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**Wiese, Catharina**

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# Economic Incentives and Policy Design for Energy Efficiency and Savings

Catharina Wiese

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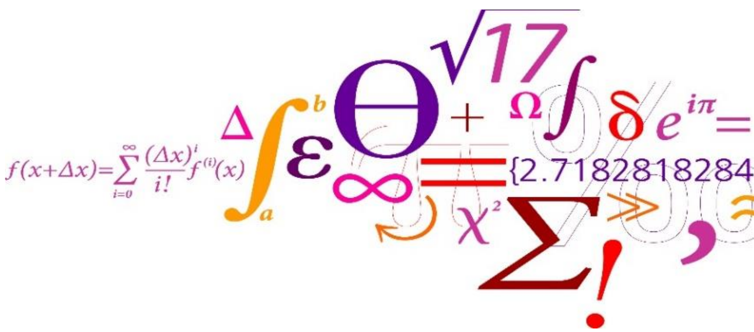

# Economic Incentives and Policy Design for Energy Efficiency and Savings

A dissertation submitted to

Technical University of Denmark
Department of Technology, Management and Economics

presented by

CATHARINA WIESE

Supervisor: Assoc. Prof. Lise-Lotte Pade

Co-supervisor: Prof. Henrik Klinge Jacobsen

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# Contents

# Summary

Energy efficiency improvements and the resulting energy savings can help to reduce final energy demand. Energy demand reductions are needed to facilitate the transition to energy systems with net-zero $CO_2$ emissions and to achieve the global climate targets set in the Paris Agreement from 2015. Various barriers, however, inhibit energy efficiency improvements and explain the existence of untapped energy efficiency potential. Realising this potential would be beneficial for energy end-users and society as a whole.

This thesis focuses on how progress in energy efficiency policy can lead to an increase in energy efficiency improvements and energy savings at the end-use level. We specifically consider potential progress in the design and implementation of policy instruments that aim at increasing the adoption of energy efficiency measures in the residential sector.

We analyse the determinants of households' investments in energy efficiency measures and the practicality to design policies that target individual households based on the observable household characteristics income, age of the household head, education, household size and the home ownership status. Directly targeting households that fail to adopt energy efficiency measures would be more effective and efficient than broadly targeting all households. We find that only some of the analysed household characteristics have a significant effect on households' investments in energy efficiency measures and the magnitude of effects is generally small. Income and home ownership status show the clearest trends in explaining households' investment decisions.

In a Danish energy-economy model, we simulate the effect of energy efficiency policies on households' investment and energy demand behaviour. The simulation of household behaviour is required in ex-ante evaluations of energy efficiency policy instruments. We demonstrate a comprehensive methodology for ex-ante evaluations of energy efficiency policies with a focus on the modelling of end-user behaviour where we specifically simulate households' investment decision for energy efficiency retrofits in Denmark. The model results suggest that if Denmark aims at achieving substantial energy savings in residential heating, it would likely require a broad mix of policy instruments, which address various barriers that keep households from investing in energy efficiency retrofits.

With respect to energy efficiency policy mixes, we review the potential existence of interaction effects between instrument combinations, which can be mitigating and reinforcing. We find that the steering mechanism of a policy instrument, the scope and the timing of implementation determine the interaction outcome. These factors could be taken into account when designing and implementing combinations of policy instruments for energy efficiency improvements in order to avoid mitigating effects and optimise reinforcing effects.

Furthermore, we assess the potential for Member States of the European Union to use their revenues from the auctioning of allowances in the European Emissions Trading System (EU ETS) to finance national energy efficiency policies, e.g. in the residential sector. Due to recent changes to the EU ETS framework, auctioning revenues are an increasing income stream for Member States. Strategically investing these revenues in energy efficiency policies could lead to various benefits such as additional and cost-effective reductions in greenhouse gas emissions and support for the political process to further tighten the cap-and-trade scheme in the future.

The diverse research methods and research contributions of this thesis may provide relevant insights for energy efficiency policy-makers on how to increase the adoption of energy efficiency measures in the residential sector. It may thereby shed some light on the questions on how to support the transition of energy systems and to mitigate climate change.

# Dansk sammenfatning

Energieffektiviseringer og de resulterende energibesparelser bidrager til at reducere det endelige energiforbrug. For at lykkes med overgangen til energisystemer med nettonuludledninger af $CO_2$ og for at nå de globale klimamål, der er fastsat i Paris-aftalen fra 2015, skal energiforbruget reduceres. Der findes dog fortsat forskellige barrierer, som hæmmer energieffektiviseringer og forhindrer udnyttelsen af hele potentialet for energieffektiviseringer. At realisere dette potentiale vil være gavnligt for slutbrugere og samfundet som helhed.

Denne afhandling fokuserer på, hvordan forbedringer i energieffektivitetspolitik kan føre til en stigning i energieffektiviseringer og energibesparelser på slutbruger-niveau. Vi arbejder specifikt med mulige forbedringer i udformningen og implementeringen af politiske instrumenter, der er rettet mod at øge energieffektivitetsforanstaltninger i husholdningssektoren.

Vi analyserer de faktorer der driver husholdningernes investeringer i energieffektivitetsforanstaltninger og muligheden for at udforme politiske instrumenter, der er rettet mod individuelle husstande baseret på de observerbare husstandskarakteristika indkomst, alder af husstandens hoved, uddannelsesniveau og hjem ejerskab status. At målrette politiske instrumenter mod husholdninger, der ikke investerer i energieffektivitetsforanstaltninger, ville være mere effektive end at målrette politiske instrumenter mod alle husholdninger. Vi opdager dertil, at kun nogle af de analyserede husstandskarakteristika har en betydelig effekt på husholdningernes investeringer i energieffektivitetsforanstaltninger, og effekterne er generelt små. Indkomst og hjem ejerskab status viser den klareste tendens til at forklare husholdningernes investeringsbeslutninger.

I en model, som beskriver Danmarks økonomi og Danmarks energisystem, simulerer vi effekten af energieffektivitetspolitik på husholdningernes adfærd med hensyn til investeringer og energiefterspørgsel. Simuleringen af husholdningernes adfærd er påkrævet for ex-ante evalueringer af politiske instrumenter for energieffektiviseringer. Vi demonstrerer en omfattende metode til ex-ante evalueringer af politiske instrumenter med fokus på modellering af husholdningernes adfærd. Vi simulerer specifikt husholdningernes investeringer i eftermontering af eksisterende bygninger for at gøre dem energieffektive. Modelresultaterne tyder på, at Danmark's ambitioner om betydelige reduktioner i varmeforbruget, sandsynligvis vil kræve en bred blanding af politiske instrumenter, der adresserer forskellige barrierer, der hæmmer husholdningerne i at investere i eftermonteringer.

Med hensyn til blandinger af politiske instrumenter for energieffektiviseringer diskuterer vi potentialet for interaktionseffekter mellem instrumentkombinationer, som kan være afbødende og forstærkende. Vi opdager, at styringsmekanismen for et politisk instrument, omfanget og tidspunktet for implementeringen bestemmer interaktionsresultatet. Disse faktorer kan tages i betragtning ved udformningen og implementeringen af kombinationer af politiske instrumenter for energieffektiviseringer for at undgå afbødende effekter og optimere forstærkende effekter.

Desuden vurderer vi potentialet for, at medlemsstater af Den Europæiske Union kan bruge deres auktionsindtægter fra det Europæiske emissionshandelssystem til finansiering af nationale energieffektivitetspolitikker, for eksempel i husholdningssektoren. På grund af de seneste ændringer i rammerne af emissionshandelssystemet er auktionsindtægter en stigende indkomst for medlemsstaterne. Strategiske investeringer af disse indtægter i nationale energieffektivitetspolitikker kan føre til fordele såsom yderligere og omkostningseffektive reduktioner i drivhusgasudledninger og støtte til den politiske proces for at stramme emissionshandelssystemet i fremtiden.

De forskellige forskningsmetoder og forskningsbidrag fra denne afhandling kan give relevante indsigter til beslutningstager om, hvordan man kan øge investeringer i energieffektivitetsforanstaltninger i husholdningssektoren. Denne afhandling kan dermed bidrage til at finde svar om, hvordan man understøtter overgangen til et lavemissionssamfund og bekæmpelsen af klimaforandringer.

# List of publications

**Paper A** Catharina Wiese, Anders Larsen, and Lise-Lotte Pade. Interaction effects of energy efficiency policies: A review. *Energy Efficiency*, 11(8):2137–2156, 2018.

**Paper B** Geraldine Henningsen and Catharina Wiese. Do household characteristics really matter? A meta-analysis on the determinants of households' energy-efficiency investments. *Under review at Energy Economics*, May 2019.

**Paper C** Kristoffer Steen Andersen, Catharina Wiese, Stefan Petrović, and Russell McKenna. Overcoming the hurdle: meeting Danish energy saving requirements by targeting household investment behavior. *Submitted to Energy Policy*, July 2019.

**Paper D** Catharina Wiese, Richard Cowart and Jan Rosenow. Auctioning revenues to foster energy efficiency: Status quo and future potential within the European Emissions Trading System. In *Proceedings of the 2019 ECEEE Summer Study*, pages 321–330, 2019. (peer-reviewed)

## Not included in this thesis

Julia Hildermeier, Christos Kolokathis, Jan Rosenow, Mike Hogan, Catharina Wiese, and Andreas Jahn. Start with smart: Promising practices for integrating electric vehicles into the grid. Regulatory Assistance Project, 2019.

Richard Cowart and Catharina Wiese. A perfect match: Using carbon revenues to finance energy efficiency. Foresight Climate & Energy, 19 December 2018.

# Chapter 1.

# Introduction

The Paris Agreement was adopted in December 2015 at the twenty-first session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC). As a main objective, it '*aims to strengthen the global response to the threat of climate change (...) by holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*' [UNFCCC, 2015].

The agreement is considered a great diplomatic success, bringing 196 nations into a common cause to agree on a global climate target [Dimitrov, 2016]. Since the adoption in 2015 it appears, however, that the nations' efforts to combat climate change are lacking behind the target [e.g. Rogelj et al., 2016]. The Intergovernmental Panel on Climate Change (IPCC) has recently confirmed the urgency to accelerate efforts in the panel's special report on global warming of 1.5 °C. The report specifically emphasises that reaching a sufficient reduction in greenhouse gas emissions and net-zero emissions by around 2050 in order to stay well below 2 °C temperature increase requires '*rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems*' [IPCC, 2018].

Indeed, energy systems around the world contribute significantly and increasingly to global greenhouse gas emissions, and are the main area of interest for this thesis. Figure 1.1 shows that global energy-related greenhouse gas emissions increased by 1.4% from 2016 to 2017, and reached a historic high of 32.5 gigatonnes of $CO_2$ equivalent. Energy systems still account for around two-thirds of greenhouse gas emissions worldwide [IRENA, 2017]. These numbers confirm that current efforts to cut energy-related emissions are not sufficient [IEA, 2018a], and that efforts to transform energy systems to align them with the global climate targets need to be accelerated. According to the International Energy Agency (IEA), the increase in energy-related greenhouse gas emissions in 2017 was the result of a rise in global energy demand due to economic growth, a decrease in fossil-fuel prices and a downward tendency in energy efficiency efforts [IEA, 2018a].

In this thesis, we focuses on the opportunity for policy interventions to counteract the identified downward tendency in energy efficiency efforts as one means to reduce final energy demand and cut energy-related greenhouse gas emissions. Section 1.2 introduces the role of energy efficiency in the transition of energy systems and motivates the need for

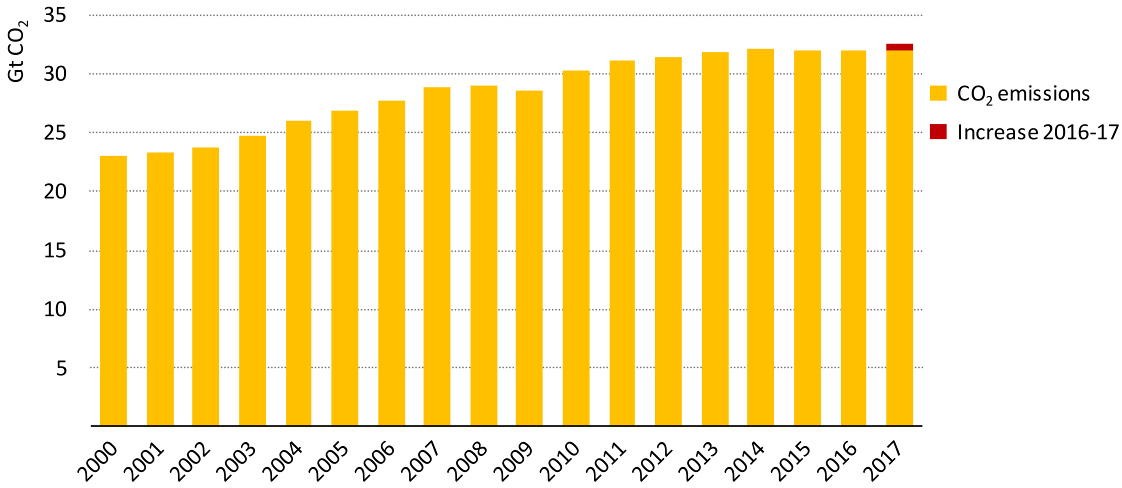


Figure 1.1.: Global energy-related $CO_2$ emissions, 2000–2017 [IEA, 2018a]

large-scale energy efficiency improvements. In section 1.3, we make the case for energy efficiency policy interventions and specify the underlying research question. Section 1.4 presents and explains the outline of this thesis. Before elaborating on the role of energy efficiency in the transition of energy systems, the following section clarifies the definitions of energy efficiency and related concepts for a clearer understanding throughout this thesis.

## 1.1. Definitions of energy efficiency and related concepts

The research presented in this thesis revolves around the concepts of energy efficiency and savings as a means to reduce final energy demand, specifically by implementing energy efficiency policy instruments. Throughout this thesis we make use of the following definitions.

- *Final energy demand* includes all energy, including electricity, heat and various fuels, supplied to and consumed by energy end-users/end-use sectors, e.g. private households, firms, the residential, commercial, industry, or transport sector. It excludes energy used in the production and processing of energy, and losses in the transmission and distribution. These energy uses and losses are part of the *primary energy demand*, which measures total energy demand, e.g. at country level.

- *Energy efficiency* generally denotes the ratio of energy output to energy input. Energy output in the context of final energy demand, i.e. on the end-use level, specifically refers to the provision of energy services, e.g. space heating, cooling and lighting, and other activities that require energy input, e.g. production processes of goods.[1] The inverse of the ratio is widely used as an energy efficiency indicator and is referred to as *energy intensity*. Energy intensities can be computed at a country level, where it is the ratio of total primary energy demand divided by the gross domestic product of the country, and also at the end-use level. For example, space heating energy consumption (energy input) per square meter of space heated (energy output) serves as an energy efficiency indicator in the residential sector [IEA, 2014b, 2018c].

- An *energy efficiency improvement* delivers a certain energy service with less energy input (e.g. square meters of space heated to a certain temperature with less energy needed to obtain that output). Examples of *energy efficiency measures* at the end-use level that lead to an *energy efficiency improvement* include installing high efficiency boilers, air conditioners and home appliances, upgrading the level of insulation for various building envelop components, and deploying high efficiency motors and processes in industry. An *energy efficiency improvement* requires both technological change, which makes energy-efficient technologies available, and change in end-users' behaviour with respect to their individual investment decisions in favour of existing *energy efficiency measures*. The latter is of particular interest in this thesis.

- The *energy efficiency potential*, i.e. the energy saving potential from energy efficiency improvements, can be divided into the following categories [Nadel et al., 2004, Schlomann, 2014]. First, the technical potential represents the total energy that could be saved by any efficiency measure that is available now or in a certain future, regardless of costs or the end-users' willingness to adopt the measure. Second, the economic potential represents the fraction of the technical potential that is cost-effective from a societal perspective, i.e. where the benefits to society would outweigh the costs associated with realising that potential. Third, the profitable energy efficiency potential is cost-effective from an end-user's private perspective, typically considering the investment in an *energy efficiency measure* and its operating costs on the cost side, and potential energy cost savings on the benefit side.[2,3]

[1] These are examples of energy services commonly mentioned in the literature. For a comprehensive review see Fell [2017].

[2] Evaluating the cost-effectiveness of energy efficiency potential requires net present value calculations of costs and (future) benefits. These calculations depend largely on the included costs and benefits, and the choice of discount rate. Both the included costs and benefits, and the discount rate should reflect the perspective of the evaluation. The social discount rate should, e.g., be used to calculate the net present value to society over the long term, while the lending rate should be used for evaluating cost-effectiveness from an end-user's private perspective [National Action Plan for Energy Efficiency, 2008]. Considerations on the costs and benefits of energy efficiency improvements from different perspectives are taken up in Chapter 2.

[3] There exist different categorisations of energy efficiency potential. The categorisation that we choose, serves to illustrate the different layers of energy efficiency potential and introduce the evaluation of cost-effectiveness.

- *Energy savings* denote a reduction in *final energy demand*. Savings can be achieved through either an *energy efficiency improvement* as defined previously, or a reduction in end-users' total demand for energy services (e.g. space heating to a lower overall temperature) and energy-using products and technologies. The latter requires energy end-users to curtail demand for energy services and energy-using products and technologies, or to meet demand using non-commercially traded energy (e.g. letting laundry dry outside instead of using a tumble dryer).

- *Energy efficiency policy instruments* include market-based, financial, regulatory, information provision and voluntary instruments. These instruments give an incentive, establish a requirement or create the opportunity for energy end-users to adopt *energy efficiency measures*, and aim at realising untapped *energy efficiency potential* to eventually reduce *final energy demand*.

The list serves as an introduction to key concepts applied in this thesis. It is not meant to provide an exhaustive overview of all concepts related to energy efficiency. For additional definitions see e.g. Pérez-Lombard et al. [2013].

## 1.2. Energy efficiency and the energy transition

The importance of energy efficiency improvements has always been linked to various policy objectives. The most prominent ones are enhanced reliability in the security of energy supply by reducing the dependence on energy imports, economic growth by increasing productivity, and reductions in greenhouse gas emissions. Energy efficiency improvements can help to achieve all these objectives [e.g. Blazejczak et al., 2014, Ürge-Vorsatz et al., 2016, Pollitt et al., 2017, Thema et al., 2018]. In this section, we elaborate on the environmental objective and specifically the role of energy efficiency in the transition of energy systems.

The long-term transition away from fossil fuel-based energy systems to systems with net-zero $CO_2$ emissions by around 2050 requires extensive changes in current energy production and consumption patterns. In particular, high shares of renewable energy sources in energy supply and reductions in final energy demand are needed [IPCC, 2018, IRENA, 2017]. Energy efficiency improvements are one means to achieve energy savings and reduce final energy demand; see Section 1.1.

Indeed, evidence shows that energy efficiency improvements have substantially contributed to counteract the persistent increase in demand for energy services on a global scale [IEA, 2018c].[4] Moreover, realising a larger fraction of energy efficiency potential

[4]Demand for energy (services) still shows an increasing trend in most regions around the world due to, e.g., increased economic activity, population growth and lifestyle effects, such as demand for larger buildings and more appliances. The trend differs greatly across regions and is most pronounced in emerging economies [IEA, 2018c]. Also in Europe, however, final energy demand has increased over the last five years due to the just mentioned reasons [Tzeiranaki et al., 2019].

is projected to further counteract increasing demand and eventually reduce final energy demand [IRENA, 2017, IEA, 2018b, IPCC, 2018, Frauenhofer ISI, 2019]. In recent years, energy efficiency improvements have already been key to reducing energy demand on different end-use levels, e.g. in households [ODYSSEE-MURE, 2019b, Danish Energy Agency, 2018], and residential and commercial buildings [Rose and Thomsen, 2015, Diefenbach et al., 2018].

Energy savings and reductions in final energy demand are primary purposes of energy efficiency improvements when considering the environmental objective to reduce greenhouse gas emissions. They furthermore yield *multiple benefits*[5] [IEA, 2014a, 2018b, Thema et al., 2018] that explain the environmental objective and underline the role of energy efficiency in the energy transition.

First, energy savings reduce the amount of primary energy that is needed to produce final energy such as electricity and heat. In the majority of energy systems, both electricity and heat generation are still fossil fuel-based [IEA, 2018d]. Thus, energy savings directly reduce primary energy demand for fossil fuels and consequently energy-related global greenhouse gas emissions [IEA, 2018c] and local air pollution [Kanada et al., 2013, Thema et al., 2018]. Without energy efficiency improvements over the period 2000–2017, global energy-related greenhouse gas emissions would have been 12% higher in 2017 at around 36 instead of 32 gigatonnes of $CO_2$ equivalent as presented in Figure 1.1 [IEA, 2018c]. These numbers imply that energy efficiency improvements across the global economy are the largest source of emissions abatement in the energy sector [IEA, 2019].

Second, considering the needed increase in the share of renewable energy sources, many countries have introduced renewable energy targets typically formulated as a given share in final energy demand. By reducing final energy demand, energy savings directly contribute to achieve these targets and to enhance their overall feasibility because less renewable energy capacity is needed to reach a given share [IRENA, 2017, Lechtenböhmer et al., 2017]. The increased adoption of energy efficiency measures and renewable energy sources as a combined approach can, therefore, achieve energy systems with net-zero $CO_2$ emissions at lower cost [Connolly et al., 2016, IRENA, 2017].

Third, energy efficiency improvements have the potential to unlock further benefits at various stakeholder levels that are not directly related to energy systems but may increase the political and social acceptance of extensive system changes. Investments in energy efficiency measures may have a direct and positive effect on employment in sectors that provide energy-efficient technology and materials, such as the building industry [Reuter et al., 2017, Pollitt et al., 2017, Diefenbach et al., 2018]. Employment effects, moreover, may lead to additional tax revenue in the public budgets [Pollitt et al., 2017, Diefenbach

[5] The multiple benefits framing of energy efficiency proposes that energy efficiency improvements have many environmental, economic and social benefits, and that these benefits are currently not properly understood and taken account of in decision-making [IEA, 2014a]. Various terms have been used to represent this framing, e.g. multiple impacts [Thema et al., 2018], considering that not all impacts of energy efficiency improvements are necessarily benefits, such as more costly maintenance for energy-efficient technology. However, this thesis uses the term multiple benefits according to the seminal work of the IEA [2014a].

et al., 2018]. Furthermore, energy efficiency improvements in buildings may improve indoor climate. Both improved indoor climate and reduced local air pollution have a positive impact on human health and well-being [Thomson et al., 2009, Thema et al., 2018].

These benefits of energy efficiency improvements will directly or indirectly facilitate a long-term energy transition and play a key role in aligning energy systems with the global climate targets defined in the Paris Agreement.[6]

## 1.3. Research question

The multiple benefits of energy efficiency receive increasing attention in energy research [e.g. Ürge-Vorsatz et al., 2016, Reuter et al., 2017, Thema et al., 2018, 2019]. In a recent study, Thema et al. [2018] quantify and monetise multiple benefits of energy efficiency improvements with respect to air pollution, human health, economic growth, resource savings and avoided energy generation in Member States of the European Union. They find that including these benefits in cost-benefit evaluations of various energy efficiency measures in the residential, commercial, industry and transport sector would render a majority of the considered measures cost-effective from a societal perspective. The study findings furthermore indicate that most energy efficiency measures would even be cost-effective, when only accounting for the investment on the cost side and energy cost savings on the benefit side. Various studies confirm the existence of both economic and profitable energy efficiency potential [e.g. Mata et al., 2015, Rosenow et al., 2018, IEA, 2018c, Thema et al., 2018, Frauenhofer ISI, 2019]. The existence of untapped profitable potential also substantiates the existence of an energy efficiency gap, which represents the gap between profitable potential and the actually realised energy efficiency improvements by energy end-users. The energy efficiency gap and its existence has been subject for discussion since almost three decades, see, e.g., Hirst and Brown [1990], Jaffe and Stavins [1994], Golove and Eto [1996], Allcott and Greenstone [2012], Gillingham and Palmer [2014], Stadelmann [2017], Gerarden et al. [2017].

In this thesis, we aim at investigating how to realise a larger fraction of energy efficiency potential by implementing effective energy efficiency policies, given that the following two prerequisites hold.

(1) There exists an untapped economic potential that is cost-effective from a societal perspective and this potential would become even larger when taking the multiple benefits of energy efficiency improvements to society into account.

(2) Energy end-users fail to adopt even profitable energy efficiency measures, which implies an untapped cost-effective potential from the end-users' private perspective. There exists an energy efficiency gap.

[6] For further benefits of energy efficiency see e.g. IEA [2014a], Pollitt et al. [2017], Thema et al. [2018], ODYSSEE-MURE [2019a].

Both prerequisites are widely used justifications for policy intervention to increase the adoption of end-use energy efficiency measures from an economic perspective. This thesis takes departure in economic theory, thus, both prerequisites denote the underlying rationale for the overall research question:

> *How can progress in energy efficiency policy effectively increase the adoption of energy efficiency measures by energy end-users?*

In Section 2.1 and Section 4.2 we furthermore introduce a discussion beyond the strict economic perspective taking into account the global climate targets and considering environmental limits.

Progress in energy efficiency policy means any improvement in the design and implementation of policy instruments that contributes to the instruments' effectiveness to increase the adoption of energy efficiency measures and achieve end-use energy savings. In this context, policy design refers to the choice of the policy instrument or a mix of policy instruments and the target group, while considering factors that determine the success or failure to realise the policy objective when implementing a certain instrument or mix of instruments. These factors include the impact of an instrument on its designated target group given the instrument's steering mechanism, feasibility considerations and general strengths and weaknesses of the instrument. The research conducted in preparation of this thesis focuses on the instrument level of energy efficiency policy, while it does not specifically address challenges around policy governance in specific jurisdictions. Furthermore, while energy end-users generally comprise all end-use sectors, we concentrate on energy efficiency policy in the residential sector, particularly in a developed country context, and to a minor extent the small- and medium-sized industry sector. The thesis excludes energy demand for transportation. Overall, by addressing the defined research question, we aim at providing knowledge to an applied research field, where the findings may finally contribute to policy-making in a world with major challenges with respect to climate change mitigation and the need for energy system changes.

## 1.4. Outline of the thesis

The remainder of this thesis is structured as follows.

- **Chapter 2** elaborates on the justifications for energy efficiency policy, while reflecting on the distinction between economic and profitable energy efficiency potential, and presents various barriers that inhibit energy efficiency improvements. The chapter furthermore presents a range of policy instruments that aim at reducing these barriers and increasing the adoption of energy efficiency measures.

- **Chapter 3** presents the individual papers that contribute to this dissertation and that are listed on page 11. We specifically explain each paper's objectives, research methods and main results.

- **Chapter 4** summarises and discusses the overall results of this thesis. The chapter also addresses limitations of energy efficiency, i.e. reasons for why energy efficiency measures may deliver only a fraction of the predicted energy savings. Furthermore, we include an outlook to energy saving approaches beyond energy efficiency improvements.
- **Chapter 5** reflects on Chapter 1–4 and concludes the thesis.
- **Appendices A, B, C, and D** contain the original full papers presented in Chapter 3.

# Chapter 2.

# Background: energy efficiency policy

The existence of untapped economic and profitable energy efficiency potential, see Section 1.1, is the most widely used justification for policy intervention to increase the adoption of end-use energy efficiency measures, as introduced in the previous chapter. In order to increase adoption, however, policy instruments need to address the underlying reasons for why the potential has remained untapped.

In the literature related to research on energy efficiency improvements, it is well-established that a number of barriers to energy efficiency exist.[1] These barriers have been extensively discussed and categorised in various ways, particularly in connection with the energy efficiency gap; see, e.g., Jaffe and Stavins [1994], Golove and Eto [1996], Jaffe et al. [2004], Sorrell et al. [2004], Gillingham et al. [2009], Linares and Labandeira [2010], Allcott and Greenstone [2012], Gillingham and Palmer [2014], Gerarden et al. [2017], Stadelmann [2017]. The discussions on barriers to energy efficiency focus on barriers that explain why energy end-users fail to realise profitable energy efficiency potential. In the context of policy intervention and its justification, the distinction between economic and profitable potential is, however, not trivial.

In Section 2.1, we first present barriers to the adoption of profitable energy efficiency measures from the end-users' private perspective and justify policy intervention under these barriers. We then discuss a broader scope for policy intervention, which also considers barriers to realising economic energy efficiency potential. We furthermore take into account the need to accelerate efforts that align energy systems with the global climate targets and continue the line of arguments from Section 1.2. Section 2.2 presents existing energy efficiency policy instruments that address and reduce different barriers to energy efficiency and aim at increasing the adoption of energy efficiency measures.

## 2.1. Barriers to energy efficiency and the scope for policy intervention

Drawing on the extensive literature that discusses barriers to energy efficiency, this section first presents the most commonly defined barriers to the adoption of energy efficiency measures that would be privately profitable. We present the barriers to profitable energy

[1] We adopt the widely used term 'barriers to energy efficiency' to denote conditions that inhibit energy efficiency improvements.

efficiency potential from three different perspectives: (1) an economic perspective with focus on rational behaviour of energy end-users; (2) an economic perspectives with focus on market failures; and (3) a behavioural economic perspective.[2]

**Barriers to profitable energy efficiency potential** Economic theory assumes that individuals have complete information and behave rationally when making decisions in perfect markets. Individuals are furthermore assumed to have stable preferences over time [Mas-Colell et al., 1995, p. 3ff.], i.e. decision utility at the time of choice is the same as experienced utility after a choice has been made [Kahneman and Thaler, 2006]. Under these assumptions any rejection of energy efficiency measures, even though they seem profitable, reveals an individual's underlying preferences, and reflects a rational evaluation of the relevant costs and benefits [Sorrell et al., 2004].

(1) There may exist barriers to seemingly profitable energy efficiency measures that can be explained by rational behaviour of energy end-users.[3]

- *Heterogeneity* among end-users with respect to their individual preferences and usage profiles may result in substantially varying costs and benefits associated with adopting an energy efficiency measure across potential adopters [e.g. Metcalf and Hassett, 1999]. Heterogeneity may therefore explain why energy efficiency measures, although they appear to be profitable for the average end-user, are not privately profitable and are rejected in particular instances [Jaffe and Stavins, 1994, Golove and Eto, 1996, Sorrell et al., 2004, Gillingham and Palmer, 2014, Gerarden et al., 2017].

- *Hidden costs* refer to costs or loss of benefits that are not captured in simple cost-benefit calculations. These costs or loss of benefits include, e.g., time costs of searching for and installing an energy efficiency measure, inconvenience during the installation, and potentially lower quality of the provided energy service compared

[2] The concept of a barrier originates from the economics literature [Sorrell et al., 2004]. The large majority of discussions on barriers to energy efficiency and justifications for policy intervention are therefore based on rationales derived from economic theory. Section 2.1 also draws on economic theory to introduce the topic and presents a theoretical discussion on barriers to energy efficiency. Empirical evidence on the relevance and magnitude of each individual barrier to energy efficiency is still remarkably limited, most often due to the empirical challenge to isolate different barriers in end-users' decisions to adopt energy efficiency measures [Gerarden et al., 2017, Stadelmann, 2017]. Empirical studies tend to investigate barriers in the context of policy instruments that aim at reducing a certain barrier. Section 2.2 refers to these studies when introducing energy efficiency policy instruments.

[3] These barriers take account of that the profitability of energy efficiency measures is typically predicted in engineering models [Gillingham and Palmer, 2014] and depends on assumptions with respect to, among others, average usage profiles and (future) energy prices. Engineering models are largely not able to capture end-users' individual decision context. Generally, they are prone to overstate energy efficiency potentials [e.g. Gillingham and Palmer, 2014, Gerarden et al., 2017, Fowlie et al., 2018]. This section, however, introduces barriers to energy efficiency given that models correctly find, on average, profitable energy efficiency potential. Section 4.1 takes up various limitations to energy efficiency, including technical explanations for why energy efficiency measures may deliver only a fraction of the predicted energy savings.

to a less energy-efficient alternative [Sorrell et al., 2004, Gillingham and Palmer, 2014]. The costs are hidden to observers, however, not to the individual energy end-user, who makes the decision to adopt a certain energy efficiency measure. Thus, they may render a seemingly profitable energy efficiency measure unprofitable in the individual decision context [Schleich, 2007].

- *Risk* plays a role when investing in (irreversible) energy efficiency measures entails uncertainty with respect to technology performance and future energy cost savings [Jaffe and Stavins, 1994, Gillingham and Palmer, 2014]. In the presence of risk, applying stringent investment criteria, e.g. short required payback periods, and rejecting seemingly profitable energy efficiency measure may be a rational behaviour [Sorrell et al., 2004].

(2) Market failures, i.e. violations of the underlying assumptions with respect to perfect markets, constitute barriers to energy efficiency when they bias individuals' decision making to the detriment of profitable energy efficiency improvements. The following market failures are commonly defined as barriers to energy efficiency.

- *Imperfect information* refers to the situation where end-users lack information about the availability of and the energy saving potential from energy efficiency improvements. In that situation, end-users may not be sufficiently informed to recognise the existence of profitable energy efficiency potential and may therefore be unable to realise the potential [Gillingham et al., 2009, Ramos et al., 2015, Gerarden et al., 2017].

- *Liquidity constraints* may prevent energy end-users from adopting energy efficiency measures when they have high upfront costs, which are assumed to be higher than for less energy-efficient alternatives [Gillingham and Palmer, 2014, Gerarden et al., 2017]. These constraints constitute a (capital) market failure when they result from asymmetric information between the borrower and lender of capital. Having asymmetric information on capital markets, an end-user who has private information on the energy cost savings of an energy efficiency measure may be unable to convince a lender of the financial potential if the savings are costly to evaluate for the borrower [Gerarden et al., 2017].[4]

- *Split incentives* or *principal-agent problems* represent a barrier to energy efficiency when one party (the principal) decides to invest in an energy efficiency measure, while a second party (the agent) benefits from the investment [Gillingham et al., 2009]. The most prevalent example refers to the landlord-tenant problem: The

[4]Liquidity constraints do not always imply a market failure, but may instead reflect that certain end-users are high-risk borrowers. Constraining liquidity for these end-users represents an efficient capital market outcome [Sorrell et al., 2004]. Several studies, however, find a positive correlation between income and end-users' propensity to invest in energy efficiency measures [Henningsen and Wiese, 2019] suggesting that a lack of financial resources represents a barrier to energy efficiency, even if it does not result from market failure.

landlord of a building may invest in, e.g., upgrading the level of building insulation, while the tenant pays the energy bill and would benefit from the energy efficiency improvement in the form of energy cost savings. In this situation, the landlord may have a low incentive to invest when the costs cannot be passed on to the tenant. Similarly, the tenant may have a low incentive to invest when she is likely to move out before benefiting from the energy cost savings [e.g. Jaffe and Stavins, 1994, Jaffe et al., 2004, Sorrell et al., 2004, Schleich, 2007, Ástmarsson et al., 2013].

- *Adverse selection* as a result of *asymmetric information* refers to a situation where the supplier of an energy efficiency measure, which would be profitable from an end-user's private perspective, may be unable to perfectly transfer this information because the energy efficiency potential of the measure is unobserved [Akerlof, 1978, Howarth and Sanstad, 1995]. Thus, all suppliers would have an incentive to claim that a certain measure improves energy efficiency. Because the energy efficiency potential is unobserved, however, end-users may ignore it in their investment decisions [Sorrell et al., 2004].

Market failures cause individuals to make inefficient decisions, i.e. to behave irrationally [Mas-Colell et al., 1995, p. 311ff.]. Thus, in the presence of imperfect and asymmetric information, liquidity constraints, split incentives or adverse selection in the markets for energy efficiency measures, end-users may fail to realise energy efficiency potential that would be privately profitable, i.e. that would minimise (maximise) their costs (energy cost savings).

(3) Focusing on individuals' decision-making behaviour, the field of behavioural economics challenges the underlying assumptions of standard economic theory and instead allows for deviations from perfect rationality and stable preferences [Shogren and Taylor, 2008, Gillingham and Palmer, 2014]. More specifically, in the context of energy efficiency, behavioural insights challenge end-users' ability to rationally solve complex optimisation problems, i.e. the trade-off between upfront costs and future energy cost savings, prior to the decision to adopt an energy efficiency measure. Those instances where end-users' observed decision-making behaviour appears to deviate from what rational choice theory predicts, represent behavioural 'anomalies', which also are increasingly discussed as barriers to energy efficiency [Sorrell et al., 2004, Sanstad et al., 2006, Gillingham et al., 2009, Gillingham and Palmer, 2014, Gerarden et al., 2017, Stadelmann, 2017].

- *Bounded rationality* suggests that individuals' behave rationally, however, under cognitive constraints to process information [Simon, 1955]. Under these constraints, individuals may use decision heuristics or rules of thumb to simplify complex decisions, even when having perfect information. As a result of this simplification, energy end-users may undervalue the energy saving potential of efficiency improvements and therefore fail to realise profitable potential [Gillingham et al., 2009]. Bounded rationality may therefore lead to irrational decisions in certain circumstances [Gillingham and Palmer, 2014]. When the costs associated with making a complex decision are too high in relation to the potential benefits, however, paying limited attention to the energy saving potential from energy efficiency improvements may as well be a perfectly rational reaction [Sallee, 2014, Palmer and Walls, 2015, Schleich et al., 2016].

