - Stock levels** | MELISA contains stock levels per type of lamp per household (VHK, 2015). | 5% LFL, 40% CFL, 38% HL, 15% GLS and 2% LED. |
| **Reference case - Utilization behavior** | MELISA contains the amount of burning hours per year (VHK, 2015). | 450-700 burning hours per type of lamp per year. |
| **Harmonization approach** | Data can be calculated from a bottom-up perspective to obtain macro-scale values. The power per type of lamp multiplied with the amount of burning hours per type of lamp multiplied with the amount of lamps per household. | Average electricity use is 596 kWh/hh/y, with a big contribution of HL (362 kWh/hh/y) and GLS (119 kWh/hh/y) |
| **STEECM list – New technologies** | New technologies are the same as reference case technologies, also derived from (VHK, 2015). Costs have been extracted from the same database. Data for alternative lamp replacement has been extracted from Schleicher (2011) and Palmer et al. (2012). | CFL and LED prices of +- 5 EUR(2013) and 14 EUR(2013) |
| **STEECM list – Maintenance and utilization behavior** | Various utilization and maintenance STEECMs originate from Bürger (2010), Schleicher (2011) and Palmer et al. (2012). | 119 kWh/hh/y for switching off unneeded light and 116 kWh/hh/y for installing light sensors. |
| **STEECP – adoption** | VHK (2015) allows the use of detailed descriptions of average types of lamps with corresponding energy use. Therefore, technology replacement STEECMs could theoretically be executed for 100%. Utilization behavior | 100% for technology replacement. |

| | | |
|---|---|---|
| | STEECM adoption originates from Palmer et al. (2012). Realistic values from (Leighty & Meier, 2011). | 85-100% for switching off unneeded light and sensors.<br><br>Realistically, still 75-80% adoption. |
| **Other** | Schleich et al. (2014) presents detailed data on lighting rebound effects after replacement. | 5-7% for replacement to more efficient types of lamps. |

Most lighting STEECMs have medium *information availability*. Knowledge for planning requires some technical expertise, so it is assumed that most technology replacement- and maintenance behavior STEECMs have personal-technical *required knowledge for planning*. The *implementation time* is in most cases more than one hour, which negatively influences the *implementation difficulty*. Most STEECMs have almost no additional time during usage. *Check-up frequency* is apart from 'switching off unneeded lights' a one-time intervention.

N*on-energy benefits* differ per STEECM type and per type of technology. Technology replacement STEECMs include changes to habits and have a temporal effect, so rebound effects have been added. LEDs are considered to have medium non-energy benefits, while CFL replacement is considered as a negative score on non-energy benefits, due to toxicological issues (mercury), lower aesthetic performance and delayed start-up time (Aman et al., 2013). The *impact on comfort level* is in most cases low or medium, except for 'switching off unneeded lights'.

### 4.1.5. Refrigeration and freezing

Data elements of refrigeration & freezing are presented in Table 21. Refrigeration & freezing requires a relatively constant supply of energy. Although not the largest EEUS, refrigeration & freezing energy savings potentials are relatively high according to Enerdata (n.d.) and Bürger (2010).

*Table 21 Data specifications of the STEECM database for refrigeration & freezing. Sources: See column 2.*

| **Data description refrigeration & freezing** | | |
|---|---|---|
| **Element** | Data description | Key values |
| **Reference case - Specification of technologies** | Refrigerators have been labelled under the Ecodesign directive, which can also be applied to the existing stock from label C to A+++, corrected to 2013 by extrapolating the EEI trend line for cold appliances, available in the same report. Next to this, Specific freezer data in kWh/hh/y is extracted from HMWEVL (2015), which only presented one average value. | From C (540 kWh/y) to A+++ (152 kWh/y)<br><br>Average freezer 343 kWh/y |
| **Reference case - Stock levels** | Stock levels have been described per label by VHK et al. (2014). Ownership data comes from Destatis (2014). Age distribution data comes from Suljug & Hillenstedt (2007), who indicate likelihood of replacement. Rüdenauer & Gensch (2007) describe a division of different types of freezers in the household stock. | Refrigerator<br><br>A+++ 1%<br>A++ 14%<br>A+ 56%<br>A 28%<br>B 1%<br>C 0% |

| | | |
|---|---|---|
| | | 75% chest freezers 25% upright freezers<br>Ownership:<br>Refrigerator 123% Freezer 57% |
| **Reference case - Utilization behavior** | Suljug & Hillenstedt (2007) and Schleicher (2011) describe detailed utilization behavior data. Despite being from 2007, behavior was assumed to not have changed very much in the past eight years. Specific utilization behavior includes external temperatures, number of door openings, average refrigerator temperature etc. | Various figures. |
| **Harmonization approach** | Data has been aggregated from absolute bottom-up data through the available data of VHK et al. (2014). | |
| **STEECM list – New technologies** | Various sources discuss new refrigerators and freezers Topten.eu (2015) is used to describe new freezers. Refrigerator data is extracted from VHK et al. (2014). There are many more types with even lower energy use, but direct comparison with respect to size and type is not possible and therefore are left out. Economic data from VHK et al. (2014) and HMWEVL (2015). | Replacement reduces refrigerator energy use up to 135 kWh/refrigerator/year and more than 200 for an old freezer.<br>+-620 EUR(2013) for new freezer and +-740 EUR(2013) for new refrigerator. |
| **STEECM list – Maintenance and utilization behavior** | Maintenance and utilization behavior STEECMs originate from Suljug & Hillenstedt (2007), Palmer et al. (2012) and IEA (2005a). | STEECMs differs from 8-80 kWh/refrigerator/y. |
| **STEECP – adoption** | Refrigerators and freezers that are older than 10 years or label A or older are eligible for replacement. Most STEECMs are related to average values, which theoretically can be 100% adopted. Utilization behavioral STEECMs based on Suljug & Hillenstedt (2007) have descriptions on which part has unfavorable behavior. Realistic adoption from Leighty & Meier (2011). | 28-46% for replacement.<br>42-75% for temperature-related STEECMs.<br>Realistically mostly 28-70%. |
| **Other** | It is assumed that the EU-28 data for refrigerators is representative for Germany, as they use a correction factor of 1 in their report to alter outcome data. | |

*Information availability* is different per STEECM. Only limited information is available on utilization behavioral STEECMs. Only technology replacement requires technical personnel. Most STEECMs could be implemented by anyone. The *implementation time* is mostly less than one hour, especially if replacement is done by delivery. The *implementation difficulty* is thus for all refrigeration & freezing STEECMs medium or low. Most refrigeration & freezing STEECMs need no or low additional time during usage. *Check-up frequency* depends on the STEECM, but there are relatively a lot of utilization behavioral refrigeration & freezing STEECMs that require additional time. Besides replacement, most refrigeration & freezing STEECMs have low or negative *non-energy benefits*, because most services are not noteworthy increased. Hence, the *impact on comfort level* differs a lot between each refrigeration & freezing STEECM.

### 4.1.6. Washing & drying

Specifications for washing & drying STEECMs are illustrated in Table 22.

*Table 22 Data specifications of the STEECM database for washing & drying. Sources: See column 2.*

| Data description washing & drying | | |
|---|---|---|
| **Element** | Data description | Key values |
| **Reference case - Specification of technologies** | No specific types have been recovered that could be applied on a micro-scale and macro-scale. Average values are extracted from Elsland et al. (2013). | Washing machine +-175 kWh/y<br>Dryer +- 232 kWh/y. |
| **Reference case - Stock levels** | Stock levels have been extracted from Destatis (2014). | Ownership rate:<br>Washing machine 99% Dryer 40% |
| **Reference case - Utilization behavior** | Utilization behavior has been extracted from VHK et al. (2014) and A.I.S.E. (2013), for example the average amount of washing cycles and how many cycles are full or not. | |
| **Harmonization approach** | Only the average value for 2013 was known, not per specific label. The macro-scale was calculated from a bottom-up perspective by multiplying the average yearly energy use with the ownership rate and the amount of households. | |
| **STEECM list – New technologies** | No technology replacement STEECMs for washing & drying have been included due to the expected low impact on energy use. No non-energy costs have to be made. | |
| **STEECM list – Maintenance and utilization behavior** | Utilization behavior STEECMs also have been extracted from VHK et al. (2014), A.I.S.E. (2013) and Palmer et al. (2012). | Savings possible between 12 and 87 kWh/washing machine.<br>On average 185 cycles/year, 40% of the washes is less than 75% full and +-30% of the washes is on high temperatures. |
| **STEECP – adoption** | Average values have been used, so adoption potential is equal to ownership rate. | |

| | | |
|---|---|---|
| **Other** | Rebound-factors for appliances are 0% Barbu et al. (2013). | |

*Information availability* differs per STEECM from low to high. All washing & drying STEECMs can be implemented by anyone. Most washing & drying STEECMs have a short *implementation time*. These outcomes make the *implementation difficulty* low as well. Most washing & drying STEECMs require low or medium additional time during usage, due to longer washing programs and clothes gathering. *Check-up frequency* depends on the STEECM, but there are relatively a lot of washing & drying STEECMs that require additional time. Besides replacement, most washing & drying STEECMs have low or negative *non-energy benefits*, because most services are not noteworthy increased. Hence, the *impact on comfort level* has different values among the washing & drying STEECMs.

## 4.2. STEECM analysis

The STEECM analysis is presented in the same order as the analysis framework. First, a general comparison of STEECMs is given. Then, outcomes for a more realistic STEECP are presented. Finally, several policy interventions are modeled. Outcomes will be presented per type of STEECM according to the colors in Table 23.

*Table 23 Color references for tables with favored STEECMs per type of measure.*

| **Color reference type of STEECM electricity and natural gas** | |
|---|---|
| Renovation electricity | Renovation natural gas |
| Technology replacement electricity | Technology replacement natural gas |
| Maintenance behavior electricity | Maintenance behavior natural gas |
| Utilization behavior electricity | Utilization behavior natural gas |
| **Low score compared to outcomes in the list** | High score compared to outcomes in the list |

Furthermore, grey scales indicate the relative energy savings or costs compared to the other numbers for each column to better visualize variations per parameter. The scales go from low (light grey) to high (dark grey). Percentages next to total energy savings are presented in brackets as part of the yearly German final residential natural gas and electricity use to obtain better insights on aggregated impact (+-1450 PJ/y).

### 4.2.1. STEECM comparison

The list of STEECMs consists of 39 measures of which two-thirds are linked to electricity and one-third to natural gas. The complete list of STEECMs is found back in Appendix A. The list of STEECMs has a combined theoretical STEECP of +-1100 PJ/y. This is somewhere around 40% of the yearly final residential energy consumption (+-2600 PJ/y in 2013) (excluding transport) and almost 80% of gas and electricity consumption. However, various forms of double-counting substantially reduce the combined theoretical STEECP of the complete list. Nevertheless, the value of the combined STEECP indicates that the order of magnitude of the impact of the available STEECMs on German final residential energy use is not over- or underestimated. The combined STEECP also suggests that STEECMs theoretically have a significant impact on German residential energy use. Total investments costs are around 300 billion euros (2013), which is more than 10% of the German GDP. This suggests that there could be some serious economic constraints to the execution of all these STEECMs, thus reducing the realistic energy and energy costs savings potential. Especially renovation and boiler replacement are expensive STEECMs.

#### *4.2.1.1. Technical optimization*

Table 24 gives an overview on STEECMs with a favorable micro-scale technical impact. Seven of the top ten STEECMs with favorable micro-scale energy savings are related to SH. The abundance of SH

STEECMs is not unexpected, due to the high share of SH in the final residential energy consumption. This outcomes also illustrates that not only SH energy use is high, but the micro-scale energy savings as well. The top five STEECMs contain renovation, utilization- and maintenance behavioral STEECMs, such as boiler replacement, lowering the thermostat or insulation of pipes and radiators, which indicates that it is favorable to combine different types of measures. Electricity related STEECMs are underrepresented and have smaller absolute energy savings compared to SH STEECMs. DHW, lighting and stand-by use represent various types of EEUSs.

Favorable STEECMs with natural gas as energy carrier is almost the same as the combined list, but electricity STEECMs are replaced by natural gas DHW measures. It is clear that the replacement of natural gas boilers drastically improves the micro-scale energy use of SH compared to non-renovated dwellings. Utilization behavioral STEECMs with the highest micro-scale energy savings are *lowering the thermostat 1 °C, delaying the heating system* and *closing bedroom windows at night*. DHW is represented by *aerated showerheads gas*, *shower for 5 minutes* and *repair leaks in hot water system*. DHW STEECMs have smaller energy savings, which is in line with the difference in average energy use of DHW and SH, since DHW is five times smaller than SH (Figure 8). Relative contributions of energy savings compared to the average EEUS energy use are less than 15% for non-renovation and boiler replacement, which indicates that combinations of natural gas related STEECMs need to be applied to obtain high relative energy savings.

STEECMs with electricity as energy carrier have lower absolute micro-scale energy savings than natural gas related STEECMs. Electrical DHW adds another 1100 kWh to the total electricity use, so DHW relative residential energy savings have to be carefully addressed. Next to DHW, lighting STEECMs have the highest micro-scale electricity savings. Standby usage is still high and refrigeration & freezing and washing & drying can considerably reduce their energy use as well. At least one STEECM of each included electricity related EEUS is represented in the list. However, lighting STEECMs are overrepresented with four out of ten in the list. Relative electricity savings are in most cases more than 20% of the respectable EEUS, which is much higher than for natural-gas related STEECMs. There is no clear difference in relative energy savings between different electricity related EEUSs. Appendix B: Detailed overview on technical favorable micro-scale STEECMs presents more detailed technical parameters per energy carrier.

Table 25 displays favorable STEECMs with regard macro-scale theoretical adoption potential and STEECP. *Investment costs, total energy costs saved, difficulty to implement measure* and *impact on comfort level* are added to Table 25 to give additional insights on the likelihood that the STEECMs are adopted by households.