- *Reference-dependent preferences* imply that individuals' preferences may not be stable but dependent on comparisons to certain reference points [Kahneman and Tversky, 1979]. This dependency may manifest in the form of *loss aversion*. Loss averse end-users may perceive high upfront costs of energy efficiency measures as a loss and value this loss higher than potential future gains (i.e. compared to a reference point with zero payoff) [Gillingham and Palmer, 2014]. *Loss aversion* may therefore keep end-users from adopting energy efficiency measures [Schleich et al., 2016].

Those behavioural 'anomalies', where decision utility at the time of choice deviates from experienced utility after a choice has been made [Kahneman and Thaler, 2006], are defined as behavioural failures equivalent to market failures [Gillingham and Palmer, 2014] and lead to inefficient decisions, i.e. irrational behaviour.

From a strict economic perspective, only market failures (2) justify energy efficiency policy intervention [Jaffe and Stavins, 1994, Jaffe et al., 2004, Gillingham et al., 2009]. The underlying rationale stems from welfare economic theory: If energy efficiency policy intervenes in order to correct market failures in the markets for energy efficiency measures, the intervention would enable energy end-users to make efficient decisions that maximise the end-users' private utility, i.e. minimise (maximise) their costs (energy cost savings).[5] Including the behavioural economic perspective, also the presence of behavioural failures (3) justify energy efficiency policy intervention drawing on the same underlying rationale [Gillingham and Palmer, 2014]. A policy that intervenes in end-users' rational decision behaviour (1), however, would reduce utility of energy end-users, which reject an energy efficiency measure after a rational evaluation of the relevant costs and benefits.

The scope for policy intervention becomes broader when also considering the energy efficiency potential that would be optimal to realise from a societal perspective, i.e. that would maximise net benefits to society over the long term. The economic energy efficiency potential is larger than the aggregate profitable potential when energy efficiency improvements lead to benefits that do not directly accrue to the individual end-user but at a societal level. We highlight two main points that influence the economic energy efficiency potential: (1) the presence of environmental externalities of energy production and consumption, which represents a widely used argument for a broader scope for policy intervention; and (2) the potential for multiple benefits of energy efficiency and their inclusion in cost-benefit evaluations. In this context we discuss barriers to realising economic energy efficiency potential. Furthermore, we take into account climate

[5] This perspective is based on the assumption that multiple market failures in the markets for energy efficiency measures exist. Thus, it acknowledges second-best policy making as a starting point [Bennear and Stavins, 2007].

targets and how binding targets may further alter the scope for energy efficiency policy intervention.

**The broad scope for policy intervention** Most discussions on the social optimum of energy efficiency improvements consider environmental externalities and cost-benefit evaluations of actual policy implementation to correct market and behavioural failures [e.g. Jaffe et al., 2004, Sanstad et al., 2006, Gillingham et al., 2009].

(1) The environmental externalities of energy production and consumption that are not reflected in energy prices do not explain why energy end-users fail to adopt energy efficiency measures that are privately profitable even under current market prices [Jaffe et al., 2004, Sorrell et al., 2004]. They, however, cause a divergence between private incentives and the societal interest and cause overconsumption of energy because end-users have a too small incentive to save energy, i.e. to adopt energy efficiency measures, from the societal perspective. Environmental externalities lead to market failure [Mas-Colell et al., 1995, p. 350ff.] and constitute a barrier to energy efficiency when they are not internalised. Thus, they justify policy intervention, which does not directly intervene in the markets for energy efficiency measures but which may internalise the externalities by increasing the energy price on energy markets to align private incentives with the societal interest.

(2) Policy intervention to correct market and behavioural failures will only be optimal from a societal perspective if the benefits of actual policy implementation exceed its costs, e.g. government expenditure, administrative burdens and distortionary effects [e.g. Jaffe et al., 2004, Sanstad et al., 2006, Gillingham et al., 2009]. Continuing the line of arguments in Section 1.2, cost-benefit evaluations of energy efficiency policies would change when taking into account the multiple benefits of energy efficiency, which have so far not been properly understood and included in mainstream policy evaluations [IEA, 2014a, Thema et al., 2019]. This deficiency can also be defined as a barrier to energy efficiency because including all societal benefits beyond considerations of reduced environmental externalities would increase the energy efficiency potential that is optimal to realise from a societal perspective. Thus, it would further increase the scope for energy efficiency policy intervention and potentially affect policy choice, design, and implementation. The quantification and monetisation of the energy system benefits of energy efficiency improvements, see Section 1.2, would enable policy-makers to, e.g., trade off and potentially prioritise energy efficiency against supply-side policy interventions (while also accounting for their multiple benefits) [Thema et al., 2018]. A complete assessment of benefits would help to realise energy efficiency potential at end-use levels where policy intervention maximises net benefits to society.[6]

[6] The quantification of multiple benefits of energy efficiency improvements receives increasing attention in energy research, as introduced in Chapter 1. It, however, remains a challenge to understand the causal link from energy efficiency improvements to the individual benefits in order to actually take them into account in decision making [Thema et al., 2019]. Including the multiple benefits framework in this chapter shall therefore bee seen as an attempt to introduce a broader scope for energy efficiency policy intervention, which will potentially receive further attention in future research.

Section 1.2 introduces the multiple benefits of energy efficiency in the context of the transition of energy systems and the achievement of global climate targets. This context entails a further scope for energy efficiency policy intervention considering a practical approach with respect to target achievements. Many jurisdictions, among those the European Union, have implemented ambitious energy efficiency targets in order to comply with the global climate targets set in the Paris Agreement [e.g. European Union, 2018]. Due to the various barriers to energy efficiency, the achievement of energy efficiency targets requires policy intervention, which may even need to incentivise the adoption of energy efficiency measures that are not cost-effective (yet). Binding targets may therefore broaden the scope for energy efficiency policy intervention outside the standard economic justifications.

Taking a societal perspective and considering the need to accelerate efforts that align energy systems with the global climate targets, this thesis recognises a broad scope for energy efficiency policy intervention. This broad scope for policy intervention goes beyond the strict economic perspective to only correct market and behavioural failures in order to minimise (maximise) end-users' private costs (benefits) and instead aims at maximising the net benefits of energy efficiency improvements to society. The maximisation of net benefits to society implies both the implementation of policy instruments that enable end-users to adopt energy efficiency measures that are privately profitable and interventions that align the end users' private decisions with the societal interest while taking into account the costs of realising economic energy efficiency potential and all multiple benefits.

The following section presents various energy efficiency policy instruments that policy-makers may implement in order to address and reduce different barriers to energy efficiency.

## 2.2. Policy instruments

There exists a variety of instruments that policy-makers can implement when aiming at increasing the adoption of energy efficiency measures. This section is mostly concerned with energy efficiency policy instruments that target households, buildings, and the small- and medium-sized industry sector. The section draws to a great extent on the literature review conducted in Paper A. Wiese et al. [2018] divide energy efficiency policy instruments into five broad categories: market-based, financial, informational, regulatory and voluntary. Each of these categories are further explained in the following, highlighting the addressed barriers to energy efficiency and introducing the instruments' strengths and weaknesses.[7]

[7] The potential risk for a rebound effect due to an energy efficiency improvement in the sense that the relative price reduction for energy services may increase final energy demand is defined as a general limitation to energy efficiency. This limitation is discussed in Section 4.1.

**Market-based instruments** Market-based instruments that imply a direct intervention in the markets for energy efficiency measures have been defined as a policy framework that specifies the outcome to be achieved by market actors, e.g. a certain amount of energy savings, without prescribing the means to achieve this outcome, i.e. the type of intervention implemented or technology supported [Rosenow et al., 2019]. Two types of instruments fit in with this definition: (1) energy efficiency obligations, and (2) auction mechanisms for energy efficiency measures.[8]

Existing energy efficiency obligations greatly differ from each other in terms of the design, implementation and governance [Bertoldi et al., 2015, Fawcett et al., 2019]. They, however, commonly define a quantitative energy saving target for energy companies, usually suppliers or distributors, who are obliged to meet the target by increasing the adoption of energy efficiency measures in end-use sectors, e.g. the residential and industry sector [Bertoldi et al., 2013]. The means of increasing the adoption of energy efficiency measures is not prescribed. Energy companies most often achieve energy savings by offering financial incentives for energy efficiency measures, information and technical assistance to energy end-users. Thus, at the end-use level, energy efficiency obligations translate into different instruments and have the potential to address different barriers to energy efficiency, such as liquidity constraints and imperfect information, depending on the chosen means [Giraudet and Finon, 2015].

The flexibility with respect to compliance may incentivise that energy efficiency obligations achieve energy savings cost-effectively [Rosenow et al., 2019], which has been confirmed by evaluations of several existing obligations [Bertoldi et al., 2010, Rosenow and Bayer, 2017, Rosenow et al., 2019]. The actual cost-effectiveness of energy efficiency obligations, however, highly depends on details with respect to the design, implementation and governance of each individual obligation [Eyre et al., 2009, Mundaca and Neij, 2009, Fawcett et al., 2019]. The administrative costs associated with setting up and overseeing energy efficiency obligations, e.g., increase with the complexity of an obligation because establishing rules and targets, and measuring and verifying additional energy savings becomes difficult [Rosenow and Bayer, 2017]. Energy companies typically pass on their costs to meet an obligation to end-users' energy bills [Rosenow et al., 2019]. Thus, end-users ultimately finance energy efficiency obligations. This mechanism has recently raised large political and public concern in the United Kingdom and Denmark [Fawcett et al., 2019], where the costs to energy companies have increased due to the focus on low-income households as a target group for energy efficiency measures in the United Kingdom and the depletion of the cheapest energy efficiency measures in Denmark [ATEE, 2017].

Auction mechanisms allow market actors to bid energy efficiency measures in tendering programmes or forward capacity markets [Rosenow et al., 2019]. Germany, e.g., has launched a competitive efficiency tender for the support of energy efficiency invest-

[8]Taxes on emissions or energy use and tradable permits may internalise the environmental externalities of energy production and consumption and thereby incentivise energy efficiency improvements through market mechanisms. They do not, however, directly intervene in the markets for energy efficiency measures and are therefore not included in this section. They are included in Paper A.

ments across various sectors [Langreder et al., 2019] and also Denmark is planning to implement a tender for investments in energy efficiency measures in the industry sector and buildings [Danish Ministry of Energy, Utilities and Climate, 2018]. Experience with auction mechanisms for energy efficiency improvements is, however, still low and mainly in a pilot stage [Rosenow et al., 2019].

**Financial instruments** Financial instruments include subsidies and improved access to capital for investments in energy efficiency measures, i.e. direct payments, tax rebates, grants and low-cost loans [Gillingham and Palmer, 2014], most often for specific technologies or appliance purchases [Galarraga et al., 2016]. They reduce end-users' liquidity constraints to invest in energy efficiency measures and address loss aversion by cutting potentially high upfront costs [Linares and Labandeira, 2010].

Empirical findings show that financial instruments effectively increase the adoption of energy efficiency measures, such as energy-efficient appliances [Datta and Gulati, 2014, Datta and Filippini, 2016] and building renovations [Scheer et al., 2013, Alberini and Bigano, 2015, Diefenbach et al., 2018]. The effectiveness of a financial instrument, however, finally depends to a large extent on the share of free-riders. Free-riders make use of a financial incentive although they would have invested in energy efficiency measures without the incentive and thus, increase the instrument's associated costs without adding to its effectiveness [Malm, 1996, Grösche and Vance, 2009, Houde and Aldy, 2014]. The costs of financial instruments are possibly high and if they are covered by distortionary taxes [Gillingham and Palmer, 2014], they may cause an excess burden to society.

**Informational instruments** Information on energy efficiency may be provided to end-users through certificates and labels, energy audits, and information campaigns. These instruments specifically address barriers to energy efficiency associated with imperfect or asymmetric information, and limited attention.

Certificates and labels show information on the energy efficiency of buildings (energy performance certificates) and appliances (energy labels), and thereby enable end-users to make more informed investment decisions [e.g. Ramos et al., 2015]. Ramos et al. [2015] collect a comprehensive overview of empirical studies that investigate the effect of both certificates and labels on consumers' decision-making process. Assessing renting prices for dwellings and sales prices of different appliances, these studies find that consumers positively value certificates and labels in terms of willingness to pay for certified buildings and labelled appliances. In recent studies, also Stadelmann and Schubert [2018] and Bjerregaard and Møller [2019] conclude that energy labelling increases the sale of energy-efficient appliances. Information provision through energy labels is, in the behavioural economics literature, also discussed as a nudging instrument in the sense that energy labels are intended to reduce the complexity of an investment decision and thereby simplify end-users' decision making without limiting their choice set [Newell and Siikamäki, 2014, Nielsen et al., 2016]. Recent research in behavioural economics specifically focuses on how consumers cognitively perceive energy labels using experimental designs [e.g. Newell and Siikamäki, 2014, Blasch et al., 2017].

Energy audits provide tailored information on profitable energy efficiency potential to households and industries [Ramos et al., 2015]. Particularly in the industry sector, audits have been found to positively affect the adoption of energy efficiency measures [Annunziata et al., 2014, Backlund and Thollander, 2015, Chiaroni et al., 2017, Fresner et al., 2017], however, e.g. Barbetta et al. [2015] and Larsen et al. [2006] find only a limited effect for audits in public buildings and the Danish industry sector, respectively.

Informational instruments generally increase awareness and knowledge among end-users regarding the availability and energy saving potential from energy efficiency improvements. The empirical evidence on the effectiveness of informational instruments, however, is mixed [Ramos et al., 2015] and suggests that informational instruments alone are not sufficient to effectively increase the adoption of energy efficiency measures.

**Regulatory instruments** In the context of energy efficiency policy, regulatory instruments are implemented as codes and standards, specifically building codes and minimum energy performance standards for appliances and technologies. Building codes are typically defined as a maximum limit of energy use per square meter per year for new buildings. Minimum energy performance standards for appliances and technologies usually set a minimum level of energy efficiency, i.e. the ratio of energy (service) output to energy input, that an appliance or technology must meet. Both instruments are prescriptive. On one side, they enforce producers to supply energy-efficient buildings, building components, appliances and technologies, and on the other side, they impose end-users to invest in these buildings, building components, appliances and technologies. Having this impact on producers' and consumers' decision making, regulatory instruments limit the need for information or complex cognitive abilities to evaluate different energy efficiency measures before making an investment decision and thereby remove barriers to energy efficiency associated with imperfect information and bounded rationality [e.g. Linares and Labandeira, 2010]. Furthermore, regulatory instruments may help to overcome split incentives when addressing the low incentive of landlords to invest in energy efficiency measures by an energy efficiency standard e.g. with respect to building renovations. When codes and standards ban inefficient technologies and appliances, they generally address any barrier to energy efficiency by enforcing certain investments.

Due to their prescriptive nature, regulatory instruments can be highly effective in terms of energy efficiency improvements and final energy savings, considering both building codes [Leth-Petersen and Togeby, 2001, Aroonruengsawat et al., 2012, Jacobsen and Kotchen, 2013] and minimum energy efficiency performance standards for appliances and technologies [Schiellerup, 2002, Nadel, 2002, Siderius and Nakagami, 2013]. Yet, because they prescribe the means of achieving energy efficiency improvements, they may cause high compliance costs especially on the end-use level [e.g. Linares and Labandeira, 2010].

**Voluntary instruments** Voluntary instruments refer to voluntary agreements primarily between public authorities and individual firms or groups of firms. A voluntary agreement typically includes quantitative targets with respect to energy efficiency improvements, energy savings or greenhouse gas emission reductions. Furthermore, it defines rewards and penalties in the case of compliance and non-compliance, respectively, and thereby becomes binding once a party joins the agreement [Rezessy and Bertoldi, 2011]. Voluntary agreements incentivise firms to consider energy efficiency measures in their investment decisions, in which otherwise only limited attention may have been paid to potential energy efficiency improvements.

On one side, voluntary agreements allow public authorities to set requirements that may have been unfeasible to enforce with regulation because voluntary agreements are more acceptable to firms and industries [Rezessy and Bertoldi, 2011]. Especially when combined with supporting policies such as energy audits and financial incentives, voluntary agreements have been found to be effective in terms of realised energy efficiency improvements, energy savings or greenhouse gas emission reductions [Johannsen, 2002, Rietbergen et al., 2002, Stenqvist and Nilsson, 2012]. On the other side, however, implementing voluntary agreements requires negotiating effective targets, controlling and monitoring of compliance, and sanctioning of non-compliance. These requirements may cause high administrative costs [Johannsen, 2002, Rezessy and Bertoldi, 2011].

Each of the individual instruments addresses only some of the barriers to energy efficiency. A situation where multiple barriers inhibit the adoption of cost-effective energy efficiency measures therefore requires multiple policy instruments [e.g. Tinbergen, 1952]. Indeed, several studies discuss the need to combine different energy efficiency policy instruments in policy mixes in order to effectively increase the adoption of energy efficiency measures [e.g. Rogge and Reichardt, 2016, Rosenow et al., 2016, 2017]. Combinations of energy efficiency policy instruments and the need to take into account potential interaction effects between them is the main subject of discussion in Paper A, which is the first paper presented in Chapter 3.

# Chapter 3.

# Contributions: objectives, research methods and results

This thesis is a cumulative dissertation. It is built upon and provides results from the papers listed on page 11. Figure 3.1 presents an overview of the research methods and the research contributions of Paper A, B, C and D, and shows the diversity of approaches that we have applied in addressing the overall research question of this thesis specified in Section 1.3. In this chapter, we outline each paper's objectives, research methods and main results. Chapter 4 further discusses the papers' contributions with respect to the overall research question. The original full papers can be found in Appendices A, B, C, and D.

## 3.1. Paper A

Catharina Wiese, Anders Larsen, and Lise-Lotte Pade. Interaction effects of energy efficiency policies: A review. *Energy Efficiency*, 11(8):2137–2156, 2018.

**Objectives** Energy efficiency improvements play a key role in achieving global climate targets. The European Union (EU) and many other jurisdictions have, therefore, introduced specific targets for energy efficiency improvements on, e.g., national and sectoral levels [e.g. European Union, 2018]. In order to comply with these targets, policy intervention needs to address the various barriers to energy efficiency as discussed in Section 2.1. Indeed, an evaluation of the EU's Energy Efficiency Directive (EED) shows that EU Member States have implemented or plan to implement 479 policy instruments in total, with the number of instruments ranging from one to 112 on national levels, in order to comply with the EU's energy efficiency target by 2020 [Zygierewicz, 2016]. Energy efficiency policy often means the implementation of a policy mix, i.e. a combination of multiple instruments all aiming at the same primary target to increase the adoption of energy efficiency measures and to achieve end-use energy savings.

In Paper A, we first give an overview of the range of energy efficiency policy instruments that policy-makers can choose from and second, aim to investigate potential interaction effects among these instruments. Although interaction effects among energy efficiency policy instruments receive increasing attention [Kern et al., 2017, Rosenow et al., 2017], they have not been comprehensively investigated in the policy literature.

| | **Research methods** | **Research contributions** |
|---|---|---|
| **Paper A** | Literature review | Discussion of interaction effects between combinations of energy efficiency policy instruments |
| **Paper B** | Meta-analysis | Analysis of variables that determine households' energy efficiency investments and the practicality of targeted policies |
| **Paper C** | Literature review, hybrid modelling | Simulation of households' investments in energy efficiency retrofits for ex-ante evaluation of energy efficiency policy instruments |
| **Paper D** | Descriptive data analysis | Assessment of the potential to use EU ETS auctioning revenues to finance energy efficiency policies |

Figure 3.1.: Overview of the research methods and the research contributions of Paper A, B, C, and D

We specifically aim at contributing to the emerging research on this policy issue and at identifying future research needs.

**Research methods** For the first part of the paper, we conduct a literature review of energy efficiency policy instruments, including theoretical discussions on policy design and empirical evaluations of policy implementation. Based on the literature review, we evaluate each instrument's strengths and weaknesses using the evaluation criteria effectiveness, efficiency and feasibility. The effectiveness criterion refers to an instrument's power to achieve end-use energy savings. When evaluating an instrument's efficiency, we consider its ability to achieve energy savings at least cost. An instrument's feasibility is determined by institutional demands, such as the need for organisational capacity, and governmental concerns, such as distributional impacts.

For the second part, we also conduct a literature review, specifically focusing on research that investigates interaction effects among energy efficiency policy instruments. The existing literature on this topic is still small and mostly limited to qualitative, theory-based research. We systematically assess the results from Boonekamp [2006], Braathen [2007], Child et al. [2008], Oikonomou et al. [2010], Rosenow et al. [2016]. Drawing on this literature, we first define interaction effects, then assess the underlying factors that determine interaction effects, and present specific interaction effects among various combinations of energy efficiency policies that have been identified so far.

**Results** Our review of policy instruments already served as main input in Section 2.2. The following results therefore focus on our assessment of interaction effects among policy instruments. Interaction effects among energy efficiency policy instruments are theoretically defined as the influence of one instrument on the energy saving effect of another instrument [Boonekamp, 2006]. An interaction effect can be mitigating, neutral or reinforcing. The effect is mitigating, when the energy saving effect of an instrument combination is less than the sum of the savings these instruments would achieve stand-alone. The interaction effect is neutral, when the energy savings of an instrument combination equal the sum of stand-alone energy savings. Thus, the interaction effect is reinforcing, when the energy savings of an instrument combination are larger than the sum of stand-alone energy savings.

Assessing the existing literature on interaction effects among energy efficiency policy instruments, we identify three main factors that determine whether an instrument combination will have a mitigating or reinforcing interaction: (1) the steering mechanism of the combined instruments, (2) the scope, and (3) the timing. (1) The instruments' steering mechanism refers to the type of incentive that the instruments provide to energy end-users. The type of incentive could, e.g., be determined by the instrument categories as defined in this paper. Depending on the category, an instrument steers the behaviour of a target group using different mechanisms. While information provision enables end-users to make a more informed investment decision and raises awareness, a financial incentive reduces the upfront cost of energy efficiency measures and thereby allows end-users with liquidity constraints to adopt these measures. (2) The instruments' scope refers to the overall target to which the instruments pertain. Policy instruments can directly target end-users or end-use sectors, such as financial incentives that are specifically provided to households, but also products and technologies, such as minimum energy performance standards for certain appliances. (3) The instruments' timing refers to the point in time the instruments are implemented. Instrument combinations tend to be mitigating when they apply the same steering mechanism, have the same scope and are implemented at the same time, while they tend to be reinforcing when they are different in at least one of the three categories.

The so far identified interaction effects among policy combinations focus on instruments that have the same scope and are implemented at the same time. Thus, the steering mechanism determines the interaction outcome. These interaction effects show a systematic pattern. Instrument combinations where one instrument enforces a certain energy efficiency target, e.g. regulatory instruments such as minimum energy performance standards, are more likely mitigating. Due to the enforcing mechanism of one instrument, a second instrument does not achieve additional savings beyond the binding target. Instrument combinations that are flexible regarding how the targeted end-users respond to the instruments, e.g. energy taxes and information provision, are more likely reinforcing. The flexibility implies that within this combination one instrument does not hamper, but strengthens the functionality of the other instrument.

## 3.2. Paper B

Geraldine Henningsen and Catharina Wiese. Do household characteristics really matter? A meta-analysis on the determinants of households' energy-efficiency investments. *Under review at Energy Economics*, May 2019.

**Objectives** Policy interventions that aim at increasing households' adoption of energy efficiency measures are usually broadly targeted and provide the same incentive for the majority of households. Households are, however, heterogeneous in many respects, and different households underinvest in energy efficiency measures due to different underlying barriers. To address households' individual barriers to energy efficiency, several studies have emphasised the need to design targeted policies that take into account household heterogeneity [Allcott and Greenstone, 2012, Gillingham and Palmer, 2014, Allcott et al., 2015]. Directly targeting households that fail to adopt profitable measures and, therefore, stand to gain from a policy intervention would ensure effective and efficient policy outcomes. Yet, designing policies that take into account household heterogeneity requires the existence of observable variables that reliably explain households' heterogeneous investment decisions and that are easily accessible for policy-makers. Our paper is, to the best of our knowledge, the first paper that systematically investigates the existence of such variables and discusses the practicality to design targeted energy efficiency policies.

**Research methods** To investigate the existence of observable variables that reliably explain households' heterogeneous investment decisions, we conduct a meta-analysis. Our meta-analysis integrates the empirical results from 63 publications, with a total of 167 different regression results, that analyse the effect of the frequently studied household characteristics income, age of the household head, education, household size, and home ownership status on households' propensity to invest in energy efficiency measures.

A meta-analysis extracts and aggregates the findings from several empirical studies using statistical methods. We integrate $i = 1, ..., m$ regression results for the household characteristics income, age of the household head, education, household size, and home ownership status, respectively.[1] Integrating the regression results from empirical studies that apply different methods and differ in the characteristics of the studied population, we choose a random-effects model as the basis for our meta-analysis.[2] The random-effects model allows unconditional inference by assuming that the analysed studies are a random sample from a larger population of all possible studies [Viechtbauer, 2010, Borenstein et al., 2010]. The model formally assumes that the effect sizes of all analysed studies are samples from different populations whose respective population means are distributed around an overall mean $\bar{\theta}$. More specifically, the random effects model assumes that each effect size can be described by $\theta_i = \bar{\theta} + \phi_i + \epsilon_i$, where $\theta_i$ is the effect size of the $i$th regression result, $\phi_i$ depicts the difference between the overall mean $\bar{\theta}$ and the true mean of the population from which the effect size was sampled, and $\epsilon_i$ represents the sampling error.

Based on this underlying model, we estimate the overall mean $\bar{\theta}$ of the effect sizes for each of the five analysed household characteristics. The estimates correspond to the average effect of each household characteristic on households' propensity to invest in energy efficiency measures in the entire population of studies from which the studies included in the meta-analysis are assumed to be a random sample. Using **R** package metafor [Viechtbauer, 2010], we calculate the weighted mean, $\bar{\theta}_w = \sum_i w_i \theta_i / \sum_j w_j$, where the weights $w_i$ are the inverse of the standard errors of the effect sizes. We compare the weighted mean with two further calculations of mean effects. We calculate the unweighted arithmetic mean, $\bar{\theta}_u = \sum_i \theta_i / m$, where $m$ is the total number of regression results included, and we calculate the mean effects using the study sample sizes of the respective estimates as weights.

Furthermore, we examine the variation across studies by means of a moderator-analysis. The moderator-analysis regresses the effect sizes $\theta_i$ on moderator variables, which we extract from the analysed studies. We include moderator variables that de-

[1] The number of regression results $m$ varies across household characteristics because the large majority of studies included in the meta-analysis does not consider the effect of all five characteristics on households' propensity to invest in energy efficiency measures.

[2] We focus on adoption studies where the dependent variable is either binary or (ordered) categorical. As effect sizes, we calculate semi-elasticities for continuous covariates, i.e. income and households size, and effects for each category of categorical or interval-coded covariates, i.e. age, education and home ownership, at the sample means of the respective study samples. In order to unify the effect sizes for income, age, education, household size, and home ownership across studies, we use the **R** [R Core Team, 2018] package urbin [Henningsen and Henningsen, 2018a,b].

scribe the sample, such as year of the study, country and type of energy efficiency investment under consideration, and moderator variables that describe the model specification, such as degrees of freedom and the use of study-specific covariates. The analysis serves to examine to what extent the moderator variables influence the size of the mean effect $\bar{\theta}_w$ [Viechtbauer, 2010].

We compare the results from our meta- and moderator-analyses with assumptions from neoclassical economic theory derived from a simple micro-economic investment model.

**Results** We find that significant effects exist only when using the study sample sizes as weights and for only some of the household characteristics. Overall, income and home ownership show the clearest trends in explaining households' investment decisions in energy efficiency measures. The findings for income and home ownership status are also in line with assumptions from economic theory as we derive from the micro-economic investment model. Households that have a high income and own their home are more likely to invest in energy efficiency measures than households that have a low income and rent their home. These results confirm that access to capital and financial resources play a role in households' investment decisions for energy efficiency measures, and that split incentives constitute a barrier to energy efficiency improvements. Policy-makers could use these observable household characteristics to account for heterogeneity in policy design, e.g. by targeting financial incentives at households with low income, and property owners through energy efficiency standards for rented properties.

However, the overall magnitude of the trends we find is limited. Furthermore, our moderator analysis shows that the variability of the effect sizes across studies can only partially be explained by model- and sample-specific information. This result suggests a strong situational component in the effect of household characteristics on households' investment decisions. Thus, a major part of the variability across studies exists due to unknown factors. Because of both the limited magnitude of the effects and the strong situational component in the effect of household characteristics on households' investment decisions, we conclude that it is questionable whether targeted policy design, when restricted to easily accessible variables, may serve as a widely applicable tool. Therefore, it is also uncertain whether the additional cost of targeted policies would outweigh its benefits. Simpler policy interventions may in many instances generate the same effect at lower cost. Further developments on the identification of target households are therefore necessary before targeted energy efficiency policy may be put to practice.

## 3.3. Paper C

Kristoffer Steen Andersen, Catharina Wiese, Stefan Petrović, and Russell McKenna. Overcoming the hurdle: meeting Danish energy saving requirements by targeting household investment behavior. *Submitted to Energy Policy*, July 2019.

**Objectives** To comply with Article 7 of the EU's Energy Efficiency Directive (EED) adopted in December 2018, Denmark needs to implement energy efficiency policy instruments that lead to a cumulative reduction in final energy demand of approximately 275 PJ over the period 2021 to 2030.[3] All EU Member States are required to perform ex-ante evaluations of policy instruments that are implemented to achieve these savings. Because energy use for residential heating represents one quarter of Danish final energy demand, heat savings will likely play a key role in meeting Denmark's energy saving requirement.

Ex-ante evaluation of residential energy efficiency polices that aim at incentivising heat savings, however, is difficult. It requires detailed modelling of the effect of policy intervention on households' behaviour with respect to heating demand and investments in energy efficiency measures. The latter is of particular interest in this paper. Quantitative analyses have shown that households behave as if applying high implicit discount rates in their investment decisions for energy efficiency measures [e.g., Corum and O'Neal, 1982, Jaccard and Dennis, 2006, Burlinson et al., 2018, Train, 1985] and fail to adopt measures that would be privately profitable under market conditions.[4] Within energy-economy models, these high implicit discount rates are widely used as a proxy to simulate the (slow) adoption of energy efficiency measures in the residential sector and are in this context referred to as hurdle rates.

We use the IntERACT model, which captures feedback effects between the Danish energy system and the Danish economy, to assess the potential for meeting Denmark's energy saving requirement by reducing the high discount rate implicit in households' investment decisions through policy intervention. The paper specifically focuses on investments in energy efficiency retrofits. We aim at defining a reasonable range of hurdle rates applied to investments in energy efficiency retrofits in IntERACT and at providing transparency on the role of the level of hurdle rate when simulating households' adoption of energy efficiency retrofits; furthermore, at assessing the size of a direct rebound effect, which captures households' behaviour with respect to heating demand. Overall, we aim at demonstrating the potential impact of these behavioural parameters on the results of ex-ante policy evaluations.

**Research Methods** We have divided the paper into two methodological parts. First, we review the literature with respect to empirical estimates of discount rates implicit in households' investment decisions for energy efficiency measures and consider the impact of policy intervention on households' investment behaviour. We furthermore review and discuss the use of hurdle rates in different existing energy-economy models, and specify the levels of hurdles rates that we implement in IntERACT based on our literature

[3]This amount is based on 626 PJ final energy demand in 2017 [Danish Energy Agency, 2018] because the cumulative target must correspond to average annual savings equivalent to 0.8% of Denmark's average final energy demand in the periode 2016 to 2018.

[4]We interpret high implicit discount rates not as an explanation for why households fail to invest in profitable energy efficiency measures but as a restatement of the existence of untapped profitable potential because of the various barriers to energy efficiency [Jaffe et al., 2004].

reviews.

Second, we present technical details for IntERACT and implement different hurdle rate scenarios in the model. IntERACT is a hybrid model built to assess Danish energy and climate mitigation policies. The model is based on an automated iterative soft-linking routine between the energy system model TIMES-DK and a computable general equilibrium (CGE) model of the Danish economy [Andersen et al., 2019]. We specifically focus on where in the model hurdle rates apply and how they affect the model's results. Within the TIMES modelling framework [Loulou et al., 2016], we use the option to apply hurdle rates in the form of technology specific discount rates. More specifically, hurdle rates are introduced by adding a premium to investments in specific technologies so that these investments become less attractive from a cost-minimising perspective. In order to capture the effectiveness of energy efficiency policies, we apply different levels of hurdle rates to households' investments in energy efficiency retrofits. Drawing on our literature reviews, we consider a hurdle of 25% as a reasonable upper bound for simulating households' behaviour with respect to investments in energy efficiency retrofits in the absence of policy interventions. We apply four additional levels equal to 20%, 15%, 10% and 4%, which correspond to a positive and increasing effect of energy efficiency policies on households' investment decisions for energy efficiency retrofits. In the IntERACT model, we analyse the effect of these hurdle rate scenarios on realised energy savings from energy efficiency retrofits and their contribution to achieve Denmark's energy saving requirement, the size of a direct rebound effect and the economic impact on households in terms of disposable income.

**Results** We find that reducing the hurdle rate applied to households' investments in energy efficiency retrofits from 25% to 4% would deliver 146 PJ cumulative energy savings over the period 2021 to 2030. These cumulative energy savings include a direct rebound effect of 37%[5] and correspond to around half of Denmark's cumulative energy saving requirement of the EED. A lower reduction in the level of hurdle rate to 15%, however, would deliver substantially less cumulative energy savings over the period 2021 to 2030, equal to 19 PJ. Thus, the largest energy efficiency potential is realised when the hurdle rate reduces to well below 15%. If the policy objective is to achieve substantial energy savings, this finding would suggest the need for a broad mix of policy instruments, which has the potential to reduce the hurdle rate applied to households' investments in energy efficiency retrofits to a low level.

With respect to the economic impacts, we find that reducing the hurdle rate from 25% to 4% leads to a substantial shift in disposable income across periods. While the disposable income reduces by 0.37 billion Euro in 2020, it increases by more than 0.43 billion Euro in 2030. This shift is driven by the model result that in the 4% hurdle rate scenario energy efficiency retrofits are realised earlier in time and especially before most retrofitted building components have reached their end of life. Thus, the 146 PJ cumulative energy savings, which a reduction in the hurdle rate from 25% to 4% would

[5] We further discuss rebound effects in Section 4.1.

deliver, are to a large extent full cost energy savings as opposed to marginal cost savings, which can only be realised by retrofitting building components that have reached their end of life. The disposable income increases in 2030 due to the future energy cost saving as a result of the realised energy efficiency retrofits. This finding raises the (policy) question whether an early realisation of energy efficiency retrofits should be a policy objective, or whether a more gradual approach, which relies to a larger extent on marginal cost savings, would be more cost-effective.

## 3.4. Paper D

Catharina Wiese, Richard Cowart and Jan Rosenow. Auctioning revenues to foster energy efficiency: Status quo and future potential within the European Emissions Trading System. In *Proceedings of the 2019 ECEEE Summer Study*, pages 321–330, 2019. (peer-reviewed)

**Objectives** Auctioning revenues in the EU's Emissions Trading System (EU ETS) are an increasing source of income for EU Member Sates. This increase is mainly driven by the recent introduction of the Market Stability Reserve (MSR), which addresses the current surplus of emission allowances in the EU carbon market and consequently increases the price of EU allowances. Indeed, the most recent revenue data reveal that total auctioning revenues have increased by around 46% from 2016 to 2017. Total reported revenues in 2017 amount to 5.09 billion Euros.[6]

We propose that strategically investing auctioning revenues in energy efficiency programmes would accelerate decarbonisation efforts and yield various benefits that would reinforce the EU ETS with respect to its primary objective to reduce greenhouse gas emissions cost effectively. The scientific and political discussion on the EU ETS still puts a larger emphasise on the carbon price and its ability to incentivise low-carbon investments with less focus on how the revenues generated through the auctioning of EU allowances are spent. Our paper aims at encouraging a broader debate on the ETS and its ability to reduce greenhouse gas emissions cost effectively, while considering both the carbon price and the opportunity to use auctioning revenues strategically.

**Research Methods** In order to encourage a broader debate on the ETS, we assess the potential to strategically invest EU ETS auctioning revenues in energy efficiency programmes as an alternative approach to advance the ETS and its ability to reduce greenhouse gas emissions. We theoretically discuss the benefits of strategically investing auctioning revenues in energy efficiency programmes and analyse data on Member States' currently realised use of auctioning revenues. We furthermore discuss interaction effects among the EU ETS and complementary energy efficiency policies, while taking into account the recent introduction of the MSR.

[6]This amount of 2017 auctioning revenues does not include the revenues of France, which has not reported its revenues for 2017 yet, and of Bulgaria, which has locked its report for public view.

In the assessment of the use of auctioning revenues, we use the Member States' official reporting on the use of auctioning revenues to the European Environment Agency's reporting obligations database.[7] Since 2014, Member States are required to report annually on the amounts of revenues generated through the auctioning of allowances and the use of these revenues, or the equivalent in financial value. We use the Member States' data reported in July 2018, which present the amount and use of auctioning revenues in 2017. Article 10(3) of the EU ETS Directive 2003/87/EC recommends that Member States should use at least 50% of auctioning revenues or the equivalent in financial value of these revenues for energy- and climate-related purposes. These purposes include the development of renewable energies, measures to increase energy efficiency, shift to low emission and public forms of transport, research and development for clean technologies and energy efficiency, forestry sequestration in the Union, adaptation to the impacts of climate change, coverage of administrative expenses of the management of the ETS scheme, and others. In the official reporting on the use of auctioning revenues to the European Environment Agency, Member States have to specifically reveal the purpose and type of revenue use for energy- and climate-related programmes. We assess these data and complement the assessment by verifying specific energy efficiency programmes and the use of auctioning revenues for these programmes where additional information is available.

**Results** Strategically investing auctioning revenues in energy efficiency programmes would reinforce the ETS and deliver three main benefits.

(1) Additional emission reductions would be achieved at lower economic and societal costs. Strategic investments in energy efficiency programmes would help to realise a larger fraction of cost-effective emissions reduction potential. A carbon pricing instrument alone cannot unlock this potential due to various non-price barriers to energy efficiency. The cost-effective potential would potentially remain untapped if not additional funding for energy efficiency is made available. Furthermore, energy efficiency improvements reduce the energy bill impact of carbon pricing on energy end-users [Cowart, 2011].[8]

(2) Energy efficiency improvements lead to a wide range of multiple benefits. Among those benefits are improvements in health, comfort, air quality, employment, and economic growth, see also Section 1.2.

[7] The Member States' deliveries are available at: `https://rod.eionet.europa.eu/obligations/698/deliveries`, last accessed on 9 July 2019.

[8] The policy mix for reaching decarbonisation targets cost effectively is not limited to energy efficiency policies but could also include, e.g., renewable energy support, and research and development for low-carbon technologies. However, the economic and societal cost advantages of energy efficiency and the need for funding to stimulate efficiency improvements among a large number of end-users make it a particularly important resource to utilise. These advantages are principal justifications for the policies adopted by the EU and other jurisdictions that implement the 'energy efficiency first principle'.

(3) An increase in the political will and social acceptance, as a result of the previous benefits, would support the political process to further tighten the EU ETS cap and enable more ambitious long-term decarbonisation targets.

Our analysis of the Member States' use of auctioning revenues in 2017 reveals that 55.3% of the total revenues are strategically invested in energy- and climate-related purposes, however, no more than 21.4% in energy efficiency programmes.[9] This finding suggests that Member States are largely not aware of the benefits they could achieve. The reported data also show that some of the Member States, specifically Czech Republic and Germany, have invested a large share of 2017 auctioning revenues in energy efficiency programmes. Evaluations of these programmes [e.g. Diefenbach et al., 2018] confirm the opportunity of strategically investing auctioning revenues to deliver energy savings and greenhouse gas emissions reductions, cost savings to consumers, tax revenue to the national budgets, employment, and economic growth.

Critics have frequently argued that national policies, which reduce greenhouse gas emissions in sectors covered by the ETS and reduce the demand for EU allowances, would not achieve emission reductions under the cap-and-trade system but only reduce the carbon price and the ability of the EU ETS to incentivise low-carbon investments [e.g. Baranzini et al., 2017]. However, with the introduction of the MSR, the argued 'waterbed effect' is 'punctured' [Perino, 2018]. Complementary policies that reduce the demand for allowances, increase the surplus, of which a large proportion will eventually be cancelled from the MSR. Thus, national policies can change the number of allowances issued and reduce greenhouse gas emissions under the EU ETS in the long run.[10]

[9] These findings differ slightly from the findings presented in Paper D because, as also clarified in the endnotes of the paper, Ireland revealed not to earmark auctioning revenues for specific purposes after the deadline of the paper. The new results take this change into account.

[10] Silbye and Sørensen [2019] confirm this result. Other studies that analyse the introduction of the MSR and its long-term effect on $CO_2$ emissions, however, find that national policies can increase cumulative emissions [Rosendahl, 2019, Pahle et al., 2019]. The intuition is based on the expectations of market actors. If market actors anticipate a less tight EU ETS market due to national policies that reduce emissions in the future, banking allowances would become less profitable. When the number of allowances that are banked reduces, less allowances enter the MSR and are eventually cancelled. The exact effect of the MSR is still unclear and moreover, a further revision of MSR parameters may be introduced in 2023. In order to validate our argument, we therefore need to study future analyses and consider a potential revision of the MSR in 2023.

# Chapter 4.

# Discussion

Paper A, B, C, and D are diverse with respect to their approaches to address the research question:

> *How can progress in energy efficiency policy effectively increase the adoption of energy efficiency measures by energy end-users?*

In this chapter, we discuss the overall results of this thesis and focus on how Paper A, B, C, and D contribute to progress in energy efficiency policy. Following this discussion, Section 4.1 presents limitations of energy efficiency and points out reasons for why energy efficiency measures may deliver only a fraction of the predicted energy savings. Section 4.2 introduces an outlook on concepts that focus on energy savings as a primary target and that go beyond energy efficiency improvements.

**Overall results** As initially stated, progress in energy efficiency policy means any improvement in the design and implementation of policy instruments. Paper B 'Do household characteristics really matter? A meta-analysis on the determinants of households' energy-efficiency investments' addresses potential improvements in the design of energy efficiency policies. In a meta-analysis, we investigate the existence of observable household characteristics that reliably explain households' investments in energy efficiency measures. The results of the analysis serve to discuss the practicality for policy-makers to use these household characteristics in the design of targeted energy efficiency policies. Directly targeting households that fail to adopt profitable energy efficiency measures will eventually be more effective than targeting all households. We find that household income and home ownership status show the clearest trends in explaining households' investments in energy efficiency measures. Households that have a low income and rent their home show a lower propensity to invest in energy efficiency measures than households that have a high income and own their home. These results suggest that policy-makers could use the household characteristics income and home ownership status to directly target households that face liquidity constraints and situations where split incentives inhibit energy efficiency improvements. Overall, the paper questions whether targeted policies at the individual household level are a widely applicable policy design option because the magnitude of the trends that explain households' energy efficiency investments is limited. This conclusion, however, should not rule out that policy-makers at the local, or other small-scale level, can implement targeted energy efficiency policies and consider income and home ownership status as proxies for households' individual barriers to energy efficiency. Our moderator analysis suggests that the effect of household characteristics on households' decision to invest in energy efficiency measures has a strong situational component. Further assessments that take account of this situational component would therefore be needed at the local level.

Paper C 'Overcoming the hurdle: meeting Danish energy saving requirements by targeting household investment behavior' simulates households' investment decisions for energy efficiency retrofits in the Danish IntERACT model. More specifically, we apply different levels of hurdle rates, i.e. technology specific discount rates, to energy efficiency retrofits in order to capture the effect of energy efficiency policies on households' investment behaviour. The simulation of investment behaviour and the effect of policies is highly relevant for the ex-ante evaluation of energy efficiency policies, which EU Member States are required to perform in order to document their efforts to comply with the EU's Energy Efficiency Directive (EED). Our literature review of the use of hurdle rates in existing energy-economy models reveals that hurdle rates are often introduced arbitrarily and without evidence on the applied magnitudes. We therefore provide a first step towards better understanding the role of hurdle rates within an energy-economy modelling context. To better understand the role of hurdle rates, we use investments in energy efficiency retrofits of Danish households and their contribution to Denmark's energy saving requirement of the EED as a case study. We find that a policy-induced reduction in the hurdle rate applied to households' investments in energy efficiency retrofits from 25% to 4% could deliver up to half of Denmark's energy saving requirement. Our paper does not identify or assess specific energy efficiency policy instruments that could lead to this reduction in the hurdle rate. Instead, we consider the level of hurdle rates as a proxy for the effectiveness of energy efficiency policies. The findings suggest, however, that if ambitious energy saving requirements exist, a broad mix of policy instruments would be required in order to achieve such a substantial reduction in the level of hurdle rate. This policy mix would need to address various hurdles, equivalent to barriers, for households to invest in energy efficiency retrofits. In a lab experiment, informational instruments have, e.g., shown to reduce individual discount rates by 5–10 % [Coller and Williams, 1999]. The impact of informational instruments on discount rates applied to investments in energy efficiency measures, however, may even be smaller due to the challenge to provide information to certain target groups that actually lack information. Additional policies would therefore be needed to meet the level of energy savings associated with the 4% hurdle rate scenario. A policy mix could include information provision to increase overall awareness and thereby stimulate energy efficiency investments, combined with a subsidy for investments in energy efficiency retrofits to overcome liquidity constraints and address risk averse households. As already stated in Section 2.2, several studies confirm the need for an energy efficiency policy mix [e.g. Rogge and Reichardt, 2016, Rosenow et al., 2016, 2017].

Paper A 'Interaction effects of energy efficiency policies: a review' addresses energy efficiency policy mixes and specifically discusses the relevance of interaction effects between instrument combinations. These interaction effects can be reinforcing, neutral or mitigating. Based on the existing literature on this topic, we identify three main factors that determine the interaction outcome: An instrument combination is likely mitigating when two instruments have the same target group, use the same steering mechanism and are implemented at the same time. These factors could be taken into account when designing and implementing energy efficiency policy mixes in order to avoid mitigating effects and promote reinforcing effects that optimise the instruments' combined energy saving effect. Our discussion on the relevance of interaction effects, however, is qualitative and should primarily be considered a first step towards further research on interaction effects between energy efficiency policy instruments. Especially the quantification of interaction effects across different instrument combinations could be subject to future research and could e.g. be modelled in a hybrid energy-economy model such as IntERACT used in Paper C. The IntERACT model can assess the effectiveness of individual policy instruments in terms of energy savings and different combinations of instruments, and thereby identify reinforcing and mitigating combinations.

Paper D 'Auctioning revenues to foster energy efficiency: status quo and future potential within the European Emissions Trading System' assesses the potential for EU Member States to use their revenues from the auctioning of EU allowances to finance national energy efficiency policies. The implementation of energy efficiency policy instruments involves costs. Especially the costs associated with financial instruments such as subsidies, see Section 2.2, can be high. When financed out of a national budget, these costs compete with other government expenditures. Due to this competition, energy efficiency policy instruments may eventually not be prioritised, especially when not taking into account multiple benefits of energy efficiency in cost-benefit policy evaluations. The recent assessment of Member States' National Energy and Climate Plans by the European Commission revealed, however, that the majority of Member States needs to increase energy efficiency efforts in order to achieve Europe's energy and climate targets [European Commission, 2019]. Earmarking auctioning revenues can help to increase and stabilise the amount of financial resources that are available to finance energy efficiency policies given that auctioning revenues do not simply replace other financial resources. The additionality of the strategic use of auctioning revenues needs to be monitored. The approach taken in Paper D also introduces a combined discussion on European climate and energy efficiency policy. This combination may represent an example of the 'energy efficiency first principle', which has been included in the amended version of the EU's EED for the period 2021–2030 [European Union, 2018]. The principle implies that '*energy efficiency is to be treated as an energy source in its own right*' and '*should be taken into account when setting new rules for the supply side and other policy areas*' [European Union, 2018, p. 1]. In the EU's climate policy area, the EU ETS is the primary instrument to incentivise reductions in greenhouse gas emissions. Using auctioning revenues for energy efficiency policies may align the EU ETS with the 'energy efficiency first principle'. In general, the implementation of the 'energy efficiency first principle' will likely increase energy efficiency improvements. According to Rosenow and Cowart [2019], however, it is still unclear how the principle should exactly be applied across the energy system. Future research should define concrete areas, including climate policy and the EU ETS in particular.[1]

Paper A, B, C, and D indicate how progress in energy efficiency policy can increase the adoption of energy efficiency measures. The papers specifically cover the design of targeted policies, the implementation of policy mixes, the discussion of interaction effects when designing and implementing instrument combinations, and the financing of policy instruments. The papers' insights on these topics may help to increase energy efficiency efforts and their contribution to transform energy systems and mitigate climate change. Energy efficiency, however, also has limitations, which we discuss in the following section.

## 4.1. Limitations of energy efficiency

We discuss two categories of limitations, which may reduce the energy saving impact of energy efficiency policies and individual measures: (1) rebound effects, and (2) technical and socio-technical factors. Any model that predicts energy savings and does not take these limitations into account appropriately, runs the risk to overestimate energy efficiency potentials. We furthermore suggest policy implications regarding the limitations of energy efficiency.

**Rebound effects** When energy efficiency improves through the adoption of an energy efficiency measure, the implicit price of the energy service that this measure delivers reduces. This implicit price reduction induces both substitution and income effects, which affect end-users' consumption and corresponding energy use [Borenstein, 2015, Gillingham et al., 2016]. End-users' response to changes in relative prices are the underlying reason for the potential occurrence of rebound effects.

Focusing on the end-use level, substitution and income effects may cause a direct and indirect rebound effect. The direct rebound effect is commonly defined as the increase in demand for the energy service that becomes relatively less expensive after the energy efficiency improvement because end-users substitute towards this service. Furthermore, the implicit price reduction increases end-users' real income, which means a further increase in demand for the energy service, assuming it is a normal good [Borenstein, 2015, Gillingham et al., 2016]. These increases in demand for the energy service may directly offset energy savings from the energy efficiency improvement that would have been achieved without the end-users' response [Sorrell and Dimitropoulos, 2008]. The indirect rebound effect refers to income effects on the consumption of other (normal) goods and services [Borenstein, 2015, Gillingham et al., 2016]. More specifically, the increase in end-users' real income increases not only the demand for the relatively less expensive energy service but also for other goods and services, which have embodied energy or direct energy use [Sorrell and Dimitropoulos, 2008].[2] Thus, income effects on

[1] In the climate policy area, the interaction between national energy efficiency policies and the EU ETS and its impact on the system's effectiveness in terms of greenhouse gas emission reductions needs to be taken into account, as stated in the previous chapter.

[2] The income effect of energy efficiency improvements, as part of both the direct and indirect rebound

the consumption of these goods and services may indirectly offset energy savings as a result of the energy used to deliver additional goods and services.[3]

Evidence about the scale of rebound effects largely comes from estimates of the direct rebound effect [Sorrell, 2007, Borenstein, 2015, Gillingham et al., 2016], while evidence about the indirect rebound effect is still small [Gillingham et al., 2016, Sorrell et al., 2017] and much dependent on assumptions with respect to end-users' spending behaviour when their real income increases, see e.g. Freire-González [2017]. Empirical estimates of the direct rebound effect show a large variation. Apart from car travels, which are not considered in this thesis, residential space heating is the most studied area of energy end-use. In a review of studies Sorrell [2007] finds estimates in the range of 10–58% for the short-run rebound effect and 1.4–60% for the long-run rebound for space heating.[4] In more recent studies, Aydin et al. [2017] find rebound effects of 27% and 41% among Dutch homeowners and tenants, respectively, and Volland [2016] estimates a mean rebound effect of 30% among households in the United States. These findings suggest that energy efficiency improvements in residential space heating, although partially offset by increases in energy demand for heating, yield final energy savings. Further estimates of rebound effects, however, vary widely by energy end-use, technology and other contextual factors, e.g. present energy prices and income groups [e.g. Sorrell, 2007, Borenstein, 2015, Gillingham et al., 2016, Aydin et al., 2017, Sun, 2018]. Contextual factors may also include some of the barriers to energy efficiency discussed in Chapter 2 in the sense that end-users that are e.g. imperfectly informed about the availability of and the energy saving potential from energy efficiency improvements or boundedly rational also pay less attention to relative price changes, which would reduce the rebound effect [Borenstein, 2015].

Yet, the potential occurrence of rebound effects has policy implications. From a welfare perspective, substitution and income effects, and the corresponding increases in energy use reflect a welfare improvement because end-users optimise behaviour in response to a change in relative prices [Borenstein, 2015]. From this perspective, rebound effects may be seen as a benefit instead of a limitation of energy efficiency. The welfare improvement, however, may be countered by increased losses from e.g. negative environmental externalities of energy production and consumption [Gillingham et al., 2016]. Continuing the environmental perspective, failure to take account of rebound effects

effect, largely depends on the cost of adopting energy efficiency measures. Given the existence of profitable energy efficiency potential with net monetary savings over the long term as considered throughout this thesis, the income effect is likely positive [Borenstein, 2015] and contributes to the direct and indirect rebound effect as explained.

[3]The categorisation of the rebound effect into direct and indirect, and its corresponding definitions may vary in the literature. However, the presented categorisation is most commonly applied and follows, e.g., Greening et al. [2000]. In addition to the direct and indirect rebound effect, changes in relative prices may also lead to market responses on a macroeconomic level, such as price and quantity adjustments throughout an economy [Gillingham et al., 2016]. This thesis, however, focuses on final energy demand at the end-use level and will therefore not discuss macroeconomic effects in detail.

[4]The rebound effect is expressed as a percentage of predicted energy savings that is not achieved due to the end-users' behavioural response.

could lead to less energy savings than required to achieve climate targets [Sorrell, 2007]. Reductions in final energy demand are required in order to transform energy systems to align them with the global climate targets, see Section 1.2. Energy efficiency policies may therefore be combined with policy instruments that keep the price for energy services relatively constant while energy efficiency improves, e.g. taxes on emissions or energy use, in order to reduce rebound effects [e.g. Vivanco et al., 2016]. The specific role of rebound effects in policy design and implementation, however, needs to be based on relevant evidence for individual policy contexts. Furthermore, it should be considered in combination with other reasons for why energy efficiency measures may deliver only a fraction of the predicted energy savings.

**Technical and socio-technical factors** Technical and socio-technical factors are in the literature primarily discussed in the context of energy efficiency measures within buildings, such as insulation for various building envelop components, and heating and cooling technology, or the construction of new and energy-efficient buildings. In this context, technical and socio-technical factors at three sequential stages [De Wilde, 2014, McElroy and Rosenow, 2019] may explain why energy efficiency measures may deliver only a fraction of the predicted energy savings: (1) at the prediction stage; (2) during the installation of an energy efficiency measure or the construction of an energy-efficient building; and (3) at the operational stage.[5]

(1) Especially in the context of energy efficiency measures within buildings, predictions of energy savings still rely on engineering models and simulations in many instances [McElroy and Rosenow, 2019]. As already mentioned in Section 2.1, however, engineering models are prone to overestimate energy efficiency potentials [e.g. Gillingham and Palmer, 2014, Gerarden et al., 2017, Fowlie et al., 2018] and they depend on various and potentially inaccurate assumptions. An often discussed issue in the building context refers to assumptions regarding energy use within existing buildings before the installation of an energy efficiency measure [McElroy and Rosenow, 2019]. Indeed, engineering models have been found to assume a too high pre-installation energy use and, as a result, predict an overly large energy efficiency potential [e.g. Sunikka-Blank and Galvin, 2012, Rosenow and Galvin, 2013, Brøgger et al., 2018]; known as 'prebound effect'. Thus, at the prediction stage, inaccurate modelling may overestimate the potential energy savings from energy efficiency measures.

(2) Prediction models typically assume perfect installation and maintenance of energy efficiency measures [Gillingham and Palmer, 2014]. Yet, evidence shows that if

[5] We have defined rebound effects as end-users' response to relative price changes, as they are commonly defined in the economics literature. The introduction to technical and socio-technical factors presents an engineering and sociological perspective on limitations of energy efficiency; considering that technologies are embedded in socio-technical systems. This introduction is not exhaustive, but serves to emphasise the large variety of reasons for why energy efficiency measures may deliver only a fraction of the predicted energy savings discussed in the scientific (and grey) literature.

energy-efficient technology is installed and maintained badly, its performance in terms of energy savings may decrease [McElroy and Rosenow, 2019]. At the installation or construction stage basic practical factors such as the installer's level of training and the quality of workmanship may therefore represent socio-technical explanations for why energy efficiency measures may deliver only a fraction of the predicted energy savings.

(3) At the operational stage, end-users interact with or actively use energy-efficient technology and they may do so differently than intended [McElroy and Rosenow, 2019] or heterogeneously across end-users (Chapter 2). Both unintended and heterogeneous user behaviour are typically not captured by prediction models, however, the way energy-efficient technology is ultimately used affects final energy savings [e.g. Gram-Hanssen, 2013, Hansen et al., 2018, Madsen, 2018]. Thus individual user behaviour may reduce the energy saving impact of energy efficiency measures.

These technical and socio-technical factors have so far only received limited attention regarding policy implications. They could, however, have implications at each of the presented stages. Future research could address quality standards with respect to policy evaluation, monitoring and verification in order to reveal the technical and socio-technical factors that influence realised energy savings. At the installation or construction, and the operational stage, approaches such as installer standards and user training could be assessed when they already exist or recommended for future implementation [McElroy and Rosenow, 2019].

Altogether, both rebound effects and technical and socio-technical factors represent limitations to energy efficiency. These limitations need to be taken into account in cost-benefit evaluations of energy efficiency policies as they may reduce benefits in terms of energy savings and the associated multiple benefits, and potentially increase costs of policy implementation, when, e.g., the requirements for monitoring and verification become stricter. Furthermore, when energy efficiency measures deliver only a fraction of the predicted energy savings, this deficit needs to be traced in order to judge whether or not additional energy saving efforts are required to reach the global climate targets of the Paris Agreement.[6]

## 4.2. Beyond energy efficiency

Additional energy saving efforts beyond energy efficiency improvements may be needed considering that demand for energy still shows an increasing trend in most regions around

[6] Additional to the limitations of energy efficiency discussed in this section, we note a further and more general limitation. Energy efficiency improvements alone, although playing a key role, will not be sufficient to achieve a transition to energy systems with 'net-zero' $CO_2$ emissions. Indeed, further advancements are required also with respect to e.g. electrification of energy end-use and storage technology to facilitate the integration of high shares of renewable energy sources [e.g. Kittner et al., 2017].

the world, including Europe [IEA, 2018c, Tzeiranaki et al., 2019].

In the literature related to research on energy efficiency improvements, increasing attention is therefore paid to the concept of energy sufficiency [e.g. Sorrell et al., 2017, Thomas et al., 2019, Darby and Fawcett, 2018, Toulouse et al., 2019]. According to Sorrell et al. [2017] the concept is viewed in two ways. (1) '*Some authors consider energy sufficiency to be a particular level of energy service consumption that is consistent with human well-being and environmental limits.*'. (2) '*Others consider it to be a reduction in energy service consumption that has the effect of reducing the energy and environmental impacts of that consumption*' [Sorrell et al., 2017, p. 24]. The first view defines energy sufficiency in broad terms and requires both a quantitative assessment of resource availability and sustainable depletion rates in order to define environmental limits, and a qualitative judgement on acceptable levels of energy services that are consistent with human well-being [Darby and Fawcett, 2018]. Darby and Fawcett [2018] comprehensively discuss energy sufficiency in broad terms and specifically reflect on the complex task to distinguish between human needs and wants in order to define 'acceptable levels of energy service consumption'. The second view refers to energy sufficiency as actions, which reduce the consumption of energy services beyond energy efficiency improvements in order to eventually stay within environmental limits [Sorrell et al., 2017, Thomas et al., 2019]. This view takes account of that energy efficiency improvements by definition, see Section 1.1, reduce the energy input needed to deliver a certain level of energy service in order to achieve energy savings. Energy sufficiency actions instead aim at reducing the level of energy services demanded in the first place [Thomas et al., 2019].

This section introduces the second view on energy sufficiency, and specifically the distinction between energy efficiency policy and energy sufficiency policy. We intend to somewhat broaden the major focus of this thesis on energy efficiency policy that aims at increasing the adoption of energy efficiency measures to also introduce energy sufficiency policy that promotes sufficiency actions and absolute reductions in energy (service) demand. We introduce energy sufficiency in a developed country context where there is ubiquitous energy coverage and do not consider cases where people do not have sufficient access to energy services to support their well-being, yet. Furthermore, developed countries show high per capita $CO_2$ emissions [IEA, 2018e], which likely exceed environmental limits. In this context, energy sufficiency therefore implies the need to reduce energy demand in many instances.

Energy sufficiency actions may comprise the following subcategories [Brischke et al., 2016, Sorrell et al., 2017, Toulouse et al., 2019].

- The ownership and usage of energy-intensive products and services reduce.
- Less energy-intensive services substitute energy-intensive services, such as drying washing outside instead of using a tumble dryer.
- Reasonable sizing ensures that energy is not wasted due to oversized products.
- Sharing of products can optimise demand for energy services.

- Lifestyle changes can promote low-energy practices, such as living on smaller floor space and biking instead of driving the car.

Sufficiency policies can support these actions [Bertoldi, 2017, Toulouse et al., 2017, Thomas et al., 2019]. Sufficiency policies together with energy efficiency policies should jointly aim at reducing final energy demand, which implies they should not work against each other [Thomas et al., 2019]. Energy labels and minimum energy performance standards, see Section 2.2, have been discussed to not fulfil this implication and we therefore use them to reflect on the distinction between energy sufficiency policy and energy efficiency policy. Both energy labels and minimum energy performance standards are efficiency-focused policy instruments [Darby and Fawcett, 2018]. Labels show information on the efficiency standard of appliances and technologies, while standards typically define a required ratio of energy (service) output to energy input. Especially for cold appliances and washing machines, however, energy performance standards are easier to meet when producing larger appliances out of technical reasons [Thomas et al., 2019, Darby and Fawcett, 2018]. While labels and standards may increase purchases of high efficiency appliances, they may at the same time incentivise the use of oversized appliances. A sufficiency policy could in this example introduce progressive appliance standards, which become stricter for larger appliances and may even include absolute limits on energy use per appliance instead of energy efficiency requirements [Bertoldi, 2017, Toulouse and Attali, 2018]. Further policies, which address different subcategories of energy sufficiency actions, have been proposed such as the regulation of average floor space per person [e.g. Thomas et al., 2019].

Considerations of energy sufficiency policy are, however, still limited and require future research that addresses the challenge to identify where additional energy saving efforts are needed in order to stay within environmental limits while respecting acceptable levels of energy service provision. Future research may furthermore address the challenge to overcome the reluctance of policy-makers to consider energy sufficiency actions in their decision making because the concept of energy sufficiency is mainly associated with prohibitions and inacceptable intrusiveness in people's lifestyles [Toulouse and Attali, 2018]. To overcome this challenge may require a focus on possible policy intervention that incentivises and encourages sufficiency actions, but does not prohibit other actions. While this section could be seen as an outlook to progressive research topics within the energy efficiency field, we have deliberately placed it in the discussion chapter because as Darby and Fawcett [2018] recognise '*sufficiency will always be contentious*', however, it may be an important concept to consider, '*at a time when so much is at stake for climate, biosphere and human welfare*' [Darby and Fawcett, 2018, p. 21].

# Chapter 5.

# Conclusions

Energy efficiency improvements and the resulting energy savings are expected to play a key role in the transition of energy systems to systems with net-zero $CO_2$ emissions by 2050 and the achievement of the global climate targets set in the Paris Agreement. Reaching these targets is challenging, however, at the same time highly important in order to avoid major climate disruptions. Decision-makers around the world increasingly acknowledge the urgency to accelerate efforts to combat climate change and to implement policy instruments in order to support these efforts where progress would not happen or happen too slow without policy intervention.

Policy instruments that support the achievement of energy efficiency improvements are the main subject of this thesis. Throughout the previous chapters and in Paper A, B, C, and D, we point out how progress in energy efficiency policy can effectively increase the adoption of energy efficiency measures.

We address the design of policies that target individual households based on observable household characteristics, which determine households' investments in energy efficiency measures (Paper B). Policy-makers may consider the household characteristics income and home ownership status to directly target liquidity constraint households and situations where split incentives inhibit energy efficiency improvements. We simulate households' investment decision for energy efficiency retrofits in Denmark and draw the conclusion that if Denmark aims at achieving substantial energy savings in the residential heating system, it would likely require a broad mix of policy instruments that reduce the households' hurdle to invest in energy efficiency retrofits (Paper C). With respect to policy mixes, we discuss the risk for interaction effects between instrument combinations and define factors that could be taken into account when implementing and designing policy mixes in order to avoid mitigating effects (Paper A). These factors include the steering mechanism of the instruments, the scope and the timing of implementation. Furthermore, we suggest the potential use of EU ETS auctioning revenues to finance national energy efficiency policies and assess the current use of auctioning revenues in EU Member States (Paper D). In 2017, Member States have used 21.4% of total auctioning revenues (5.09 billion Euros) to finance energy efficiency programmes. Because auctioning revenues will likely increase over the next years, there exists an increasing opportunity to strategically use auctioning revenues for energy- and climate-related purposes and to thereby achieve several benefits, such as additional and cost-effective greenhouse gas emission reductions.

Overall, also the following topics may get further attention in future research and policy-making.

- The assessment of economic energy efficiency potential at various end-use levels, considering all costs and multiple benefits of energy efficiency improvements, may increase the potential that would be optimal to realise from a societal perspective. This assessment needs to take into account the discussed limitations of energy efficiency in Chapter 4 as they may reduce benefits and increase costs. A complete assessment across end-use sectors may reveal which sector has the highest economic potential and may be prioritised when defining the target sectors of energy efficiency policies.
- Barriers that inhibit the adoption of energy efficiency measures are often measure-specific and depend on situational circumstances at the end-use level. The identification of these measure-specific barriers and situational circumstances may enable policy makers to design and implement policy instruments that take them into account and address them appropriately.
- The quantification of interaction effects between instrument mixes may ensure that mitigating effects do not reduce the potential energy savings from energy efficiency policy interventions. The importance of this topic will likely increase in relevance the more instruments are implemented on national and local levels in order to comply with energy efficiency targets.

Progress in energy efficiency policy is needed in order to increase energy efficiency improvements and be able to achieve substantial reductions in energy demand that help to reach the global climate targets. According to the International Energy Agency (IEA), energy efficiency improvements could on a global scale realise more than 40% of the greenhouse gas emission reductions by 2040 to be in line with the Paris Agreement [IEA, 2018c]. The research topics covered in this thesis may contribute to progress in energy efficiency policy and help to realise a larger fraction of untapped energy efficiency potential.

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# Appendix A.

# Interaction effects of energy efficiency policies: a review

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REVIEW ARTICLE

# Interaction effects of energy efficiency policies: a review

**Catharina Wiese · Anders Larsen · Lise-Lotte Pade**

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**Abstract** Increasing energy efficiency and savings will play a key role in the achievement of the climate and energy targets in the European Union (EU). To meet the EU's objectives for greenhouse gas emission reductions, renewable energy use and energy efficiency improvements, its member states have implemented and will design and implement various energy policies. This paper reviews a range of scientific articles on the topic of policy instruments for energy efficiency and savings and evaluates the strengths and weaknesses of different measures. The review demonstrates the variety of possible instruments and points to the complex policy environment, in which not a single instrument can meet the respective energy efficiency targets, but which requires a combination of multiple instruments. Therefore, the paper in particular focuses on assessing potential interactions between combinations of energy efficiency policies, i.e. the extent to which the different instruments counteract or support one another. So far, the literature on energy efficiency policy has paid only limited attention to the effect of interacting policies. This paper reviews and analyses interaction effects thus far identified with respect to factors that determine the interaction. Drawing on this review, we identify cases for interaction effects between energy efficiency policies to assess their potential existence systematically and to show future research needs.

**Keywords** Energy efficiency · Energy savings · Policy instruments · Interaction effects · Household energy consumption · Industry energy consumption

In the original publication, 8 paragraphs under subsection Interaction cases were incorrectly set as footnotes of table 2.

C. Wiese (✉) · L.-L. Pade
Department of Management Engineering, Systems Analysis Division, Technical University of Denmark, Produktionstorvet Building 426, 2800 Kongens Lyngby, Denmark
e-mail: catwi@dtu.dk

A. Larsen
Department of Social Sciences and Business, Roskilde University, Universitetsvej 1, 4000 Roskilde, Denmark

## Introduction

Energy efficiency policy will play a key role in meeting the EU's energy targets, addressing environmental, energy security and economic challenges. Policy makers can choose from a range of policy instruments to foster future energy efficiency and savings[1] and indeed, they have chosen to implement multiple policy instruments on various policy levels all targeting efficiency and savings. Given the policy crowded environment, policy interactions are inevitable (Oikonomou et al. 2010; Rosenow et al. 2016). As the number of implemented instruments increases, so does the incidence of interactions between them. These interactions may be complementary and mutually reinforcing; however, there may

[1] We use the classical definitions of energy efficiency and savings: Energy efficiency relates to the ratio between energy consumption and the amount of energy service or production obtainable, whereas energy savings concern the absolute reduction in final energy consumed, which the end-user can achieve through investment in technical energy efficiency improvement or behavioural change. In this paper, both concepts represent the same policy target of a reduction in final energy consumption.

as well be a risk for overlapping policies and mitigating effects between them (Boonekamp 2006; Braathen 2007, Oikonomou et al. 2010; Rosenow et al. 2016).

In November 2016, the European Commission proposed a binding energy efficiency target for the EU of 30% energy savings until 2030 compared to business as usual scenario (European Commission 2016). This target will likely become even more stringent in view of the European Energy Roadmap 2050, in which the European Commission highlights that the focus in transforming the future energy system should remain on energy efficiency and savings. They propose that a sustainable transformation requires further improvement with respect to energy efficiency of new and existing buildings, efficiency investments by households and companies, and incentives for behavioural change (European Commission 2011). Considering that the need for a well-functioning instrument mix will likely increase, it is crucial for policy makers to achieve a better understanding of the effectiveness of different instruments and especially instrument combinations.

This paper provides an overview and evaluation of major energy efficiency policies that aim at increasing efficiency and savings on a household, and small and medium-scale industry level. Furthermore, it investigates the potential interaction effects between different combinations of these policies.[2] Interaction effects between energy efficiency policies are to date underrepresented in the literature (e.g. Markandya et al. 2015; Rosenow et al. 2016). This paper shall reduce the gap of knowledge by gathering and analysing interaction effects, which the limited research on this topic has identified so far. Drawing on this analysis, we define relevant influencing factors and exemplify specific interaction cases.

The structure of the paper is as follows. In section 2, we review a number of policies for energy efficiency and savings and assess these policies with respect to effectiveness, efficiency and feasibility criteria. In section 3, we focus on interaction effects between combinations of policy instruments, applying an assessment of interaction effects between energy efficiency policies. Section 4 summarises the results and discusses the need for future research and section 5 concludes the paper.

[2] Future research could make a similar assessment shifting the scope to further sectors, e.g. public, commercial and large-scale industries, where different policies and policy interactions would be relevant to investigate.

## Review of policy instruments for energy efficiency and savings

One major rational for implementing energy efficiency policy is to reduce negative externalities associated with the production and consumption of energy, i.e. primarily greenhouse gas emissions. Following traditional economic theory and assuming that negative externalities are the major market failure to address in order to reduce final energy consumption, a single instrument could cost-effectively lead to a pareto-optimal outcome (Stiglitz and Rosengaard 2015). In that case, the internalisation of external costs, e.g. through energy taxation, and the associated increase in energy prices would incentivise the reduction of (fossil) energy use by absolute savings or energy efficiency investment (Lecuyer and Bibas 2012). Applying market-based instruments as a first best solution requires fully competitive market conditions besides the externality, e.g. rationality of individuals, perfect information and lack of transaction costs. Yet, researchers in this field commonly argue that in the markets for energy efficiency and savings market failures and barriers beyond the negative externality problem exist. These market failures and barriers cause a suboptimal level of energy efficiency, i.e. from an economic point of view, energy end-users have not realised all cost-effective efficiency potential, and explain the existence of the ‘energy efficiency gap’ (Jaffe and Stavins 1994). The failures and barriers include, e.g. imperfect and asymmetric information, principal agent problems, behavioural failures, including bounded rationality, and limited access to capital.[3] Thus, the portfolio of energy efficiency policies also includes instruments addressing these failures and barriers: financial incentives, regulatory and non-regulatory measures, and information and feedback.

A large number of instruments and an equally extensive amount of literature on policies aiming at energy efficiency improvements and absolute energy savings exist. The review gives an overview of instruments promoting energy efficiency and savings at the end-use level. Thus, the considered instruments create a framework or requirement for industries or households to invest in energy efficient

[3] Market barriers include any disincentives to invest in energy efficiency or reduce energy consumption. Not all barriers can be defined as a market failure in a welfare economic perspective, e.g. uncertainty, irreversibility of energy efficiency investment and bounded rationality. For a detailed discussion on market failures and barriers to energy efficiency see for example Gillingham et al. (2009); Jaffe and Stavins (1994), Linares and Labandeira (2010).

technology and products or provide an incentive to save energy through behavioural change. As the specific implementation of a policy instrument is context dependent, the aim is to point at generally relevant policy characteristics in the following assessment.