*Table 24 Preferred STEECMs with regard to micro-scale energy savings in general and per energy carrier.*

| **Highest energy savings general per household without renovation (micro-scale)** | **Energy saved** | **Highest energy savings natural gas per household without renovation (micro-scale)** | **Energy saved** | **Highest energy savings electricity per household without renovation (micro-scale)** | **Energy saved** |
|---|---|---|---|---|---|
| Measure | kWh/hh/year | Measure | kWh/hh/year | Measure | kWh/hh/year |
| Replacement of non-condensing gas boilers for new gas boilers SFH | 6595 | Replacement of non-condensing gas boilers for new gas boilers SFH | 6595 | Aerated Showerheads electric heating | 623 |
| Replacement of non-condensing gas boilers for new gas boilers MFH | 3831 | Replacement of non-condensing gas boilers for new gas boilers MFH | 3831 | Replace 11 most used lamps | 381 |
| Lower thermostat 1 °C, gas | 1620 | Lower thermostat 1 °C | 1620 | Reduce stand-by usage | 374 |
| Insulation for radiators and pipes SFH | 1356 | Insulation for radiators and pipes SFH | 1356 | Replace HL with CFL | 284 |
| Delay start of heating season to November | 669 | Delay start of heating season to November | 669 | Air dry instead of tumble dryer | 232 |
| Aerated Showerheads electric heating | 623 | Turn off heating in unused rooms | 561 | Replace freezers for A+++ model | 202 |
| Turn off heating in unused rooms | 561 | Close bedroom window at night | 419 | Replace all refrigerators for most efficient | 135 |
| Close bedroom window at night | 419 | Aerated Showerheads gas heating | 345 | Switch off unneeded light | 119 |
| Replace 11 most used lamps | 381 | Shower for 5 minutes instead of 7 minutes | 134 | Install light sensors | 116 |
| Reduce stand-by usage | 374 | Repair leaks in hot water system | 127 | Reduce the amount of washing cycles with 50% | 87 |

*Table 25 STEECMs with the highest macro-scale STEECP for the German residential sector compared to investment costs, energy costs saved, implementation difficulty and impact on comfort.*

| STEECMs with highest theoretical energy savings potential German households (macro-scale) | Investment costs | Total energy costs saved | | Difficulty to implement measure | Impact comfort level |
|---|---|---|---|---|---|
| Measure | Billion EUR(2013) | Billion EUR(2013)/y | PJ/y | | |
| Renovate SFH, gas | 95.1 | 7.8 | 184 | very high | low |
| Replacement of non-condensing gas boilers for new gas boilers SFH | 47.0 | 2.4 | 128 | high | low |
| Lower thermostat 1 °C, gas | - | 1.6 | 94 | low | high |
| Replacement of non-condensing gas boilers for new gas boilers MFH | 21.1 | 1.8 | 94 | high | low |
| Renovate MFH gas | 79.5 | 2.7 | 87 | very high | low |
| Reduce stand-by usage | 0.7 | 4.7 | 54 | medium | very high |
| Insulation for radiators and pipes SFH | 5.1 | 1.0 | 51 | high | low |
| Replace 11 most used lamps | 3.0 | 4.1 | 47 | high | medium |
| Delay start of heating season to November | - | 0.7 | 41 | medium | medium |
| Put heating circulating pumps at from 80W to 35W | - | 0.6 | 26 | medium | medium |
| Turn off heating in unused rooms, gas | - | 0.3 | 17 | medium | very high |
| Switch off unneeded light | - | 1.5 | 17 | low | high |
| Install light sensors | 11.2 | 1.5 | 17 | medium | low |
| Aerated Showerheads gas heating | 0.5 | 1.4 | 16 | medium | low |
| Shower for 5 minutes instead of 7 minutes | - | 0.5 | 15 | low | medium |
| Reduce the amount of washing cycles with 50% | - | 1.1 | 12 | low | high |
| Unplug freezer / second refrigerator | - | 0.2 | 10 | medium | low |
| Reduce heating circulating pump to 10h use | - | 0.7 | 9 | medium | medium |
| Replace inefficient freezers for A+++ model | 11.4 | 1.2 | 8 | medium | low |
| Reduce kitchen temperature From 25 to 19 C | - | 0.5 | 7 | medium | medium |
| **Total** | | | **935 (64%)** | | |

Table 25 shows that natural gas and electricity have an equal amount of STEECMs in the list, but the first ten STEECMs are dominated by natural gas STEECMs. Renovation of gas-heated SFHs has the highest macro-scale theoretical STEECP, even with a limited theoretical adoption potential. Furthermore, behavioral SH STEECMs contribute substantially to the combined theoretical STEECP, such as *lowering thermostat 1 °C, delay heating season* and *reduce standby usage*. Electricity related savings are highest for *reduce standby usage* and *replacing 11 most used lamps*. Economically, investment costs are moreover higher in the first ten STEECMs, but there are also multiple STEECMs without investment costs. Energy costs savings are higher with higher energy savings, but electricity STEECMs are more available. Table 25 shows no clear correlation between the macro-scale theoretical STEECPs and the *difficulty to implement measure* or *impact comfort level*. The list of technically favored STEECMs represent more than 85% of the total theoretical STEECP of which the first ten STEECMs represent 70% of the total theoretical STEECP. This suggests that relatively few STEECMs are responsible for the majority of the total STEECP.

The amount of possible energy savings indicate that STEECMs could drastically improve availability and accessibility to increase STES. Varying investments and energy costs savings suggest no direct contribution to affordability with regard to the technically favored STEECMs.

Figure 9 visualizes the combination of micro- and macro-scale energy savings potentials optimized for macro-scale theoretical STEECP. The figure indicates that preferred STEECMs with the highest macro-scale STEECP do not necessarily have the highest micro-scale STEECP as well, so it is relevant to include smaller micro-scale STEECMs as well.

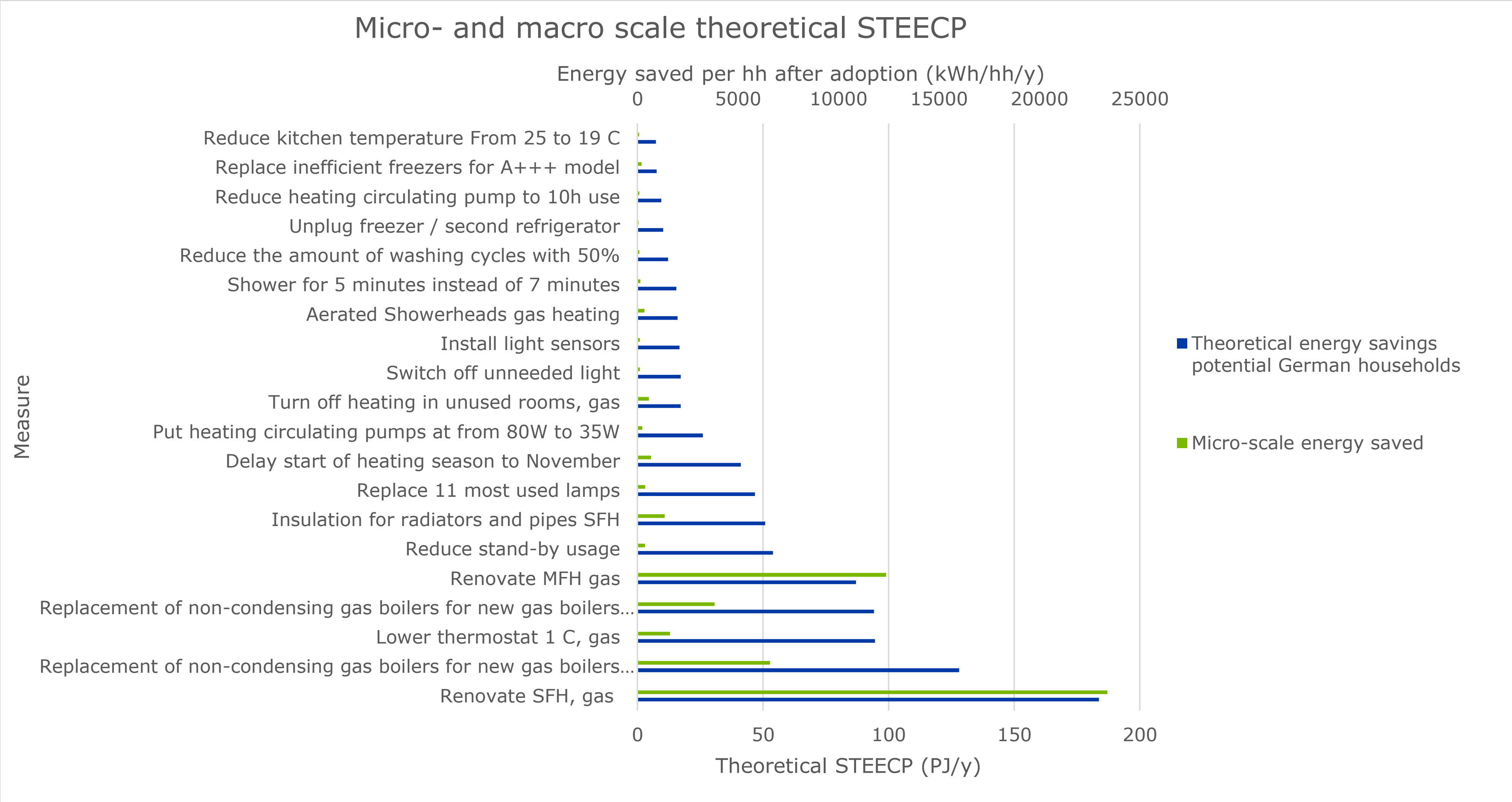


*Figure 9 Comparison of micro-scale and macro-scale STEECP for STEECMs with the highest macro-scale STEECP.*

#### 4.2.1.2. Economic aspects

Table 26 and Table 27 cover micro-scale and macro-scale economic aspects of STEECMs.

**Micro-scale**

Table 26 shows STEECMs with the highest micro-scale investment costs and the STEECMs with the highest micro-scale energy costs savings. A list of preferred STEECMs with the lowest investment costs would give a list of utilization behavioral STEECMs with no investment costs, without any differentiation. Therefore, it is more interesting to see the STEECMs with the highest micro-scale investment costs.

Most of the top ten preferred micro-scale investment costs STEECMs are in the medium or high range for *initial expenditure*, which is a significant barrier for adoption with regard to affordability. Table 26 shows that the highest investment costs are related to renovation and technology replacement of SH, which is no surprise due to the importance of SH in residential final energy use. Most of the preferred STEECMs with high investment costs also have a long *payback period,* which suggests that energy costs saved do not sufficiently compensate for additional investments. There is an equal amount of electricity and natural gas STEECMs, but again electricity STEECMs are found in the lower range and have relatively better *payback periods* than natural gas STEECMs.

The right side of Table 26 illustrates that only two micro-scale preferred STEECMs with the highest energy costs savings do not have investment costs. This amount of non-investment STEECMs is quite low, since half of the STEECMs in the database involve no investment costs. Furthermore, electricity STEECMs endup higher in the list than would be expected compared to technical savings. This differentiation is probably caused by the difference in energy price between electricity and natural gas. For example a*eriated showerhead electric heating* is found in table, while *replacing an aeriated showerhead with gas heating* is not located in the list. Appendix C gives more detailed insights in micro-scale economic aspects per energy carrier. Technical and economic aspects are combined in **Error! Reference source not found.**, which combines micro-scale investment costs with energy costs saved, with a preference for energy costs saved.

*Table 26 Micro-scale STEECMs with the highest investment costs and the highest energy costs savings per household.*

| STEECMs with highest investment costs saved per household (micro-scale) | Investment costs | Energy costs saved | STEECMs with highest energy costs savings potential per hh without renovation (micro-scale) | Investment costs | Energy costs saved |
|---|---|---|---|---|---|
| | k EUR(2013)/hh | k EUR(2013)/hh/y | | k EUR(2013)/hh | k EUR(2013/hh/y |
| Renovate MFH gas | 22.8 | 1.2 | Replacement of non-condensing gas boilers for new gas boilers SFH | 8.7 | 0.7 |
| Renovate SFH, gas | 19.3 | 2.4 | Replacement of non-condensing gas boilers for new gas boilers MFH | 3.1 | 0.4 |
| Replacement of non-condensing gas boilers for new gas boilers SFH | 8.7 | 0.7 | Aerated Showerheads electric heating | 0.0 | 0.3 |
| Replacement of non-condensing gas boilers for new gas boilers MFH | 3.1 | 0.4 | Replace 11 most used lamps | 0.1 | 0.2 |
| Replace inefficient refrigerators for most efficient | 0.7 | 0.1 | Reduce stand-by usage | 0.0 | 0.2 |
| Replace inefficient freezers for A+++ model | 0.6 | 0.1 | Lower thermostat 1 C | 0.0 | 0.2 |
| Insulation for radiators and pipes SFH | 0.5 | 0.1 | Aerated Showerheads gas heating | 0.0 | 0.2 |
| Install light sensors | 0.3 | 0.1 | Insulation for radiators and pipes SFH | 0.5 | 0.1 |
| Replacement HL with LED | 0.2 | 0.1 | Replace HL with CFL | 0.1 | 0.1 |
| Replace 11 most used lamps | 0.1 | 0.2 | Air dry instead of tumble dryer | 0.0 | 0.1 |

Table 26 illustrates that micro-scale STEECMs with the highest energy savings potential do not necessarily have high investment costs. Two STEECMs in the top five have significantly higher investment costs than the other STEECMs. The figure is somewhat skewed due to the high micro-scale costs and energy saved for boiler replacement STEECMs.

**Macro-scale**

The favorable STEECMs with regard to macro-scale investment costs and energy costs savings figures are presented in Table 27. The let part of Table 27 shows highest *theoretical investment costs* and *energy costs saved* and *payback period*. Most STEECMs with high macro-scale *theoretical investment costs* also have a high *payback period*, with almost no exceptions. This implies that STEECMs with high macro-scale *theoretical investment costs* are not suitable for realizing STES with regard to affordability. Next to this, there is no clear connection between theoretical *investment costs* and theoretical *energy costs saved,* which suggests that it is not necessary to do investments to save energy or vice versa. Also, there is an equal amount of electricity and natural gas STEECMs in the list.