Comparative assessment

Table 1 shows the assessment of energy efficiency policies, defining policy categories and applying effectiveness, efficiency and feasibility criteria. A major criterion to evaluate policies aiming at energy efficiency and savings is the extent to which they are effective in fostering energy efficiency improvements and increasing energy savings. Static efficiency (i.e. cost-effectiveness) assesses the ability of an instrument to achieve its target at least cost. This efficiency criterion requires the policy design to realise the relatively cheapest savings first. Dynamic efficiency, which will partly be included in the assessment, defines the ability of an instrument to give a long-term incentive for technological progress. The feasibility criteria refer to institutional demands, i.e. organisational capacity or knowledge that is required for the implementation of a policy, and governmental concerns, i.e. distributional impacts, administrative costs and other positive or negative effects that may be of concern for a governmental regulator. In the following, a number of theoretical and empirical studies highlight different aspects of the table.

*Market-based instruments*

A too low energy price that does not internalise the external costs caused by energy production and consumption discourages the adoption of energy efficiency and saving measures. Market-based instruments challenge this problem by adding external costs to the energy price and thereby incentivising energy efficiency and savings based on market mechanisms (e.g. Stiglitz and Rosengaard 2015).

An energy tax on consumption increases the price of energy, giving a direct incentive to reduce final energy use. However, if end-users do not respond to a change in energy prices, the effectiveness of a tax may be very small. Studies assessing energy price elasticities found inelastic energy demand in the short run, while long-run elasticities are larger (Ferrer-i-Carbonell et al. 2002; Gillingham et al. 2009). Empirical evidence on the impact of energy price changes on the adoption of energy efficient technology and innovation supports the finding of larger long-run elasticities (e.g. Ley et al. 2016; Popp 2002).

Tradable emission permits and emission taxes primarily target emission reductions and we therefore define them as an indirect energy efficiency policy. Yet, energy efficiency improvements and savings are one major way to reduce emissions. The sectors that are covered by a trading scheme or are exposed to emission taxation may pass on their abatement costs and affect final energy prices. Due to this effect, sectors not directly exposed to a price on emissions, typically households and non-energy-intensive industries, also have an incentive to reduce their energy consumption. This indirect impact on energy savings depends on the actual increase in energy prices and the relevant price elasticities (European Parliament 2013; Schleich et al. 2009).

Energy efficiency obligation (EEO) schemes exist in various ways; thus, there is no consistent definition of the incentive mechanism of this instrument. In general, EEOs set a quantitative energy savings target for energy companies (e.g. suppliers or distributors), who have to achieve the targeted reduction in end-use energy consumption in a given period. Within a tradable scheme, the obligated parties receive a certificate for energy saving achievements and can trade these certificates among one another. This instrument design is known as tradable white certificate (TWC) scheme.[4] The TWC scheme uses market mechanisms to achieve cost-effective energy savings, while an EEO scheme is based on a regulatory framework, which, however, leaves it to the obligated parties how to deliver energy savings. To reach the targeted savings, energy companies typically provide financial incentives for energy efficiency investment and/or give information on potential energy efficiency improvement. Thus, on the end-user level, where final energy savings are realised, EEO/TWC schemes translate into financial support or tailored information provision and have the potential to challenge multiple market failures and barriers to energy efficiency (Giraudet and Finon 2014). First, the instrument addresses negative externalities through investments (or purchases of certificates) to fulfil the obligation and thereby the internalisation of additional costs. Second, EEO/TWC schemes address financial barriers and information failures when

[4] See Bertoldi and Rezessy (2008) for a comprehensive overview of fundamental concepts behind tradable white certificate schemes.

**Table 1** Assessment of policy instruments for energy efficiency and savings with respect to effectiveness, efficiency and feasibility criteria

| Policies | Evaluation criteria | | | | | |
|---|---|---|---|---|---|---|
| | Effectiveness | Static/dynamic efficiency | Feasibility—institutional demands | Feasibility—governmental concerns | Summary—strengths and weaknesses | References |
| Market-based instruments | | | | | | |
| Energy tax | The effectiveness of a tax on energy use depends on the size of the tax, the relevant price elasticity and costs for consumers to reduce their energy consumption. When the price elasticity of energy demand is low or the costs for a reduction in energy consumption are high, the energy saving effect may be limited. In both cases, consumers pay the tax instead of reducing their energy consumption. | Flexibility regarding the means to reduce final energy consumption promotes cost reductions.<br>The price effect incentivises technological progress, assuming some price responsiveness. | The regulator needs to set an adequate tax rate, which gives an incentive to save energy/improve energy efficiency—optimally based on the social costs of energy production and consumption. Finding this rate may be challenging. | On the one side, taxes create a revenue, which governments can potentially use to reduce other distortive taxes in their tax system. On the other side, taxes may be regressive, thus impose a greater burden on low-income households. | A tax on energy enables to internalise external costs associated with the production and consumption of energy. The corresponding effect on energy prices gives a direct incentive for cost-effective savings, efficiency improvements and technological change. Taxes create a governmental revenue and thus the possibility for a double dividend. However, low price elasticities and the regressive nature of environmental taxes negatively affect effectiveness and feasibility respectively. | Berkhout et al. (2004);<br>Ferrer-i-Carbonell et al. (2002); Ley et al. (2016);<br>OECD (2013);<br>Popp (2002) |
| Tradable emission permits and emission tax | The energy saving effect of both instruments depends on (1) the costs for alternative abatement options, e.g. if reducing process emissions is cheaper than reducing energy consumption, the energy saving effect may be limited and (2) the permit price or level of the emission tax and the effect on final energy prices. | Flexibility regarding the means to reduce emissions promotes cost reductions.<br>The price effect incentivises technological progress. | The regulator needs to issue a quantity of permits that ensures the effectiveness of the instrument or set an adequate tax rate, which gives an incentive to reduce emissions. Especially the trading scheme requires reliable measurement and monitoring. | Taxes and auctioned emission permits create a revenue, which governments can potentially use to reduce other distortive taxes in their tax system. A free distribution of permits raises distributional issues, e.g. referring to windfall profits for the receiving firms. | Tradable emission permits and emission taxes internalise external costs and the corresponding effect on energy prices can give a direct incentive for cost-effective energy savings, efficiency improvements and technological change. Furthermore, taxes and auctioned permits create a governmental revenue and thus the possibility for a double dividend. However, low price elasticities may limit the energy saving effect. | Bertoldi et al. (2005);<br>European Parliament (2013);<br>Laing et al. (2014);<br>Schleich et al. (2009);<br>Sijm (2005) |
| EEO and TWC schemes | The instruments set a certain energy saving target, which the obligated parties need to achieve. Thus, a certain saving | The market-based policy framework (tradable scheme) and the flexibility in compliance allow for | EEOs/TWCs are demanding with respect to their policy design and operation. The measurement and verification of additional | The definition of the policy framework (target/ measurement/monitoring) involves administrative | EEO/TWC schemes address multiple market failures through a combination of market-based, regulatory, financial and information | Bertoldi and Rezessy (2008);<br>Bertoldi et al. (2010);<br>Giraudet et al. (2011);<br>Giraudet and Finon (2014); |

**Table 1** (continued)

| Policies | Evaluation criteria: Effectiveness | Static/dynamic efficiency | Feasibility—institutional demands | Feasibility—governmental concerns | Summary—strengths and weaknesses | References |
|---|---|---|---|---|---|---|
| | effect is ensured (assuming that the obligated parties fulfil their obligation). The size of the effect depends on the level of ambition. | cost-effectiveness. If the instrument leads to cost-effective energy savings, depends on the concrete policy design. | energy savings due to the obligation schemes are complex. | effort and costs, which are higher for tradable schemes. | measures. They require an administrative effort to design, implement and monitor the instrument and its functionality. This effort comes along with administrative costs, which increase with the complexity of the scheme. | Mundaca (2008); Mundaca and Neij (2009); Rosenow (2012); Togeby et al. (2007) |
| Financial incentives | | | | | | |
| Subsidies and access to capital measures | Financial support stimulates the development and implementation of energy efficient products and technology. The energy saving effect depends largely on the free-rider percentage, which increases fiscal costs without adding effectiveness. Furthermore, a rebound effect, in the sense that the price reduction may result in purchases of larger products using more energy, may decrease the energy saving effect. | The instrument financially supports certain products or technologies. The reduction in initial investment costs of the subsidised product/technology does not incentivise least-cost savings or technological progress. | Optimally, free-riders would need to be identified in order to reduce the fiscal burden. | The provision of financial support causes high fiscal costs, which may cause distributional effects. | By reducing initial investment costs, financial incentives address financial barriers to energy efficiency. They are socially and politically popular, apart from the financing issue. The incentive for energy efficiency investment from the provision of financial support is larger compared to an equivalent increase in energy prices through taxes or tradable permits, a behavioural economics issue. However, the free-rider problem and a potential rebound effect may reduce the effectiveness of the instrument. | Datta and Gulati (2014); Datta and Filippini (2016); Dubois and Allacker (2015); Galarraga et al. (2013); Galarraga et al. (2016); Grösche and Vance (2009), Hou et al. (2016); Markandya et al. (2009); Nauleau et al. (2015) |
| Regulatory measures | | | | | | |
| Codes and standards | Regulatory measures can be highly effective when they set legislative or normative efficiency requirements beyond usual business practice. Yet, mandatory energy efficiency improvements may cause a rebound effect, which reduces the energy saving effect of these measures. | Regulation prescribes the means of achieving energy efficiency and savings. This inflexibility negatively affects static and dynamic efficiency due to potentially high implementation costs and a low incentive to overachieve standards with innovation, | The implementation of regulation is relatively easy. Yet, ensuring the adequacy of the regulated saving option and the monitoring process requires a well-informed regulator. Furthermore, the regulator should constantly update codes and standards, when technology advances fast. | The regulator may question if regulatory measures can in the long run be more effective/efficient than market forces. | Regulatory measures are prescriptive and therefore address information failures, principal agent problems and bounded rationality, and accelerate technology diffusion. Due to their relatively easy implementation and potential effectiveness, codes and standards are popular instruments. However, the prescriptive characteristic of the measures | Augustus de Melo and de Martino Jannuzzi (2010); Jacobsen (2016); Kjærbye et al. (2010); Lu (2006); Nadel (2002); Rosenquist et al. (2006); Schiellerup (2002) |

**Table 1** (continued)

| Policies | Evaluation criteria | | | | | |
|---|---|---|---|---|---|---|
| | Effectiveness | Static/dynamic efficiency | Feasibility—institutional demands | Feasibility—governmental concerns | Summary—strengths and weaknesses | References |
| | | unless a tightening is likely. | | | may lead to high implementation costs. Furthermore, when technology advances fast, there is a risk that standards may deter instead of promote technological progress. | |
| Information and feedback | | | | | | |
| Information provision | The energy saving effect of information provision is hard to assess. It depends on the information design and the individual market situation, e.g. do market participants actually miss information. | Both static and dynamic efficiency are achievable only when information is effective in changing the consumers' behaviour. | No measure-specific concerns. | No measure-specific concerns. | Information measures address incomplete or asymmetric information and behavioural failures, such as bounded rationality. Information is not intrusive and therefore socially and politically popular. However, the energy saving effect is unsure. | Abrahamse et al. (2007); Amecke (2012); Annunziata et al. (2014); Barbetta et al. (2015); Ek and Söderholm (2010); Kjærbye (2008); Larsen and Jensen (1999); Ramos et al. (2015); Steg (2008) |
| Feedback provision | Depending on its quality, frequency and persistency, feedback provision can change energy consumption behaviour and have a significant energy saving effect. However, consumers might as well increase their energy consumption when the feedback shows an unexpectedly low consumption level. The outcome depends on the individual behaviour of end-users. | The installation of smart meters is cost-intensive. These costs can be considered as sunk costs when the installation is e.g. due to regulation. Low cost, e.g. web-based feedback options can be cost-effective. | No measure-specific concerns. | No measure-specific concerns. | Feedback measures make energy consumption more visible and shall increase the awareness among consumers of their individual consumption quantity and potential to control it. However, the instrument requires user engagement, which might limit its potential effectiveness. | Allcott and Rogers (2014); Buchanan et al. (2015); Fischer (2008); Gleerup et al. (2010); Hargreaves et al. (2013); Leiva et al. (2016); Zvingilaite and Togeby (2015) |
| Non-regulatory measures | | | | | | |
| Voluntary agreements | The effectiveness of voluntary agreements highly depends on the individual policy framework: Are negotiated targets | Voluntary agreements provide flexibility in terms of compliance, thus, they are potentially cost-effective. | The measure requires a policy framework, which includes negotiating effective targets, controlling/monitoring compliance and sanctioning non-compliance. | Negotiating and monitoring an agreement causes administrative costs. Industries may get too much influence on policy | Voluntary agreements allow the regulator to set requirements that would have been infeasible with regulation, because the agreements are more | Henriksson and Söderholm (2009); Johannsen (2002); Krarup and Ramesohl (2002); Price (2005); |

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**Table 1** (continued)

| Policies | Evaluation criteria | | | | | |
|---|---|---|---|---|---|---|
| | Effectiveness | Static/dynamic efficiency | Feasibility—institutional demands | Feasibility—governmental concerns | Summary—strengths and weaknesses | References |
| | beyond business as usual efficiency improvements? Is an agreement implemented in combination with incentives that give a motivation to join and/or to comply? Is credible monitoring and sanctioning of non-compliance ensured? Is there an implicit threat for legislative regulation? | Agreements that are negotiated on a sector level support the diffusion of knowledge and innovation. | | making, thus there is a risk for lobbyism. | acceptable by industry. When the requirements are beyond business as usual efficiency improvements, the agreement has an additional energy saving effect. Yet, the agreement requires a well-functioning institutional framework and negotiations, which are demanding for the agreement parties. | Rezessy and Bertoldi (2011); Rietbergen et al. (2002); Stenqvist and Nilsson (2012) |

providing financial incentives for energy efficiency investments and information respectively.

Furthermore, auction mechanisms for energy efficiency investments, e.g. in terms of tendering schemes and capacity market participation, use market-based bidding processes to foster energy efficiency and savings at lowest costs. E.g. in Europe, Germany has launched a tendering program for the support of industrial energy saving investments and the United Kingdom are testing, whether energy efficiency measures could compete in capacity markets (OECD/IEA 2017). However, these mechanisms are to date less established and in a pilot stage.

### *Financial incentives*

Financial incentives address the issue of high investment costs, which constitute a potential barrier for energy efficiency improvements, motivating energy efficiency investments through subsidies (direct payments, tax rebates, grants and loans). Policy makers typically choose to apply these instruments to incentivise specific product purchases (Galarraga et al. 2016) and to support certain technologies (Bertoldi et al. 2013). Empirical findings show that financial incentives increase energy efficiency investment (Datta and Filippini 2016; Datta and Gulati 2014; Markandya et al. 2009); however, they are also associated with two main drawbacks: the free-rider problem and the rebound effect.[5] Researchers in the field have investigated that households and industries are likely to free ride on financial support provided (e.g. Grösche and Vance 2009) and further that subsidies on a product level may increase the number demanded of that product and increase final energy consumption (e.g. Galarraga et al. 2013).

[5] Free-riders are agents who make use of an incentive program, although they would have invested in energy efficiency improvements without any financial support. The free-riding problem therefore challenges the additionality of energy savings achieved through financial incentives. The rebound effect causes an increase in final energy consumption and may occur due to an effective price reduction once energy efficiency improves (Greening et al. 2000). Alternatively, an increase in the total number and the size of certain energy consuming products in use may increase final energy consumption, when e.g. a subsidy reduces initial investment costs (Galarraga et al. 2013; Markandya et al. 2015).

*Regulatory measures*

Within energy efficiency policy, regulatory measures translate into codes and standards, e.g. building codes or energy performance standards. Thus, they typically enforce producers to supply energy efficient options and impose consumers to reduce their energy consumption by installing or purchasing a particular product. Having this impact on decision-making, regulatory measures tackle information failures, bounded rationality and principal agent problems (Linares and Labandeira 2010). As a number of case studies have analysed, appliance standards have a significant energy saving potential (e.g. Augustus de Melo and de Martino Jannuzzi 2010; Lu 2006; Rosenquist et al. 2006; Schiellerup 2002). Further, Kjærbye et al. (2010) show that the tightening of the Danish building codes has been effective with respect to energy consumption per $m^2$. However, building codes give no incentives to achieve efficiency and savings beyond the compliance threshold (e.g. Jacobsen, 2016).

*Information and feedback*

Suboptimal investment in energy efficiency may occur to a significant extent due to information and behavioural failures[6] (e.g. Ramos et al. 2015). Information campaigns, certificates, labels and audits, or feedback measures can address these failures. Certificates and labels give information on the energy efficiency performance of certain products, e.g. buildings and residential appliances. Energy audits provide tailored information on cost-effective energy efficiency and saving potential, mainly on a household or firm level, whereas feedback measures reveal consumers' energy use, e.g. through smart meters, which provide detailed and frequent information on energy consumption, or bills with comparative data (Ramos et al. 2015). Ramos et al. (2015) provide a comprehensive overview of empirical results, which investigate the effect of certificates and labels on the consumers' decision-making process. Looking at sales prices or rents of different energy products, these results show that consumers positively value both measures. Barbetta et al. (2015) provide a case study, in which the provision of information does not have a significant effect on the implementation of energy efficiency investments. They conclude that within public non-residential buildings in Italy, information is not sufficient to promote investments. Further studies have found similar results with respect to the energy saving potential of information provision (e.g. Kjærbye 2008; Larsen and Jensen 1999). Gleerup et al. (2010) study the impact of immediate feedback via text messages or email on household electricity consumption and find energy savings of about 3% due to the feedback measure. Yet, Buchanan et al. (2015) indicate potential problems associated with feedback measures and question their effectiveness, particularly focusing on the necessity of user engagement. In general, the impact of information and feedback measures is unclear.

*Non-regulatory measures*

Rezessy and Bertoldi (2011) define voluntary agreements as, '*tailor-made negotiated covenants between the public authorities and individual firms or groups of firms which include targets and timetables for action aimed at improving energy efficiency or reducing GHG emissions and define rewards and penalties*' (Rezessy and Bertoldi 2011: 7121). As this definition indicates, voluntary agreements primarily target the industry sector; thus, various agreement schemes between governments and industries exist. Johannsen (2002) evaluates the Danish agreement scheme on energy efficiency between the national energy agency and energy-intensive industries. He concludes that the agreement has an impact on the firms' investment behaviour; however, administrative costs are high for both, government and firms. Rietbergen et al. (2002) analyse the long-term agreements on industrial energy efficiency improvement in the Netherlands targeting the energy-intensive manufacturing industry. They conclude that the agreements are effective given ambitious targets, supporting measures (e.g. energy audits, financial incentives and support schemes for innovation) and credible monitoring.

## Energy efficiency and the policy mix

The preceding assessment shows the variety of instruments policy makers can choose from when targeting energy efficiency improvements and a reduction in energy consumption. Indeed, an evaluation of the European Energy Efficiency Directive shows that the member states of the EU have implemented or will implement 479

[6] Information problems include imperfect, asymmetric information and split incentives, and behavioural failures refer to any departure from perfect rationality.

policy measures in total to comply with the European energy efficiency target. The number of policies per country ranges from one to 112 (European Parliament 2012). On a national level, governments commonly implement these policies in a policy mix, i.e. a combination of instruments all aiming at the same primary target of efficiency improvements and savings. Different rationales, of which some are characteristic for energy efficiency policy, explain the use of policy combinations.

As the previous section indicated, market failures and barriers, which lead to a lower energy efficiency level than would be optimal, are a major justification for implementing multiple policies in order to address all existing failures and barriers (Gillingham et al. 2009; Linares and Labandeira 2010; Markandya et al. 2015). According to Tinbergen (1952), who the policy mix literature frequently refers to (e.g. Braathen 2007; Oikonomou et al. 2010; Rosenow et al. 2016), there should be one instrument per market failure to overcome the failure and reach a more efficient outcome. Braathen (2007) discusses this approach and makes the justified case for applying more instruments than market failures when one instrument alone cannot overcome all aspects of a particular failure. Nevertheless, the existence of multiple market failures in the markets for energy efficiency justifies the use of policy combinations. This rationale not only applies with respect to energy efficiency policy, but also constitutes a basic economic rationale that reducing market failure increases social welfare (e.g. Stiglitz and Rosengaard 2015).

Furthermore, the imperfection or failure of a policy instrument itself due to political feasibility or acceptance may lead to the implementation of multiple policy instruments. In the case of energy efficiency, exemptions from regulation for some selected target groups are common practice and lead to distortive incentives for energy efficiency and savings. Additional instruments may repair these distortions of among others energy tax exemptions in particular due to competitiveness reasons (Council Directive 2003/96/EC). In that case one instrument compensates for the weakness of the other instrument and thereby increases the robustness of achieving given policy targets. Thus, policy making, which certainly cannot be exogenous of the wider political process, may require various policy approaches and therefore the implementation of instrument combinations.

The specific characteristic of energy efficiency policy that it can target different groups of end-users, and also products and technologies, represents another rationale for the combination of multiple instruments. The potential to realise reductions in final energy consumption is diverse. E.g., energy savings are achievable on an industry and on a household level, moreover, through technological efficiency improvements and behavioural change. Considering this complexity, it is reasonable that not a single instrument can achieve energy efficiency improvements and savings, but a combination of instruments, which address the various target groups and aim at different behavioural factors. The following section 3 will investigate the potential interactions between instruments in a policy mix.

## Interaction effects of energy efficiency policies

The implementation of multiple instruments all targeting a reduction in energy consumption inevitably promotes interactions between these instruments. While a number of studies looks at the interactions between energy and climate policies (Spyridaki and Flamos 2014), especially between the EU emissions trading scheme and policies for renewable energy use (e.g. Del Rio 2010; 2007; Fischer and Preonas 2010; Gawel et al. 2014; OECD 2011; Sorrell et al. 2003), only a limited number of research has addressed interactions between policies directly aiming at energy efficiency and savings. The following section first clarifies the specific definition of interaction effects. Second, in order to get an overview of how researchers have assessed interactions between energy efficiency policies so far, section 3.2 provides a literature review of relevant studies. Third, section 3.3 further assesses the results and conclusions that these studies have drawn. The assessment aims at investigating specific factors that influence the interaction effect between instrument combinations and highlighting certain patterns looking at interaction cases, and thereby at contributing to the research on interaction effects between energy efficiency policies.

### How interaction is defined

Boonekamp (2006) introduced a definition of interactions between energy efficiency policies and this definition became dominant in the literature. It states that a policy interaction means the influence of one measure on the energy saving effect of another measure and this influence can be mitigating, neutral or reinforcing. An instrument combination is mitigating or overlapping when the combined saving effect is less than the sum of the saving effects these instruments would achieve stand-alone. When the combined effect is larger, the combination is reinforcing or complementary (Oikonomou et al. 2010; Rosenow et al. 2016). Thus, for a neutral combination, the combined saving effect is equal to the sum of the individual saving effects.

This dominating definition for interactions between energy efficiency policies focuses on, first, direct interactions on the instrument level, which '*may occur when the targets or design characteristics of a policy instrument may affect the functioning or result of another policy instrument*' (Spyridaki and Flamos 2014: 1091); second, on the impact of interactions on energy savings, i.e. the effectiveness of instrument combinations. Thus, the assessment of interaction effects between combinations of energy efficiency policies largely leaves out of consideration other policy evaluation criteria, e.g. cost-effectiveness or feasibility concerns, as e.g. applied in the comparative assessment of individual energy efficiency policies in this paper (see Table 1). We will further discuss this limitation in section 4.

## Literature review

The majority of research on interactions between energy efficiency policies applies qualitative, theory-based approaches, which may reflect the complex policy setting described in section 'Energy efficiency and the policy mix'. These approaches commonly focus on policy design characteristics as a main source of interactions and assess their specific cause and effect during the implementation and operation of policy instrument combinations. The following review presents the limited literature that addresses interactions between instruments for energy efficiency and savings and shows its particular research focus.

Boonekamp (2006) conducts an ex-post analysis of interactions between household energy efficiency policies in the Netherlands from 1990 to 2003, e.g. building codes, information measures and financial incentives. He applies a qualitative approach using a matrix of policy combinations to assess pairwise interaction effects. As a basic element of the assessment, Boonekamp defines four different conditions for a successful implementation of saving options: availability, sufficient knowledge, no restrictions, and motivation. Considering overlaps or synergies in the conditions, which different policies address, he assesses the strength and type of interactions between policy combinations. Within his quantitative approach, which is an exception in the predominantly qualitative research on energy efficiency policy interactions, he quantifies the interaction effects between three major measures (energy tax, investment subsidy and regulation of gas use for space heating) using a bottom-up energy simulation model. Simulating the combined saving effect of these measures, Boonekamp's results show mitigating effects between them. As a concluding remark, he claims that a higher efficiency requirement and intensity of measures may increase mitigating interaction effects and further challenge the effectiveness of policy combinations. To benefit from reinforcing interactions a better tuning and timing of combinations is necessary.

Braathen (2007) conducts a case study analysis and assesses interactions between various environmental policies, among those, instrument mixes for residential energy efficiency in the United Kingdom. He identifies possible positive interactions between instruments, e.g. considering the effect of information provision, and negative interactions, e.g. looking at flexibility restrictions and redundancy issues. The article emphasises that interaction effects are case specific; thus, policy makers need to evaluate both possible interaction outcomes within their specific social, political and economic context in order to apply effective and efficient instrument mixes. Braathen's study builds on a project at Organisation for Economic Co-operation and Development (OECD): 'Instrument mixes for Environmental Policy' (OECD 2007).

Child et al. (2008) analyse interactions between TWCs and other instruments that aim at a more sustainable use of energy in Europe, i.e. tradable green certificates, the EU emissions trading scheme and energy efficiency policies (namely building energy certificates; energy taxes; subsidies; soft loans; performance standards and appliance labelling; voluntary/negotiated agreements; and information, education and audits). In their research framework, they compare and assess the design and implementation process of TWCs and energy efficiency policies, e.g. with respect to policy objectives and obligated parties, and thereby identify potential complementarities or overlaps when they operate simultaneously. Child et al. primarily consider TWCs as an instrument that provides financial support and therefore emphasise its reinforcing saving effect due to a larger amount of affordable energy savings in combination with all other energy efficiency policies.

Oikonomou et al. (2010) make use of the energy and climate policy interactions (ECPI) model developed by University of Groningen and National Technical University of Athens. The ECPI model is a decision support tool for policy makers, incorporating their individual preferences, and uses a qualitative multi-criteria framework for the (ex-ante) analysis of policy interactions. Taking into account environmental, socio-political, financial, macro-economic and technological criteria, the tool measures, if interacting combinations of instruments provide an added value (see also Oikonomou et al. 2014; Oikonomou et al. 2012; Oikonomou and Jepma 2008). Oikonomou et al. (2010) use the ECPI model to assess different instrument combinations that address energy end-users: energy and carbon tax, subsidies for energy efficiency, labelling in buildings and white certificates. They find that only subsidies show a reinforcing interaction effect in combination with the other instruments. However, as the results highly depend on the policy makers' preferences, the use of the model aims at emphasising that the analysis of interaction effects should consider multiple criteria and does not provide a generally applicable rating of interaction effects.

Rosenow et al. (2016) conduct an analysis of policy instrument combinations within building energy efficiency in 14 EU countries. They analyse the results of both a theory-based evaluation of policy combinations and a survey among experts within the field of energy efficiency policy to identify the effectiveness of different combinations and illustrate common combinations in the building sector (e.g. voluntary agreements with purchase subsidies and information measures with regulation). The analysis shows that policy makers have implemented many reinforcing policy combinations in the building sector. However, a major finding is also that purchase subsidies and access to capital measures, which governments commonly apply, tend to overlap and reduce the energy saving effect in combination. Rosenow et al. conclude that these results are important to elaborate on, but emphasise that the simplified approach of the theoretical assessment, which focuses on the effectiveness of policy combinations and does not take into account further policy goals, limits the validity. Thus, future research should conduct more contextual analysis. The study partly builds on results from the EU-funded project 'Energy Saving Policies and Energy Efficiency Obligation Schemes' (Rosenow et al. 2015).

The international initiative bigEE—'bridging the information gap on Energy Efficiency in buildings'—studies how to combine policies and measures for energy efficiency in buildings and appliances to achieve potential but still untapped energy efficiency improvements.[7] The initiative, which a number of research institutes for technical and policy advice on energy and climate challenges initiated, focuses on how policies can potentially reinforce one another and finally recommends specific policy packages for building and appliance energy efficiency. Within both domains, a general recommendation is to combine minimum performance standards with information measures and financial incentives to first encourage the market penetration of energy efficient products and subsequently be able to strengthen the performance standard to achieve higher future efficiency levels.

## Interaction assessment

To what extent policy instruments interact depends to a certain degree on their context, i.e. specific design characteristics and framework conditions. However, other factors determine interaction effects context-independent. The following assessment identifies those influencing factors and discusses specific interaction cases with respect to their interaction outcome.

### *Influencing factors*

What factors determine, if there is a risk for mitigating or potential for reinforcing effects between instrument combinations? By reference to the relevant literature, we identify influencing factors and divide them in three broad categories: steering mechanism, scope and timing (Fig. 1).

The category *steering mechanism* comprises the type of incentive that a policy provides, i.e. how it shall steer the behaviour of the relevant target group. Rosenow et al. (2015, 2016) and Boonekamp (2006) consider the steering mechanism in their interaction assessment by reflecting on the class, type and function of two or more policies in combination. Rosenow et al. (2016) point out that combinations within the same policy class are typically mitigating and define six different policy classes: taxation, purchase subsidy, access to capital, minimum standards, underpinning measurement standards, and information and feedback. Similarly,

[7] http://www.bigee.net/media/filer_public/2013/11/28/bigee_txt_0006_pg_how_policies_need_to_interact_2.pdf (Accessed 18 January 2018)

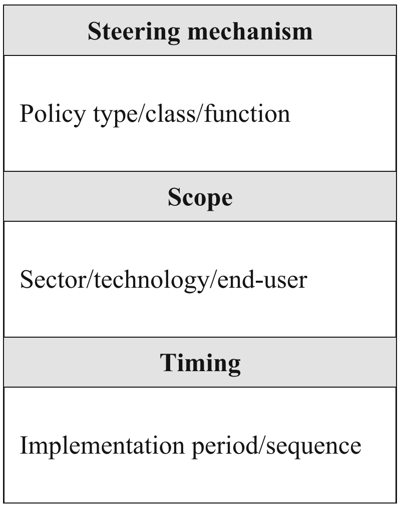


**Fig. 1** Influencing factors of interaction effects

Boonekamp (2006) concludes that instruments of the same type, which he divides into legislation, taxes, information and agreements, tend to interact. Furthermore, Boonekamp defines four different conditions for a successful implementation of saving options and applies these conditions to assess interaction effects between policy combinations qualitatively. The conditions for a successful implementation of saving options include availability of saving options, sufficient knowledge, the removal of restrictions, and motivation. Boonekamp follows the logic that two or more instruments addressing the same condition, e.g. ensuring sufficient knowledge, have a mitigating, combined saving effect. Correspondingly, Rosenow et al. (2015) argue that policies fulfilling the same function, e.g. increasing the energy price, reducing the price for energy efficiency options or enabling individuals to take account of energy in their purchase decision, are likely to cause a mitigating interaction. By definition, the steering mechanism of a policy has a direct impact on the behaviour of the targeted energy end-users. Thus, from the end-users' perspective, the policy class, type or function determines their behavioural response, which in turn is an important factor that defines the final saving effect of (combinations of) instruments. End-users respond to instruments when the underlying mechanism drives them to change behaviour. Using the conditions for a successful implementation of Boonekamp (2006), this change is obtainable when instruments provide the potential to save energy, knowledge about the potential and finally a motivation to benefit from the potential. Policy instruments encourage these drivers by minimising existing barriers, which discourage end-users to invest in energy efficiency and savings, as mentioned before. E.g., information and feedback make the energy saving potential more visible to the end-users and enable them to be more aware of energy in their consumption behaviour of energy services. Rogge and Reichardt (2016) and Rosenow et al. (2017) discuss this point using the concept of comprehensiveness of a policy mix, which *'captures how extensive and exhaustive its elements are'* (Rogge and Reichardt, 2016: 1627) and furthermore, which *'can be assessed according to the degree to which it considers relevant failures and barriers'* (Rosenow et al. 2017: 97).[8] Drawing on that discussion, in the context of interaction effects, two instruments are reinforcing if they contribute to the comprehensiveness of a policy mix and are mitigating if they do not, thus if they use the same steering mechanism. In other words, considering combinations of energy efficiency policies, the degree to which their policy function encourages the same behavioural response determines potential interaction effects, which are mitigating when two instruments steer the same behavioural driver of energy efficiency improvement and reinforcing otherwise.

The instrument *scope* indicates the sector, the technology or the specific energy end-user that an instrument addresses, thus the overall target to which a certain policy pertains. Energy efficiency policy can target different groups of end-users, also products and technologies. Thus, interactions between policy combinations exist only between policies with the same scope (Boonekamp 2006; Rosenow et al. 2016; Rosenow et al. 2015; Simoes et al. 2015). Therefore, both Boonekamp (2006) and Rosenow et al. (2016) focus their analysis on instruments targeting building energy efficiency.

The *timing* factor indicates that two or more instruments can only directly interact when they act simultaneously (Boonekamp 2006; Rosenow et al. 2016). Furthermore, policies may interact when their implementation follows in sequence (Boonekamp 2006; Sorrell et al., 2003), e.g. expected changes in regulation may both reinforce or mitigate present regulation. However, the existing research on interactions of energy efficiency

[8] This definition of comprehensiveness is not exhaustive. For a full discussion see Rogge and Reichardt (2016) and Rosenow et al. (2017).

policies focuses on interactions at one point in time (Kern et al. 2017).[9]

The general intuition behind the categorisation of influencing factors is that the relevance in interactions of two or more instruments increases to the extent that they apply the same steering mechanism, have the same scope and act at the same time. Instruments tend to be reinforcing when they are different in at least one of the three categories. I.e., when two or more instruments target the same sector at the same time, the interaction between them is most likely mitigating when they also use the same steering mechanism, but reinforcing when they are different with respect to this factor. This categorisation is very straightforward and simple; however, considering the accumulated amount of energy efficiency policies in force, researchers may use this framework as a starting point for a more profound assessment of policy interaction effects.

*Interaction cases*

Table 2 presents interaction cases, which the literature on interactions between energy efficiency policies (section 'Literature review') has analysed and discussed. Referring back to the influencing factors, the instrument combinations in Table 2 target the same scope at the same time; thus, the steering mechanism determines the interaction outcome. The combined saving effect of instrument combinations can be mitigating or reinforcing, as Boonekamp (2006) introduced. The aim is to highlight those determinants that are relevant from a general perspective and not only apply in the specific context of the studies.

(1) Boonekamp (2006) and Braathen (2007) classify the combination of a performance standard with an energy tax as mitigating. Boonekamp (2006) argues that the target group of a standard, which sets a high and legally binding requirement, has to fulfil this standard, while a tax would not lead to the implementation of additional measures to increase energy efficiency. Thus, he points at the prescriptive policy mechanism of performance standards, which force the energy end-user to save energy, thus no further motivation is needed, and defines this mechanism as the reason for the mitigating interaction. Braathen (2007) takes this combination as an example for mitigating interaction effects, which hinder the effective and efficient functioning of both instruments and cause redundancies and unnecessary administrative costs.

(2) Furthermore, Boonekamp (2006) assesses that the combination of an energy tax with financial incentives, i.e. different subsidy schemes, can be mitigating or reinforcing depending on the specific application of the subsidy. On the one side, Boonekamp (2006) discusses that both instruments target the motivation of energy end-users to invest in energy saving options and together they provide too much motivation, i.e. only one instrument would have led to the same investment decision. On the other side, he argues that a subsidy, which specifically motivates saving options that are not yet established and still expensive, can have a reinforcing interaction with an energy tax. In that case, consumers would not have chosen to implement these saving options only motivated by a tax. Thus, the target of a subsidy scheme, i.e. proven or not yet established saving options, determines the interaction outcome.

(3) Rosenow et al. (2016) highlight that a tax on energy has a reinforcing interaction with all other instruments they include in their analysis. They argue that the direct price effect of a tax generally increases the incentive and motivation of end-users to invest in energy efficient technology and reduce energy consumption, i.e. to use financial incentives, implement regulation or join voluntary agreements. Thus, the price mechanism of a tax strengthens the functionality of other instruments. Furthermore, Child et al. (2008) classify the combination of an energy tax with a TWC scheme as reinforcing and reason that with a tax as the single instrument, end-users may choose to pay the tax when it is expensive to reduce consumption. The combination with a white certificate scheme, which implies the provision of financial incentives, increases the amount of affordable energy saving options and the final energy saving effect.

(4) Assessing the combination of EEOs with financial incentives, Rosenow et al. (2016) point out that the obligation scheme implies a capped saving level,

[9] Kern et al. (2017) analyse the development of policy mixes for energy efficiency over time. Yet, the assessment of sequencing interactions between energy efficiency policies is a field for future research.