*Table 27 STEECMs with highest macro-scale investment costs and energy costs saved with corresponding payback period.*

| STEECMs with highest theoretical investment costs savings (Macro-scale) | Investment costs | Theoretical energy costs saved | Payback period | STEECMs with highest theoretical energy cost savings (Macro-scale) | Investment costs | Theoretical energy costs saved | Payback period |
|---|---|---|---|---|---|---|---|
| | Billion EUR(2013) | Billion EUR(2013)/y | 1 Short/2 Medium/3 Long/4 Very Long | | Billion EUR(2013) | Billion EUR(2013)/y | 1 Short/2 Medium/3 Long/4 Very Long |
| Renovate SFH, gas | 95.1 | 7.8 | **4** | Renovate SFH, gas | 95.1 | 7.8 | **4** |
| Renovate MFH gas | 79.5 | 2.7 | **4** | Reduce stand-by usage | 0.7 | 4.7 | **1** |
| Replacement of non-condensing gas boilers for new gas boilers SFH | 47.0 | 2.4 | **4** | Replace 11 most used lamps | 3.0 | 4.1 | **1** |
| Replacement of non-condensing gas boilers for new gas boilers MFH | 21.1 | 1.8 | **4** | Renovate MFH gas | 79.5 | 2.7 | **4** |
| Replace inefficient freezers for A+++ model | 11.4 | 1.2 | **3** | Replacement of non-condensing gas boilers for new gas boilers SFH | 47.0 | 2.4 | **4** |
| Install light sensors | 11.2 | 1.5 | **3** | Replacement of non-condensing gas boilers for new gas boilers MFH | 21.1 | 1.8 | **4** |
| Replace inefficient refrigerators for most efficient | 8.3 | 0.5 | **4** | Lower thermostat 1 °C, gas | 0.0 | 1.6 | **1** |
| Replacement HL with LED | 7.3 | 3.3 | **2** | Switch off unneeded light | 0.0 | 1.5 | **1** |
| Insulation for radiators and pipes SFH | 5.1 | 1.0 | **3** | Install light sensors | 11.2 | 1.5 | **3** |
| Replacement GLS with LED | 2.8 | 1.1 | **2** | Aerated Showerheads gas heating | 0.5 | 1.4 | **1** |
| **Total** | **288.8** | **23.2** | | **Total** | **258.2** | **29.5** | |

STEECMs with the highest energy costs savings differ a lot from the macro-scale STEECMs list with high investment costs, but the combined investment costs are still very high (258 billion versus 289 billion). Most of the preferred STEECMs are natural gas STEECMs. The STEECM with the highest macro-scale theoretical *total energy costs saved* is the renovation of SFHs with gas heating. This STEECM also has a high *initial expenditure* and *payback period* score, which makes adoption less favorable. At the same time, the two STEECMs that follow SFH renovation still have a significant total *energy costs saved*, while the *initial expenditure* is low and the *payback period* is short, which favors adoption. Four STEECMs have a long or very long *payback period,* but half of the STEECMs is eligible for adoption to contribute to affordability. Electricity STEECMs are higher located in the list than technical parameters would indicate, which is mainly caused by higher electricity prices compared to natural gas prices per kWh.

#### 4.2.1.3. Socio-behavioral aspects

In addition to techno-economic parameters, socio-behavioral parameters have been developed to shed a light on other preferences that influence or pose barriers to adoption of STEECMs. Table 28 shows the STEECMS with the lowest *implementation difficulty* and the STEECMs with the lowest *impact on comfort level.*

*Table 28 List of preferred STEECMs with regard to implementation difficulty and lowest impact on comfort level.*

| Measures that have the lowest difficulty to be implemented | Theoretical energy savings potential | Measures that have the lowest impact on comfort level | Theoretical energy savings potential |
|---|---|---|---|
| | PJ/y | | PJ/y |
| Change washing temp from 40 C to 30 °C | 4 | Renovate MFH gas | 87 |
| Use dishwasher only when full | 4 | Replace inefficient refrigerators for most efficient | 7 |
| Reduce the amount of washing cycles with 50% | 12 | Replace inefficient freezers for A+++ model | 8 |
| Reduce hot washes to 40 °C | 2 | Renovate SFH, gas | 184 |
| Close bedroom window at night, gas | 3 | Replacement HL with LED | 41 |
| Reduce refrigerator door opening by 50% | 1 | Replacement of non-condensing gas boilers for new gas boilers SFH | 128 |
| Switch off unneeded light | 17 | Replacement GLS with LED | 13 |
| Air dry instead of tumble dryer | 6 | Replacement of non-condensing gas boilers for new gas boilers MFH | 94 |
| Only use full washing machine | 2 | Install light sensors | 17 |
| Lower thermostat 1 °C, gas | 94 | Repair leaks in hot water system | 2 |
| **Total** | **145 (10%)** | **Total** | **579 (40%)** |

STEECMs with a low *implementation difficulty* have varying theoretical STEECPs, but more than half of the STEECMs have an impact on energy use of less than 10 PJ/y. There are much more electricity STEECMs than natural gas STEECMs. All STEECMs in the table are utilization behavior STEECMs related to EC. The total theoretical STEECP of implementation favored STEECMs is 10% of yearly residential final electricity and natural gas use. *Lower thermostat 1 °C* is responsible for almost two-thirds of the combined energy savings, which somewhat distorts the outcome. Double-counting in the list mainly occurs for washing & drying STEECMs, which limitedly overestimates the total due to the low contribution per STEECM.

Preferred STEECMs regarding *impact on comfort level* are completely different from the preferred STEECMs with the lowest *implementation difficulty*. Most STEECMs are related to renovation or technology replacement. All EEUSs except for washing & drying are included. The combined theoretical STEECP of favorable

STEECMs is also significantly higher than favorable STEECMs with low *implementation difficulty* with 40% of yearly natural gas and electricity final residential energy use. However, double-counting is probably much higher due to the overrepresentation of SH renovation and SH technology replacement.

Figure 10 compares the *difficulty to implement measure* parameter with the *impact on comfort level* parameter. The correlation is not very strong, but there is a downward trend noticeable. The outcome is influenced by a double point in the bottom right (natural gas renovation). Without these two STEECMs the $R^2$ would be 0.38, which still indicates a small correlation. Hence, STEECMs with a low *difficulty to implement measure* tend to have a higher *impact on comfort level.*

STEECMs below the trend line have are from different EEUSs and represent various measure types. For example, *unplug second refrigerator (10 PJ/y), replacement GLS with LED (13 PJ/y), aerated showerhead gas heating (16 PJ/y)* and *install light sensors (17 PJ/y), shower 5 minutes instead of 7 minutes (15 PJ/y), delay start heating season to November (41 PJ/y), insulation of radiators and pipes SFH (51 PJ/y) and replacement of non-condensing gas boilers for new gas boilers MFH (94 PJ/y)*. STEECMs under the line have a total STEECP of 257/y PJ with some indirect double-counting for SH. Socio-behavioral outcomes indicate that there are substantial possibilities to contribute to availability and accessibility of STES by taking acceptability into account.

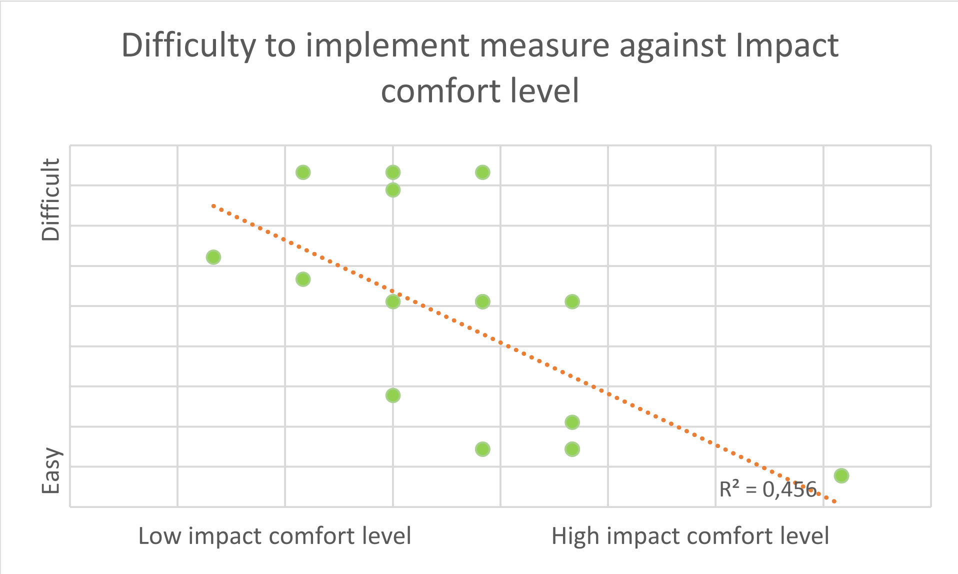


*Figure 10 Comparison STEECMs with highest STEECP between difficulty to implement measure and impact on comfort level.*

### 4.2.2. Realistic energy savings potential

Table 29 shows the realistic adoption potential based on literature findings, along with the realistic STEECP.

*Reduce stand-by usage, replacing the 11 most used lamps* and *air dry instead of tumble dry* are the electricity STEECMs with the highest realistic macro-scale STEECP. Next to this, all types of STEECMs are included. Utilization behavior STEECMs have the highest contribution to save energy and thus improve availability and accessibility. Replacement of lamps and refrigerators is still much faster than conventional replacement of around (+-30% instead of +-10% of the stock/y). The combined realistic electricity STEECP is 159 PJ/y, which is almost one-third of the German residential final electricity use.

*Table 29 Possible energy savings of preferred STEECMs when literature-based realistic adoption is applied.*

| Measures that have the highest savings potential based on surveys in literature (electricity) | Energy saved | Realistic adoption potential | Realistic energy savings potential | Measures that have the highest savings potential based on surveys in literature (natural gas) | Energy saved | Realistic adoption potential | Realistic energy savings potential |
|---|---|---|---|---|---|---|---|
| | kWh/hh/y | % | PJ/y | | kWh/hh/y | % | PJ/y |
| Reduce stand-by usage | 374 | 77% | 41 | Lower thermostat 1 °C, gas | 1620 | 28% | 65 |
| Replace 11 most used lamps | 381 | 67% | 37 | Renovate SFH, gas | 23385 | 2% | 53 |
| Air dry instead of tumble dryer | 232 | 56% | 19 | Turn off heating in unused rooms, gas | 561 | 44% | 35 |
| Switch off unneeded light | 119 | 79% | 14 | Delay start of heating season to November | 669 | 28% | 27 |
| Install light sensors | 116 | 77% | 13 | Replacement of non-condensing gas boilers for new gas boilers SFH | 6595 | 3% | 26 |
| Replace freezers for A+++ model | 202 | 28% | 8 | Renovate MFH gas | 12376 | 1% | 22 |
| Reduce kitchen temperature From 25 to 19 °C | 83 | 68% | 8 | Close bedroom window at night, gas | 419 | 28% | 17 |
| Reduce the amount of washing cycles with 50% | 87 | 60% | 8 | Insulation for radiators and pipes SFH | 1356 | 7% | 14 |
| Unplug freezer / second refrigerator | 58 | 73% | 6 | Replacement of non-condensing gas boilers for new gas boilers MFH | 3831 | 2% | 12 |
| Replace all refrigerators for most efficient | 135 | 28% | 5 | Shower for 5 minutes instead of 7 minutes | 134 | 49% | 9 |
| **Total** | | | **159** | **Total** | | | **281** |

Natural gas STEECMs with the highest realistic STEECP are *lower thermostat 1 °C, Renovate SFH, gas* and *turn off heating in unused rooms*. The realistic adoption potential is significantly lower than for electricity STEECMs. However, the combined realistic STEECP of preferable STEECMs is still more than twice the size of electricity STEECMs. Both represent savings of around one-third of German residential final natural gas or electricity use. All four STEECM types are included, but the top five is dominated by utilization behavior STEECMs. This outcome indicates that utilization behavior is the most important type of measure to improve availability and accessibility to enhance STES.

In general, the STEECM with the largest realistic STEECP is *lower thermostat 1 °C*. Surprisingly, renovation of gas-heated SFHs still has the second highest realistic STEECP, even with a realistic adoption potential of only 2%. However, this percentage would still be a significant increase compared to the current yearly German renovation rate, which is around 1% (Bettgenhäuser, 2013). Furthermore, there a fair amount of preferable technology replacement and renovation STEECMs, which strengthens the decision to include technology replacement and renovation in this research.

**Technical limitations**

Execution of technology replacement and renovation STEECMs could be limited by available stocks and technical personnel. Statista (2015) shows that there are almost 350,000 electrical technicians and 270,000 heating technicians in Germany. Varying sources indicate that replacing a heating system takes between 8 and 27 hours for two persons (ServiceMagic.co.uk, n.d.; Heatex, n.d.). On average, Germans work for 1388 hours per year in 2013 (OECD, 2014). There are more than six million non-condensing natural gas boilers that could be replaced by condensing gas boilers (Bettgenhauser & Boermans, 2011). Assuming these figures are a correct representation of the available and required time to replace boilers, replacing all non-condensing boilers is calculated by:

*6,000,000 boilers /(270,000 technicians * 1388 working hours / 2 employees per replacement / 8 or 27 hours per boiler replacement) = between four months and one year.*

This outcome indicates that the boiler replacement STEECMs could be executed within a one year timeframe. However, this outcome seems quite unlikely, so probably are more aspects that limit the amount of one of these parameters. For example, heating technicians are also occupied with maintenance of all heating systems and also with other types of technology replacements. Furthermore, not all of their 1388 hours are available for replacement. A significant amount of time is spent on planning and administration.

Limitations on stock levels have been too hard to figure out within the available time of this study and therefore are not further quantified.

### 4.2.3. Time and disruption scenarios

Table 30 and Table 31 show technically favored STEECMs during an STES issue with a small and a severe supply disruption for various timescales.

#### *4.2.3.1. Small disruption scenarios*

The very short timescale only contains four STEECMs with a STEECP of more than 10 PJ/y and there are only seven favorable STEECMs. The combined savings are modest (+-115 PJ/y), but still around 7.5% of yearly natural gas and electricity energy use. However, more than half of the theoretical energy savings could be achieved by delaying the heating season to November. All EEUSs are involved, except for lighting. Natural gas STEECMs are only utilization behavior measures, while electricity STEECMs have an equal division between maintenance- and utilization behavior.

Preferred STEECMs within the short timescale have a 50% higher combined theoretical STEECP than the very-short timescale, which is around 13% of final German residential electricity and natural gas use. *Delay start of heating season to November* still has a relatively high influence on the total. Next to this, all STEECMs have more than 10 PJ/y in potential energy savings. Four of the favorable STEECMs are small technology replacements, two are maintenance behavior and four utilization behavior. Only three STEECMs are natural gas related, but their combined STEECP is half of the total list. This outcome suggests that electricity requires more small STEECMs to achieve the same amount of absolute energy savings.

Favorable STEECMs in the medium timescale are completely the same compared to the short timescale. This overlap is mainly caused by the 'medium' threshold for implementation difficulty, which limits eligible STEECMs, such as boiler replacement. Hence, the opportunity to conduct larger technology replacement does not increase the total technical STEECP of favored STEECMs during a small energy disruption.