**Table 2** Mitigating and reinforcing interaction effects between combinations of energy efficiency policies

| Instrument combination | Mitigating | Reinforcing | References |
|---|---|---|---|
| *(1)* Energy tax and performance standard | x | | Boonekamp (2006); Braathen (2007) |
| *(2)* Energy tax and financial incentives | x | x | Boonekamp (2006) |
| *(3)* Energy tax and EEOs/TWCs, financial incentives, regulation, voluntary agreements, energy labelling schemes | | x | Child et al. (2008) (for TWCs); Rosenow et al. (2016) |
| *(4)* EEOs/TWCs and financial incentives | x | x | Child et al. (2008); Rosenow et al. (2016) |
| *(5)* EEOs/TWCs and voluntary agreements | x | | Child et al. (2008); Rosenow et al. (2015) |
| *(6)* Performance standards and financial incentives | x | x | Rosenow et al. (2015); bigEE |
| *(7)* Subsidies and access to capital measures | x | | Rosenow et al. (2016) |
| *(8)* Information measures and all other instruments | | x | Boonekamp (2006); Braathen (2007); Child et al. (2008) (for TWCs); Rosenow et al. (2016); bigEE |

which entails that financial incentives on top of the scheme would not achieve additional savings, and classify this combination as mitigating. Thus, similar to the policy mechanism of performance standards in *(1)*, the predefined energy saving target of EEOs limits the effectiveness of additional financial incentives. On the contrary, Child et al. (2008) conclude that the combination of TWCs with financial incentives is reinforcing, because the increase in total compensation for energy efficiency investment (increase in financial support available) accelerates technology diffusion of energy efficient equipment. However, they also consider that this combination may be an unnecessary use of resources once a technology becomes standard in the market.

(5) Rosenow et al. (2015) classify the combination of voluntary agreements with EEOs as mitigating and argue that the obligation scheme sets a certain energy saving target, so that a voluntary agreement, which targets the same sector and aims at a similar saving level, would not generate additional savings. Child et al. (2008), when assessing the combination of TWCs and voluntary agreements, highlight the challenge of the measurement and verification of savings, which the voluntary agreement scheme achieves, as being eligible to count as a saving certificate.

(6) On one side, the combination of performance standards with financial incentives is mitigating, when the financial support finances investments that are required by the performance standard, as Rosenow et al. (2015) evaluate. In that case, the legally binding target of the standard entails that additional financial incentives do not increase effectiveness, but the number of free-riders, here defined as agents that make use of a subsidy, although they have to do a certain investment to fulfil the standard. On the other side, the bigEE project argues that financial incentives in combination with performance standards are important to trigger energy efficiency investments, especially in the presence of high financing barriers. Thus, this combination of policies ensures a broad market introduction of energy efficient products and finally enables policy makers to tighten the standard and achieve higher future efficiency levels.

(7) Furthermore, Rosenow et al. (2016) discuss that two instruments, which both provide a financial incentive for energy efficiency investments, cause a mitigating interaction, when the recipient had made the same investments in the presence of only one of the two instruments. In that case, the benefit recipient is overpaid.

(8) All studies categorise the provision of information, especially via labelling schemes, as mutually reinforcing. Thus, providing information supports the effectiveness of all other instruments and vice versa. E.g. Braathen (2007) illustrates that a label increases the awareness of consumers and therefore their responsiveness to energy prices. This effect finally increases the effectiveness of a price-increasing tax on energy. Moreover, consumers may be more attentive to a label due to a tax. Thus, the policy mechanism of information provision to increase the awareness of end-users towards their energy consumption determines the mutually reinforcing interaction with other instruments. Yet, Braathen (2007) also mentions the

exceptional case that the provision of too much information, e.g. due to the implementation of various different labelling schemes, may cause confusion and a mitigating combined effect. Considering the combination of information provision (in particular building certificates) with financial incentives, Child et al. (2008) furthermore point out that information provision may increase the free-rider problem. I.e., the increase in awareness entails that more consumers would increase their energy efficiency investments without financial incentives, but are still able to receive them.

These interaction cases show a systematic pattern. First, a combination of instruments that enforce a certain target of energy efficiency or savings, e.g. performance standards and EEOs, is more likely mitigating. Due to the fixed and legally binding target of one instrument, the second instrument does not achieve additional savings beyond the target. Considering the steering mechanism as the influencing factor, we can conclude that an enforcing mechanism causes more likely a redundancy and therefore a mitigating interaction because the enforcement ensures that a certain saving potential is achieved and the targeted energy end-users do not need additional knowledge or motivation to be incentivised to invest in energy efficiency and increase energy savings. Second, a combination of instruments that are flexible regarding how the target group responds to this instrument, e.g. energy taxes and information measures, is more likely reinforcing. The flexibility entails that within this combination one instrument does not hamper, but strengthen the functionality of the other instrument. Therefore, their effectiveness is higher in combination. In that case the functioning of one steering mechanism, e.g. energy price increase, does not make information provision redundant, but both mechanisms together have the potential to complement one another, in this example by providing motivation and knowledge, and maximise the final energy saving effect. Braathen (2007) draws a similar conclusion.

## Discussion

The interaction assessment highlights critical influencing factors, which policy makers should take as a starting point when investigating potential mitigating or reinforcing effects between combinations of energy efficiency policy. Furthermore, it assesses cases of instrument combinations and the interaction effects between them. The identification of these interaction effects will become even more important, when energy efficiency and saving targets increase in stringency and policy mixes need to become more effective. The direct and straightforward way to increase the energy saving effect of a policy mix would be to maximise reinforcing effects and minimise mitigating interactions. This argumentation draws on the predominant research focus on effectiveness as the main goal to achieve, however, does not take into account further criteria, which influence policy making.

In contrast, Rosenow et al. (2015) remark that '*it may be legitimate to combine policy instrument types even if the overall effect on energy savings is diminishing*' (Rosenow et al. 2015: 18). Drawing on a discussion on double regulation from Sorrell et al. (2003), they argue that the avoidance of mitigating interactions should not be the only objective, but that it needs a broader assessment of circumstances, in which these interactions might be acceptable or unacceptable. The combination of financial incentives and energy performance standards can illustrate the argument. Rosenow et al. (2015) evaluate that this combination is mitigating, when the financial support finances investments that are required by the performance standard. However, the financial support might only make it affordable for e.g. low-income households to be able to comply with the standard. In that case, the perceived mitigating interaction addresses social equity concerns. Thus, including governmental concerns beyond the energy saving target in the assessment of this policy combination could change the evaluation of the interaction effect.

Furthermore, researchers have paid only limited attention on the impact of interactions on the efficiency or cost-effectiveness of instrument combinations. Boonekamp (2006) and Rosenow et al. (2016) do not consider cost-effectiveness in their assessments and Rosenow et al. argue that this is due to a lack of evidence on the cost side. In the OECD project report (OECD 2007) efficiency considerations are limited to the theoretical discussion that policy makers should add additional instruments to an existing instrument mix at the lowest marginal costs possible and only if marginal benefits are larger than marginal costs. Braathen (2007) mentions the case that overlapping instruments cause redundancies and thus unnecessary administrative costs. Administrative costs are also part of the multi-criteria approach of the ECPI model, besides compliance and transaction costs (Oikonomou et al. 2014, 2012, 2010). However, the existing research has not thoroughly assessed the impact of interactions on efficiency or administration and compliance costs of instrument combinations.

Future work on interaction effects of energy efficiency policies should extend the predominant research focus and include assessment criteria beyond effectiveness, such as efficiency and feasibility. Furthermore, the research on interactions between energy efficiency policies is largely limited to qualitative and theory-based approaches. Thus, the quantification of interaction effects between policy combinations is an area, where a gap of knowledge exists. Future research should investigate case studies of instrument combinations, where relevant data on the (cost-)effectiveness of specific instruments, stand-alone and in combination, is available. Considering the challenges to empirically derive the impact of energy efficiency policies in real world applications, there may be a need for controlled experiments, which could test and evaluate different combinations of instruments. Various studies have already used this approach to investigate the effect of single instruments (e.g. Allcott and Rogers 2014; Gleerup et al. 2010). A careful combination of qualitative and quantitative results of (multi-criteria) interaction assessments could sharpen the analysis of interactions between energy efficiency policies. In particular, the combination could enable to make concrete statements on the magnitude and importance of interaction effects. I.e., the results could clarify, if mitigating interactions are a major problem that should make us reduce the number of applied instruments or how reinforcing effects could optimise the implementation of a policy mix for energy efficiency and savings. The existing research has not drawn conclusions on the magnitude and importance of interactions, although information on this issue may be most important for policy making.

## Conclusion

Policy makers can choose to implement various policy instruments to foster future energy efficiency and savings. These instruments all have their individual strengths and weaknesses, which policy makers should balance in the process of finding the appropriate instrument(s) for a specific policy context. In many cases, they choose to implement not only one instrument, but a combination of instruments, which all target energy efficiency improvements and savings. In that case, interactions between these instruments are inevitable. By definition, interactions can be reinforcing, neutral or mitigating depending on the combined saving effect of instrument combinations. The interaction assessment of this paper shows that the steering mechanism, the scope and the timing of two or more instruments influence the interaction outcome. Furthermore, the assessment identifies that a combination of instruments that enforce a certain target of energy efficiency and savings is more likely mitigating, while a combination of instruments that are flexible regarding how the target group responds to this instrument is more likely reinforcing. However, the existing research on interaction effects of energy efficiency policies is restricted to mainly qualitative results focusing on the energy saving effect of instrument combinations as the main evaluation criterion. Thus, the magnitude and importance of interaction effects is yet unclear.

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**Compliance with ethical standards**

**Conflict of interest** The authors declare that they have no conflict of interest.

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# Appendix B.

# Do household characteristics really matter? A meta-analysis on the determinants of households' energy-efficiency investments

# Do Household Characteristics Really Matter? A Meta-Analysis on the Determinants of Households' Energy-Efficiency Investments

Géraldine Henningsen[a,*], Catharina Wiese[a]

[a] *Department of Management, Technical University of Denmark, Produktionstorvet 426, 2800 Kongens Lyngby, Denmark*

**Abstract**

Most environmental policies that aim to encourage households to invest in more climate-friendly technologies and retrofits, e.g., solar panels, electric cars, or attic insulation, are broadly targeted and do not take households' individual investment behaviour into account. Scholars have, therefore, emphasised the need to account for household heterogeneity in policy design in order to ensure effective and efficient policy outcomes. However, such a policy design requires the existence of easily accessible household characteristics, which can reliably and consistently explain households' investment behaviour in a variety of investment scenarios. Using the vast empirical literature on the determinants of households' investments in energy-efficient home improvements as a case study, we conduct a meta-analysis to: (i) determine the magnitude of the effects of easily accessible household characteristics, and; (ii) test the stability of these effects under a variety of circumstances. We integrate the empirical results from 63 publications that investigate the impact of socio-economic characteristics on households' energy-efficiency investments and examine potential model- and sample-specific factors to explain the variation in the estimated effects. Our findings for the household characteristics: income, age, education, household size, and home ownership, show that significant effects only exist for some of these characteristics, with income and home ownership showing the greatest impact. Furthermore, the results confirm a strong situational component in the effect of these household characteristics on households' investment decisions, which challenges

the practicality of a tailored policy design.

*JEL classification:* Q40, D12, D04

*Keywords:* Household heterogeneity, Environmental policy, Climate, Meta analysis

## 1. Introduction

Policy interventions to encourage households to invest in climate-friendly and energy-efficient technologies and home-improvements are usually broadly targeted. Thus, they provide similar incentives for the majority of households. However, households are not identical but are instead heterogeneous in many respects. Therefore, they face different barriers to investment (Allcott and Greenstone, 2012), such as imperfect information, liquidity constraints, or split incentives, which discourage them from investing in new technology or engaging in retrofitting that would be privately and socially profitable (e.g., Jaffe and Stavins, 1994; Gillingham et al., 2009).

To properly address potential investment barriers, scholars have, therefore, emphasised the need to design targeted policies that account for household heterogeneity (e.g., Stern, 1992; Allcott and Greenstone, 2012; Gillingham and Palmer, 2013; Allcott et al., 2014). The intuition is straightforward: if only a subset of households fails to adopt profitable investment options and, therefore, stands to gain from a policy intervention, specifically targeting these households will be more effective and eventually more cost-effective than targeting all households.

However, despite the emphasised need to design targeted policies, it remains unclear whether systematic and exploitable patterns in households' investment behaviour exist. Although observable investment decisions show considerable heterogeneity (e.g., Newell and Siikamäki, 2013, 2015), households' individual investment barriers are difficult and costly to detect. Thus, in order to realistically consider household heterogeneity in policy

*Corresponding author

*Email addresses:* gehe@dtu.dk (Géraldine Henningsen), catwi@dtu.dk (Catharina Wiese)

design, the existence of observable variables that are easily accessible for policy makers or policy modellers and that can consistently and reliably explain households' heterogeneous investment decisions is a basic prerequisite.

To investigate the existence of such variables, we conduct a meta-analysis based on the large number of empirical studies that analyse the effect of socio-economic characteristics on households' investments in climate-friendly and energy-efficient technologies and retrofitting (e.g., Ameli and Brandt, 2015; Aravena et al., 2016; Mills and Schleich, 2010a, 2012; Smiley, 1979; Trotta, 2018a).[1] By integrating the results from 63 individual studies with a total of 167 different regression results, we investigate the existence of systematic and stable patterns across the following five standard characteristics: income, age, education, household size, and home-ownership status as determinants of households' investment behaviour. Furthermore, we compare the empirical effects of the five variables with five hypotheses that are derived from a simple micro-economic investment model in order to assess the alignment of the empirical results with economic theory. We use these results to determine whether standard household characteristics can significantly and consistently explain the heterogeneity in households' investment behaviour, so that policy makers and policy modellers can use these characteristics as proxies to incorporate household heterogeneity in policy design. Our analysis is, to the best of our knowledge, the first to approach this question systematically.

The article is structured as follows: section 2 describes the theoretical investment model and formulates the hypotheses; section 3 introduces our analysis, discusses the search for relevant literature, and presents the empirical findings; section 4 discusses these findings with respect to potential limitations and compares them to our theoretical hypotheses; finally, section 5 concludes. Due to methodological constraints or limitations on data availability, we had to dismiss studies that empirically analyse the effect of socio-economic characteristics on households' energy-efficiency investments. A detailed overview of these studies is provided in table A.12 in AppendixA.1.

[1]We subsequently gather all investments in climate-friendly and energy-efficient technological and retrofitting home improvements under the term 'investments in energy-efficiency'.

## 2. Model and Hypotheses Formulation

To set a theoretical framework for the analysis of the empirical results, we define a simple investment model such as suggested by Allcott and Greenstone (2017). Households can improve the climate impact of their home by investing in portable or non-portable assets, e.g., energy-efficient appliances, building envelope renovations, or solar panels.

Let $\theta_{ij} = (e_{ij}, \xi_{ij}, c_{ij}, \mathcal{T}_{ij})'$ be a vector, where $i = 1, \ldots, \mathcal{I}$ is the household index, and $j \in \mathcal{J}_i$ indicates a specific climate friendly investment from the set of all feasible investment measures, $\mathcal{J}_i$, available to household $i$. $e_{ij}$ is the expected monetary present day value (PDV) of eventual energy savings of the investment; $\xi_{ij}$ is the expected PDV of the monetised non-monetary benefits of the investment (e.g., better indoor climate, warm glow, etc.); $c_{ij}$ are the monetary costs of the investment and $\mathcal{T}_{ij}$ are the expected monetised non-monetary costs (e.g., due to disruptive and time-consuming construction work). We set up the following expected utility function:

$$E(U(y_i, e_{i0}, \mathcal{B}_{i0}, \Theta_i, \mathbf{I}_i)) = y_i - e_{i0} + \mathcal{B}_{i0} + \sum_{j \in \mathcal{J}_i} I_{ij}(e_{ij} + \xi_{ij} - c_{ij} - \mathcal{T}_{ij}), \qquad (1)$$

where $y_i$ is household income, a proxy for wealth[2]; $e_{i0}$ is the PDV of the expenditures of the future baseline energy consumption without investments; $\mathcal{B}_{i0}$ are the monetised non-monetary benefits of the status quo; $\Theta_i = \{\theta_{ij}; j \in \mathcal{J}_i\}$ is the set of costs and benefits of all energy-efficient measures available to household $i$; $I_{ij}$ is a dummy variable indicating whether household $i$ adopts investment option $j$, and $\mathbf{I}_i = \{I_{ij}; j \in \mathcal{J}_i\}$.[3]

These variables, except for $y_i$ and $I_{ij}$, are usually unobserved latent variables. Therefore, we suggest expressing them through functions that depend on the following five observable household characteristics: income, $y_i$, age, $a_i$, education, $d_i$, household size,

[2] We expect overall wealth to be more relevant than income. However, because data on wealth is rarely included in empirical studies, we do not include it in our model.

[3] We assume that all potential investments in set $\mathcal{J}_i$ are independent. Consequently, some energy-efficient measures are package solutions, when their conservation effect depends on the combination of several investments, e.g., a household with two potential investments A and B has three options: 'A', 'B', or 'A and B'.

$z_i$, and the household's ownership status, $o_i$, which indicates whether a household owns or rents its home. The expected utility function extends to:

$$\begin{aligned} E(U(y_i, e_{i0}, \mathcal{B}_{i0}, \Theta_i, \mathbf{I}_i)) = y_i &- e_{i0}(y_i, a_i, d_i, z_i, o_i) + \mathcal{B}_{i0}(y_i, a_i, d_i, z_i, o_i) \\ &+ \sum_{j \in \mathcal{J}_i} I_{ij}(e_{ij}(y_i, a_i, d_i, z_i, o_i) + \xi_{ij}(y_i, a_i, d_i, z_i, o_i) \\ &- c_{ij}(y_i, a_i, d_i, z_i, o_i) - \mathcal{T}_{ij}(y_i, a_i, d_i, z_i, o_i)) \end{aligned} \tag{2}$$

Drawing on this function, equation (3) shows the effect of adopting investment $j$ on the expected utility of household $i$:

$$\begin{aligned} \lambda_{ij}(\cdot) = e_{ij}&(y_i, a_i, d_i, z_i, o_i) + \xi_{ij}(y_i, a_i, d_i, z_i, o_i) \\ &- c_{ij}(y_i, a_i, d_i, z_i, o_i) - \mathcal{T}_{ij}(y_i, a_i, d_i, z_i, o_i), \end{aligned} \tag{3}$$

where $\lambda_{ij} = E(U(\cdot) \,|\, I_{ij} = 1) - E(U(\cdot) \,|\, I_{ij} = 0)$, which in our simple investment model corresponds to the net present value (NPV) of investment $j$. The NPV depends on the monetary and non-monetary costs and benefits, which we assume are functions of heterogeneous household characteristics. Thus, income, age, education, household size and ownership status determine whether $\lambda_{ij}$ is positive, negative, or neutral and, therefore, whether it affects households' propensity to invest. In the following, we formulate hypotheses considering how each of the five household characteristics affects $\lambda_{ij}$ and the propensity to invest. The hypotheses serve as benchmarks in the evaluation of our empirical results in section 4.

### *2.1. Income*

**Hypothesis 1** *The higher the income, the higher the propensity for the household to invest. This effect increases with the capital intensity of the investment.*

Irrespective of the income level, most households stand to benefit from improving the energy-efficiency of their home, either through monetary savings, $e_{ij}$, or non-monetary benefits, $\xi_{ij}$. Thus, the main effect of income is determined on the cost side. Although pure purchasing costs are likely to be the same for all households, capital costs may vary considerably between income groups. High income households have better access to capital and might face lower interest rates than low income households because the former own more assets, which can be used as collateral. Thus, monetary costs $c_{ij}$ are expected to be lower for high income households than for low income households. This effect is reinforced the larger the investment sum associated with an energy-efficiency measure. On the other hand, households with a higher income face higher opportunity costs connected to the time spent implementing the measure, which might increase the non-monetary costs $\mathcal{T}_{ij}$ for these households. This will particularly affect time-intensive investments.

*2.2. Age*

**Hypothesis 2** *The effect of age on a household's propensity to invest is ambiguous for capital-intensive investments with long amortisation periods.*

On the one hand, increasing age reduces the value of investment benefits because elder household heads have a shorter time horizon to accumulate the benefits. Thus, the PDV of monetary, $e_{ij}$, and non-monetary benefits, $\xi_{ij}$, decreases with age, which lowers the propensity to invest for elder household heads.[4] A longer expected amortisation period of an investment reinforces this effect.

On the other hand, increasing age reduces both monetary and non-monetary costs. Considering monetary costs, $c_{ij}$, increasing age decreases credit constraints (Jappelli, 1990; Lyons, 2003) and the capital costs of elder households, as elder households will, on average, own more assets than younger household heads.[5] Again, larger investment sums reinforce this effect. Considering the non-monetary costs, $\mathcal{T}_{ij}$, we expect that the share of labour income to total income decreases for most households with increasing

[4]For simplicity, we assume a common discount rate across all households.

[5]This assumption is only valid until a certain age, after which capital costs eventually increase sharply because lenders evaluate the risk of giving loans to elderly households as high.

age (Aaronson et al., 2014). Elder household heads will, on average, have *ceteris paribus* (e.g., for a given total income) a lower marginal income from labour and, consequently, they have lower opportunity costs of leisure time. Thus, the higher the household head's age, the lower the costs linked to lost leisure time as a consequence of time-intensive investments.

*2.3. Education*

**Hypothesis 3** *The higher the educational attainment, the higher a household's propensity to invest. This effect increases with the expected amortisation period of the investment.*

Empirical analyses find a significant and negative effect of higher educational attainment on the discount rate that an investing individual applies to future benefits (Harrison et al., 2002). In other words, individuals with a longer education are, on average, more patient and, hence, more willing to wait for future benefits. Thus, we expect that the higher the educational attainment, the higher the assigned present day value of future monetary, $e_{ij}$, and non-monetary benefits, $\xi_{ij}$, and consequently, the higher the household's propensity to invest. This effect is reinforced the longer the amortisation period of the investment.

*2.4. Household size*

**Hypothesis 4** *The effect of household size on the propensity to invest is ambiguous for capital-intensive investments, but positive for less capital-intensive investments.*

Household size is primarily a control variable and, therefore, it impacts the propensity to invest through other variables. On the one hand, a larger household size correlates, *ceteris paribus*, with greater demand for energy services. If these energy services are provided more efficiently after an investment, larger households benefit over-proportionally through larger energy savings. This effect increases the propensity of the household to invest. On the other hand, a larger household size means, *ceteris paribus*, a lower per capita income, which eventually translates into higher costs of financing capital-intensive investments and, thus, a lower propensity to invest. Thus, for capital-intensive investments, this lower propensity to invest may cancel out the higher propensity due to the larger benefits, and overall results in an ambiguous net-effect of the variable.

### *2.5. Home ownership*

**Hypothesis 5** *Home ownership increases a household's propensity to invest. This effect reinforces with the capital intensity of the investment.*

Renting is commonly considered a barrier to investments within the home due to the challenge of allocating costs and benefits between property owners and tenants (Jaffe and Stavins, 1994). The barrier is strongest for capital-intensive investments. Whilst households that own and live in their home would gain all monetary, $e_{ij}$, and non-monetary benefits, $\xi_{ij}$, of an investment, tenants do not benefit from, e.g., the increase in real-estate value resulting from a home improvement. Thus, they are unable to reap the full benefits of the investment. We, therefore, expect the propensity to invest to be lower for households that rent compared to those that own. This argumentation becomes less strong when considering minor investments in, e.g., energy-efficient appliances or light bulbs. The costs and benefits of minor investments are most likely the same for owners and renters.

## 3. Analysis

### *3.1. Literature Search*

To identify relevant publications, we screened the literature for empirical studies that analyse the determinants of households' energy efficiency investment decisions both under market conditions and as a reaction to policies in either an authentic or in an experimental (hypothetical) setting. We focused our search on the following three broad categories: real market behaviour, stated preference studies—mainly choice experiments—, and policy evaluations, and used the following keywords: 'energy efficiency', 'energy efficiency investment', 'energy efficiency households', and 'determinants energy efficiency investments' in the literature databases: Google Scholar, Scopus, EconStor, and EconPapers. We included all studies that investigated investment decisions regarding minor investments, e.g., light bulbs, thermostats, or smaller insulation or weatherisation projects, medium investments, e.g., water heaters or appliances, and major investments, e.g., building insulation, solar panels, heating systems, or windows and doors. For each identified and relevant study, we also conducted a forward and backward citation search in all four databases to identify further relevant publications that had not come up in our initial search. In order to generate a comprehensive sample, we included both peer reviewed and grey literature in our search (Stanley, 2001). The search was conducted during 2017 and 2018.

We screened all studies that contained relevant empirical analyses for household characteristics that are both frequently used and easily accessible to modellers and policy makers. The studies included a multitude of different household characteristics as covariates, of which the most frequently used were: income, age, education, household size, and home ownership. Other frequently included characteristics were race and number of children living in the household, whilst variables such as household debt, employment status, and gender were used infrequently. Environmental attitudes and political affiliation are often included covariates—especially in the political science and psychological literature. However, as these household characteristics are normally not easily accessible to policy modellers and policy makers as they require extensive surveying, we did not include them in our meta-analysis. Given these results, we focused on the following five household characteristics: income, age of household head, education of household head, household size, and home ownership.

From the potentially relevant literature, we selected publications that fulfilled the following criteria:

- present empirical results of the determinants of private households' investment choices in energy efficiency,

- contain at least one of the five selected household characteristics as a covariate,

i.e., the publications included in our analysis present empirical results that allow inference about the propensity of households to invest in measures that would improve the households' energy efficiency.

We found a total of 104 relevant publications that matched the two criteria (a more detailed overview of all 104 publications can be found in the online appendix of this article). However, we had to discard 41 publications because of insurmountable methodological differences or an absence of vital statistical information, which meant that extracting comparable effect measures was impossible.

The empirical analyses reported in the identified publications differ significantly in terms of their methodological approaches, which in some cases prevents a direct comparison of the regression coefficients.[6] The main empirical approaches used in the 104 publications include: pairwise correlations between energy efficiency investments and household characteristics (three publications), the regression of factor loadings, derived from multiple energy efficiency investments, on household characteristics (three publications), the regression of investment sums or tax rebates on household characteristics (12 publications), and the impact of household characteristics on a household's likelihood to invest in energy efficiency (83 publications). Only the latter approach provided a sufficient number of comparable observations that could be included in our meta-analysis (79 publications in total). All other empirical approaches failed to provide the critical number of comparable observations to support reliable results in a meta-analysis.

Where standard errors, p-values, or t-values were missing in the publication, i.e., the significance of the coefficient estimate was only indicated by asterisks, we calculated the standard errors of the coefficient estimates at the thresholds as defined by the published asterisks (e.g., by assuming a p-value of 0.05 for two asterisks or if indicated otherwise in the study by the corresponding p-value) and assumed a default p-value of 0.5 for sta-

[6]E.g., the magnitude of regression coefficients from studies where the endogenous variable is continuous is incomparable to the magnitude of regression coefficients from studies where the endogenous variable is binary or categorical.

tistically insignificant coefficient estimates. Using this approach will in almost all cases create standard errors for the coefficient estimates that are upwards biased, hence, they will reflect the additional insecurity connected to the respective observation in the subsequent meta-analysis. In order to test whether our default choice of 0.5 for insignificant coefficient estimates had any impact on our results, we ran a sensitivity analysis setting the default p-value to $\{0.2, 0.4, 0.5, 0.7, 0.9\}$, respectively. The impact was negligible (at the fourth decimal) and, hence, we proceeded with a default p-value of 0.5 for statistically insignificant coefficient estimates.

Where vital summary statistics were missing in the publication, we first contacted the authors of the study. If summary statistics were not provided by the authors, we tried to find approximate estimates for the missing variable means through secondary statistics, assuming that the study used a representative sample from the population of interest. However, despite our efforts, we had to discard another 16 studies from the meta-analysis due to missing summary statistics, so that our final sample comprises 63 publications with a total of 167 regression results.

If a publication included several estimations, we refrained from calculating the mean effect of the variable of interest across all included estimations, and instead included all the estimation results that were either based on different samples or sub-samples, or addressed different choice categories, e.g., insulating the roof and purchasing solar panels. Following Houtven et al. (2017) we later accounted for the panel structure of our data by using cluster robust standard errors.

Table 1 gives an overview of all publications that have been included in our meta-analysis. Furthermore, in order to preserve the relevant results from all excluded studies, we generated Table A.12 (see appendix), which only compares the direction of the effects of the variables of interest on households' propensity to invest in energy efficiency. Although a mere effect-counting study cannot provide the same in-depth analysis as a meta-analysis, we argue that the results, nevertheless, may be important additional indicators for the quantification of the overall effect of the five household characteristics on the propensity to invest.

Table 1: Publications included in the meta-analysis

| **Publications** | | |
|---|---|---|
| Abeliotis et al. (2011) | Alberini et al. (2014) | Allen et al. (2015) |
| Ameli and Brandt (2015) | Andor et al. (2016) | Aravena et al. (2016) |
| Baldini et al. (2018) | Blasch et al. (2017a) | Blasch et al. (2017b) |
| Bollinger and Gillingham (2012) | Braun (2011) | Brechling and Smith (1994) |
| Burlinson (2017) | Brounen et al. (2013) | Cirman et al. (2013) |
| Collins and Curtis (2017) | Das et al. (2018) | Datta and Filippini (2016) |
| Dato (2018) | Dieu-Hang et al. (2017) | Di Maria et al. (2010) |
| Durham et al. (1988) | Bruderer Enzler et al. (2014) | Fujii and Mak (1984) |
| Frondel and Vance (2013) | Gamtessa (2013) | Gans (2012) |
| Gillingham et al. (2012) | Gillingham and Tsvetanov (2018) | Hamilton et al. (2016) |
| Hasset and Metcalf (1995) | McCoy and Lyons (2017) | Jakob (2007) |
| Johnson-Carroll et al. (1987) | Kesternich (2010) | Ledesma-Rodriguez (2014) |
| Leicester and Stoye (2013) | Martínez-Espiñeira et al. (2014) | Meier and Tode (2015) |
| Michelsen and Madlener (2012) | Mills and Schleich (2009) | Mills and Schleich (2010a) |
| Mills and Schleich (2010b) | Mills and Schleich (2012) | Murray and Mills (2011) |
| Nauleau (2014) | Newell and Siikamäki (2015) | Neveu and Sherlock (2016) |
| Noonan et al. (2015) | Palmer et al. (2015) | Pon and Alberini (2012) |
| Qiu et al. (2014) | Ramos et al. (2016) | Sahari (2017) |
| Sardianou (2007) | Scasny and Urban (2009) | Schleich et al. (2017) |
| Schwarz et al. (2014) | Trotta (2018b) | Trotta (2018a) |
| Tsvetanov and Segerson (2014) | Walsh (1989) | Welsch and Kühling (2009) |

*3.2. Extraction of effect measures and moderator variables*

Our meta-analysis focusses on adoption studies where the dependent variable is either binary or (ordered) categorical. However, even within this group of publications, a multitude of different estimation methods have been applied. Our sample comprises studies that use linear probability models, binary logistic regression models, binary probit regression models, ordered probit regression models, multivariate probit regression models, multinomial logistic regression models, or OLS in combination with a dependent variable that varies between 0 and 1 (e.g., shares). Overall, the majority of the analyses are based on micro data at the household level, whilst some analyses are based on locally aggregated data (e.g., at the ZIP code level). These methodological differences prevent a direct comparison of the coefficient estimates from different analyses. Furthermore, differences in the measurement units of continuous covariates (e.g., income measured in \$1000 or \$10,000) and different encodings of categorical or interval-coded covariates (e.g., three income categories versus six income categories) aggravate this problem.

To overcome the problem of comparability, we use the **R** (R Core Team, 2018) package urbin (Henningsen and Henningsen, 2018a,b) to calculate semi-elasticities for continuous covariates, $\epsilon_k = \frac{\partial P(Y=1|X=x)}{\partial x_k} \cdot x_k$, and effects for each category of categorical or interval-coded covariates, $E_k = P(Y=1|X=x, x_k=1) - P(Y=1|X=x, x_k=0)$, at the sample means of the respective study samples. In cases where categorical or interval-coded covariates are grouped in different ways or where the base category differs, we used package urbin to unify the number of categories, interval-bounds, and base categories across all studies. Furthermore, we used urbin to calculate the semi-elasticities from categorical or interval-coded covariates and effects from continuous covariates in order to unify the effect measures across all studies. Finally, we used urbin to redress results from ordered probit regression models and multinomial logistic regression models into results from regression models with a binary response variable. To derive approximate standard errors for the calculated semi-elastisticities and effects that could be used as weighting factors in the meta-analysis, we followed the approach described in Henningsen and Henningsen (2018b) and implemented in urbin.[7]

Next to the effect measures, we also extract a number of moderator variables from the publications (see table 2 for details). Because our effect measures are, in most cases, only a sub-set of the covariates that explain a household's likelihood of investing in energy efficiency, the variance in our effect measures may be the result of either the characteristics of the respective sample and/or the model specification that was chosen by the analyst. To take these different influences into account, we extract two

[7]The online-appendix to this publication provides a detailed description of the modifications and calculations performed on the coefficient estimates, sample means, and standard errors of each included publication.

Table 2: Variable names and definitions

| Name | Definition |
|---|---|
| *Effect measures*: | |
| elaIncome | Semi-elasticity of continuous income variable |
| effAgeMid/Old | Effect of interval coded variable age, where the base category is 18–35 years, the medium category is 36–50 years, and the senior category is 51–80 years. |
| effEdu | Effect of categorical variable education, where the base category is 'below university/college' and the second category is 'some university/college or higher'. |
| elaHZ | Semi-elasticity of variable household size. |
| effOwn | Effect of binary variable home-ownership, where the base category is 'no ownership'. |
| *Moderator variables:* | |
| year | Year of publication. |
| sampleZ | Number of observations in study. |
| nCov | Number of covariates in study. |
| share | Share of adopters in sample. |
| country | Country where study was conducted, with 0 = multiple OECD countries, 1 = Canada, 2 = USA, 3 = Ireland, 4 = UK, 5 = Germany, 6 = Southern Europe, 7 = Central Europe, 8 = Northern Europe. |
| experiment | Categorical variable of whether the study has been conducted as an experiment (field and hypothetical), with the base category 'no experiment'. |
| investment | Categorical variable describing the size of the investment, with the base category 'minor investment', comprising smaller investments such as light bulbs or programmable thermostats, the second category 'medium investment', comprising medium-sized investments such as appliances or boilers, and category 'major investment', comprising large investments such as retrofits or solar panels. |
| house | Categorical variable indicating whether the regression model includes covariates that describe the building. |
| social | Categorical variable indicating whether the regression model includes covariates that describe the social status of a household or attitudinal variables. |
| politic | Categorical variable indicating whether the regression model includes covariates that describe the political orientation of the household. |
| price | Categorical variable indicating whether the regression model includes covariates that describe energy prices or price levels. |
| temp | Categorical variable indicating whether the regression model includes heating degree days or other climatic variables. |

Table 3: Descriptive statistics

| Statistic | N | Mean | St. Dev. | Min | Pctl(25) | Pctl(75) | Max |
|---|---|---|---|---|---|---|---|
| year | 167 | 2011 | 7.64 | 1983 | 2010 | 2016 | 2018 |
| sampleZ | 167 | 38,273.00 | 296,365.50 | 50 | 1,107.5 | 15,031.5 | 3,817,392 |
| nCov | 167 | 21.67 | 9.66 | 5 | 14 | 28 | 43 |
| share | 167 | 0.39 | 0.28 | 0.00 | 0.12 | 0.63 | 0.95 |
| country = 1 | 167 | 0.08 | 0.27 | 0 | 0 | 0 | 1 |
| country = 2 | 167 | 0.23 | 0.42 | 0 | 0 | 0 | 1 |
| country = 3 | 167 | 0.08 | 0.27 | 0 | 0 | 0 | 1 |
| country = 4 | 167 | 0.14 | 0.35 | 0 | 0 | 0 | 1 |
| country = 5 | 167 | 0.14 | 0.35 | 0 | 0 | 0 | 1 |
| country = 6 | 167 | 0.11 | 0.31 | 0 | 0 | 0 | 1 |
| country = 7 | 167 | 0.10 | 0.30 | 0 | 0 | 0 | 1 |
| country = 8 | 167 | 0.02 | 0.15 | 0 | 0 | 0 | 1 |
| experiment = 1 | 167 | 0.18 | 0.39 | 0 | 0 | 0 | 1 |
| investment = 1 | 167 | 0.26 | 0.44 | 0 | 0 | 1 | 1 |
| investment = 2 | 167 | 0.61 | 0.49 | 0 | 0 | 1 | 1 |
| house = 1 | 167 | 0.75 | 0.43 | 0 | 1 | 1 | 1 |
| social = 1 | 167 | 0.62 | 0.49 | 0 | 0 | 1 | 1 |
| politic = 1 | 167 | 0.03 | 0.17 | 0 | 0 | 0 | 1 |
| price = 1 | 167 | 0.25 | 0.44 | 0 | 0 | 0.5 | 1 |
| temp = 1 | 167 | 0.17 | 0.38 | 0 | 0 | 0 | 1 |

groups of moderator variables: moderator variables that describe the sample (year, share, country, experiment, and investment) and moderator variables that serve as proxies for the model specification (degrees of freedom, house, politic, price, and temp). Table 3 provides the summary statistics for the moderator variables. It reveals that our sample is biased towards more recent data sets. Furthermore, the sample size of the studies varies considerably, which reflects the broad type of publications included in our meta analysis that range from small choice experiments to studies with data sets covering millions of households over several countries.