*Table 30 Possible STEECMs for a small energy disruption for very short, short and medium timescale.*

| STEECMs with small disruption; very short timescale | Theoretical energy savings potential | STEECMs with small disruption; short timescale | Theoretical energy savings potential | STEECMs with small disruption; medium timescale | Theoretical energy savings potential |
|---|---|---|---|---|---|
| | PJ/y | | PJ/y | | PJ/y |
| Delay start of heating season to November | 41 | Delay start of heating season to November | 41 | Delay start of heating season to November | 41 |
| Put heating circulating pumps at from 80W to 35W | 26 | Replace HL with CFL | 41 | Replace HL with CFL | 41 |
| Shower for 5 minutes instead of 7 minutes | 15 | Put heating circulating pumps at from 80W to 35W | 26 | Put heating circulating pumps at from 80W to 35W | 26 |
| Unplug freezer / second refrigerator | 10 | Aerated Showerheads gas heating | 16 | Aerated Showerheads gas heating | 16 |
| Reduce heating circulating pump to 10h use | 9 | Shower for 5 minutes instead of 7 minutes | 15 | Shower for 5 minutes instead of 7 minutes | 15 |
| Reduce kitchen temperature From 25 to 19 °C | 7 | Replacement GLS with LED | 13 | Replacement GLS with LED | 13 |
| Adjust temperature of refrigerator 5 to 7-7,5 °C | 5 | Unplug freezer / second refrigerator | 10 | Unplug freezer / second refrigerator | 10 |
| | | Reduce heating circulating pump to 10h use | 9 | Reduce heating circulating pump to 10h use | 9 |
| | | Replace freezers for A+++ model | 8 | Replace freezers for A+++ model | 8 |
| | | Reduce kitchen temperature From 25 to 19 °C | 7 | Reduce kitchen temperature From 25 to 19 °C | 7 |
| **Total** | **115 (8%)** | **Total** | **187 (13%)** | **Total** | **187 (13%)** |

*Table 31 Possible STEECMs for a severe energy disruption for very short, short and medium timescale.*

| STEECMs with severe disruption; very short timescale | Theoretical energy savings potential | STEECMs with severe disruption; short timescale | Theoretical energy savings potential | STEECMs with severe disruption; medium timescale | Theoretical energy savings potential |
|---|---|---|---|---|---|
| | PJ/y | | PJ/y | | PJ/y |
| Lower thermostat 1 °C, gas | 94 | Lower thermostat 1 °C, gas | 94 | Replacement of non-condensing gas boilers for new gas boilers SFH | 128 |
| Delay start of heating season to November | 41 | Insulation for radiators and pipes SFH | 51 | Lower thermostat 1 °C, gas | 94 |
| Put heating circulating pumps at from 80W to 35W | 26 | Replace 11 most used lamps | 47 | Replacement of non-condensing gas boilers for new gas boilers MFH | 94 |
| Shower for 5 minutes instead of 7 minutes | 15 | Delay start of heating season to November | 41 | Insulation for radiators and pipes SFH | 51 |
| Reduce the amount of washing cycles with 50% | 12 | Put heating circulating pumps at from 80W to 35W | 26 | Replace 11 most used lamps | 47 |
| Unplug freezer / second refrigerator | 10 | Switch off unneeded light | 17 | Delay start of heating season to November | 41 |
| Reduce heating circulating pump to 10h use | 9 | Install light sensors | 17 | Put heating circulating pumps at from 80W to 35W | 26 |
| Reduce kitchen temperature From 25 to 19 °C | 7 | Aerated Showerheads gas heating | 16 | Switch off unneeded light | 17 |
| Adjust temperature of refrigerator 5 to 7-7,5 °C | 5 | Shower for 5 minutes instead of 7 minutes | 15 | Install light sensors | 17 |
| Close bedroom window at night, gas | 3 | Reduce the amount of washing cycles with 50% | 12 | Aerated Showerheads gas heating | 16 |
| **Total** | **224 (15%)** | **Total** | **337 (23%)** | **Total** | **531 (37%)** |

#### 4.2.3.2. Severe disruption scenarios

During a severe disruption, STEECMs could theoretically reduce German residential final natural gas and electricity use with 15-37%. Table 31 reveals that in general, there is less STEECM overlap in the severe disruption scenarios compared to small disruption scenarios. The combined theoretical STEECP in the very-short timescale is twice the size of a small disruption in the very-short timescale (224 PJ/y compared to 115 PJ/y), which is +-15% of German final residential electricity and natural gas use. All EEUSs are involved, except for lighting. Also, the first five STEECMs have a substantially higher STEECP than the last five STEECMs, which signifies that the impact of some STEECMs dwarfs the others.

The difference in theoretical STEECP between the very short-term and the short-term in a severe disruption scenario is substantial (113 PJ/y), which implies that timescale increases possible energy savings. There is a mix of utilization behavior, maintenance behavior and small technology replacement, which confirms the relevance of including multiple types of STEECMs.  Overrepresentation of SH, DHW and lighting in the list indicates indirect double-counting. The relative impact of utilization behavior STEECMs is more than half of the theoretical STEECP. There is an equal division in the amount of natural gas and electricity STEECMs, but natural gas represents three quarters of the savings. This implies that natural gas remains more important in severity scenarios.

The list of favorable STEECMs during a medium timescale and severe disruption scenario totals 531 PJ/y, which is almost 200 PJ/y more than the favorable STEECMs in the short timescale scenario. The combined energy savings are more than one-third of German final residential electricity and natural gas use. The main difference between short- and medium term is caused by the appearance of boiler replacement STEECMs. The first five STEECMs are all natural gas related and represent almost 70% of the combined theoretical STEECP of the list. Furthermore, the STEECMs list contains three utilization behavior measures, three maintenance behavior measures and four technology replacement measures. This division of STEECMs indicates that longer time availability shifts preferences from utilization behavioral STEECMs to technology replacement STEECMs. However, utilization behavior still represents almost one-third of the combined energy savings. Furthermore, overrepresentation of SH, DHW and lighting leads to substantial indirect double-counting. It is also uncertain whether all theoretical technology replacement is actually executed in a one year timeframe.

### 4.2.4. Policy interventions

Most ES issues do not occur without policy interventions that try to prevent shortfalls from happening (IEA 2005a). Three policy interventions are addressed: (1) information and awareness campaign, (2) price signals and (3) financial support schemes.

#### 4.2.4.1 Informational and awareness campaign

Table 32 presents a list of preferred STEECMs with the highest theoretical STEECP when an informational and awareness campaign is executed.

*Table 32 Favored STEECMs on a medium timescale for a small disruption, severe disruption and a severe disruption with low costs influenced by an informational campaign. Source: Own creation.*

| Information and awareness campaign, STEECMs during small disruption | Theoretical energy savings potential | Information and awareness campaign, STEECMs during large disruption | Theoretical energy savings potential | Information and awareness campaign, STEECMs during severe disruption without costs | Theoretical energy savings potential |
|---|---|---|---|---|---|
| | PJ/y | | PJ/y | | PJ/y |
| Replacement of non-condensing gas boilers for new gas boilers SFH | 128 | Replacement of non-condensing gas boilers for new gas boilers SFH | 128 | Lower thermostat 1 °C, gas | 94 |
| Replacement of non-condensing gas boilers for new gas boilers MFH | 94 | Lower thermostat 1 °C, gas | 94 | Delay start of heating season to November | 41 |
| Insulation for radiators and pipes SFH | 51 | Replacement of non-condensing gas boilers for new gas boilers MFH | 94 | Put heating circulating pumps at from 80W to 35W | 26 |
| Replace 11 most used lamps | 47 | Insulation for radiators and pipes SFH | 51 | Switch off unneeded light | 17 |
| Delay start of heating season to November | 41 | Replace 11 most used lamps | 47 | Shower for 5 minutes instead of 7 minutes | 15 |
| Put heating circulating pumps at from 80W to 35W | 26 | Delay start of heating season to November | 41 | Reduce the amount of washing cycles with 50% | 12 |
| Install light sensors | 17 | Put heating circulating pumps at from 80W to 35W | 26 | Unplug freezer / second refrigerator | 10 |
| Aerated Showerheads gas heating | 16 | Switch off unneeded light | 17 | Reduce heating circulating pump to 10h use | 9 |
| Shower for 5 minutes instead of 7 minutes | 15 | Install light sensors | 17 | Reduce kitchen temperature From 25 to 19 °C | 7 |
| Unplug freezer / second refrigerator | 10 | Aerated Showerheads gas heating | 16 | Adjust temperature of refrigerator 5 to 7-7,5 °C | 5 |
| **Total** | **445 (31%)** | **Total** | **531 (37%)** | **Total** | **239 (16%)** |

The list of favorable STEECMs is very different from Table 30 and the combined theoretical STEECP is more than twice the amount of general small disruption scenario for a medium timescale (445 PJ/y compared to 187 PJ/y). However, indirect double-counting probably has a higher influence in combined STEECP with the conventional small disruption scenario due to the overrepresentation of SH STEECMs. Increased information availability decreases the *implementation difficulty* enough to allow bigger technology replacement STEECMs (e.g. boiler replacement) in a small disruption scenario. These large technology replacement STEECMs have a higher theoretical STEECP than most utilization- or maintenance behavior STEECMs. The amount of natural gas STEECMs has increased substantially compared to conventional small disruption scenario as well. Hence, an informational campaign positively influences the opportunities to have favorable STEECMs to enhance availability and accessibility in a small disruption scenario.

An informational and awareness campaign during a severe disruption does not change the list of preferred STEECMs compared to a scenario without an informational and awareness campaign. This outcome indicates that STEECMs with a very high implementation difficulty, such as natural gas renovation, do not decrease enough to become attractive to be adopted. An information and awareness campaign during a severe disruption scenario does not improve the favorable STEECMs to enhance availability and accessibility to improve STES.

The addition of *payback period* and *initial expenditure* constraints halves the combined theoretical STEECP to 239 PJ/y. This is still around 15% of German final residential electricity and natural gas use. Again, utilization behavior SH STEECMs are responsible for the majority of the combined STEECP.

#### 4.2.4.2 Price signals

Table 33 shows a list of preferred STEECMs when energy prices are modestly increased and a list of preferred STEECMs with substantial price increases.

A scenario with a small disruption with price signals and optimization for highest total energy costs saved strongly favors electricity STEECMs, which is mainly caused by the price difference between electricity and natural gas. Six STEECMs have no investment costs. The *payback period* of each STEECM has substantially improved. This indicates that price signals increase the preference for ECMs compared to EEMs. The combined theoretical STEECP is 162 PJ/y, which is +-10% of the German final residential electricity and natural gas use. The top five STEECMs contain four technology replacement STEECMs, which indicates that it still benefits to invest some money to save more money. Furthermore, all EEUSs are involved.

The combined STEECP is more than twice the size of favored STEECMs during a small disruption (484 PJ/y compared to 162 PJ/y). The amount of natural gas and electricity STEECMs are equally divided, but natural gas STEECMs have a much higher theoretical STEECP. This outcome illustrates significant influence of energy prices on STEECMs that could be taken when the payback period has to be limited. Half of the STEECMs consider technology replacement. Only three STEECMs are utilization behavior measures. More STEECMs have a medium *payback period* than during a small disruption, which indicates that households are more prepared to invest during a severe disruption compared to a small disruption. Hence, price signals enable substantial potential energy savings with improved affordability to enhance STES.

*Table 33 Favorable STEECMs with highest macro-scale energy costs saved for a small disruption and a severe disruption with a price signal policy intervention.*

| **Total energy cost saved price signals (50% increase) STEECMs during small disruption** | **Theoretical energy savings potential** | **Total investment costs** | **Total energy costs saved** | **Payback period** |
|---|---|---|---|---|
| | PJ/y | Billion EUR(2013) | Billion EUR(2013)/y | 1 Short/2 Medium/3 Long/4 Very Long |
| Replacement HL with CFL | 41 | 3 | 5 | 1 |
| Install light sensors | 17 | 11 | 2 | 3 |
| Aerated Showerheads gas heating | 16 | 0 | 2 | 1 |
| Replace inefficient freezers for A+++ model | 8 | 11 | 2 | 3 |
| Replacement GLS with LED | 13 | 3 | 2 | 2 |
| Unplug freezer / second refrigerator | 10 | 0 | 1 | 1 |
| Remove ice | 4 | 0 | 1 | 1 |
| Aerated Showerheads electric heating | 7 | 0 | 1 | 1 |
| Delay start of heating season to November | 41 | 0 | 1 | 1 |
| Reduce kitchen temperature From 25 to 19 C | 7 | 0 | 1 | 1 |
| **Total** | **164 (11%)** | **29** | **18** | |
| **Total costs saved price signals (200% increase) STEECMs during severe disruption** | **Theoretical energy savings potential** | **Total investment costs** | **Total energy costs saved** | **Payback period** |
| | PJ/y | Billion EUR(2013) | Billion EUR(2013)/y | 1 Short/2 Medium/3 Long/4 Very Long |
| Replace 11 most used lamps | 47 | 3 | 12 | 1 |
| Replacement of non-condensing gas boilers for new gas boilers SFH | 128 | 47 | 7 | 3 |
| Replacement of non-condensing gas boilers for new gas boilers MFH | 94 | 21 | 5 | 2 |
| Switch off unneeded light | 17 | 0 | 5 | 1 |
| Install light sensors | 17 | 11 | 4 | 2 |
| Aerated Showerheads gas heating | 16 | 0 | 4 | 1 |
| Replace inefficient freezers for A+++ model | 8 | 11 | 4 | 2 |
| Reduce the amount of washing cycles with 50% | 12 | 0 | 3 | 1 |
| Lower thermostat 1 C, gas | 94 | 0 | 3 | 1 |
| Insulation for radiators and pipes SFH | 51 | 5 | 3 | 2 |
| **Total** | **484 (33%)** | **99** | **51** | |

### *4.2.4.3. Financial support scheme*

Subsidizing technology replacement and renovation does not change favorable STEECMs when energy costs savings are optimized. The payback period has improved considerably though. Lighting and SH STEECMs dominate the list, which suggests a substantial amount of indirect double counting. Half of the STEECMs are technology replacement, three are few utilization behavior and two maintenance behavior. Combined energy savings are around 30% of German residential final electricity and natural gas use. However, the main improvement of the financial support scheme is enhancing affordability.

*Table 34 Favorable STEECMs with highest macro-scale energy costs saved for a severe disruption with a financial support scheme policy intervention.*

| **Total costs saved financial support scheme (50% subsidy) STEECMs during severe disruption** | **Theoretical energy savings potential** | **Total investment costs** | **Total energy costs saved** | **Payback period** |
|---|---|---|---|---|
| | PJ/y | Billion EUR(2013) | Billion EUR(2013)/y | 1 Short/2 Medium/3 Long/4 Very Long |
| Replace 11 most used lamps | 47 | 1.5 | 4.1 | 1 |
| Replacement of non-condensing gas boilers for new gas boilers SFH | 128 | 23.5 | 2.4 | 3 |
| Replacement of non-condensing gas boilers for new gas boilers MFH | 94 | 10.6 | 1.8 | 3 |
| Lower thermostat 1 C, gas | 94 | 0.0 | 1.6 | 1 |
| Switch off unneeded light | 17 | 0.0 | 1.5 | 1 |
| Install light sensors | 17 | 5.6 | 1.5 | 2 |
| Aerated Showerheads gas heating | 16 | 0.2 | 1.4 | 1 |
| Replace inefficient freezers for A+++ model | 8 | 5.7 | 1.2 | 2 |
| Reduce the amount of washing cycles with 50% | 12 | 0.0 | 1.1 | 1 |
| Insulation for radiators and pipes SFH | 51 | 2.5 | 1.0 | 2 |
| **Total** | **484 (33%)** | **50** | **18** | |

# 5. Discussion

The combination of two extensive topics (EEC and ES), modelled on multiple scales (timescale and micro-macro scale) generates valuable theoretical- and practical insights, but also leads to a variety of discussion points. This section is split-up into limitations (5.1) and implications (5.2).

## 5.1. Limitations

Limitations are encountered on several levels. Outcomes of other literature are compared to results found in this study, the model approach is debated and data usage is examined.

### 5.1.1. Outcomes comparison

Only a limited amount of literature is available on hybrid bottom-up quantification of both EEMs and ECMs and even less on quantified contributions of STEECMs to STES.

Table 35 is created to simplify data comparison with relevant literature. Comparing outcomes with other literature is sometimes a bit tricky, because part of the data of this research originates from literature that could be used as comparison. Outcomes of micro-scale and macro-scale energy savings potentials of STEECMs are in the same order of magnitude compared to similar energy savings potential studies (Bürger, 2010; Palmer et al., 2012; Pehnt et al., 2009), which will be quantified further below. Also, this study increases the amount of researched aspects of residential EECM assessment, since most of these studies only focus on technical aspects or economic aspects of EEC.

Considering specific EEUSs, lighting STEECMs have a higher electricity related macro-scale theoretical STEECP (+- 80 PJ/y without direct double-counting) than refrigeration & freezing STEECMs (+-45 PJ/y). The impact of these two EEUSs is the different way around in Bürger (2010), who presents +-75 PJ/y for refrigeration & freezing measures and +-36 PJ/y for lighting measures. This might be caused by the use of European data for lighting data, which assumes higher average lighting energy use compared to his study. Also, refrigeration & freezing STEECMs could be somewhat lower due to partial refrigerator & freezer technology replacement in this study compared to full replacement in Bürger (2010). Nevertheless, combined theoretical STEECP of electricity STEECMs are around 300 PJ/y, compared to around 400 PJ/y for Bürger (2010), which is in the same order of magnitude and Bürger (2010) includes all EEUSs.

The combined realistic STEECP of all STEECMs (540 PJ/y) is 50% bigger than the combined estimated STEECP of Palmer et al. (2012) (360 P/y), which is similar to differences in residential final energy use between the UK and Germany. However, their study applies a constant realistic adoption as '62.5% of the theoretical adoption potential', and they do not take renovation- and boiler replacement STEECMs into account, which lowers the validity of directly comparing outcomes. At the same time, outcomes of favored STEECMs to improve availability and accessibility have a clear preference for SH, DHW and lighting EECMs, which is also found back in their study. Also, favored STEECMs present in most tables are similar to EECMs that come forward other publications (Ürge-Vorsatz et al., 2009).

Potential energy savings from building related aspects, such as renovation and natural gas boiler replacement are difficult to compare with other literature, because there are many configurations to setup building EECMs. The preference order that favors SH and lighting STEECMs with regard to macro-scale investment costs and energy costs savings is also found back in Pehnt et al. (2009). Outcomes in their study (+-250 PJ) are only a third of this study, but they only cover technology replacement and renovation, and have no double-counting.

*Table 35 Overview of STEECM comparisons, disruption scenarios and policy interventions with regard to STEECP, investment costs and energy costs savings.*

| Combined theoretical STEECP of top ten favored STEECMs | Combined energy savings potential medium timescale | Savings compared to German final residential natural gas and electricity use | Total investment costs | Total energy costs saved |
|---|---|---|---|---|
| Colors depict type of results | PJ/y | % | Billion EUR(2013) | Billion EUR(2013)/y |
| Technical optimization (highest theoretical STEECP) | 806 | 56% | € 252 | € 27 |
| Economic investment optimization (highest investment costs total) | 628 | 43% | € 289 | € 23 |
| Energy costs savings optimization (highest energy costs savings) | 738 | 51% | € 258 | € 30 |
| Implementation difficulty optimization (lowest) | 145 | 10% | € - | € 6.4 |
| Impact on comfort level optimization (lowest) | 579 | 40% | € 284 | € 22 |
| Realistic technical optimization (realistic STEECP) | 338 | 23% | € 37 | € 12 |
| Small disruption scenarios (very short / short / medium timescale) | 115 / 187 / 187 | 8% / 13% / 13% | 0 / 27 / 27 | 3,8 / 12 / 12 |
| Severe disruption scenarios (very short / short / medium timescale) | 222 / 337 / 531 | 15% / 23% / 37% | 0 / 20 / 88 | 6.4 / 14 / 17 |
| Small disruption information and awareness campaign | 443 | 31% | € 88 | € 14 |
| Severe disruption information and awareness campaign | 531 | 37% | € 88 | € 17 |
| Severe disruption costs limits information and awareness campaign | 237 | 16% | € - | € 4.5 |
| Small disruption energy price increase | 162 | 11% | € 29 | € 18 |
| Severe disruption energy price increase | 484 | 33% | € 99 | € 51 |
| Financial support scheme | 484 | 33% | € 50 | € 18 |

Historical data from Table 3 shows that energy use decreased during energy shortfalls with 5-40% for various regions and timescales, with a majority of the cases between 10% and 20% (Leighty & Meier, 2011; Pasqiuer, 2011; ESMAP, 2010). Combined theoretical STEECP outcomes without constraints leads to much higher possible energy savings (40-60%). Combined realistic STEECPs (23%) end at the higher part of historical energy shortfalls, but when indirect double-counting is taken into account, possible energy savings end up in the 10-20% range. This indicates that the realistic STEECP is similar to historical data. Small disruption and various timescale scenarios have possible energy savings of 8-13% of German final residential natural gas and electricity demand, which also remains in the historical perspective. Severe disruption and various timescales scenarios are 15-40% of German final residential natural gas and electricity use, which is more unlikely with regard to historical energy savings. This could be caused by overestimation of technology replacement in a short timeframe. Combined theoretical STEECPs of favorable STEECMs during policy intervention scenarios remain in the 5-40% range, but are often higher than 30%, which suggests some overestimation compared to historical data.

In general, overestimation of combined STEECP could be explained by the use of theoretical STEECP to assess favored STEECMs. However, not enough insights and data were available to apply realistic adoption for all scenarios. It remains difficult to directly compare these outcomes with the outcomes of this research, since most energy shortfalls include different sectors and different types of regions. Nonetheless, theoretical STEECP is not incorrect, but it gives a maximum amount of energy or energy costs savings.

### 5.1.2. Limitations to model approach

The STEECM model enables multiple pathways to assess STEECM contributions to STES. However, several issues have been encountered that possibly limit relevant and valid outcomes on some STEEC- and STES-related issues.

Firstly, investment costs have not been annualized and discounted, which limits the economic applicability of the model on a longer timescale. This could make more costs figures more dynamic. Also, several other economic feedbacks, such as various forms of learning and scarcity have not been explicitly included, which could have an influence on economics during an energy shortfall (ESMAP, 2010). For example, nation-wide execution of DHW maintenance could improve maintenance time by experience, but too few installers could lead to scarcity in workforce, which could higher the costs of maintenance. However, micro- and macro-scale economic feedbacks during a STES issue are not well enough understood to be quantitatively included in the STEECM model.

Secondly, the economic non-market failure EEC barriers could be translated to *split incentives* (Fleiter et al., 2011). In this case, split incentives have an influence on decisions, because costs and benefits are not divided equally (Gillingham et al., 2012). For example the tenant-landlord dilemma, where cost savings are for the landlord, while the tenant wants to improve the EE of the dwelling or the different way around. According to Leighty & Meier (2011), preferences in households vary between home owners and renters, which confirms the split-incentives barrier. In their research, home owners favor EE by improving technology, except for low-cost investments like weatherization. On the contrary, renters favor EC, except for use of lighting, which might be caused by higher number of lamps in homeowner households. Wada et al. (2012) approaches split incentives between low-income and high-income households, who apply significantly different discount rates.

Furthermore, the number of STEECMs that each household is willing to adopt has not been included. Results have been presented as a list of ten STEECMs. This does not always mean that all ten STEECMs will be executed. Some studies suggest that most households only adopt a limited amount of EECMs per intervention moment (van Lidth de Jeude & Noach, 2014). At the same time, once a household has adopted a few EECMs, they are more willing to invest in new EECMs (van Lidth de Jeude & Noach, 2014). Thus, adoption of EECMs could be an incentive to take more EECMs. However, multiple EECM adoption pathways and feedbacks have not been specifically quantified yet, if possible at all. Additionally, their study does not take STES issues into account, which could underestimate the amount of STEECMs that households are willing to adopt during an energy shortfall. Without clear insights in these aspects of adoption behavior, it remains relevant to present a list of ten favorable STEECMs.

Another model issue is that only specific rebound-effects and direct double-counting are included. Indirect and structural double-counting and rebound-effects could lead to more realistic outcomes on impact and lists of favorable STEECMs. However, increased complexity does not always benefit the effectivity of a model. This would make the model reliant on even more assumptions, which is a common issue for bottom-up energy use models (Kavgic et al., 2010).

Also, combining both energy carriers in one analysis could give a skewed picture of opportunities per energy carrier. Outcomes are calculated from a final energy perspective. The primary energy factor of German electricity production is two-and-a-half times bigger than for natural gas (Bettgenhäuser, 2013), thus underestimating the actual impact of residential electricity use on supply-side ES. However, other EECM studies and most data sources present their results in final energy, which makes final energy comparison easier. Also, the preferred technically optimized primary energy STEECMs are still in the same order, but electricity STEECMs have obtained a relatively higher impact, but the original difference between electricity and natural gas is too big to be compensated by primary energy factors. Next to this, most tables have equal amounts of electricity and natural gas STEECMs, so both are equally represented.

Trianni et al. (2014) warns for unknown dependencies between EECM parameters, which could influence possible outcomes of preferred STEECMs and the STEECP of these STEECMs. This also applies to the STEECM parameters of this research. Techno-economic parameters are interrelated through energy use and energy costs, which is solved by analyzing both types of aspects in other tables. Socio-behavioral parameters have been clustered in a few larger parameters (implementation difficulty and comfort level), which could have a bigger risk for inter-relations. For example, no link is added between *information availability* and *implementation time*, while these parameters could have an influence on each other. Nonetheless, complexity is not well enough understood to further quantify interrelations.

### 5.1.3. Data availability and application

Despite extensive data correction and data gathering methods, some limitations regarding data availability and applicability are worthwhile to discuss.

Firstly, extensive data requirements have limited the scope of this research to the residential sector. This restricts a more comprehensive national overview on improved natural gas and electricity STES.

Secondly, harmonization allows that some EEUSs are described in more detail than others, which leads to the presence of general and more specific STEECMs. More specific STEECMs potentially have a lower STEECP compared to STEECMs based on a less detailed EEUS. The difference in detail level could influence the opportunity to end up in the results tables. For example, STEECMs regarding washing & drying have been specifically described and lack in most outcomes, such as lowering washing temperature from hot washes to 40 °C and reduce temperature from 40 °C to 30 °C. At the same time, some SH STEECMs are more general and found back in each table, such as renovation of SFHs. However, presented STEECMs still describe specific actions, which can be independently executed. The low presence could be caused by a low impact in general as well.

Furthermore, the use of socio-behavioral data, even though information mainly originates from scientific literature, remains challenging, especially around residential energy related behavior (Thøgersen & Grønhøj, 2010). Data gathering, application and data interpretation are still a big issue in behavioral energy science (Ibid.). So far, quantifications of non-techno-economic STEECMs parameters is scarce and disperse (Ürge-

Vorsatz et al., 2009). For example, Wallenborn (2014) criticized the way rebound behavior is framed. Surveys regarding energy savings may indicate that the willingness to take action is high, but there can be high discrepancies between the findings and the actual choices that someone makes (Ek & Söderholm 2010). Data availability for this study encounters similar issues. However, utilized socio-behavioral parameters are based on most recent scientific insights and newly developed parameters are based on own data gathering, which compensates for lacking data. Also, the multi-criteria approach prevents too large influence from specific socio-behavioral parameters.

Next to this, no specific distinction is made between forecasted utilization behavior energy use and actual utilization behavior energy use. Osterhage et al. (2015) argues that in non-renovated buildings forecasted energy use in kWh per $m^2$ is substantially overestimated (20-40% higher) compared to actual energy use. At the same time energy use in renovated buildings is underestimated. In total, their actual energy savings potential is lower (60% instead of 80%) than expected. They see this difference as a specific type of rebound effect, which needs to be studied in more detail. The scope of their study cannot be directly aggregated to the entire German residential sector, so this effect has not been included.

## 5.2. Implications

This research adds to studies that have attempted to quantitatively approach contributions of STEECMs with regard to STES by quantifying various impacts of STEECMs. The STEECM model enables more detailed technical, economic and socio-behavioral characterization of residential EECMs compared to other residential bottom-up EECM models for the specific short-term timeframe. This structure adds to existing extensive industry sector EECM characterization frameworks from for example Trianni et al. (2014) and Fleiter et al. (2012). These characterized parameters enable better ex-ante understanding of theoretical and realistic adoption with corresponding technical and economic impact, and lists of preferable STEECMs under various disruption and policy intervention scenarios within a one-year timeframe. Especially the implementation difficulty and impact on comfort level have not specifically been included as limitations to residential ex-ante EEC bottom-up modelling before. Also, the attempt to find out constraints on available stocks and workforce is something that is rarely included in EEC research.

Furthermore, this study adds to insights into requirements for setting up of a reliable STEECM database and strategies to gather and process available data for quantifying STEECMs in a structured way. The applied method is far from perfect, but by combining relevant recent studies, insights in data structuring have been improved.

This study could be useful for a variety of stakeholders, such as governments, large companies and the society as a whole. Depending on the scenario, stakeholders could get much faster insights in which STEECMs should be targeted to obtain the largest contributions to STES and which policy interventions are suitable for assistance. The STEECM model could be translated to a tool that assess more types of STES scenarios for a variety of regions. STEEC and STES are topics that are very context dependent, so each region requires an updated set of STEECMs.

# 6. Conclusion and recommendations

An ex-ante hybrid bottom-up STEECM model has been developed to improve insights on how STEECMs can contribute to STES from various perspectives. An extensive literature study has been conducted to find out all requirements of a valid and reliable hybrid bottom-up model.