The average study in our sample includes 22 covariates, with the largest model specification including as many as 43 covariates. This raises the question of the degree to which the results from such analyses are hampered by multicollinearity. Although multicollinearity generally does not generate any bias in the estimates, it, nevertheless, creates imprecise estimates, which are overly sensitive to changes in the model specification.[8]

[8] In order to test for the impact of the number of covariates on the size of the calculated standard errors of our effect measures, we regressed the standard errors from all six effect measures on 'nCov' and 'sampleZ'. However, none of the estimation models was statistically significant and, therefore, we conclude that this problem is negligible in our sample.

Finally, Table 3 shows that the distribution over the shares of adopters in each study is right-skewed. This finding is not surprising given the fact that most studies in our sample look at major investments, for which the uptake is generally low.

*3.3. Results*

Table 4: Unweighted mean effects, mean effects weighted with standard error, mean effects weighted with sample size

| | Mean | Std. Err. | z | p-value | CI Lower | CI Upper |
|---|---|---|---|---|---|---|
| Income unweighted | 0.02962 | 0.02158 | 1.37233 | 0.16996 | -0.01268 | 0.07192 |
| Income weighted | 0.01025 | 0.00784 | 1.30691 | 0.19124 | -0.00512 | 0.02563 |
| Income sample size | 0.02946 | 0.00886 | 3.32539 | **0.00088** | 0.01210 | 0.04682 |
| AgeMid unweighted | -0.01086 | 0.05515 | -0.19698 | 0.84385 | -0.11895 | 0.09722 |
| AgeMid weighted | 0.00267 | 0.00900 | 0.29646 | 0.76688 | -0.01498 | 0.02032 |
| AgeMid sample size | -0.00959 | 0.01184 | -0.81008 | 0.41789 | -0.03279 | 0.01361 |
| AgeOld unweighted | -0.00705 | 0.08149 | -0.08655 | 0.93103 | -0.16677 | 0.15266 |
| AgeOld weighted | 0.00424 | 0.01188 | 0.35725 | 0.72091 | -0.01904 | 0.02753 |
| AgeOld sample size | -0.00668 | 0.01491 | -0.44817 | 0.65403 | -0.03591 | 0.02255 |
| Edu unweighted | 0.02351 | 0.03919 | 0.59983 | 0.54862 | -0.05330 | 0.10031 |
| Edu weighted | 0.00294 | 0.00929 | 0.31645 | 0.75166 | -0.01526 | 0.02114 |
| Edu sample size | 0.01794 | 0.00712 | 2.52024 | **0.01173** | 0.00399 | 0.03189 |
| HZ unweighted | 0.03319 | 0.05205 | 0.63759 | 0.52374 | -0.06883 | 0.13521 |
| HZ weighted | 0.00273 | 0.00829 | 0.32948 | 0.74179 | -0.01351 | 0.01897 |
| HZ sample size | 0.03027 | 0.01437 | 2.10646 | **0.03516** | 0.00211 | 0.05844 |
| Own unweighted | 0.03445 | 0.03631 | 0.94887 | 0.34269 | -0.03671 | 0.10562 |
| Own weighted | 0.02356 | 0.01281 | 1.83863 | 0.06597 | -0.00155 | 0.04867 |
| Own sample size | 0.03505 | 0.00862 | 4.06793 | **0.00005** | 0.01816 | 0.05193 |

Table 4 provides an overview of the mean effects of all six effect measures (Income, AgeMid, AgeOld, Edu, HZ, and Own). We calculated the unweighted arithmetic mean, $\bar{\theta} = \sum_i \frac{\theta_i}{m}$, where $\theta_i$ is the effect measure of the $i$th regression result and $m$ is the total number of results included. We also calculate the weighted mean, $\bar{\theta} = \frac{\sum_i w_i \theta_i}{\sum_i w_i}$ where—as it is standard—the weights $w_i$ are the inverse of the standard errors of the effect measures. Using **R** package metafor (Viechtbauer, 2010), we calculate the weighted means by means of a random effects model. Given that our effect measures stem from studies that significantly differ in their model specifications, we cannot rule out that our effect measures are in fact drawn from different populations (Becker and Wu, 2007). Contrary to a simple weighted mean (the fixed effect model), which assumes that all effect measures are drawn from the same target population with one mean $\bar{\theta}$ and, hence, assume that each effect measure can be described by $\theta_i = \bar{\theta} + \epsilon_i$, the random effects estimator assumes that effect measures are samples from different populations whose respective population means are distributed around a grand mean $\bar{\theta}$. Hence, the random effects model assumes that each effect measure can be described by $\theta_i = \bar{\theta} + \phi_i + \epsilon_i$, where $\phi_i$ depicts the difference between the grand mean $\bar{\theta}$ and the true mean of the population from which the effect measure was sampled. The random effects model allows, therefore, unconditional inference by assuming that the sample of studies is a random sample from a larger population of all possible studies (Viechtbauer, 2010; Borenstein et al., 2010).

Following Houtven et al. (2017), we also calculate the mean effects using the study sample sizes, sampleZ, of the respective estimates as weights. Whilst Houtven et al. (2017) apply this approach because of non-reported standard errors of the effect measures, our reason to apply it is different and is due to the non-linearity of the estimation models used in most of our studies.

We use a binary probit regression model to exemplify the problem that arises from this non-linearity. Figure 1 plots the Gaussian link function of the probit regression model. The Gaussian link function, defining the probability of adoption $P(Y = 1|X = x) = \Phi(\mathbf{X}'\beta)$, is the cumulative density function of a standard normal distribution. However, as the semi-elasticity, our effect measure, from a probit regression model is calculated as $\frac{\partial P(Y = 1|\mathbf{X} = \mathbf{x})}{\partial x_k} \cdot x_k = \phi(\mathbf{x}'\beta) x_k \beta_k$, the size of the semi-elasticity will *ceteris paribus* be influenced by the value of the probability density function $\phi(\mathbf{x}'\beta)$, which in turn is determined by the probability of an average household in the sample adopting the energy efficiency measure. E.g., in a case where the probability of adoption for the average household is 0.5, the derivative of the cumulated density function at this point corresponds to the peak value of the probability density function. Hence, the value of the probability density function that is used to calculate the semi-elasticity will be large, whilst if the average household in the sample has a rather small or rather large likelihood of adopting a measure, the corresponding value on the probability density function will

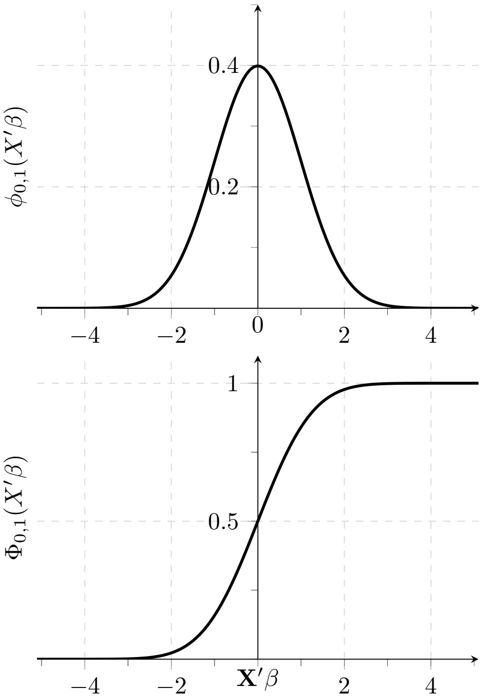


Figure 1: Cumulative and probability density function of a normal distribution

be small and, hence, all things equal, the corresponding semi-elasticity and its standard errors will be closer to zero.

One could argue that this characteristic of the semi-elasticities compromises the comparability of the effect measures across different samples and that all semi-elasticities should instead be calculated at the mode of their respective probability density functions. We argue that, as we are interested in the effect measure of the *average* household from each study, this approach would no longer represent the true mean effect of our sample, but would grossly overestimate the mean semi-elasticity.

However, in order to overcome the problem that smaller semi-elasticities *ceteris paribus* correspond with smaller standard errors, we chose to include a more neutral weighting factor, sample size, in our analysis. The effect of this choice becomes apparent in table 4, where the mean effects weighted by sample size are considerably larger than the mean effect weighted by the inverse standard error. In order to account for the influence of the adoption share on the corresponding semi-elasticities, we, therefore, included the adoption shares as an additional moderator variable in our analyses.

Tables 5 to 10 report the results of the weighted least squares estimations for all six effect measures, where we follow the standard approach of using the inverted standard errors of the effect measures.[9] We estimate four different model specifications: specification one only includes sample-related moderator variables, the second specification only includes model-related moderator variables, which in fact are of little interest for the analyses and only serve as control variables, whilst the third and fourth specifications estimate the full model.

Unlike meta-analyses based on experimental studies, which mainly test differences in the mean effects between different treatment groups, our sample is based on regression analyses with many different combinations of covariates. As discussed in the previous

[9]One could argue that as all six effect measures might be correlated, it would be appropriate to estimate a system of equations. However, the equation set up does not imply an apparent correlation of the error terms, which would necessitate such a step. Also, not taking an eventual correlation of the error terms into account will, at most, result in less efficient estimates and, hence, to more conservative results, but will not lead to biased results.

Table 5: Moderator analyses for effect 'Income'

| | *Dependent variable:* elaIncome | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| year | −.001*** | | −.001** | −.001** |
| | (.0003) | | (.0003) | (.0005) |
| country = 1 | −.004 | | .048* | .038 |
| | (.017) | | (.025) | (.029) |
| country = 2 | −.015* | | .029 | .033 |
| | (.009) | | (.028) | (.028) |
| country = 3 | −.003 | | .006 | .013 |
| | (.014) | | (.021) | (.023) |
| country = 4 | −.009 | | .020 | .014 |
| | (.010) | | (.019) | (.021) |
| country = 5 | −.013 | | .026 | .034 |
| | (.012) | | (.031) | (.030) |
| country = 6 | .026** | | .060** | .059** |
| | (.013) | | (.029) | (.029) |
| country = 7 | .003 | | .029 | .031 |
| | (.011) | | (.019) | (.019) |
| country = 8 | −.014 | | .044 | .052 |
| | (.010) | | (.040) | (.039) |
| experiment | −.010 | | −.031 | −.031 |
| | (.014) | | (.020) | (.022) |
| investment = 1 | .008 | | −.002 | −.003 |
| | (.012) | | (.013) | (.014) |
| investment 2 | .003 | | .004 | −.0002 |
| | (.011) | | (.012) | (.012) |
| share | .107*** | | .136*** | .157*** |
| | (.035) | | (.047) | (.044) |
| share2 | −.101** | | −.123** | −.137*** |
| | (.040) | | (.049) | (.051) |
| log(df) | | −.002 | | .002 |
| | | (.003) | | (.005) |
| df | | | −0.00000*** | |
| | | | (0.00000) | |
| house | | −.013 | −.030* | −.029* |
| | | (.011) | (.015) | (.015) |
| social | | .006 | .023 | .028* |
| | | (.007) | (.016) | (.016) |
| politic | | −.022 | .059 | −.004 |
| | | (.023) | (.037) | (.029) |
| Price | | .010 | .010 | .003 |
| | | (.007) | (.013) | (.012) |
| temp | | .004 | −.009 | −.017 |
| | | (.010) | (.016) | (.015) |
| constant | 2.008*** | .035 | 1.602** | 2.217** |
| | (.571) | (.028) | (.672) | (.898) |
| Observations | 135 | 135 | 135 | 135 |
| $R^2$ | .228 | .045 | .302 | .284 |
| Adjusted $R^2$ | .138 | .0003 | .180 | .158 |
| Residual Std. Error | .368 (df = 120) | .396 (df = 128) | .359 (df = 114) | .364 (df = 114) |
| F Statistic | 2.531*** (df = 14; 120) | 1.008 (df = 6; 128) | 2.466*** (df = 20; 114) | 2.256*** (df = 20; 114) |
| *Note:* | | | | *p<0.1; **p<0.05; ***p<0.01 |

Table 6: Moderator analyses for effect 'AgeMid'

| | *Dependent variable:* effAgeMid | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| year | .001 | | .001 | .0004 |
| | (.001) | | (.001) | (.001) |
| country = 1 | .004 | | .019 | .025 |
| | (.040) | | (.023) | (.021) |
| country = 2 | −.005 | | .072*** | .069*** |
| | (.023) | | (.020) | (.021) |
| country = 3 | −.041*** | | −.034 | −.036 |
| | (.014) | | (.023) | (.024) |
| country = 4 | −.012 | | .035 | .008 |
| | (.014) | | (.024) | (.017) |
| country = 5 | .002 | | .051*** | .048*** |
| | (.019) | | (.017) | (.018) |
| country = 6 | .014 | | .069*** | .069*** |
| | (.020) | | (.024) | (.025) |
| country = 7 | −.017 | | .005 | .004 |
| | (.036) | | (.025) | (.025) |
| country = 8 | −.018 | | .116*** | .115*** |
| | (.015) | | (.032) | (.032) |
| experiment | −.020 | | −.035 | −.040* |
| | (.037) | | (.024) | (.023) |
| investment = 1 | .004 | | −.010 | −.006 |
| | (.016) | | (.017) | (.015) |
| investment 2 | −.001 | | −.005 | −.004 |
| | (.008) | | (.007) | (.006) |
| share | −.019 | | −.060 | −.070* |
| | (.066) | | (.042) | (.040) |
| share2 | .054 | | .066 | .083* |
| | (.065) | | (.054) | (.050) |
| log(df) | | .0003 | | −.004 |
| | | (.003) | | (.004) |
| df | | | −0.00000** | |
| | | | (0.00000) | |
| house | | −.027*** | −.017 | −.019 |
| | | (.006) | (.013) | (.013) |
| social | | −.0001 | .048*** | .049*** |
| | | (.007) | (.017) | (.017) |
| politic | | −.132*** | −.166*** | −.165*** |
| | | (.008) | (.016) | (.016) |
| Price | | .002 | .014 | .008 |
| | | (.008) | (.021) | (.019) |
| temp | | −.006 | −.074*** | −.076*** |
| | | (.007) | (.021) | (.021) |
| constant | −2.120 | .024 | −2.189 | −.720 |
| | (2.138) | (.026) | (1.830) | (1.254) |
| Observations | 96 | 96 | 96 | 96 |
| $R^2$ | .139 | .220 | .447 | .434 |
| Adjusted $R^2$ | −.010 | .167 | .299 | .283 |
| Residual Std. Error | .311 (df = 81) | .282 (df = 89) | .259 (df = 75) | .262 (df = 75) |
| F Statistic | .932 (df = 14; 81) | 4.176*** (df = 6; 89) | 3.029*** (df = 20; 75) | 2.872*** (df = 20; 75) |
| *Note:* | | | | *p<0.1; **p<0.05; ***p<0.01 |

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Table 7: Moderator analyses for effect 'AgeOld'

| | *Dependent variable:* effAgeOld | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| year | .002 | | .001 | .001 |
| | (.002) | | (.002) | (.001) |
| country = 1 | .003 | | .017 | .022 |
| | (.075) | | (.053) | (.051) |
| country = 2 | −.012 | | .136*** | .129*** |
| | (.046) | | (.035) | (.038) |
| country = 3 | −.089*** | | −.072 | −.076 |
| | (.031) | | (.050) | (.051) |
| country = 4 | −.039* | | .030 | .005 |
| | (.023) | | (.032) | (.028) |
| country = 5 | .006 | | .113*** | .107*** |
| | (.041) | | (.032) | (.033) |
| country = 6 | −.031 | | .035 | .026 |
| | (.047) | | (.070) | (.075) |
| country = 7 | −.042 | | .003 | −.001 |
| | (.071) | | (.054) | (.055) |
| country = 8 | −.045 | | .198*** | .195*** |
| | (.041) | | (.038) | (.040) |
| experiment | −.035 | | −.050 | −.054 |
| | (.069) | | (.049) | (.050) |
| investment = 1 | −.005 | | −.039 | −.035 |
| | (.027) | | (.027) | (.025) |
| investment 2 | −.005 | | −.006 | −.005 |
| | (.012) | | (.011) | (.010) |
| share | .037 | | −.108 | −.121 |
| | (.144) | | (.121) | (.119) |
| share2 | .043 | | .115 | .132 |
| | (.140) | | (.124) | (.123) |
| log(df) | | .001 | | −.006 |
| | | (.006) | | (.008) |
| df | | | −0.00000 | |
| | | | (0.00000) | |
| house | | −.061*** | −.043 | −.045 |
| | | (.015) | (.029) | (.028) |
| social | | .007 | .097*** | .097*** |
| | | (.019) | (.026) | (.027) |
| politic | | −.223*** | −.278*** | −.277*** |
| | | (.019) | (.040) | (.039) |
| Price | | .010 | .041 | .037 |
| | | (.013) | (.031) | (.030) |
| temp | | −.020 | −.142*** | −.141*** |
| | | (.017) | (.033) | (.035) |
| constant | −3.780 | .047 | −2.865 | −1.439 |
| | (4.611) | (.058) | (3.123) | (2.667) |
| Observations | 96 | 96 | 96 | 96 |
| $R^2$ | .155 | .237 | .449 | .445 |
| Adjusted $R^2$ | .009 | .186 | .303 | .297 |
| Residual Std. Error | .427 (df = 81) | .387 (df = 89) | .358 (df = 75) | .360 (df = 75) |
| F Statistic | 1.064 (df = 14; 81) | 4.608*** (df = 6; 89) | 3.061*** (df = 20; 75) | 3.010*** (df = 20; 75) |
| *Note:* | | | | *p<0.1; **p<0.05; ***p<0.01 |

Table 8: Moderator analyses for effect 'Edu'

| | *Dependent variable:* effEdu | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| year | −.004* | | −.003*** | −.004*** |
| | (.002) | | (.001) | (.001) |
| country = 1 | −.004 | | .009 | .011 |
| | (.036) | | (.029) | (.027) |
| country = 2 | −.025 | | .009 | −.002 |
| | (.037) | | (.034) | (.031) |
| country = 3 | −.009 | | .020 | −.015 |
| | (.035) | | (.031) | (.029) |
| country = 4 | −.031 | | .053 | .036 |
| | (.036) | | (.043) | (.040) |
| country = 5 | −.039 | | −.040 | −.052* |
| | (.038) | | (.031) | (.030) |
| country = 6 | −.010 | | .027 | .005 |
| | (.037) | | (.033) | (.030) |
| country = 7 | .041 | | .040 | .019 |
| | (.050) | | (.030) | (.030) |
| country = 8 | −.004 | | −.033 | −.026 |
| | (.035) | | (.031) | (.028) |
| experiment | −.010 | | .001 | −.019 |
| | (.015) | | (.022) | (.020) |
| investment = 1 | −.032 | | −.029 | −.034 |
| | (.021) | | (.022) | (.025) |
| investment 2 | −.023 | | −.025 | −.031 |
| | (.018) | | (.020) | (.023) |
| share | .128*** | | .069 | .072 |
| | (.041) | | (.049) | (.047) |
| share2 | −.160*** | | −.127** | −.128** |
| | (.051) | | (.050) | (.051) |
| log(df) | | −.007*** | | −.015** |
| | | (.002) | | (.007) |
| df | | | −0.00000** | |
| | | | (0.00000) | |
| house | | −.018 | −.061*** | −.054*** |
| | | (.017) | (.019) | (.019) |
| social | | −.013* | −.034** | −.025* |
| | | (.007) | (.014) | (.014) |
| politic | | −.050*** | −.084** | −.080** |
| | | (.016) | (.037) | (.033) |
| Price | | −.012 | −.030* | −.028** |
| | | (.011) | (.016) | (.014) |
| temp | | .019* | .035** | .039** |
| | | (.010) | (.017) | (.020) |
| constant | 7.984* | .086*** | 7.034*** | 9.253*** |
| | (4.721) | (.027) | (2.421) | (2.323) |
| Observations | 94 | 94 | 94 | 94 |
| $R^2$ | .336 | .124 | .470 | .480 |
| Adjusted $R^2$ | .218 | .064 | .324 | .338 |
| Residual Std. Error | .283 (df = 79) | .310 (df = 87) | .263 (df = 73) | .260 (df = 73) |
| F Statistic | 2.853*** (df = 14; 79) | 2.059* (df = 6; 87) | 3.233*** (df = 20; 73) | 3.376*** (df = 20; 73) |
| *Note:* | | | | *p<0.1; **p<0.05; ***p<0.01 |

Table 9: Moderator analyses for effect 'HZ'

| | *Dependent variable:* elaHZ | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| year | .0001 | | .002 | .002 |
| | (.001) | | (.002) | (.002) |
| country = 1 | −.054*** | | −.043 | −.042 |
| | (.007) | | (.032) | (.035) |
| country = 2 | −.0001 | | .079 | .009 |
| | (.019) | | (.066) | (.045) |
| country = 5 | −.016 | | .026 | −.014 |
| | (.013) | | (.039) | (.027) |
| country = 6 | −.022** | | .053 | .009 |
| | (.010) | | (.055) | (.046) |
| country = 7 | −.020** | | −.040 | −.040 |
| | (.010) | | (.074) | (.065) |
| country = 8 | −.032*** | | .024 | −.017 |
| | (.009) | | (.058) | (.058) |
| experiment | .035*** | | −.041 | −.037 |
| | (.011) | | (.063) | (.057) |
| investment = 1 | −.083** | | −.084*** | −.095*** |
| | (.039) | | (.030) | (.035) |
| investment = 2 | −.080** | | −.068 | −.079* |
| | (.038) | | (.045) | (.045) |
| share | .018 | | −.068 | −.060 |
| | (.038) | | (.072) | (.074) |
| share2 | −.065 | | .024 | −.012 |
| | (.062) | | (.077) | (.088) |
| log(df)) | | −.009* | | −.022** |
| | | (.005) | | (.009) |
| df | | | −0.00000*** | |
| | | | (0.00000) | |
| house | | −.005 | .014 | .020 |
| | | (.017) | (.073) | (.064) |
| social | | −.013 | .019 | .008 |
| | | (.013) | (.061) | (.058) |
| price | | −.007 | −.018 | .010 |
| | | (.011) | (.043) | (.033) |
| temp | | .003 | −.060 | −.018 |
| | | (.008) | (.067) | (.068) |
| constant | −.183 | .103* | −4.119 | −4.419 |
| | (1.213) | (.056) | (3.668) | (3.509) |
| Observations | 61 | 61 | 61 | 61 |
| $R^2$ | .213 | .087 | .301 | .354 |
| Adjusted $R^2$ | .016 | .004 | .024 | .099 |
| Residual Std. Error | .373 (df = 48) | .376 (df = 55) | .372 (df = 43) | .357 (df = 43) |
| F Statistic | 1.081 (df = 12; 48) | 1.054 (df = 5; 55) | 1.087 (df = 17; 43) | 1.387 (df = 17; 43) |

*Note:* *p<0.1; **p<0.05; ***p<0.01

Table 10: Moderator analyses for effect 'Own'

| | *Dependent variable:* effOwn | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| year | .002** | | .004*** | .004** |
| | (.001) | | (.001) | (.002) |
| country = 1 | .033** | | .035 | .032 |
| | (.015) | | (.049) | (.045) |
| country = 2 | .020 | | .030 | −.065 |
| | (.033) | | (.060) | (.082) |
| country = 3 | .051** | | .103*** | .080* |
| | (.024) | | (.038) | (.044) |
| country = 4 | −.044 | | .042 | .085* |
| | (.036) | | (.034) | (.050) |
| country = 5 | −.053 | | −.064 | −.083 |
| | (.036) | | (.053) | (.052) |
| country = 6 | .048 | | .054 | .015 |
| | (.054) | | (.087) | (.088) |
| country = 7 | .033 | | .002 | −.042 |
| | (.028) | | (.051) | (.053) |
| country = 8 | −.060* | | −.123 | −.156* |
| | (.033) | | (.086) | (.085) |
| experiment | −.078*** | | −.065 | −.063 |
| | (.029) | | (.050) | (.049) |
| investment = 1 | .019 | | .012 | .009 |
| | (.015) | | (.016) | (.015) |
| investment 2 | .023 | | .025 | .023 |
| | (.016) | | (.017) | (.014) |
| share | .181* | | .136* | .183** |
| | (.097) | | (.080) | (.092) |
| share2 | −.189** | | −.170** | −.217** |
| | (.091) | | (.086) | (.092) |
| log(df) | | .003 | | −.031*** |
| | | (.007) | | (.010) |
| df | | | −0.00000*** | |
| | | | (0.00000) | |
| house | | −.034* | −.052* | −.081** |
| | | (.020) | (.031) | (.036) |
| social | | .023 | −.038 | −.070 |
| | | (.015) | (.044) | (.046) |
| politic | | −.029 | −.026 | −.102* |
| | | (.027) | (.055) | (.061) |
| Price | | .024* | .019 | .059 |
| | | (.014) | (.031) | (.036) |
| temp | | .005 | .053 | .109** |
| | | (.016) | (.043) | (.055) |
| constant | −3.711** | .004 | −7.250*** | −7.431** |
| | (1.704) | (.065) | (2.334) | (3.177) |
| Observations | 70 | 70 | 70 | 70 |
| $R^2$ | .467 | .157 | .681 | .623 |
| Adjusted $R^2$ | .331 | .077 | .551 | .469 |
| Residual Std. Error | .320 (df = 55) | .376 (df = 63) | .262 (df = 49) | .285 (df = 49) |
| F Statistic | 3.442*** (df = 14; 55) | 1.961* (df = 6; 63) | 5.225*** (df = 20; 49) | 4.052*** (df = 20; 49) |

*Note:* *p<0.1; **p<0.05; ***p<0.01

section, the average study contains around 22 different covariates, which means that we cannot rule out correlations between pairs or multiple variables that might have an effect on the effect size of our variables of interest (either by inflating the effect size through a mediation or confounding effect or by supressing the effect size). If one assumes a critical degree of correlation between at least one of the five household characteristics and another covariate in the regression equation, effect measures from studies that include the covariate will differ from effect measures from studies that do not, as in the latter case, the omission of that covariate will create an omitted variable bias. The degree to which this becomes a problem will depend on the correlation between the household characteristic and this particular covariate and will most likely affect studies to different degrees, depending on their respective household sample. Attempts to overcome this shortcoming in meta-studies on regression coefficients have been conducted for linear regression models with continuous dependent variables and covariates (see e.g., Becker and Wu, 2007, for an overview). However, to the best of our knowledge no approach has been suggested to date to handle this problem for results from non-linear regression models, models with binary outcome variables, and for model specifications with categorical covariates. Therefore, we follow the suggestions by Eagly and Wood (1994); Stanley and Jarrell (1989); Stanley (2001) and Doucouliagos and Paldam (2006) and include further moderator variables that address differences in the model specifications of the respective studies. However, given the vast number of different variables that are included in the studies, we have no realistic way of fully controlling the impact of each of these variables on the coefficient estimates of our variables of interest. Therefore, we attempt to proxy this influence by including dummy variables that indicate whether covariates of a specific type were included in the regression model.

We run the standard residual tests for normality and heteroscedasticity, identify and remove some outliers with high leverage, and use Ramsey's RESET test to test all 18 model specifications. However, despite no apparent misspecifications of the regression model and despite a considerable number of moderator variables in the full model specification, even the model specification with the best fit can only explain around 30% of the variance in our effect measures (only taking the adj. $R^2$ values into account). On the one hand, this low fit implies that other important factors may influence the variation of our effect measures. On the other hand, we have to acknowledge that our effect measures are themselves rather noisy, which increases the overall noise of the regression models and will further depress the (adjusted) $R^2$ values.

Finally, following Houtven et al. (2017), we take the panel structure of our data into account by calculating cluster robust standard errors using the sandwich package (Zeileis, 2004; Berger et al., 2017).

## 4. Discussion

Can household characteristics consistently explain the heterogeneity in households' energy efficiency investments? Our results indicate that systematic patterns across the five standard characteristics as determinants of households' energy efficiency investments exist, though to a varying degree across all five household characteristics:

- Our results show a positive correlation between income and a household's propensity to invest in energy efficiency for all three weighing strategies. The findings listed in Table A.12 (see appendix) confirm this result. The majority of studies find a positive correlation between income and propensity to invest. However, the magnitude of the income effect on a household's propensity to invest remains small. A household with twice the income shows an increase in the propensity to invest of between 0.7 and 2.1 percentage points.

- The effect of age is ambiguous and statistically insignificant for all three weighing strategies. Elder households seem to have a slightly higher propensity to invest than middle-aged households, but the difference is too small to be of economic significance. The correlations listed in Table A.12 also show an ambiguous trend, with a similar amount of studies finding a negative/positive correlation.

- Education has a weakly positive effect on households' propensity to invest in energy efficiency. Household heads with at least some college education are between 0.3 and 2.4 percentage points more likely to invest in energy efficiency than households who did not attend college. In addition, the majority of studies in Table A.12 find a positive correlation between higher education and the propensity to invest.
- Household size has an overall positive effect on the propensity to invest. A doubling of the members in a household increases the average household's propensity to invest by between 0.2 and 2.3 percentage points.
- Home ownership seems to have the strongest positive effect on a household's propensity to invest. A household who own their home are between 2.4 and 3.5 percentage points more likely to invest in energy efficiency than a household who rent their home. Studies included in Table A.12 largely confirm the positive effect of ownership on households' propensity to invest.

Interpreting the trends in effect sizes, we have to point out that the mean effects for the most part are statistically insignificant from zero considering a 5% significance level. Furthermore, only 6 studies included in the meta-analysis consider the effect of all five household characteristics. Thus, the estimated mean effects for the different household characteristics are based on different subsets of our sample. The magnitude of the effect sizes for all five household characteristics should, therefore, be compared with caution, having this limitation in mind.

Tables 5 to 10 report the results for our moderator analysis. Focusing on the sample specific moderator variables in specifications 3 and 4, we find statistically significant differences in effect sizes for income, age, education and ownership across countries, in comparison to studies based on observations from multiple OECD countries as baseline. These findings may reflect country-specific differences that affect households' energy efficiency investments. The positive effect on the effect size for old-age in the USA, Germany and Northern Europe may, e.g., reflect easier access to capital for investments for elder households compared to younger households in these countries/regions compared to the average OECD country. Ireland and UK show a positive and significant effect on the effect size for ownership. This finding may show that split incentives play a larger role in Ireland and UK, so that homeowners have a larger incentive to invest in energy efficiency than tenants. The opposite may be the case in Canada, which shows a significant and negative effect on the effect size for ownership. However, at this stage, we can only speculate on the cause of cross country differences.

The investment moderators controlling for investment intensity unexpectedly show no statistically significant effects on the effect sizes for all household characteristics. We take a closer look at the effect of investment intensity in Table 11 and in the following paragraph. Altogether, as discussed in the previous section, the low (adjusted) $R^2$ values of the moderator analyses (specification 3 and 4) for income, age, education, household size and home ownership, suggest that a major part of the variance in the study results exists due to other unknown and, most likely, situational factors.

Table 11: Predicted effect measures for the three investment levels

| | Investment class | | |
|---|---|---|---|
| | 0 | 1 | 2 |
| Income | 0.0318 | 0.0302 | 0.0357 |
| AgeMid | 0.0056 | -0.0046 | 0.0003 |
| AgeOld | 0.0083 | -0.0311 | 0.0020 |
| Edu | 0.0513 | 0.0225 | 0.0264 |
| HZ | 0.0747 | -0.0096 | 0.0062 |
| Own | 0.0321 | 0.0440 | 0.0571 |

Although the investment moderators for investment intensity show no statistically significant effect on the effect measures, we find insightful trends for the predicted values of our effect measures, given the three investment levels. We compare the predicted values with our hypotheses from section 2. Table 11 shows how the predicted effect measures for the five household characteristics change with the investment class from 0 = minor investment to 2 = major investment.

- A higher income shows a positive effect on a household's propensity to invest across all investment classes with the largest impact for major investment. Considering the difference in effect sizes between minor, medium, and major investments, this difference confirms our hypothesis that the income effect, to some degree, strengthens as the capital intensity of the investment increases. The positive and reinforcing effect of income confirms that financial resources and access to capital play a relevant role in households' investment decision.

- Age shows a mixed effect across investment classes for both age groups with small effect sizes especially for major investments. Thus, age appears to have a limited effect on households' propensity to invest across investment classes. Drawing on our investment model, we hypothesised an ambiguous effect of age, for major investments in particular, arguing with two opposing effects when age increases. Our empirical findings for both age categories may confirm our hypothesis; however, we cannot draw an unambiguous conclusion.

- The effect of having a higher education on a household's propensity to invest is largest for minor investments. Higher education increases the propensity to invest in minor energy efficiency improvements by 5.13 percentage points. The effect size is lower for medium and major investments. This result contradicts our hypothesis that the effect of education increases, the longer the amortisation period of an investment, i.e., the more capital-intensive an investment. Instead of being a pure effect of educational attainment, the larger effect for minor investments compared to medium and major investments may instead reflect the fact that households with a higher education tend to have a more environmentally-friendly attitude, which may correlate with a higher propensity for minor changes towards more energy efficiency.

- The effect of household size is positive and much larger for minor investments compared to medium and major investments. This finding confirms our hypothesis that larger households with higher demand for energy services compared to smaller households benefit over-proportionally from efficiency improvements through larger energy savings. The effect size is negative and/or smaller for medium and major investments, which suggests that a lower per capita income for larger households indeed decreases these households' financial ability to make medium or major efficiency investments. However, given the low predictive quality of the regression model, these results should be read with care.

- The predicted effect sizes for ownership show a clear and increasing trend across investment classes. This finding confirms our hypothesis that households that own their home are more likely to invest in energy efficiency than households that rent, and that this effect increases with the capital intensity of the investment. Home ownership appears to be the major determinant of households' energy efficiency investments. This result suggests that split incentives are a considerable barrier to energy efficiency improvements in the residential sector.

Our results confirm that households that own their home, have a high income, and fewer household members are most likely to invest in costly energy efficiency measures. Thus, these households appear to face fewer barriers to investing in large energy efficiency improvements than households that rent their home, have a low income, and a large household size.

The positive effect of income on a household's propensity to invest confirms that access to capital and financial resources plays an essential role in a household's efficiency investment decision. Targeting access to capital measures or incentive payments on households with low income that likely face liquidity constraints may increase the effectiveness of these policies. Moreover, we find the effect of home ownership on a household's propensity to invest most pronounced. This result confirms that split incentives present a considerable barrier to energy efficiency improvements. Households that rent their homes are less likely to invest. However, considering the fact that tenants are often not allowed to make investment decisions without the property owner's permission, targeting tenants with energy efficiency policies would probably not increase their investment propensity and would, thus, have a negative effect on the policy outcome. Policies to overcome split incentives could instead target property owners, e.g., through efficiency standards for rented properties.

## 5. Conclusion

Our empirical findings show–unsurprisingly–that income and ownership status reveal the clearest trends in explaining households' energy efficiency investments. This corresponds with our initial hypotheses, which we derived from the theoretical investment model. Policy makers and modellers could potentially use these readily observable household characteristics to account for heterogeneity in policy design. However, two things are worth noting. First, the magnitude of the trends we find is limited. Differences between groups of households account for, at most, single digit percentage points, which questions the economic significance of the results. Secondly, before designing targeted policies, the additional costs should be balanced with the expected benefits. Given the magnitude and insecurity, and especially the strong situational impact on the magnitude and direction of the average effects we found in our meta-analysis, it is uncertain whether any eventual benefits of more targeted policies would outweigh the additional costs of implementation. It is, therefore, questionable whether targeted policy measures really are a valid policy option beyond small and obvious areas of application. Indeed, simpler policy measures, such as carbon taxes, may in many instances generate the same effect at lower cost.

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## Declarations of interest

None.

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## AppendixA. Tables and figures

### *AppendixA.1. Further empirical evidence for heterogeneity in household energy efficiency investment behaviour*

Table A.12 summarises further empirical evidence of heterogeneity in households' energy efficiency investments, which we could not include in our meta-analysis due to methodological constraints or limitations on data availability.

Column (1) and (2) define the study under consideration and the country of origin of the studied data. Column (3) describes the type of investment decision that each study investigates. Activity level "0" represents minor investments, mainly considering investment behaviour with respect to energy-efficient light bulbs. Activity level "1" refers to investments of a medium size, e.g., appliances. Activity level "2" corresponds to large retrofit investments, which include envelope renovations, solar panels, and heating systems. Column (4) indicates the sample size of the analysis. Columns (5)-(9) show the estimated coefficient of regression of a household's decision to invest in energy efficiency on the characteristics income, age, education, household size and home ownership, which are identified by the studies under consideration. A positive (negative) coefficient, indicating higher (lower) propensity to invest in energy efficiency, is represented by "+" ("−"). "∅" marks the case where a study does not address one or more of the respective determinants. The values in parenthesis show the t-statistics for the estimates, where bold font indicates statistical significance. Given the coefficients and standard errors, we computed the t-values when a study did not directly report them. "NA" indicates that t-values were unobtainable or unsuitable for the applied methodology. These cases also include studies with categorical estimates (frequently used for the determinants income, age and education), which implies two issues: First, non-linear effects, which we indicate by "+/−" and second, different t-values for each category, which we report as "NA" because finding a weighted average was not possible due to missing summary statistics. A bold font "NA" again indicates statistical significance, as reported in the studies.

Studies that apply multiple models, i.e., consider different subgroups or dependent variables, appear in multiple rows. We provide further information on these and all other studies in the Online Appendix.

Table A.12: Further Evidence for Heterogeneity in Household Energy Efficiency Investment Behaviour

| Study | Country | Activity level | N | Income | Age | Education | Household size | Home ownership |
|---|---|---|---|---|---|---|---|---|
| Achtnicht and Madlener (2014) | Germany | 2 | 379 | + **(-61.69)** | − **(-6.15)** | − (0.11) | ∅ | ∅ |
| | | 2 | 379 | + **(-4.75)** | − **(-2.05)** | + **(1.86)** | ∅ | ∅ |
| Akhtar (2017) | Pakistan | 1 | 404 | − NA | − NA | − NA | ∅ | ∅ |
| Barr et al. (2005) | UK | 0/1/2 | 1265 | + **NA** | + **NA** | + **NA** | − **NA** | + **NA** |
| Busic-Sontic et al. (2017) | UK | 2 | 1581 | − NA | − **NA** | + NA | ∅ | ∅ |
| Busic-Sontic and Fuerst (2017) | Germany | 2 | 2948 | − NA | − **NA** | + NA | ∅ | ∅ |
| | | 2 | 2939 | + **NA** | − **NA** | + **NA** | ∅ | ∅ |
| Charlier (2015) | France | 2 | 16 111 | + NA | + **(4.98)** | ∅ | ∅ | + **(10.20)** |
| Charlier (2013) | France | 0/2 | 16 780 | +/− NA | +/− NA | +/− **NA** | ∅ | + **(2.23)** |
| | | 0/2 | 16 780 | +/− NA | +/− NA | + **NA** | ∅ | + (1.56) |
| De Groote et al. (2016) | Belgium | 2 | 8471 | + **(10.75)** | + **NA** | − **NA** | + **NA** | + **(3.85)** |
| Dubin and Henson (1988) | USA | 2 | 688 | + **(9.47)** | ∅ | ∅ | ∅ | ∅ |
| Ferguson (1993) | Canada | 2 | 450 | + **(2.81)** | + **(3.08)** | ∅ | ∅ | ∅ |
| Friedman et al. (2018) | Israel | 2 | 451 | + (0.50) | − **(−1.68)** | − (−0.35) | + (1.51) | − (−1.30) |
| Goto et al. (2011) | Japan | 1 | 841 | + NA | + **NA** | ∅ | − NA | ∅ |
| Grösche et al. (2013) | Germany | 2 | 2128 | + (0.3) | ∅ | ∅ | ∅ | ∅ |
| | | 2 | 2128 | − (-1.44) | ∅ | ∅ | ∅ | ∅ |
| | | 2 | 2128 | + (0.89) | ∅ | ∅ | ∅ | ∅ |

Table A.12: Further Evidence for Heterogeneity in Household Energy Efficiency Investment Behaviour

| **Study** | **Country** | **Activity level** | **N** | **Income** | **Age** | **Education** | **Household size** | **Home ownership** |
|---|---|---|---|---|---|---|---|---|
| | | 2 | 2128 | + (0.17) | ∅ | ∅ | ∅ | ∅ |
| Hartman and Doane (1986) | USA | 2 | 507 | + **(5.35)** | − **(-4.26)** | ∅ | ∅ | + **(4.00)** |
| Hartman (1988) | USA | 2 | 658 | ∅ | ∅ | ∅ | ∅ | + **(-3.10)** |
| Houde (2014) | USA | 1 | 49279 | + **NA** | + **NA** | +/− **NA** | − **NA** | ∅ |
| | | 1 | 76115 | + **NA** | + **NA** | +/− **NA** | − **NA** | ∅ |
| | | 1 | 76115 | +/− NA | +/− NA | +/− NA | + **NA** | ∅ |
| Islam (2014) | Canada | 2 | 298 | ∅ | − (−0.64) | +/− NA | ∅ | ∅ |
| Karlin et al. (2014) | USA | 0/1/2 | 540 | + **NA** | + **NA** | + **NA** | ∅ | + **NA** |
| Leelakulthanit (2014) | Thailand | 0 | 555 | + (1.76) | 0 (0) | − (−0.51) | ∅ | ∅ |
| Long (1993) | USA | 2 | 5871 | + **(8.02)** | + **(2.49)** | ∅ | − (−1.42) | ∅ |
| Mendelsohn (1977) | USA | 2 | 5539 | + **(4.32)** | +/− NA | ∅ | ∅ | ∅ |
| | | 2 | 5539 | + **(2.28)** | +/− NA | ∅ | ∅ | ∅ |
| Miller et al. (2014) | USA | 0/1/2 | 11115 | +/− NA | ∅ | + NA | + (0.75) | + **(19.81)** |
| Mills and Schleich (2012) | EU and Norway | 1 | 4915 | ∅ | ∅ | + **NA** | ∅ | ∅ |
| | | 1 | 4915 | ∅ | ∅ | + **NA** | ∅ | ∅ |
| Min et al. (2017) | Korea | 1 | 1000 | + **(4.00)** | + **(3.76)** | + **(3.08)** | ∅ | ∅ |
| Nair et al. (2010) | Sweden | 0/1/2 | 1045 | + **NA** | − **NA** | + **NA** | ∅ | ∅ |
| O'Doherty et al. (2008) | Ireland | 1 | 23526 | + **(10)** | +/− **NA** | ∅ | ∅ | + **NA** |

Table A.12: Further Evidence for Heterogeneity in Household Energy Efficiency Investment Behaviour

| **Study** | **Country** | **Activity level** | **N** | **Income** | **Age** | **Education** | **Household size** | **Home ownership** |
|---|---|---|---|---|---|---|---|---|
| Olsthoorn et al. (2017) | EU | 2 | 6265 | + **(2.50)** | + (0.77) | − (−0.13) | − **(−4.62)** | ∅ |
| Powers et al. (1992) | USA | 2 | 690 | + **(2.68)** | − (−0.67) | + **(2.48)** | − (−0.63) | ∅ |
| Reynolds et al. (2012) | Saint Lucia | 0 | 264 | +/− **NA** | +/− **NA** | ∅ | ∅ | ∅ |
| | | 0 | 264 | +/− **NA** | +/− NA | ∅ | ∅ | ∅ |
| Rowlands et al. (2003) | Canada | 0 | 466 | + **NA** | − **NA** | + **NA** | ∅ | ∅ |
| Sardianou and Genoudi (2013) | Greece | 2 | 150 | + **(3.93)** | + **(3.46)** | + **(3.04)** | ∅ | + (0.84) |
| Scott (1997) | Ireland | 2 | 1200 | ∅ | ∅ | +/− **NA** | ∅ | ∅ |
| | | 2 | 1200 | ∅ | ∅ | + **NA** | ∅ | ∅ |
| Shen (2012) | China | 1 | 3000 | + **(1.79)** | − **(−3.65)** | + **(1.68)** | ∅ | ∅ |
| Smiley (1979) | USA | 2 | 1049 | + **NA** | − **NA** | ∅ | ∅ | ∅ |
| Song (2008) | Canada | 2 | 5717 | + **NA** | + **(2.00)** | − **(−3.00)** | ∅ | ∅ |
| Sopha et al. (2011) | USA | 2 | 960 | − **NA** | − **NA** | − **NA** | ∅ | ∅ |
| Stolyarova (2016) | France | 2 | 17618 | + **NA** | + **NA** | ∅ | + **NA** | + **NA** |
| | | 2 | 17618 | − **NA** | − **NA** | ∅ | + **NA** | + **NA** |
| | | 2 | 14861 | +/− NA | + NA | ∅ | + NA | +/− **NA** |
| | | 2 | 1350 | − NA | 0 NA | ∅ | + **NA** | − NA |
| | | 2 | 1350 | − **NA** | − NA | ∅ | + **NA** | − NA |
| Testa et al. (2016) | Italy | 0/1 | 198 | + (0.42) | − (−0.90) | − (−0.49) | ∅ | ∅ |

Table A.12: Further Evidence for Heterogeneity in Household Energy Efficiency Investment Behaviour

| **Study** | **Country** | **Activity level** | **N** | **Income** | **Age** | **Education** | **Household size** | **Home ownership** |
|---|---|---|---|---|---|---|---|---|
| Ward et al. (2011) | USA | 1 | 355 | − (-0.18) | + **(-5.51)** | − (-0.37) | ∅ | ∅ |
| Wilson (2008) | Canada | 2 | 295 | + **NA** | − **NA** | ∅ | ∅ | ∅ |
| Yang and Zhao (2015) | China | 0/1 | 526 | − NA | + **NA** | + NA | ∅ | ∅ |
| Yue et al. (2013) | China | 0/1 | 581 | + **NA** | − **NA** | + **NA** | ∅ | ∅ |
| Zhou and Bukenya (2016) | China | 1 | 1569 | +/− **NA** | + NA | + NA | − **NA** | ∅ |

**Legend: Activity level 0 = Minor investment, 1 = Medium investment/Appliances, 2 = Major investment/Retrofit.**
**"+" positive correlation, "−" negative correlation, "∅" not part of the study.**
**"NA" t-values unobtainable or unsuitable.**

# Appendix C.

# Overcoming the hurdle: meeting Danish energy saving requirements by targeting household investment behavior

# Overcoming the hurdle: meeting Danish energy saving requirements by targeting household investment behavior

Kristoffer Steen Andersen[a,b,1,*], Catharina Wiese, catwi@dtu.dk[a], Stefan Petrovic, stpet@dtu.dk[a], Russell McKenna, rkenna@dtu.dk[a]

[a] *Technical University of Denmark, DTU Management, Produktionstorvet, Building 424, 2800 Kongens Lyngby, Denmark*
[b] *The Danish Energy Agency, Carsten Niebuhrs Gade 43, 1577 Copenhagen, Denmark*

**Abstract**

The EU's Energy Efficiency Directive (EED) sets a binding target for energy savings in EU Member States. Member States are required to perform ex-ante evaluations of energy efficiency policies that are implemented to achieve these savings. Ex-ante evaluations of energy efficiency policies are difficult. They require detailed modelling of end-users' investment and energy demand behavior. This paper demonstrates a comprehensive methodology for ex-ante evaluation of energy efficiency policies directed at residential heating. Using the IntERACT model, the paper assesses the potential for meeting Denmark's EED target through a policy-induced increase in households' investments in energy efficiency retrofits. IntERACT links the energy system model TIMES-DK with a computable general equilibrium model of the Danish economy. The paper simulates the effect of energy efficiency policies on households' investment behavior by applying different levels of hurdle rates to households' investments in energy efficiency retrofits. The results show that a reduction in the level of hurdle rate from 25 % to 4 % could deliver up to half of Denmark's energy saving target for the period 2021–2030. This result includes a direct rebound effect of 37 %. The paper further quantifies spillovers in terms of adverse inter-temporal welfare effects.

*Keywords:* Energy Efficiency Directive, Rebound effect, Household behavior, Implicit discount rate, Energy-economy model

## 1. Introduction

Article 7 of the EU's Energy Efficiency Directive (EED), as adopted in December 2018, sets a target for cumulative energy savings in EU Member States for the period 2021 to 2030. The cumulative target corresponds to average annual savings equivalent to 0.8 % of the states' average final energy consumption in the period 2016–2018 (European Union, 2018). Energy savings must further be additional to a business-as-usual (BAU) scenario, i.e. a baseline scenario without new policy measures. For Denmark, the EED target corresponds to a cumulative reduction in final energy demand of 275 PJ over the period 2021–2030.[1] Energy use for residential heating represents

[*] Corresponding author
*Email address:* `krisan@dtu.dk` (Kristoffer Steen Andersen)

[1] Based on 626 PJ final energy demand in 2017 (Danish Energy Agency, 2018b).

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one quarter of current Danish final energy demand (Danish Energy Agency, 2018b), and residential heat savings will likely play a key role in meeting Denmark's energy saving requirements. In particular, several studies have documented a considerable saving potential within the existing residential building stock (e.g., Kragh and Wittchen, 2010; Tommerup and Svendsen, 2006; Wittchen and Kragh, 2014).

However, to perform ex-ante evaluations of residential energy efficiency polices in accordance with Article 7 is difficult because it requires detailed modelling of households' behavior both in terms of energy efficiency investments and energy demand. Capturing households' energy demand behavior is particularly important when an energy efficiency policy yields cost savings relative to the BAU scenario. In that case, ex-ante evaluations need to account for rebound effects because these can partially offset direct energy savings (Greening et al., 2000; Sorrell, 2009; Sorrell et al., 2009). Within existing ex-ante evaluations of energy efficiency polices in accordance with Article 7, considerable uncertainty exists as to what extent Member States account for rebound effects (Rosenow et al., 2016). Capturing households' investment behavior is a key prerequisite for determining the level of energy savings, both within the BAU scenario and the policy scenario. Households' investment behavior with respect to energy efficiency improvements is influenced by numerous factors, e.g. individual preferences, rationality constraints and external barriers to energy efficiency, which include lack of information and limited access to capital (e.g., Jaffe and Stavins, 1994; Sorrell et al., 2004). Indeed, quantitative analyses have shown, that the discount rate implicit in households' investment decisions for efficiency improvements is often an order of magnitude higher than the opportunity cost of capital or market interest rate (e.g., Burlinson et al., 2018; Corum and O'Neal, 1982; Jaccard and Dennis, 2006; Train, 1985). Within energy-economy models, high implicit discount rates are widely used as a proxy to simulate the (slow) adoption of energy efficiency investments in the residential sector (Schleich et al., 2016). In the modelling context, this behavioral parameter is referred to as 'hurdle rate', which we also use in the modelling sections of this paper. Although widely used, the hurdle rate implicit in households' investment decisions and its underlying factors remain largely unclear (Schleich et al., 2016). Thus, there is a need to better understand the role of hurdle rates in model-based policy evaluations in Denmark and beyond.

In this paper, we use the Danish IntERACT model to analyze the potential for meeting Denmark's EED target by reducing the high discount rate implicit in households' investment decisions. IntERACT is a hybrid model, which, by design, captures feedback effects between the Danish energy system, modelled in TIMES-DK, and the wider Danish macro-economy, represented in a computable general equilibrium (CGE) model. The comprehensive modelling framework allows us to (i) capture how the amount of realized energy savings in the residential sector depends on the level of hurdle rate applied to investments in heat saving measures, i.e. energy efficiency retrofits, and (ii) simultaneously gain insight into the rebound effects and the overall impact on welfare when reducing the hurdle rate. The aim of this paper is threefold: first, to define a reasonable range for the level of hurdle rate applied to investments in residential heat saving measures in IntERACT; second, to determine the potential for meeting Denmark's EED target by reducing the hurdle rate through policy intervention; third, to highlight the importance of the direct rebound effect and its impact on realized energy savings from a hurdle rate reduction.

The paper is structured as follows. Section 2 reviews the literature with respect to discount rates implicit in households' investment decisions and presents the major rationale behind our assessment. Section 3 introduces IntERACT, in particular the modelling of heating supply and demand for residential buildings. Section 4 explains the data on residential heat savings implemented in this paper. Section 5 presents our results and discusses limitations, and Section 6 concludes.

## 2. Background and literature review

In this section, we first clarify what implicit discount rates represent. We further review the literature with respect to empirical estimates of discount rates implicit in households' investment decisions for energy efficiency improvements and consider the impact of policy intervention on households' investment behavior. Finally, we explain and present the use of implicit discount rates, i.e. hurdle rates, in different energy-economy models, and specify the level of hurdle rate that we implement in IntERACT.

### *2.1. Implicit discount rates in households' energy efficiency investment decisions*

When making an energy efficiency investment decision, households face upfront costs paired with future energy cost savings. Economic discounting theory suggests that households' evaluation of these costs and benefits involves applying discount rates, which put different weights on costs and benefits dependent on if they occur upfront or in the future. However, with respect to energy efficiency investments, it is well established in the literature that individual households do not necessarily perform exhaustive net present value calculations, but that their evaluation of costs and benefits is influenced by a mix of factors (Schleich et al., 2016; Stadelmann, 2017). Thus, households may not directly apply discount rates in their decision-making process; yet, an *implicit discount rate* can be derived from observed investment decisions. The discount rate implicit in a household's investment decision reflects all factors influencing and explaining the actual investment behavior of the household within a cost-benefit framework. The rationale behind implicit discount rates together with estimates of implicit discount rates for investments in heat saving measures serve as the main backdrop for our impact assessment.

#### *2.1.1. Empirical estimates of implicit discount rates*

Empirical estimates of implicit discount rates in households' investment decisions for energy efficiency improvements are derived from consumers' revealed or stated preferences for certain investments combined with assumptions on the future costs and benefits. Since Hausman's (1979) seminal work on consumer choices for air conditioners, a number of studies have analyzed consumer investment decisions and estimated implicit discount rates for various energy-related products including appliances, refrigerators, lighting, automobiles, heating systems and building retrofits (e.g., Burlinson et al., 2018; Dubin, 1982; Meier and Whittier, 1983; Min et al., 2014; Ruderman et al., 1987; Train, 1985). Following our focus on households' investment decisions for heat saving measures, Table 1 lists implicit discount rate estimates in the literature, focusing on investments that affect households' energy demand for residential heating, i.e. energy efficiency retrofits and heating system choice.

Table 1: Implicit discount rate estimates

| Estimates | Comments | Investment type | Reference |
|---|---|---|---|
| 20.79 % | Discount rate for an average homeowner, based on data from a Canadian survey | Energy efficiency retrofits | Jaccard and Dennis (2006) |

| Continuation of Table 1 | | | |
|---|---|---|---|
| Estimates | Comments | Investment type | Reference |
| 10 % for gas-heated, 14 % for oil-heated, and 19–21 % for electricity-heated houses | Average discount rates across 10 US cities assuming no real energy price increases and upfront costs are paid in cash. Considering increasing real energy prices and mortgage financing increases the average discount rates ranging from 14–41 % for gas-heated houses, 18–60 % for oil-heated houses, and 21–90 % for electricity heated houses | Energy efficiency retrofits | Corum and O'Neal (1982) |
| 26 % for US survey, and 12 % for Pacific Northwest survey | Average discount rates assuming no real energy price increases and 15 years useful life. Estimated range: 15–35 % for US survey and 6–15 % for Pacific Northwest survey | Energy efficiency retrofits | Cole and Fuller (1982) (as cited in Train, 1985) |
| 32 % for thermal shell, and 10 % for window and door retrofits | Average discount rates assuming no real energy price increases and infinite life | Energy efficiency retrofits | Little (1984) (as cited in Train, 1985) |
| 36 % | Discount rate when controlling for consumer inattention and heuristic decision-making | Connection to district heating | Burlinson et al. (2018) |
| 9 % | Based on a Canadian survey introducing a stated choice experiment | Heating system and fuel choice | Jaccard and Dennis (2006) |
| 39–56 % for gas central space heater, 52–127 % for oil central space heater | Aggregate market discount rates between 1972 and 1980 assuming no real energy price increases and using real-world data on useful life | Heating system and fuel choice | Ruderman et al. (1987) |
| 4.4 % and 21.4 % for households with and without central air conditioning respectively | Average discount rates assuming no real energy price increases and infinite life | Heating system and fuel choice | Goett (1984) |

| Continuation of Table 1 | | | |
|---|---|---|---|
| Estimates | Comments | Investment type | Reference |
| 2.1–9.3 % | Discount rates depending on the model specification. Assuming no real energy price increases and using real-world data on useful life | Heating system and fuel choice | Dubin (1982) |
| 7–31 % | Depending on the fuel choice and assuming no real energy price increases and infinite useful life | Heating system and fuel choice | Lin et al. (1976) |
| 36 % | Average discount rate from the preferred model, assuming no real energy price increases and infinite useful life | Heating system and fuel choice | Goett (1978) (as cited in Train, 1985) |
| 6.5–16% | Depending on the model specification. Average discount rates assuming no real energy price increases and infinite useful life | Heating system and fuel choice | McFadden (1982) (as cited in Train, 1985) |
| 25% | Average discount rates assuming no real energy price increases and infinite useful life | Heating system and fuel choice | Berkovec et al. (1983) (as cited in Train, 1985) |

As shown in Table 1, the literature finds estimates ranging from 2.1 % to 127 %. The differences in discount rates among and within studies largely depend on different assumptions with respect to energy prices and the expected useful life of an investment (Train, 1985). The studies should therefore be compared with caution. However, despite the large range, estimates of implicit discount rates are generally high, and especially higher than the opportunity cost of capital or market interest rate. In other words, households largely fail to adopt energy efficiency investments that are cost-effective under market conditions because they behave as if applying high discount rates. They behave *as if* applying high discount rates because estimating a high implicit discount rate does not reveal the reasons for why consumers apply these discount rates in their investment decision (Jaffe and Stavins, 1994). Indeed, the households' decision-making process is complex and influenced by a mix of factors.

*2.1.2. Factors behind implicit discount rates*

According to Schleich et al. (2016), "*the factors behind the implicit discount rate (...) usually remain blurred and fractional.*" The majority of literature focuses on market- and to some degree behavioral failures as the main explanation for households' high implicit discount rates, specifically in the context of the energy efficiency gap discussion (Allcott and Greenstone, 2012; Howarth, 2004; Jaffe and Stavins, 1994; Ruderman et al., 1987). Schleich et al. (2016) introduce a more comprehensive framework and broaden the discussion on the factors behind households' high implicit discount rate and its implications for policy-making. They divide the underlying factors into three categories: (i) preferences, (ii) bounded rationality, rational inattention and behavioral biases, and (iii) external barriers. Preferences refer to individual time, risk, reference-dependent and pro-environmental preferences. Bounded rationality, limited attention, and behavioral biases represent household behavior that deviates from rational choice theory, while external barriers to energy efficiency include split incentives, lack of information, and capital and financial risks.[2]

(i) With respect to investment decisions for heat saving measures, households' preferences induce a high implicit discount rate when households are risk-averse. Because investments in heat saving measures entail a certain risk with respect to future cost savings and technology performance, risk aversion tends to reduce the probability that a household invests (Qiu et al., 2014), and increase the discount rate implicit in households' investment decisions. On a related note, households with reference-dependent preferences may perceive the high upfront costs of heat saving measures as a loss, meaning that loss-averse households are less likely to invest (drawing on Kahneman and Tversky (1979)). Households' environmental preferences, which may increase the probability that households invest in heat saving measures, appear less relevant for investments with high upfront costs (Ramos et al., 2016; Stern, 2000).

(ii) Bounded rationality and rational inattention may increase the implicit discount rate, even if households are perfectly informed: first, if households lack the ability to compute, process, and evaluate information (bounded rationality), or second, if processing information is associated with high opportunity cost in terms of time and effort (rational inattention) (Burlinson et al., 2018; Schleich et al., 2016). The effect of rational inattention may be lower for investments in heat saving measures considering the high upfront costs (Palmer and Walls, 2015).

(iii) External barriers may affect the implicit discount rate through e.g. split incentives, imperfect information, transaction costs and lack of financial resources. Split incentives are particularly relevant with respect to investments in heat saving measures within multi-family buildings, where the allocation of costs and benefits between property owners and tenants is challenging (e.g., Ástmarsson et al., 2013). Furthermore, the relevance of split incentives is likely increasing the higher the upfront investment. If households are imperfectly informed about saving potentials and implementation options, they may underinvest in cost-effective energy efficiency improvements. Evidence shows that better knowledge increases adoption (Scott, 1997). Transaction costs associated with the acquisition, assessment and use of information increase the upfront costs of an investment by a non-monetary component, and thus reduce the probability to invest (Howarth and Andersson, 1993). Furthermore the disturbance of construction work in the home can be considered a transaction cost representing a further investment barrier. Finally, households' liquidity constraints increase the discount rate implicit in their investment decisions and this barrier likely increases in relevance the higher the upfront costs. The external barriers, by definition, keep households from investing in heat saving measures and thus increase the discount rate implicit in households' investment decisions.

*2.1.3. The role of policy intervention*

Residential energy efficiency policies aim at increasing energy efficiency investments, thus, at reducing the discount rate implicit in the investment decisions for energy efficiency improvements. Therefore, the interaction between policies and households' implicit discount rate needs to be taken into account when using implicit discount rates to model actual household investment behavior.

[2]The framework closely relates to recent literature on barriers to energy efficiency that includes a more comprehensive view on the energy efficiency gap discussion (e.g., Gerarden et al., 2017; Gillingham and Palmer, 2014; Stadelmann, 2017).

In order to achieve a reduction in the discount rate implicit in households' investment decisions, policies need to address its underlying factors and impact them in a way that stimulates investments in energy efficiency improvements. The external barriers to energy efficiency investments are a major focus of policy interventions. Information provision through e.g. campaigns, certificates and labels, or tailored audits, address imperfect information and directly enable households to make more informed investment decisions. Several studies investigate the impact of information on energy efficiency investment behavior and find mixed, however, largely positive effects (Abrahamse et al., 2007; Barbetta et al., 2015; Ek and Söderholm, 2010; Newell et al., 1999; Newell and Siikamäki, 2014; Ramos et al., 2015). These findings confirm that improved access to information reduces households' implicit discount rate. The general impact of information provision on implicit discount rates has been studied by Coller and Williams (1999). In a lab experiment, they find that implicit discount rates for the group treated with information lie between 15 % and 17.5 %, while the control group shows discount rates between 20 % and 25 %. Furthermore, financial incentives, which help to overcome households' financial constraints, have been found to increase investments (e.g., Datta and Filippini, 2016; Datta and Gulati, 2014; Markandya et al., 2009). Both information provision and financial incentives impact the underlying factors of high implicit discount rates. While information provision may reduce households' discount rate by improving the access to information that stimulates investments in energy efficiency improvements, financial incentives, e.g. in the form of subsidies, more directly overcome the hurdle to invest by reducing upfront cost constraints, which otherwise would have induced high implicit discount rates.

To what extent policy intervention can change households' preferences depends on the underlying assumptions on consumer behavior. Neoclassical economic theory assumes that preferences are stable over time and that behavior is influenced only by prices and income constraints. However, research within behavioral economics and psychology (for an energy-related overview see Frederiks et al., 2015) suggests that policy interventions can take into account households' preferences and behavioral biases and thereby establish conditions that favor the decision to invest in energy efficiency improvements or nudge households towards certain behavior. If households are inattentive to energy efficiency as an attribute or boundedly rational, for example, information provision may reduce the behavioral bias and increase awareness (Newell and Siikamäki, 2014), or minimum energy efficiency performance standards may enforce certain investment decisions by limiting the availability of the most inefficient technologies (Gillingham and Palmer, 2014; Schleich et al., 2016). Risk and loss aversion may be addressed by policies that reduce the risk and perceived losses e.g. by providing financial support for high upfront costs.

Already today, EU Member States have implemented an energy efficiency policy mix, which consists of e.g. regulatory measures, financial incentives and market-based instruments (Wiese et al., 2018) and new policies will be designed and introduced in the future in order to meet the EU's energy saving requirements (European Union, 2018; Zygierewicz, 2016). If these policies are designed effectively, i.e. they increase awareness or create investment conditions that help to overcome households' upfront barriers to invest in energy efficiency, they will increase energy efficiency investments and reduce households' implicit discount rate.[3]

[3] Which of the underlying factors should or should not be addressed through policy interventions from a neoclassical welfare perspective is debated among economists, environmentalists and policy makers (e.g., Gillingham and Palmer, 2014). In this paper, we do not aim at contributing to this discussion, but focus on the overall potential for meeting energy saving requirements by stimulating households' investment behavior and reducing high implicit discount rates through the implementation of energy efficiency policies.

*2.2. The use of hurdle rates in energy-economy models*

The discussion on discount rates in energy-economy models involves two broad perspectives on the modelling purpose. First, a model can be used to determine what energy investments would have to be made in order to ensure the least costs to society, considering certain model restrictions, e.g. on $CO_2$-emissions. For this purpose, social discount rates should be used and a number of modelling studies indeed apply social discount rates in their assessments (e.g., Schulz et al., 2008). Second, a model can be used to simulate the actual investment behavior by adopting hurdle rates.

Table 2 gives a summary of hurdle rates applied to investment decisions in the residential sector, referring to different models and studies. These hurdle rates range from 9 % to 30 %. The majority of studies use a single hurdle rate for investments in residential heat saving measures, however, the Canadian CIMS model differentiates between investments in home renovations (20.79 %) and investments in home heating systems (9 %), estimated from a survey (Jaccard and Dennis, 2006). Kannan (2009) conducts a sensitivity analysis and considers a change in the hurdle rate from 25 % to 8.75 %, yet the choice of sensitivity is not explained in any detail.

Two studies implement a reduction in the hurdle rate as a proxy for reduced market barriers and imperfections (European Commission, 2016; Mundaca). Mundaca applies a 'conservative' hurdle rate of 30 % as the default discount rate, which he reduces to 10 % when running the model for different energy saving targets. However, the study does not provide any sources for the reduction in hurdle rate. The EU Reference Scenario 2016, modelled in PRIMES, assumes that energy efficiency policies reduce the hurdle rate for renovations of houses and for heating equipment in the residential sector (European Commission, 2016). These policies include labelling programs, financial measures and the promotion of energy service companies. However, no source is provided either for the default hurdle rate (14.75 %) or the reduced hurdle rate (12 %).

The literature reviewed in the previous sections indicates that there is no conclusive evidence neither for the level of implicit discount rate, nor the effect of policies on its underlying factors. The somewhat arbitrary use of hurdle rates in existing energy-economy models confirms this uncertainty. The approach taken in our paper should therefore be seen as a first step towards better understanding the role of hurdle rates within an energy-economy modelling context. For this purpose, we consider a hurdle of 25 % as a reasonable upper bound for simulating households' behavior with respect to investments in energy efficiency retrofits in the absence of policy measures. We further explain our approach and the use of hurdle rates in IntERACT in Section 3.1.1.

Table 2: Use of implicit discount rates in energy-economy models

| Energy modelling tool | Geographical focus | Hurdle rate | Reference |
|---|---|---|---|
| The energy system model PRIMES simulates a market equilibrium solution for energy supply and demand within each of the 27 EU member states and seven other European countries. It determines an optimal solution by finding the prices of each energy fuel that match the supply and demand of energy | EU | 14.75 % applied to renovations of houses and to heating equipment in the residential sector; modified to 12 % when including energy efficiency policies | European Commission (2016) |
| MARKAL and TIMES are dynamic linear programming model generators, which process data sets that describe a given energy system. MARKAL and TIMES generate a partial economic equilibrium model that relies on detailed input to represent global, national, or regional energy systems and their evolution | Croatia | 15% for residential space and water heating | Bozic (2007) |
| | EU | 30 % for energy efficiency technologies applicable to the residential and commercial sectors; reduced to 10 % when including energy efficiency policies | Mundaca |
| | UK | 25 % for residential energy saving measures (8.75 % sensitivity) | Kannan (2009) |
| | UK | 25 % for residential energy saving measures | Kannan and Strachan (2009) |
| | EU | 17 % for the residential sector | Simoes et al. (2013) |

| Continuation of Table 2 | | | |
|---|---|---|---|
| Energy modelling tool | Geographical focus | Hurdle rate | Reference |
| NEMS is an integrated energy-economy model that provides projections of US domestic energy-economy markets in the long-term (2030). It is used by the US Department of Energy to produce their annual energy outlook | US | 20 % for the residential sector | U.S. Energy Information Administration (2018) |
| CIMS is an integrated capital vintage model that simulates the evolution of energy-using capital stocks through retirements, retrofits, and new purchases | Canada | 20.79 % for the choice of home renovations and 9 % for the choice of home heating systems | Jaccard and Dennis (2006) |

## 3. Modelling heating supply and demand for residential buildings in IntERACT

IntERACT is a hybrid model built to assess Danish energy and climate mitigation policies. The model is based on an automated iterative soft-linking routine between an energy system model (TIMES-DK) and a computable general equilibrium (CGE) model.

This section presents methodological details with respect to: first, the supply of residential heating, modelled in TIMES-DK; second, the implementation of hurdle rates in TIMES-DK and its implications; third, the demand for residential heating, derived from the CGE model; fourth, the soft-linking routine between TIMES-DK and the CGE model.

### *3.1. Residential heating supply in TIMES-DK*

TIMES-DK is a multi-regional model, which covers the entire Danish energy system based on the TIMES modelling framework (Loulou et al., 2016). Aside from residential heating supply, the TIMES-DK model used in this paper also models residential appliances, energy service supply for 10 economic sectors, refinery, and district heating and electricity supply. TIMES-DK is solved as a linear programming problem minimizing total discounted system costs under perfect foresight until 2030. See Balyk et al. (2019), for further documentation of TIMES-DK including its geographical representation and time slice aggregation.

TIMES-DK models the cost of district heating (DH), individual heating options (HO) and heat saving measures for residential buildings, where DH and HO compete with heat saving measures. This segmentation allows the model to determine the trade-off between investing in DH, HO and heat saving measures when satisfying residential heating demand. Figure 1 illustrates the supply of residential heating in TIMES-DK. The rectangles in Figure 1 denote processes, the vertical lines indicate commodities, while the arrows represent energy flows.

The whole Danish residential building stock is represented in TIMES-DK based on the Danish Building and Housing Register (Danish Ministry of Housing, Urban and Rural Affairs, 2014). The model aggregates the building stock according to construction period, building type, position relative to existing DH areas, and region. The construction period is divided into before and after 1972,

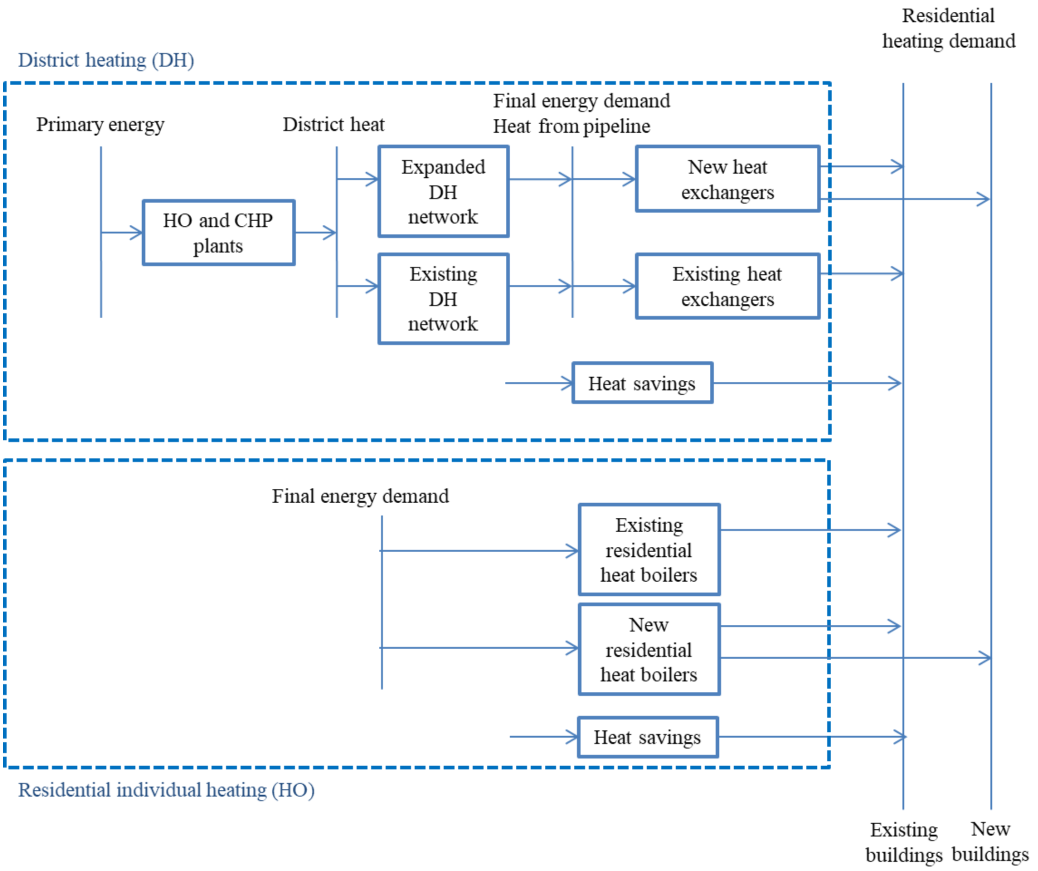


Figure 1: Supply of residential heating in TIMES-DK

and new buildings. This division reflects the stricter requirements in terms of energy performance for new constructions, introduced in 1972. New buildings (i.e. constructed in 2010 or after) comply with the current Danish building code. The building type (single- and multi-family) determines the type of heating supply technology that is available for a building. The location relative to existing DH areas (central, decentral and individual) allows for a differentiation by cost, efficiency and availability of DH. Central DH systems are located in larger cities, have higher installed capacities, more consumers and higher grid efficiency compared to decentral systems. Residential buildings within or close to these areas include DH among their heating supply options. All the remaining residential buildings belong to individual areas, i.e. without access to DH. Altogether, we categorize the residential building stock into 36 groups in total.[4] With respect to heat saving measures, TIMES-DK includes cost curves for the 24 groups of existing buildings (constructed

[4]Table A.1 in Appendix A presents the categorization of the residential building stock in TIMES-DK.

before or after 1972). Heat savings measures are not available for the 12 groups of new buildings.