A detailed reference case is the basis of the STEECM model. From this reference case, STEECMs could be setup that contain certain energy savings potentials. EEC barriers pose constraints to reach the theoretical STEECP and how preferable each STEECM is. Next to common technical and economic data, EEC barriers have been translated into ten socio-behavioral and two indirect economic parameters. Theoretical or realistic energy savings potentials or energy costs savings potentials of certain lists of favored STEECMs indicate the impact on final energy use and costs. Altered final energy demand influences STES positively or negatively with regard to availability, accessibility, affordability and acceptability. The STES situation generates or is influenced by EEC policies. Five STEEC-related STES policies have been found of which three have been used to simulate policy intervention scenarios. Data limitations have restricted the application of a more robust realistic potential, so most results are presented as the theoretical potential of a list of favorable STEECMs.

The STEECM model requires a lot of data from various sources, so a detailed approach to properly structure data has been developed as well. Normalization, correction and harmonization factors have been gathered to obtain sufficient data to assess STEECMs on a micro-scale and macro-scale.

On a technical micro-scale natural gas SH STEECMs have the highest absolute impact on final residential energy use, while electricity STEECMs have the highest relative contribution per EEUS. Technology replacement often has a higher impact than utilization behavior in cases where a specific STEECM is not yet executed. Regarding technical macro-scale optimization, the top ten favorable STEECMs with the highest theoretical STEECP are dominated by SH renovation, technology replacement and utilization behavior. Combined impact of the STEECMs is more than 80% of total German final residential electricity and natural gas use, but care should be taken with substantial indirect double-counting. Nevertheless possible yearly energy savings are extensive and suggest important contribution to availability and accessibility.

With regard to economic micro-scale optimized STEECMs, renovation and large technology replacement (boilers, refrigerators) have the highest investment cost, which limits their contribution with respect to affordability. STEECMs with the highest micro-scale theoretical energy costs savings do not necessarily involve high investment costs, which induces better opportunities to contribute to affordability. Electricity STEECMs become more favorable, since electricity costs are higher than natural gas costs. Macro-scale STEECMs with the highest investment costs and STEECMs with the highest theoretical energy costs savings encounter similar outcomes to micro-scale economic favored STEECMs. Favored STEECMs with the highest theoretical energy costs savings only regards technology replacement or utilization behavior.

Preferable STEECMs with advantageous socio-behavioral characteristics differ a lot between implementation difficulty and impact on comfort level. Implementation difficulty favors solely utilization behavior STEECMs and impact on comfort level mainly favors technology replacement and renovation. Hence, different STEECMs contribute to acceptability, depending on which socio-behavioral parameter is favored. Both socio-behavioral aspects are slightly negatively correlated, which increases the difficulty to adopt measures.

STEECMs with the highest realistic STEECP lower the combined energy savings to a more realistic level of 23% of German final residential electricity- and natural gas use. A lot of technically favored theoretical STEECMs also exist in the favored realistic STEECMs list, but technology replacement and renovation have a much lower contribution to enhance availability and accessibility in a realistic situation compared to theoretical energy savings. Natural gas STEECMs end up higher than electricity STEECMs in the same ratio as German residential natural gas and electricity use are related.

Preferable STEECMs in a medium disruption scenario have a smaller combined STEECP (8-15%), but still much higher than conventional yearly EE improvement. There is little difference between very short, short and medium timescales, which implies that implementation and comfort constraints are too high to take bigger STEECMs to improve STES. Nevertheless, availability and accessibility are noticeably improved. None of these STEECMs are renovations or large technology replacements, so affordability is less impacted than conventional technical optimization. Favored STEECMs in a severe disruption scenario have a combined STEECP that is more than twice the size of a small disruption scenario. Energy savings could be realized between 15-37% of German final residential natural gas and electricity use.

An information and awareness campaign substantially improves the combined impact of the list of favored STEECMs compared to a conventional small disruption scenario with regard to availability and accessibility. This is mainly caused by the increased possibility to conduct more difficult technology replacement, which at the same time worsens affordability. The list of preferred STEECMs during a severe disruption scenario with an informational campaign is not changed compared to a conventional severe disruption scenario. Adding cost limitations decreases the combined theoretical STEECP of the list of favorable STEECMs to 16%, which is still a substantial impact on availability and accessibility.

Price signals alter preferable STEECMs a lot and drastically improve the payback period, which indicates that the affordability of STEECMs becomes more favorable. The combined macro-scale theoretical STEECP remains at a substantial level for both a small (11%) and a severe disruption (33) scenario, but lower than without the price signals. This is mainly caused by the higher importance of electricity STEECMs, which have higher energy costs savings per unit of energy saved. Nevertheless, affordability is positively impacted with regard to other severe disruption scenarios.

Financial support schemes improve affordability for households as well. The list of favored STEECMs have a combined macro-scale STEECP equal to a conventional severe disruption scenario, but with better payback periods.

Hence, STEECMs have substantial opportunities to contribute to STES with regard to availability, accessibility, affordability and acceptability. Depending on the favored dimension, timescale and severity of disruption, various lists of favored STEECMs impact energy use, energy related costs, implementation and comfort level. In most cases, policy interventions bring additional contributions to improve favorable STEECMs to enhance STES.

## 6.1. Recommendations

This study provides quite some openings for further research. Firstly, to get a better overview on a complete national STEECP in a situation with an STES risk, other sectors could be involved as well. Additional parameters to measure more in-depth technical, economic and socio-behavioral aspects differ per sector, so combinations have to be handled with care.

Secondly, one of the least understood aspects of this study is energy saving behavior and more specifically behavior during an STES issue. Dynamic development of adoption behavior has not been specifically included in this study. A possible approach to obtain more insights on dynamic STEECM adoption and interactions between households could be to apply an agent-based approach.  For example, Hicks et al. (2015) conducted an agent-based approach on residential lighting choices. Constraints, such as impact on comfort level are applicable to which STEECMs are preferred.

Thirdly, it could be interesting to have a further look into other crisis-related literature to see how individual and group behavior could be operationalized. For example, Walsh et al. (2015) describes opportunities to conduct quick changes in policies after the occurrence of an unusual event, such as a severe flood or a train accident.

Furthermore, it could be useful to add environmental parameters to describe acceptability in a more detailed way. For example, linking energy use to certain $CO_2$ emissions.

Constraints on stock levels and available technical personnel to conduct technology replacement and renovation is only limitedly included in this study. A more detailed data search could give valuable insights on how many technologies could be replaced and how many buildings could be renovated to obtain an improved adoption potential for these types of STEECMs.

Next to this, economic analysis could be extended by monetizing implementation time in the same way as other researchers have calculated the VoLL or directly comparing investment costs with the costs of a kWh not delivered. Leisure time or working time could be seen as a certain amount of money per hour. This could make results more comparable.

## Acknowledgements

I have consulted many experts on various energy efficiency and energy security topics to obtain more in-depth knowledge on the different segments of my research. At first, I would like to thank Ecofys to offer me the opportunity to write my thesis at their offices in Utrecht and Berlin. Then, I would like to thank my main supervisors Prof. Dr. Kornelis Blok, Dr. Ir. Machteld van den Broek, and Katja Dinges for their thorough guidance how to properly conceptualize and execute my research. Next to this, I would like to thank all the experts at Ecofys from various units that offered some of their precious time to assist me in my quest for short-term energy efficiency and conservation data and concepts. Furthermore, I would like to thank Dr. Barbara Schlomann and Tobias Fleiter of Fraunhofer ISI, Dr. Gregoire Wallenborn of Université Libre de Bruxelles, Sara Pasquier and Luis Munuera of the IEA, Ing. Andrea Trianni of Politecnico Milano, Gustavo Haydt of Empresa de Pesquisa Energética, Joris Berkhout of Quintel, Dr. Mithra Moezzi of Portland State University and Dr. Alan Meier of the University of California to share their expert views on various parts of my research.

## 7. References

A.I.S.E., 2013. *The case for the "A.I.S.E. low temperature washing" initiative*. Brussels: A.I.S.E.

Aman, M.M. et al., 2013. Analysis of the performance of domestic lighting lamps. *Energy Policy*, 52, pp.482–500. Available at: http://dx.doi.org/10.1016/j.enpol.2012.09.068.

Ang, B.W., Choong, W.L. & Ng, T.S., 2015. Energy security: Definitions, dimensions and indexes. *Renewable and Sustainable Energy Reviews*, 42, pp.1077–1093. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1364032114008892.

Ballarini, I., Corgnati, S.P. & Corrado, V., 2014. Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project. *Energy Policy*, 68, pp.273–284. Available at: http://dx.doi.org/10.1016/j.enpol.2014.01.027.

Barbu, A., Griffiths, N. & Morton, G., 2013. *Achieving energy efficiency through behaviour change: what does it take?*, Available at: http://www.engerati.com/sites/default/files/Day2-1440-AncaDianaBarbu-EUW2013.pdf.

BDH, 2015. *Efficient systems and renewable energies: Technology and Energy Panel*. Koln: Bundesindustrieverband Deutschland Haus-, Energie- und Umwelttechnik e.V.

Bettgenhäuser, K., 2013. *Integrated Assessment Modelling for Building Stock - A Technical, Economical and Ecological Analysis*. Darmstadt: Technische Universitat Darmstadt.

Bettgenhauser, K., Boermans, T., 2011. *Umweltwirkung von Heizungssystemen in Deutschland*. Cologne: Ecofys.

Bettgenhauser, K., de Vos, R., Grozinger, J., Boermans, T., 2014. *Deep renovation of buildings An effective way to decrease Europe's energy import dependency Deep renovation of buildings An effective way to decrease Europe's energy import dependency*. Cologne: Ecofys.

Blom, I., Itard, L. & Meijer, A., 2011. Environmental impact of building-related and user-related energy consumption in dwellings. *Building and Environment*, 46(8), pp.1657–1669. Available at: http://dx.doi.org/10.1016/j.buildenv.2011.02.002.

BMWi, 2014a. *Energiedaten: Gesamtausgabe*. Berlin: Bundesministerium fur Wirtschaft un Energie.

BMWi, 2013. *Report on the calculation of "cost-optimal levels of minimum energy performance requirements"*. Berlin: Bundesministerium fur Wirtschaft un Energie.

BMWi, 2014b. Zahlen und Fakten Energiedaten. Berlin: Bundesministerium fur Wirtschaft un Energie.

Boonekamp, P.G.M., 2006. Evaluation of methods used to determine realized energy savings. *Energy Policy*, 34, pp.3977–3992.

Braun, F.G., 2010. Determinants of households' space heating type: A discrete choice analysis for German households. *Energy Policy*, 38(10), pp.5493–5503. Available at: http://dx.doi.org/10.1016/j.enpol.2010.04.002.

Braungardt, S. et al., 2014. *Study evaluating the current energy efficiency policy framework in the EU and providing orientation on policy options for realising the cost-effective energy-efficiency / saving potential until 2020 and beyond Report on behalf of DG ENER*. Karlsruhe/Vienna/Rome: Fraunhofer ISI; PwC; TU Wien.

Brown, Z. & Cole, R.J., 2009. Influence of occupants' knowledge on comfort expectations and behaviour. *Building Research & Information*, 37(March 2015), pp.227–245.

Bürger, V., 2009. *Identification, Quantification and Systematization of technical and behavioral potentials for saving electricity in household consuption ( Identifikation, Quantifizierung und Systematisierung technischer und verhaltensbedingter Stromeinsparpotenziale priv*. Freiburg; Oko Institut e.V.

Bürger, V., 2010. Quantification and Systematisation of the Technical and Behaviour Related Electricity Savings Potential in German Households. *Zeitschrift für Energiewirtschaft*, 34(1), pp.47–59.

Cagno, E. & Trianni, A., 2014. Evaluating the barriers to specific industrial energy efficiency measures: An exploratory study in small and medium-sized enterprises. *Journal of Cleaner Production*, 82, pp.70–83. Available at: http://dx.doi.org/10.1016/j.jclepro.2014.06.057.

Chai, K.H. & Yeo, C., 2012. Overcoming energy efficiency barriers through systems approach-A conceptual framework. *Energy Policy*, 46, pp.460–472. Available at: http://dx.doi.org/10.1016/j.enpol.2012.04.012.

Croucher, M., 2011. Potential problems and limitations of energy conservation and energy efficiency. *Energy Policy*, 39(10), pp.5795–5799. Available at: http://dx.doi.org/10.1016/j.enpol.2011.07.011.

Delmas, M. a., Fischlein, M. & Asensio, O.I., 2013. Information strategies and energy conservation behavior: A meta-analysis of experimental studies from 1975 to 2012. *Energy Policy*, 61, pp.729–739. Available at: http://dx.doi.org/10.1016/j.enpol.2013.05.109.

Dena, 2010. dena-Netzstudie II – Zusammenfassung. *Vgb Powertech*, pp.1–28. Berlin: Deustche Energie-Agentur GmbH.

Destatis, 2014. Wirtschaftsrechnungen. Ausstattung privater Haushalte mit ausgewählten Gebrauchsgütern. Wiesbaden: Statischischer Bundesamt. Available at: https://www.destatis.de/DE/Publikationen/Thematisch/EinkommenKonsumLebensbedingungen/EinkommenVerbrauch/EVS_AusstattungprivaterHaushalte2152601139004.pdf?__blob=publicationFile.

Destatis, 2013. *Wohnverhältnisse privater Haushalte, Fachserie 15 Sonderheft 1 - 2013*. Wiesbaden: Statistischer Bundesamt.

DoE, 2013. *Energy Assurance and Emergency Operations Plan*. Las Vegas: US Department of Energy.

EconomyWatch, 2015. GDP Deflator Data for All Countries [Online]. Available at: http://www.economywatch.com/economic-statistics/economic-indicators/GDP_Deflator/ [Accessed April 22, 2015].

Eichhammer, W., Fleiter, T., Schlomann, B., Faberi, S., Fioretto, M., Piccioni, N., Lechtenbohmer, S., Schuring, A., Resch, G., 2009. *Study on the Energy Savings Potentials in EU Member States, Candidate Countries and EEA Countries Final Report for the European Commission Directorate-General Energy and Transport*. Karlsruhe: Fraunhofer ISI. Available at: http://ec.europa.eu/energy/efficiency/studies/efficiency_en.htm.

Ek, K. & Söderholm, P., 2010. The devil is in the details: Household electricity saving behavior and the role of information. *Energy Policy*, 38(3), pp.1578–1587.

Elsland, R., Eichhammer, W. & Schlomann, B., 2013. *Is enough electricity being saved ? Impact of energy efficiency policies addressing electrical household appliances in Germany until 2030*. Karlsruhe: Fraunhofer ISI. Available at: http://proceedings.eceee.org/papers/proceedings2013/6-069-13_Elsland.pdf?returnurl=http://proceedings.eceee.org/visabstrakt.php?event=3&doc=6-069-13.

Enerdata, 2015. ODYSSEE database [Online]. Available at: http://www.indicators.odyssee-mure.eu/energy-efficiency-database.html.

Enerdata, Fraunhofer ISIS; Science Centre North Rhine-Westphalia; Wuppertal Institute for Climate, E. and E.E.E.G., Energy Efficiency Potentials in Europe [Online]. Available at: http://www.eepotential.eu/esd.php.

ESMAP, 2010. *Central America Regional Programmatic Study For The Energy Sector: Managing An Electricity Shortfall*. Washington DC: Energy Sector Management Assistance Program.

European Commission, 2014a. *Communication from the commission to the European Parliament and the Council - European Energy Security Strategy*. Brussels: European Commission.

European Commission, 2014b. *Energy Efficiency and its contribution to energy security and the 2030 Framework for climate and energy policy*. Brussels: European Commission.

European Commission, 2013. *Member States' Energy Dependence: An Indicator-Based Assessment*. Brussels: European Commission. Available at: http://ec.europa.eu/economy_finance/publications/occasional_paper/2013/pdf/ocp145_en.pdf.

Fleiter, T., Hirzel, S. & Worrell, E., 2012. The characteristics of energy-efficiency measures - a neglected dimension. *Energy Policy*, 51, pp.502–513. Available at: http://dx.doi.org/10.1016/j.enpol.2012.08.054.

Fleiter, T., Worrell, E. & Eichhammer, W., 2011. Barriers to energy efficiency in industrial bottom-up energy demand models - A review. *Renewable and Sustainable Energy Reviews*, 15(6), pp.3099–3111. Available at: http://dx.doi.org/10.1016/j.rser.2011.03.025.

Fraunhofer, Technical University Munich, GfK, I., 2014. *Energieverbrauch des Sektors Gewerbe, Handel, Dienstleistungen (GHD) in Deutschland für die Jahre 2011 bis 2013*. Karlsruhe: Fraunhofer ISI.

Fraunhofer-ISE, 2014. *IEA HPP Annex 42 : Heat Pumps in Smart Grids Task 1 (i): Market Overview*. Freiburg: Fraunhofer ISE.

Gillingham, K., Harding, M. & Rapson, D., 2012. Split incentives in residential energy consumption. *Energy Journal*, 33(2), pp.37–62.

Gillingham, K., Newell, R.G., Palmer, K., 2009. *Energy Efficiency Economics and Policy*. Washington DC: Resources of the Future.

Giraudet, L.-G., Guivarch, C. & Quirion, P., 2012. Exploring the potential for energy conservation in French households through hybrid modeling. *Energy Economics*, 34(2), pp.426–445. Available at: http://dx.doi.org/10.1016/j.eneco.2011.07.010.

Gottwalt, S. et al., 2011. Demand side management-A simulation of household behavior under variable prices. *Energy Policy*, 39(12), pp.8163–8174. Available at: http://dx.doi.org/10.1016/j.enpol.2011.10.016.

Gracceva, F. & Zeniewski, P., 2014. A systemic approach to assessing energy security in a low-carbon EU energy system. *Applied Energy*, 123, pp.335–348. Available at: http://dx.doi.org/10.1016/j.apenergy.2013.12.018.

Greller, M. et al., 2010. Universelle Energiekennzahlen für Deutschland - Teil 2: Verbrauchskennzahlentwicklung nach Baualtersklassen. *Bauphysik*, 32(1), pp.1–6. Available at: http://doi.wiley.com/10.1002/bapi.201010001.

De Groote, W., 2005. *Potential of short-term energy efficiency and energy saving measures in Belgium*. Brussels: E-ster.

Growitsch, C. et al., 2014. The Costs of Power Interruptions in Germany: A Regional and Sectoral Analysis. *German Economic Review*, pp.1–17.

Grunspar, 2015. EcoSavers Duschkopf [Online]. Available at: http://www.gruenspar.de/ecosavers-showerhead.html [Accessed May 23, 2015].

Harvard, 2007. *A Summary of Error Propagation*. Cambridge MA: Harvard University.

Haydt, G., Leal, V. & Dias, L., 2013. Uncovering the multiple objectives behind national energy efficiency planning. *Energy Policy*, 54, pp.230–239.

Haydt, G.B., 2011. *A multi-objective decision support methodology for developing national energy efficiency plans*. Porto: University of Porto.

HEA, 2013. *Energietipps*. Berlin: Fachgemeinschaft fur effiziente Energieanwendung.

Heatex, Central heating systems installations/Boiler replacement [Online]. Available at: http://www.heatexgroup.co.uk/index.php?option=com_content&view=article&id=51&Itemid=55 [Accessed June 30, 2015].

Hicks, A.L., Theis, T.L. & Zellner, M.L., 2015. Emergent Effects of Residential Lighting Choices: Prospects for Energy Savings. *Journal of Industrial Ecology*, 00(0), p.n/a–n/a. Available at: http://doi.wiley.com/10.1111/jiec.12281.

Hitchcock, G., 1993. An integrated framework for energy use and behaviour in the domestic sector. *Energy and Buildings*, 20(2), pp.151–157.

HMWEVL, 2015. *Strom effizient nutzen*. Hessen: Hessisches Ministerium fur Wirstchaft, Energie, Verkehr und Landesentwicklung.

IEA, 2014. *Energy Efficiency Indicators : Fundamentals on Statistics*. Paris: International Energy Agency. Available at: http://www.iea.org/termsandconditionsuseandcopyright/.

IEA, 2007. *Energy Security and Climate Policy Assessing Interactions*. Paris: International Energy Agency. Available at: http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=1883.

IEA, 2013. *Germany overview*. Paris: International Energy Agency.

IEA, 2005a. *Saving Electricity in a Hurry: Dealing with Temporary Shortfalls in Electricity Supplies*. Paris: International Energy Agency. Available at: http://www.iea.org/textbase/nppdf/free/2005/savingElec.pdf.

IEA, 2005b. *Saving Oil in a Hurry*. Paris: International Energy Agency.

IEA, 2011. *The IEA Model of Short-term Energy Security (MOSES) - Primary Energy Sources and Secondary Fuels*. Paris: International Energy Agency.

Janda, K.B. & Moezzi, M., 2013. Broadening the Energy Savings Potential of People: From Technology and Behavior to Citizen Science and Social Potential. , ACEE Summer Study on Energy Efficiency in Buildings 2013(1), pp.3–8.

Jewell, J., Cherp, A. & Riahi, K., 2014. Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices. *Energy Policy*, 65, pp.743–760. Available at: http://dx.doi.org/10.1016/j.enpol.2013.10.051.

Kanellakis, M., Martinopoulos, G. & Zachariadis, T., 2013. European energy policy-A review. *Energy Policy*, 62, pp.1020–1030. Available at: http://dx.doi.org/10.1016/j.enpol.2013.08.008.

Kavgic, M. et al., 2010. A review of bottom-up building stock models for energy consumption in the residential sector. *Building and Environment*, 45(7), pp.1683–1697. Available at: http://dx.doi.org/10.1016/j.buildenv.2010.01.021.

Kemma, R. et al., 2007. *Eco-design of Boilers - Task 3 - Consumer Behaviour & Local infrastructure*. Delft: Van Holsteijn en Kemna BV.

Kemna, R., 2014a. *Average EU building heat load for HVAC equipment*. Delft: Van Holsteijn en Kemna BV.

Kemna, R., 2014b. *Ecodesign Impact Accounting - Part 1 - Status Nov. 2013*. Delft: Van Holsteijn en Kemna BV.

Kemna, R. et al., 2007. *Eco-design of water heaters*. Delft: Van Holsteijn en Kemna BV. Available at: http://mands.ucoz.kz/_ld/0/61_002_WHeater_stu.pdf.

Kockat, J. & Rohde, C., 2012. *The challenges , dynamics and activities in the building sector and its energy demand in Germany - D2.1 of WP2 from Entranze Project*. ENTRANZE Project.

Koopmans, C.C. & Te Velde, D.W., 2001. Bridging the energy efficiency gap: Using bottom-up information in a top-down energy demand model. *Energy Economics*, 23, pp.57–75.

Kruyt, B. et al., 2009. Indicators for energy security. *Energy Policy*, 37, pp.2166–2181.

Leighty, W. & Meier, A., 2011. Accelerated electricity conservation in Juneau, Alaska: A study of household activities that reduced demand 25%. *Energy Policy*, 39(5), pp.2299–2309. Available at: http://dx.doi.org/10.1016/j.enpol.2011.01.041.

Leiserowitz, A. et al., 2008. Saving Energy at Home and on the Road: A Survey of Americans' Energy Saving Behaviors, Intentions, Motivations, and Barriers. *Change*, (703), pp.1–47. Available at: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Saving+energy+at+home+and+on+the+road:+A+survey+of+Americans'+energy+saving+behaviors,+intentions,+motivations,+and+barriers#0.

Van Lidth de Jeude, M., Noach, C., 2014. *Energiebesparing: De relatie tussen verbruiks- gedrag en investeren Energiebesparing*. Utrecht: Ecofys.

Loga, T., Stein, B., Diefenbach, N., Born, R., 2015. *Deutsche Wohngebäudetypologie zur Verbesserung der Energieeffizienz von typischen Wohngebauden*. Darmstadt: Insitut Wohnen und Umwelt.

Longoria, S., Voreyer, D., Pucci, D., Cruz, R., Khan, M., Williams, G., 2014. *State of California Energy Assurance Plan*. Vacaville: Aanko Technologies Inc.

Marbek Resource Consultants, 2007. *BC Hydro 2007 Conservation Potential Review: The Potential for Electricity Savings through Technology Adoption , 2006 – 2026 Residential Sector in British Columbia*. Vancouver: Marbek Resource Consultants and Ghoulem Research.

Mata, É., Sasic Kalagasidis, A. & Johnsson, F., 2013. Energy usage and technical potential for energy saving measures in the Swedish residential building stock. *Energy Policy*, 55, pp.404–414.

Moezzi, M. et al., 2009. *Behavioral Assumptions in Energy Efficiency Potential Studies*. Oakland: California Institute for Energy and Environment.

Moezzi, M. & Janda, K.B., 2014. From "if only" to "social potential" in schemes to reduce building energy use. *Energy Research and Social Science*, 1, pp.30–40. Available at: http://dx.doi.org/10.1016/j.erss.2014.03.014.

Narula, K. & Reddy, B.S., 2015. Three blind men and an elephant: The case of energy indices to measure energy security and energy sustainability. *Energy*, 80, pp.148–158. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360544214013103.

De Nooij, M., Koopmans, C. & Bijvoet, C., 2007. The value of supply security. The costs of power interruptions: Economic input for damage reduction and investment in networks. *Energy Economics*, 29(2), pp.277–295.

De Nooij, M., Lieshout, R. & Koopmans, C., 2009. Optimal blackouts: Empirical results on reducing the social cost of electricity outages through efficient regional rationing. *Energy Economics*, 31(3), pp.342–347. Available at: http://dx.doi.org/10.1016/j.eneco.2008.11.004.

NREL, 2013. NREL National Residential Efficiency Measures Database Home Page [Online]. Available at: http://www.nrel.gov/ap/retrofits/ [Accessed February 25, 2015].

ODYSSEE-MURE, 2013. *Energy Efficiency Trends in the EU: Lessons from the Odyssee-Mure Project*. Grenoble: Enerdata.

OECD, 2014. Average annual hours actually worked per worker [Online]. Available at: http://stats.oecd.org/Index.aspx?DatasetCode=ANHRS [Accessed June 30, 2015].

Osterhage, T. et al., 2015. Ergebnisse einer energetischen Sanierung: Abweichung zwischen Energiebedarf und Verbrauch - ist nur der Nutzer Schuld? *Bauphysik*, 37(2), pp.100–104. Available at: http://doi.wiley.com/10.1002/bapi.201510012.

Palmer, J., Terry, N., Pope, P., 2012. *How Much Energy Could be Saved by Making Small Changes to Everyday Household Behaviours?* Cambridge: Cambridge Architectural Research.

Pasqiuer, S.B., 2011. *Saving Electricity in a Hurry - Update 2011*. Paris: International Energy Agency.

Pehnt, D.M. et al., 2009. *Klimaschutz, Energieeffizienz und Beschäftigung Potenziale und volkswirtschaftliche Effekte einer ambitionierten Energieeffizienzstrategie für Deutschland*. Berlin: Ifeu; Fraunhofer ISI; GWS; Prognos.

Petermann, T. et al., 2011. *Was bei einem Blackout geschieht - Folgen eines langandauernden und großräumigen Stromausfalls*. Berlin: Edition sigma.

Petersdorff, C., Dinges, K., Bosquet, M., Offermann, M., 2014. *Energieabhängigkeit von Russland durch Energie- effizienz reduzieren Kurzstudie Energieabhängigkeit von Russland durch Energieeffizienz reduzieren - Kurzstudie*. Cologne: Ecofys.

Praktiknjo, A.J., Hähnel, A. & Erdmann, G., 2011. Assessing energy supply security: Outage costs in private households. *Energy Policy*, 39(12), pp.7825–7833.

Quintel, 2015. Energy Transition Model - Your free, independent, comprehensive, fact-based scenario builder [Online]. Available at: http://www.energytransitionmodel.com/ [Accessed March 18, 2015].

Rüdenauer, I. & Gensch, C., 2007. *Environmental and economic evaluation of the accelerated replacement of domestic appliances*. Freiburg: Oko Institut e.V.

RWI, F., 2013. *Erhebung des Energieverbrauchs der privaten Haushalte für die Jahre 2009-2010*. Essen: heinisch-Westfalisches Institut fur Wirtschafstsforschung. Available at: http://www.bmwi.de/Dateien/BMWi/PDF/bericht-erhebung-des-energieverbrauchs-private-haushalte-2006-2008,property=pdf,bereich=bmwi,sprache=de,rwb=true.pdf.

Schleicher, T., 2011. *Effizienz-Ranking „ Stromsparen in Haushalten "*. Berlin: Oko Institut e.V.

Schlomann, B., 2014. *Design of Effective Energy Efficiency Policies*. Utrecht: Utrecht University.

Schlomann, B., Geiger, B., Gruber, E., Kleeberger, E., 2014. *Energieverbrauch des Sektors Gewerbe, Handel, Dienstleistungen (GHD) in Deutschland für die Jahre 2007 bis 2010*. Karlsruhe: Fraunhofer ISI.

Schlomann, B., Reuter, M., Lapillonne, B., Pollier, K., Rosenow, J., 2014. *Monitoring the "Energiewende" - Energy efficiency indicators for Germany*. Karlsruhe: Fraunhofer ISI.

Schmid, K.D. & Stein, U., 2013. *Explaining Rising Income Inequality in Germany, 1991-2010*. Dusseldorf: Macroeconomic Policy Institute.

ServiceMagic.co.uk, A guide to boiler replacement [Online]. Available at: http://www.servicemagic.co.uk/files/2012/01/boiler-replacement-servicemagic.co_.uk_.jpg [Accessed June 30, 2015].

Simcock, N. et al., 2014. Factors influencing perceptions of domestic energy information: Content, source and process. *Energy Policy*, 65, pp.455–464.

Sorrell, S. et al., 2000. *Barriers to Energy Efficiency in Public and Private Organisations*. Sussex: SPRU.

Sovacool, B.K. & Saunders, H., 2014. Competing policy packages and the complexity of energy security. *Energy*, 67, pp.641–651. Available at: http://dx.doi.org/10.1016/j.energy.2014.01.039.

Statista, 2015. Ahnzahl der elektro- und informationstechnischen Handwerksbetriebe in Deutschland von 2011 bis 2014 [Online]. Available at: http://stats.oecd.org/index.aspx?DataSetCode=ANHRS [Accessed June 30, 2015].

Stieß, I. & Dunkelberg, E., 2013. Objectives, barriers and occasions for energy efficient refurbishment by private homeowners. *Journal of Cleaner Production*, 48, pp.250–259. Available at: http://dx.doi.org/10.1016/j.jclepro.2012.09.041.

Suljug, A., Hillenstedt, A., 2007. *Preparatory Studies for Eco-design Requirements of EuPs - Lot 13: Refrigerators & Freezers*. Bonn: University of Bonn.

Swan, L.G. & Ugursal, V.I., 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews*, 13, pp.1819–1835.

Thøgersen, J. & Grønhøj, A., 2010. Electricity saving in households-A social cognitive approach. *Energy Policy*, 38(12), pp.7732–7743. Available at: http://dx.doi.org/10.1016/j.enpol.2010.08.025.

Thomas, D.S. & Schüle, D.R., 2009. *Measuring and reporting energy savings for the Energy Services Directive how it can be done*. Wuppertal: Wuppertal Institut fur Umwelt, Klima und Energie Available at: www.evaluate-energy-savings.eu.

Topten.eu, 2015. Topten refrigerator efficiency [Online]. Available at: http://www.topten.eu/english/household/refrigerator_inbuilt/without_freezer.html [Accessed May 29, 2015].

Trianni, a. & Cagno, E., 2012. Dealing with barriers to energy efficiency and SMEs: Some empirical evidences. *Energy*, 37(1), pp.494–504. Available at: http://dx.doi.org/10.1016/j.energy.2011.11.005.

Trianni, A., Cagno, E. & De Donatis, A., 2014. A framework to characterize energy efficiency measures. *Applied Energy*, 118, pp.207–220. Available at: http://dx.doi.org/10.1016/j.apenergy.2013.12.042.

UBA, 2012. *Energieeffizienzdaten für den Klimaschutz*. Frankfurt Am Main: Umwelt Bundesamt.

Ürge-Vorsatz, D. et al., 2009. Bottom-up assessment of potentials and costs of CO2 emission mitigation in the buildings sector: Insights into the missing elements. *Energy Efficiency*, 2, pp.293–316.

VHK, 2015. Copy of Model for European Light Sources Analysis (MELISA). Delft: Van Holsteijn en Kemna B.V.

VHK, Vito, Viegand-Maagoe, Wuppertal Institut fur Klima, Umwelt, E., 2014. *Cold Appliances , Washing Machines , Dishwashers , Washer-Driers , Lighting , Set-top Boxes and Pumps: Final report*. Delft/Brussel: Van Holsteijn en Kemna B.V.

Vidmar, K., 2010. Importance of Finding and Defining Energy Conservation Measures. *Strategic Planning for Energy and the Environment*, 30(February 2015), pp.45–63.

Wada, K. et al., 2012. Energy efficiency opportunities in the residential sector and their feasibility. *Energy*, 48(1), pp.5–10. Available at: http://dx.doi.org/10.1016/j.energy.2012.01.046.

Wallenborn, G., 2014. The tragedy of energy efficiency. An interdisciplinary analysis of rebound effects. , pp.133–144. Brussels: Universite Libre de Bruxelles.

Wallenborn, G. & Wilhite, H., 2014. Rethinking embodied knowledge and household consumption. *Energy Research & Social Science*, 1, pp.56–64.

Walsh, C.L. et al., 2015. Are wildcard events on infrastructure systems opportunities for transformational change? *Futures*, 67, pp.1–10. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0016328715000063.

Wolf, A. & Wenzel, L., 2014. Regional diversity in the costs of electricity outages: Results for German counties. *Utilities Policy*, pp.1–11. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0957178714000733.

Yohanis, Y.G., 2012. Domestic energy use and householders' energy behaviour. *Energy Policy*, 41, pp.654–665. Available at: http://dx.doi.org/10.1016/j.enpol.2011.11.028.

# Appendix A: List of STEECMs

More detailed data on preferred STEECMs with small disruption and various timescales.

*Table 36 List of STEECMs applied in the ex-ante hybrid bottom-up STEECM model.*

| Measure | End-use category | Source |
|---|---|---|
| Replacement of non-condensing gas boilers for new gas boilers SFH | Space Heating | BDH, 2015 |
| Replacement of non-condensing gas boilers for new gas boilers MFH | Space Heating | Loga et al, 2015 |
| Insulation for radiators and pipes SFH | Space Heating | Palmer et al., 2012 |
| Renovate MFH gas | Space Heating | BDH, 2013 |
| Renovate SFH, gas | Space Heating | BDH, 2015 |
| Put heating circulating pumps at from 80W to 35W | Space Heating | Schleicher, 2011 |
| Reduce heating circulating pump to 10h use | Space Heating | Schleicher, 2011 |
| Lower thermostat 1 °C | Space Heating | IEA, 2005 |
| Turn off heating in unused rooms | Space Heating | Palmer et al., 2012 |
| Close bedroom window at night | Space Heating | Palmer et al., 2012 |
| Delay start of heating season to November | Space Heating | Palmer et al., 2012 |
| Usage of timeswitch for electric heating | Domestic Hot Water | Schleicher, 2011 |
| Use dishwasher only when full | Domestic Hot Water | Palmer et al., 2012 |
| Aerated Showerheads electric heating | Domestic Hot Water | IEA, 2005 |
| Aerated Showerheads gas heating | Domestic Hot Water | IEA, 2005 |
| Shower for 5 minutes instead of 7 minutes | Domestic Hot Water | IEA, 2005 |
| Repair leaks in hot water system | Domestic Hot Water | Palmer et al., 2012 |
| Replace freezers for A+++ model | Refrigeration and freezing | Topten.eu., 2013 |
| Replace all refrigerators for most efficient | Refrigeration and freezing | VHK, 2014 |
| Adjust temperature of refrigerator 5 to 7-7,5 °C | Refrigeration and freezing | Suljug and Hillenstedt, 2007 |
| Reduce kitchen temperature 1 °C | Refrigeration and freezing | Suljug and Hillenstedt, 2007 |
| Reduce kitchen temperature From 25 to 19 °C | Refrigeration and freezing | Suljug and Hillenstedt, 2007 |
| Unplug freezer / second refrigerator | Refrigeration and freezing | IEA, 2005 |
| Only essential items in refrigerator | Refrigeration and freezing | Own |
| Reduce door opening by 50% | Refrigeration and freezing | Suljug and Hillenstedt, 2007 |
| Remove ice | Refrigeration and freezing | Palmer et al., 2012 |
| Replacement HL with LED | Lighting | Own |
| Replacement GLS with LED | Lighting | Own |
| Replace HL with CFL | Lighting | Haydt, 2011 |
| Replace GLS with CFL | Lighting | Haydt, 2011 |

| | | |
|---|---|---|
| Replace 11 most used lamps | Lighting | Schleicher, 2011 |
| Switch off unneeded light | Lighting | IEA, 2005 |
| Install light sensors | Lighting | Palmer et al., 2012 |
| Change washing temp from 40 °C to 30 °C | Washing & Drying | A.I.S.E. 2013 |
| Reduce hot washes to 40 °C | Washing & Drying | VHK, 2014 |
| Use switches to prevent standby usage | Washing & Drying | VHK, 2014 |
| Reduce the amount of washing cycles with 50% | Washing & Drying | VHK, 2014 |
| Only use full washing machine | Washing & Drying | A.I.S.E. 2013 |
| Air dry instead of tumble dryer | Washing & Drying | Palmer et al., 2012 |
| Reduce stand-by usage | General | Schleicher, 2011 |

# Appendix B: Detailed overview on technical favorable micro-scale STEECMs

*Table 37 Favorable STEECMs with regard to micro-scale general energy savings.*

| Highest energy savings general per household without renovation (micro-scale) | Energy use frozen | Energy use new | Energy saved | Relative energy saved |
|---|---|---|---|---|
| Measure | kWh/hh/y | kWh/hh/y | kWh/hh/year | % |
| Replacement of non-condensing gas boilers for new gas boilers SFH | 23277 | 16682 | 6595 | 28% |
| Replacement of non-condensing gas boilers for new gas boilers MFH | 9180 | 5349 | 3831 | 42% |
| Lower thermostat 1 C | 12462 | 10842 | 1620 | 13% |
| Insulation for radiators and pipes SFH | 12462 | 11106 | 1356 | 11% |
| Delay start of heating season to November | 12462 | 11793 | 669 | 5% |
| Aerated Showerheads electric heating | 1134 | 510 | 623 | 55% |
| Turn off heating in unused rooms | 12462 | 11901 | 561 | 5% |
| Close bedroom window at night | 12462 | 12043 | 419 | 3% |
| Replace 11 most used lamps | 596 | 215 | 381 | 64% |
| Reduce stand-by usage | 498 | 124 | 374 | 75% |

*Table 38 Favorable STEECMs with regard to micro-scale natural gas energy savings.*

| Highest energy savings natural gas per household without renovation (micro-scale) | Energy use frozen | Energy use new | Energy saved | Relative energy saved |
|---|---|---|---|---|
| Measure | kWh/hh/y | kWh/hh/y | kWh/hh/year | % |
| Replacement of non-condensing gas boilers for new gas boilers SFH | 23277 | 16682 | 6595 | 53% |
| Replacement of non-condensing gas boilers for new gas boilers MFH | 9180 | 5349 | 3831 | 31% |
| Lower thermostat 1 C | 12462 | 10842 | 1620 | 13% |
| Insulation for radiators and pipes SFH | 12462 | 11106 | 1356 | 11% |
| Delay start of heating season to November | 12462 | 11793 | 669 | 5% |
| Turn off heating in unused rooms | 12462 | 11901 | 561 | 5% |
| Close bedroom window at night | 12462 | 12043 | 419 | 3% |
| Aerated Showerheads gas heating | 690 | 345 | 345 | 13% |
| Shower for 5 minutes instead of 7 minutes | 690 | 556 | 134 | 5% |
| Repair leaks in hot water system | 2645 | 2518 | 127 | 5% |

*Table 39 Favorable STEECMs with regard to micro-scale electricity energy savings.*

| Highest energy savings electricity per household without renovation (micro-scale) | Energy use frozen | Energy use new | Energy saved | Energy saved per end-use |
|---|---|---|---|---|
| Measure | kWh/hh/y | kWh/hh/y | kWh/hh/year | % |
| Aerated Showerheads electric heating | 1134 | 510 | 623 | 24% |
| Replace 11 most used lamps | 596 | 215 | 381 | 64% |
| Reduce stand-by usage | 498 | 124 | 374 | 75% |
| Replace HL with CFL | 363 | 79 | 284 | 48% |
| Air dry instead of tumble dryer | 232 | 0 | 232 | 100% |
| Replace freezers for A+++ model | 343 | 141 | 202 | 59% |
| Replace all refrigerators for most efficient | 291 | 156 | 135 | 52% |
| Switch off unneeded light | 596 | 477 | 119 | 20% |
| Install light sensors | 596 | 480 | 116 | 19% |
| Reduce the amount of washing cycles with 50% | 174 | 87 | 87 | 50% |

# Appendix C: Detailed overview on the economically favorable micro-scale STEECMs

*Table 40 Favorable STEECMs with regard to micro-scale natural gas energy costs savings.*

| STEECMs with highest energy costs savings potential per hh without renovation (micro-scale) (natural gas) | Investment costs | Energy costs frozen | Energy costs new | Energy costs saved |
|---|---|---|---|---|
| | EUR(2013)/hh | EUR(2013/hh/y | EUR(2013/hh/y | EUR(2013/hh/y |
| Replacement of non-condensing gas boilers for new gas boilers SFH | 8710 | 2357 | 1689 | 668 |
| Replacement of non-condensing gas boilers for new gas boilers MFH | 3094 | 930 | 542 | 388 |
| Lower thermostat 1 C | 0 | 1338 | 1164 | 174 |
| Aerated Showerheads gas heating | 38 | 328 | 164 | 164 |
| Insulation for radiators and pipes SFH | 485 | 1262 | 1124 | 137 |
| Delay start of heating season to November | 0 | 1338 | 1266 | 72 |
| Turn off heating in unused rooms | 0 | 1338 | 1277 | 60 |
| Close bedroom window at night | 0 | 1338 | 1293 | 45 |
| Shower for 5 minutes instead of 7 minutes | 0 | 115 | 93 | 22 |
| Repair leaks in hot water system | 0 | 443 | 421 | 21 |

*Table 41 Favorable STEECMs with regard to micro-scale electricity energy costs savings.*

| STEECMs with highest energy costs savings potential per hh without renovation (micro-scale) (electricity) | Investment costs | Energy costs frozen | Energy costs new | Energy costs saved |
|---|---|---|---|---|
| | EUR(2013)/hh | EUR(2013/hh/y | EUR(2013/hh/y | EUR(2013/hh/y |
| Aerated Showerheads electric heating | 38 | 539 | 243 | 297 |
| Replace 11 most used lamps | 89 | 284 | 102 | 182 |
| Reduce stand-by usage | 19 | 245 | 67 | 178 |
| Replace HL with CFL | 66 | 173 | 38 | 135 |
| Air dry instead of tumble dryer | 0 | 110 | 0 | 110 |
| Replace inefficient freezers for A+++ model | 619 | 163 | 67 | 96 |
| Replace inefficient refrigerators for most efficient | 743 | 139 | 74 | 64 |
| Switch off unneeded light | 0 | 284 | 227 | 57 |
| Install light sensors | 280 | 284 | 228 | 55 |
| Reduce the amount of washing cycles with 50% | 0 | 87 | 43 | 43 |