In this paper, residential heating supply in TIMES-DK includes a number of constraints to mitigate the winner-takes-all-property of linear programming models, i.e. that the cheapest technology captures the whole market. These constraints are used to ensure a more realistic adoption and phase out of supply technologies for residential heating (i.e. boilers, heat pumps and DH heat exchangers). First, a growth constraint on each fuel-specific supply technology limits the maximum annual change in heating output delivered by said technology to each specific building category. For example, the heating output from natural gas boilers may only decrease by 10 % on an annual basis for individual single family houses. Second, we use share constraints, which set a minimum share of total heating services delivered by each a fuel-specific supply technology to a specific building category. The minimum share is reduced over time. Without these constraint, oil boilers would be phased out immediately in TIMES-DK. However, by including the share constraints, final energy demand for oil (used in residential oil boilers) is reduced from around 9 PJ in 2017 to 1 PJ in 2030. The values that go into these growth and share constraints have been guided by historical trends and expert judgment.

To fully isolate the effect of reducing the hurdle rate applied to investments in energy efficiency retrofits, we use exogenous prices for electricity and district heating within TIMES-DK. These prices are based on Danish Energy Agency (2018a). This choice in part reflects that preliminary research has found that the level of investment in residential energy efficiency retrofits affects the price of electricity and district heating within TIMES-DK. However, the possible interaction between energy efficiency policy, and electricity and district heating capacity and production will be subject of future research.

We calibrate the residential heating supply in TIMES-DK on energy statistics till the year 2017. For future modelling years (i.e. years after 2017), changes in the residential heated area drive demand for heating services. The demand for $m^2$ of heated area is based on the simulation model SMILE (Hansen et al., 2013), which makes a long-term forecast of housing demand by type of building, supply area and region.[5] The calibration of residential heating supply feeds into the iterative loop between heating supply and demand from TIMES-DK and the CGE model, which we will explain further in Section 3.3.

*3.1.1. Implementation of hurdle rates in TIMES-DK*

We use the option to add hurdle rates, in the form of technology specific discount rates, to the TIMES modelling framework (Loulou et al., 2016) in order to capture households' investment behavior. Based on Section 2, we consider a hurdle rate of 25 % as a reasonable upper bound for capturing households' behavior with respect to investments in energy efficiency retrofits in the absence of policy measures. Thus, the 25 % hurdle rate defines our baseline scenario. We define a social discount rate as the lower bound because public policy should provide society with a return at least equal to the social discount rate. The Danish Ministry of Finance recommends a social discount rate equal to 4 % (Danish Ministry of Finance, 2013).

To provide transparency on the role of the level of hurdle rate, we consider three additional magnitudes, namely 10 %, 15 % and 20 %, and apply these to households' investment decisions for

[5]SMILE does not consider the demand for new versus existing buildings. Instead, TIMES-DK determines the construction rates for new buildings as the difference between housing demand (from SMILE) and the existing stock remaining after demolition. Within TIMES-DK, we assume a demolition rate of 0.5 % annually for each of the 24 groups of existing houses.

Table 3: Hurdle rate premium applied to residential energy efficiency retrofit investments

| Hurdle rate | 4% | 10% | 15% | 20% | 25% |
|---|---|---|---|---|---|
| Premium | 0% | 63% | 119% | 174% | 226% |

Economic life time = 25 years; general discount rate = 4 %

heat saving measures, specifically energy efficiency retrofits. Throughout the modelling sections, we refer to these levels as hurdle rate scenarios.

With respect to space heating systems, we draw on the estimation by Jaccard and Dennis (2006) and apply a hurdle rate of 9 %. Jaccard and Dennis (2006) argue that the lower estimated discount rate for residential heating systems compared to energy efficiency retrofits reflects that households face less barriers, e.g. less risk in terms of final energy savings, when investing in energy-efficient heating systems. In the context of this paper, we add two further arguments for applying a lower hurdle rate to households' investment decision for heating systems. First, within a Danish setting, part of the households' investment decision is delegated to energy providers. They are obliged by law to use a social discount rate of 4 % when determining whether or not to expand or replace a collective heating network (i.e. natural gas or district heating). Second, within the IntERACT model, we make use of a number of fuel-specific growth and share constraints to guide the future choice of heating system technologies. These constraints likely capture some of the behavioral barriers related to investments in residential heating systems (see Section 3). We keep the hurdle rate for residential heating systems constant at 9 % in all scenarios, reflecting that this paper focuses on policy interventions related to households' investment decision for energy efficiency retrofits.

Within the TIMES modelling framework, hurdle rates are implicitly introduced by adding a premium to investments in specific technologies. The premium makes investments in these technologies less attractive from a cost minimizing perspective. The premium is determined based on the level of general discount rate, the economic lifetime of a technology and the level of hurdle rate.[6] In this paper, we assume an economic lifetime of 25 years for heat saving measures and a general discount rate of 4 % for all investments in these measures. Table 3 shows the correspondence between the level of hurdle rate and the investment premium for the hurdle rates considered within this paper.

Applying a hurdle rate of 25 % adds a premium to the investment of 226 %. We assume that the premium does not reflect an actual monetary flow. Thus, when reporting the level of retrofit investment from TIMES-DK to the CGE model, we exclude the premium. In case the premium reflects actual monetary flows or affects household welfare (e.g. if the premium reflects leisure time spent on the investment decision), the approach taken in this paper will underestimate the impacts on household income and utility within the CGE model.

### *3.2. Residential heating demand in the CGE model*

The CGE model is a single country multi-sector model. In its present form, the model consists of 18 economic sectors, a government and a single representative household. It is calibrated on national account statistics, using 2015 as the benchmark year. The representative household earns income from supplying factors of production (labor and capital) to firms. The utility function

[6]See Appendix B for the formula used to calculate the investment premium within TIMES.

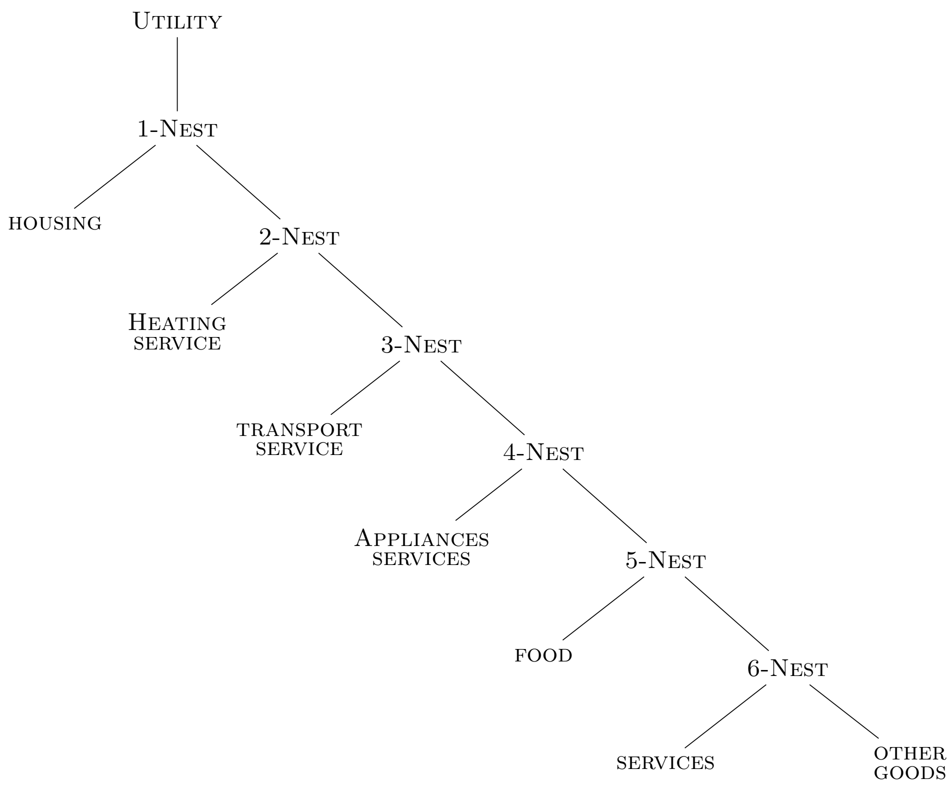


Figure 2: Nesting utility function of the representative household

of the household builds on the Danish macroeconomic model ADAM (Knudsen, 2012), however, unlike ADAM it includes an explicit representation of the household's demand decisions for energy services related to heating, transport and appliances. Figure 2 illustrates the nesting structure of the Stone Geary utility function that we use. The Stone Geary specification allows to specify both commodity-specific substitution and income elasticities. The substitution elasticity captures how a change in the relative price of a commodity affects demand compared to other commodities, whereas the income elasticity captures how a change in the disposable income changes the demand for a commodity. In the IntERACT model, the substitution elasticities determine the direct rebound effects, whereas the income elasticities determine the indirect rebound effects. Income and substitution elasticities related to the demand for transport services, appliances, food, and other goods and services are based on a separate study (Thomsen, 2019). Elasticities for housing are taken from Knudsen (2012).

For use in this paper, we calibrate the income and substitution elasticity for heating demand to reflect previous econometric studies. Over the past decades, Danish studies have estimated a partial price elasticity of residential heating demand ranging from -0.25 to -0.5 (Thomsen, 2019). To capture this range and the implied uncertainty concerning the direct rebound, we consider three different levels for the substitution elasticity (central, low and high). The central substitution elasticity is calibrated such that the CGE model replicates a partial price elasticity of -0.38. The low (high) substitution elasticity is calibrated to replicate a partial price elasticity of -0.25 (-0.50). We calibrate the income elasticity for heating demand based on the assumption that households will consume the same level of heating service per $m^2$ as income rises, if the price of residential heating remains constant.This assumption is in line with the assumptions made in previous econometric studies for Denmark (Thomsen, 2019). The number of $m^2$ is exogenous in IntERACT (based on projection from SMILE). This allows us to calibrate the income elasticity of heating demand until the income effect alone (i.e. assuming a fixed price of heating service) leads to a growth in residential heating demand equal to the growth in $m^2$ from SMILE. This calibration results in an income elasticity for heating demand of around 0.11. That is, a 1 % increase in disposable income results in a modest 0.11 % increase in the demand for heating service.

*3.3. Iterations between residential heating supply and demand*

Figure 3 illustrates the automated iterative soft-linking routine used to balance heating service supply and demand within IntERACT. We initialize the iterative routine by running TIMES-DK (1* in Figure 3). The TIMES-DK solution dictates the future residential heating supply function in the subsequent CGE model run; in terms of future fuel mix, energy efficiency improvements, fuel tax rates, the price of electricity and district heating, and heating service investments within the residential sector. The CGE model run results in an updated heating service demand, which is fed back to TIMES-DK. After three iterations between TIMES-DK and the CGE model, we observe full convergence in residential heating costs and demands between the two models, including convergence in fuel tax revenues and investments.

Equation 1 expresses how the future heating supply function in the CGE model is adjusted based on the TIMES-DK solution. Equation 1 (formally a Leontief zero profit condition) reflects the complementarity condition that heating services will only be produced if the profit from this activity is non-negative. In other words, heating services ($CES_{year}$) will only be supplied within the CGE model, if the price of heating services (the right hand side of the equation) is equal to

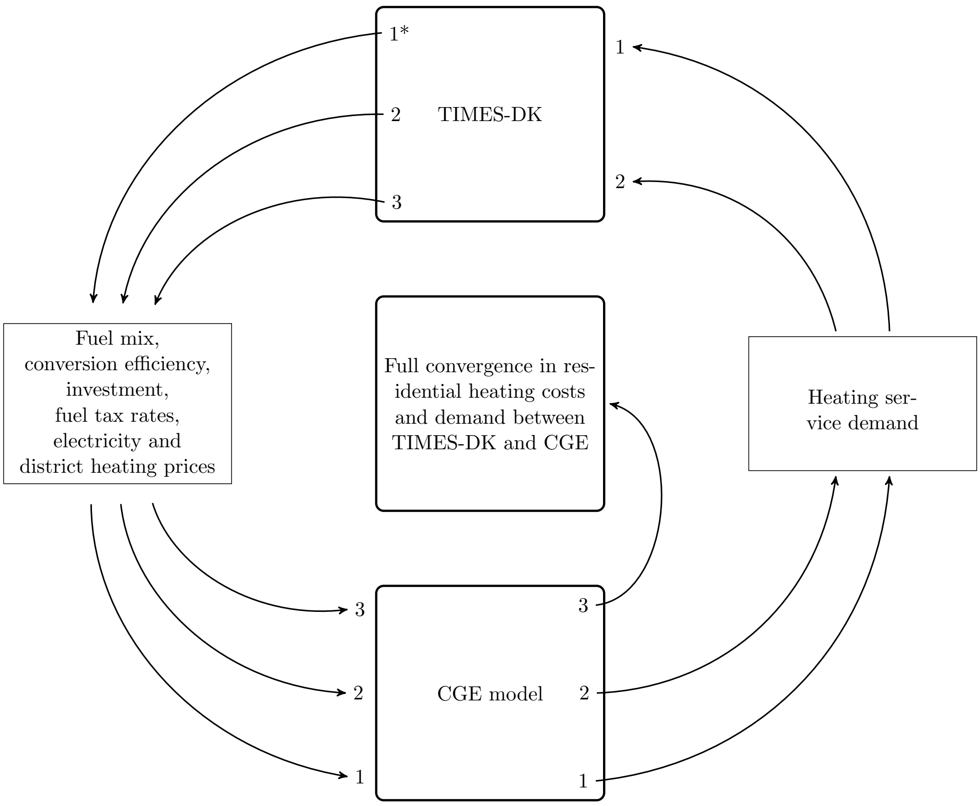


Figure 3: Iterations between heating supply and heating demand within the IntERACT model

the cost of heating services (the left hand side of equation).[7]

We update the cost side of Equation 1 for future modelling years by accounting for the change in conversion efficiency (first term on the left-hand-side) and by updating fixed fuel cost shares (second term on the left-hand-side). The change in conversion efficiency is determined by dividing the change in fuel use (measured in monetary terms) relative to 2015, the benchmark year in the CGE model, with the change in heating service output relative to 2015. We update fuel cost shares in the CGE model based on future fuel cost shares from TIMES-DK (measured in monetary terms). To ensure consistency in the fuel cost shares between the two models, we further account for changes in residential fuel tax rates and changes in the price of electricity and district heating. Updating tax rates further ensures convergence in residential fuel tax revenues between TIMES-DK and the CGE model.

In addition to updating the zero profit condition for residential heating supply in the CGE model, we account for the impact of households' investments in boiler technology and energy efficiency retrofits. This is done by adjusting the disposable income of the representative household in the CGE model using a lump-sum transfer that matches the investment demand from TIMES-DK in future years. Within the CGE model, the lump-sum transfer is then used to buy the commodity *Housing* to capture the monetary flow associated with these investments.

Equation 2 highlights how we update residential heating service demand within TIMES-DK based on the CGE model solution. This is done by multiplying the aggregated housing demand in 2015 with the heating demand index from the CGE model in order to get to a new level of aggregated heating demand for future years in TIMES-DK. This aggregated heating demand is subsequently split into 12 demand groups, to differentiate demand by building type, supply area and region, using future shares from the exogenous SMILE projection (Hansen et al., 2013).

[7]See Andersen et al. (2019) for a complete discussion of the in IntERACT applied linking methodology using mixed complementarity.

Equations for soft-linking routine within IntERACT

$$\underbrace{\left[\frac{\frac{\sum_f x_{f,\text{year}}^{\text{TIMES-DK}}}{\sum_f x_{f,2015}^{\text{CGE}}}}{\frac{\sum_{b,s,r} d_{b,s,r,\text{year}}^{\text{TIMES-DK}}}{\sum_{b,s,r} d_{b,s,r,2015}^{\text{TIMES-DK}}}}\right]}_{\substack{\text{Change in conversion efficiency}\\ \text{relative to CGE benchmark}}} \cdot \underbrace{\sum_f \left[\frac{x_{f,\text{year}}^{\text{TIMES-DK}}}{\sum_f x_{f,\text{year}}^{\text{TIMES-DK}}} \cdot pf_{f,\text{year}} \cdot (1+\text{tax}_{f,\text{year}})\right]}_{\text{Updated fixed cost shares}} \geq pces_{\text{year}}, \quad \underbrace{ces_{\text{year}}}_{\substack{\text{Complementary}\\ \text{variable}}} \tag{1}$$

$$d_{b,s,r,\text{year}}^{\text{TIMES-DK}} = \underbrace{\frac{\text{smile}_{b,s,r,\text{year}}}{\sum_{b,s,r} \text{smile}_{b,s,r,\text{year}}}}_{\text{Future share of building type}} \cdot \underbrace{\text{smile}_{b,s,r,2015}}_{\substack{\text{Benchmark year}\\ \text{heating demand}}} \cdot \underbrace{\overline{ces}_{\text{year}}}_{\substack{\text{Demand index}\\ \text{from the CGE model}}} \tag{2}$$

where we have used the following abbreviations

| | |
|---|---|
| Indices | |
| $f$ | Fuel |
| $b$ | Building type |
| $s$ | Supply area |
| $r$ | Region |
| Variables | |
| $pces_{\text{year}}$ | Heating price (CGE model) |
| $ces_{\text{year}}$ | Heating demand (CGE model) |
| $pf_{f,\text{year}}$ | Fuel price (harmonized across the CGE and TIMES-DK model) |
| Parameters | |
| $d_{b,s,r,\text{year}}^{\text{TIMES-DK}}$ | TIMES-DK heating demand by building type, supply area and region |
| $x_{f,2015}^{\text{CGE}}$ | CGE benchmark fuel input quantity (in monetary units, real 2015 prices) |
| $x_{f,\text{year}}^{\text{TIMES-DK}}$ | TIMES-DK fuel input quantities (in monetary units, real 2015 prices) |
| $\text{tax}_f$, year | CGE fuel tax rate calculated based on tax revenues from TIMES-DK output |
| $\text{smile}_{b,s,r}$ | SMILE projection of housing demand by building type, supply are and region |
| $\overline{ces}_{\text{year}}$ | Heating demand index from last CGE model iteration (Index 2015 = 1) |

## 4. Data on residential heat saving potential

The data on residential buildings used within TIMES-DK is based on a stationary heat loss model (Petrović and Karlsson, 2014). The model calculates the existing demand for space heating and domestic hot water, and the potentials and costs of heat saving measures for all existing residential buildings in Denmark (Karlsson et al., 2016; Petrović and Karlsson, 2016). Heat saving potentials and costs are calculated for several retrofit levels for the different components of a

Table 4: Cost of energy efficiency retrofits for each type of building component (2015-Euro/m$^2$ by building area)

| **Building component** | **Heat saving measure** | **Full cost** | **Marginal cost** |
|---|---|---|---|
| Wall | Adding insulation 100 mm | 295 | 121 |
| | Adding insulation 200 mm | 289 | 215 |
| | Adding insulation 300 mm | 483 | 309 |
| Roof | Adding insulation 100 mm | 27 | 20 |
| | Adding insulation 200 mm | 40 | 34 |
| | Adding insulation 300 mm | 54 | 47 |
| Floor | Adding insulation 50 mm | 47 | 47 |
| | Adding insulation 100 mm | 47 | 47 |
| | Adding insulation 150 mm | 47 | 47 |
| Window | Installing C windows | 336 | 0 |
| | Installing B windows | 352 | 16 |
| | Installing A windows | 368 | 32 |
| | Installing A+ windows | 384 | 48 |
| Ventilation | Installing ventilation systems with heat recovery | 81 | 81 |

Source: Petrović and Karlsson (2014)

building envelope - floors, walls, roofs, windows and ventilation systems, see Table 4. The heat saving potential for each retrofit level is calculated as a difference between heating demand before and after a retrofit. The full and marginal costs of heat saving measures used in this paper are based on Kragh and Wittchen (2010) and Wittchen and Kragh (2014).

Full costs reflect the cost of replacing a functioning building component with a new and more energy-efficient version. For example, the full cost of a new window conforming with the legally required minimum energy standard is 336 Euro/m$^2$, while the full cost of a window fulfilling the highest energy standard is 384 Euro/m$^2$. Marginal costs capture the additional cost of energy saving measures when replacing an end-of-life building component, i.e. excluding costs associated with replacing the building component. Thus, the marginal cost of replacing a window with a window meeting the legally required minimum energy standard is zero, as the replacement would be realized in any case, whereas the marginal cost of a window meeting the highest energy standard is 48 Euro/m$^2$.

For use in this paper, both the marginal and full cost potentials have been aggregated into 100 steps for each of the 24 groups of existing buildings. Thus, in total we include 2400 steps of full and marginal cost savings. Figure 4 illustrates these steps and shows the full and marginal cost curves for residential heat saving measures. Appendix C gives a detailed presentation of how the heat saving potentials are implemented in TIMES-DK by region, building type, building area and building age. The total technical potential corresponds to 93.2 PJ.

We apply two types of constraints in TIMES-DK in order to first, capture the limited availability of energy efficiency retrofit investments at marginal cost, and second, ensure a realistic adoption of energy efficiency retrofits towards 2030. First, within any given year, the marginal cost potential is determined by the age distribution of building components, i.e. the share of end-of-life building components. We assume that 5 % of the technical potential for each of the 2400 cost

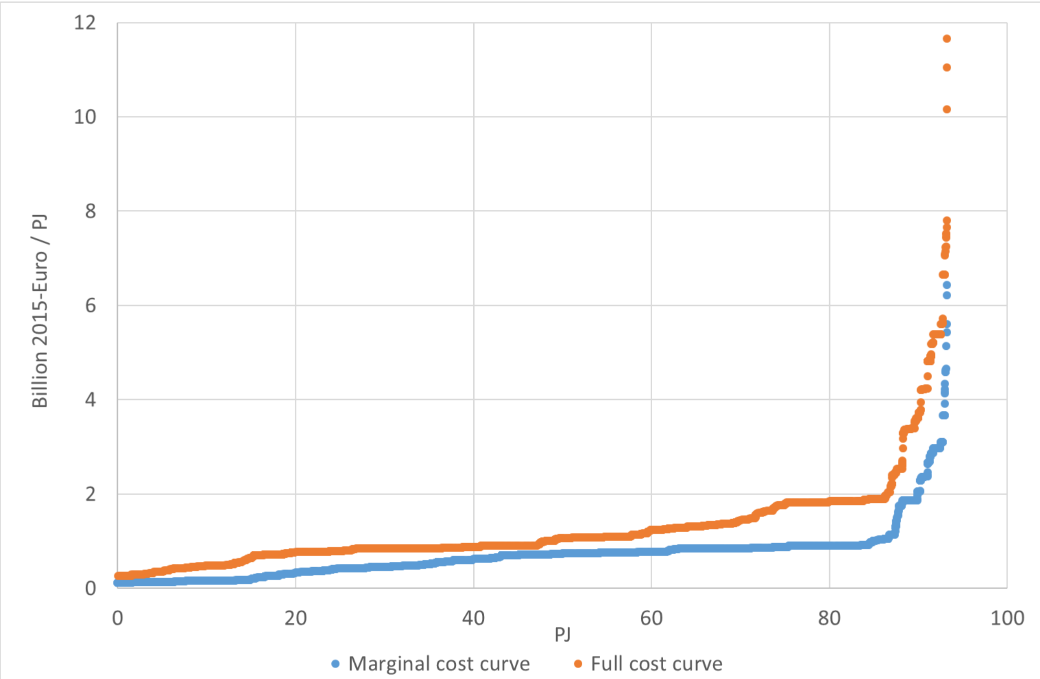


Figure 4: Full and marginal cost curves for residential energy efficiency retrofits

steps is available at marginal cost in 2020. This share increases linearly to 40 % in 2030. This increase corresponds to the assumption that about 3 % of the technical potential becomes available at marginal cost every year. Second, to ensure a realistic adoption of energy efficiency retrofits in the short-term, we introduce a constraint that limits the sum of realized marginal and full cost potentials to 30 % of the total technical potential for each of the 2400 cost steps in 2020. This constraint increases linearly to 100 % in 2030, reflecting that marginal and full cost investments are mutually exclusive within each of the 2400 steps. We consider these assumptions as a reasonable initial attempt at capturing the technical barriers associated with energy efficiency retrofit investments. However, due to their significance further work should be dedicated to verifying and improving the assumptions.

## 5. Results and discussion

This section determines the potential for meeting Denmark's EED target by stimulating households' investments in building energy efficiency retrofits through policy intervention. We apply different levels of hurdle rate, which serve as a proxy for the effectiveness of energy efficiency policies to stimulate investments. Drawing on Section 2, we consider a hurdle rate of 25 % to reflect the complete absence of energy efficiency policies, whereas a hurdle rate of 4 % reflects a very effective mix of policies. The section highlights how the level of hurdle rate impacts final energy demand and realized energy savings. Furthermore, it discusses how behavioral assumptions related to residential heating demand influence the rebound effect associated with a reduction in the applied hurdle rate. The section concludes by examining the economic impact of each hurdle rate scenario in terms of costs related to residential heating demand (investments and fuel costs) and household disposable income. While presenting our modelling results, we also discuss policy implications and model limitations.

*5.1. Reduction in final energy demand*

Table 5 presents final energy demand in the baseline scenario (hurdle rate 25 %), and the reduction in final energy demand for each hurdle rate scenario. The baseline scenario shows a reduction in final energy demand from 163 PJ to 150 PJ over the period 2017–2030. This trend is driven by the combined effect of new boiler technology, technology switching (in particular towards heat pumps), energy efficiency retrofits for existing buildings, and newly constructed, more energy-efficient buildings. All hurdle rate scenarios lead to a further reduction in final energy demand relative to the baseline scenario. Reducing the hurdle rate from 25 % to 4 % yields a reduction in final energy demand by 16.1 PJ in 2030. Table 5 furthermore highlights the cumulative energy savings over the period 2021–2030, which have been calculated by interpolating changes in energy demand over the years 2020, 2025 and 2030. The results suggest that reducing the 25 % baseline hurdle rate could lead to cumulative savings between 11 PJ and 146 PJ over the period 2021–2030. Thus, a policy mix, which effectively reduces the baseline hurdle rate to 4 %, could potentially deliver half of Denmark's cumulative energy saving requirement of the EED (see Section 1). This substantial contribution to cumulative energy savings reflects that the 4 % hurdle rate scenario leads to front loading of final energy savings; i.e. in the 4 % hurdle rate scenario final energy demand reduces by 11.5 PJ relative to the baseline already in 2020. These initial energy savings count towards the cumulative saving target each year through the entire period 2021–2030.

From a policy perspective, it is further interesting to note that the absolute level of savings is relatively insensitive with respect to a reduction in the hurdle rate from 25 % to 15 %, as final energy demand is reduced by on average no more than 2.7 PJ in 2030. Thus, if the policy goal is to achieve substantial energy savings, this result stresses the importance of applying policy measures that have the potential to reduce the hurdle rate to well below 15 %. Drawing on the discussion in Section 2, such a substantial reduction in the level of hurdle requires policies that address multiple of the factors behind households' high implicit discount rates; suggesting, the need for a broad mix of energy efficiency policies.

*5.2. Realized full and marginal cost energy savings*

Existing studies on residential heat savings in Denmark tend to focus on the marginal cost potentials for energy savings in the residential building stock (e.g., Kragh and Wittchen, 2010; Tommerup and Svendsen, 2006; Wittchen and Kragh, 2014). From a policy perspective, however, it is important to take into account that the availability of marginal cost potentials may be limited – at least in the short run. Ambitious energy efficiency policies may therefore also have to rely on full cost potentials. This section covers this policy aspect.

Figure 5 illustrates the level of realized full and marginal cost savings for each hurdle rate scenario over the period 2020–2030. At a hurdle rate of 25 %, 4.2 PJ of energy savings are realized in 2030; i.e. less than 5 % of the total technical saving potential (93.2 PJ). At a hurdle rate of 4 %, realized energy savings increase to 29 PJ in 2030. However, this magnitude of energy savings still corresponds to less than a third of the total technical potential.[8]

[8] Appendix C contains more details regarding the distribution of energy savings for the 24 groups of existing

Table 5: Final energy demand and cumulative savings under different hurdle rate scenarios (PJ)

| | Baseline final energy demand | Change in final energy demand relative to baseline | | | |
|---|---|---|---|---|---|
| **Hurdle rate** | **25%** | **20%** | **15%** | **10%** | **4%** |
| 2017 | 162.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2020 | 159.9 | 0.0 | -0.7 | -4.8 | -11.5 |
| 2025 | 155.2 | -1.1 | -2.0 | -6.1 | -14.9 |
| 2030 | 150.3 | -1.7 | -2.7 | -6.9 | -16.1 |
| Cumulative savings 2021-2030 | | -11 | -19 | -61 | -146 |
| Contribution to Danish EED target | | 4 % | 7 % | 22 % | 53 % |

Furthermore, Figure 5 highlights how the energy savings delivered by marginal and full cost savings depend on the level of hurdle rate. When applying a hurdle rate of 25 % or 20 %, only marginal cost savings are realized. This finding reflects that within these scenarios, the hurdle rate is prohibitive for investing in full cost heat saving measures. To achieve substantial energy savings and comply with the EU's energy and climate targets, most EU Member States, including Denmark, need to increase the scale and depth of energy efficiency retrofits (State of Green, 2018). Within the present modelling context, increasing the depth of retrofits corresponds to a higher share of realized full cost potential. In order to realize a higher share of full cost potential the hurdle rate needs to be reduced to 10 % or even 4 %. This level of reduction requires a broad mix of energy efficiency policies, as also mentioned in the previous section. To reduce the barrier of high upfront costs associated with deep retrofits, particularly investment subsidies may be needed in order to overcome the financial hurdle to invest.

*5.3. The direct rebound effect*

Rosenow et al. (2016) highlight the uncertainty regarding how EU Member States account for rebound effects within their ex-ante evaluations of the EED. To underscore the importance of demand behaviour for ex-ante evaluations, this section discusses the scale of the direct rebound within IntERACT for residential heating demand.

Considering four levels of substitution elasticity related to residential heating demand, Table 6 shows how the choice of substitution elasticity impacts final energy demand in 2030 both within the 25 % and the 4 % hurdle rate scenario. Table 6 includes the three substitution elasticities discussed in Section 3.2 (lower, central and upper estimate) where each estimate reflects a certain implicit heating price elasticity. We further consider a substitution elasticity of zero to capture final energy demand in the absence of a direct rebound effect. This allows us to define the direct rebound effect as the percentage reduction in the realized savings in 2030 relative to the specification with a zero substitution elasticity.

Depending on the choice of substitution elasticity, the baseline final energy demand varies between 146.5–152.7 PJ in 2030. A higher elasticity of substitution leads to a higher level of final energy demand in the baseline scenario, reflecting that the average price of heating services is falling

buildings

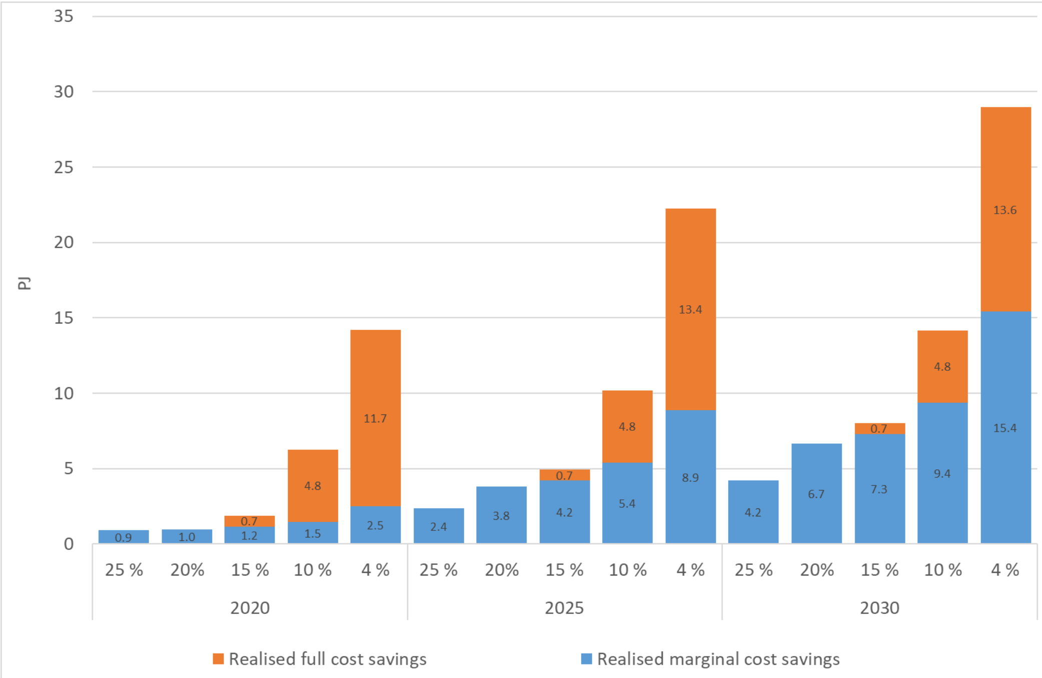


Figure 5: Realized full and marginal cost energy savings in 2020, 2025 and 2030

towards 2030. This falling price trend is driven by four main factors (i) energy efficiency retrofits investments, (ii) more efficient boiler technologies and fuel switching, (iii) newly constructed and energy-efficient buildings, and (iv) the combined effect of a renewable subsidy and tax reforms, which reduces the tax on electricity for residential heating. Within the 4 % hurdle rate scenario, the additional investments in energy efficiency retrofits reduce the average price of heating services by further 20 % relative to the 25 % hurdle rate scenario. As a consequence, we see a large effect of the choice of substitution elasticity on the level of final energy demand, which varies between 121.2–142.5 PJ.

The choice of substitution elasticity also greatly affects the reduction in final energy demand from a policy-induced reduction in the hurdle rate. Assuming a zero substitution elasticity for residential energy demand, as it is done in many energy-economy models, we see a reduction in final energy demand equal to 25.5 PJ in 2030. When assuming an upper estimate of substitution elasticity, the final energy demand is only reduced by 10.1 PJ. This result underscores the necessity to take into account demand behavior when implementing ex-ante evaluations of energy efficiency policies.

Table 6 shows the uncertainty range regarding the direct rebound effect, which varies between 20–60 %. The central estimate of substitution elasticity used in this paper results in a direct rebound effect of 37 %. This scale of the direct rebound effect lies within the range found in recent studies. Aydin et al. (2017) estimate a 27 % direct rebound for the residential sector, using a sample of 563,000 households in the Netherlands. A recent Danish study, using an approach comparable to Aydin et al. (2017), found that the direct rebound effect for Danish single family houses lies within the range of 30–40 % (Danish Energy Agency, 2016).

The scale of the direct rebound suggests that to realize the full energy saving potential from reducing the hurdle rate, policy makers need to consider measures to either reduce or circumvent the rebound effect. Within a standard neoclassical framework this could be achieved by raising the cost of energy, e.g. imposing additional taxes on heating demand and fuel consumption. From a behavioral economics perspective, moralization may convince households that their contribution to energy savings is socially beneficial and thereby reduce the rebound effect (Oikonomou et al., 2009).

Table 6: The impact of the heating service substitution elasticity on the rebound effect in 2030

| Substitution elasticity | Implicit heating price elasticity | Final energy demand 2030 (PJ) | | Change in final energy demand 2030 (PJ) | Direct rebound |
|---|---|---|---|---|---|
| | | HurdleRate 25% | HurdleRate 4% | | |
| Zero | 0 | 146.5 | 121.0 | -25.5 | 0 % |
| Lower estimate | -0.25 | 148.6 | 128.2 | -20.5 | 20 % |
| Central estimate | -0.38 | 150.3 | 134.2 | -16.1 | 37 % |
| Upper estimate | -0.50 | 152.5 | 142.5 | -10.1 | 60 % |

*5.4. The impact on households*

This section describes the impact of a reduction in the level of hurdle rate on residential heating costs and household disposable income. A key benefit of using the IntERACT model for policy evaluations is that the model allows for a comprehensive assessment of household welfare. This assessment is possible because IntERACT keeps track of both changes in investments and prices within the energy system, and how these changes affect the overall consumption choice and utility of the representative household. A partial bottom-up approach (e.g. applying the TIMES-DK model without linking it to a CGE model) would limit the scope for capturing the policy impact on household welfare as this would ignore the general equilibrium feedback (e.g. rebound effects).

Figure 6 shows the composition of annual residential heating costs within the baseline and hurdle rate scenarios. Annual heating-related expenses vary between 4.1–4.6 billion 2015-Euro over the period 2020–2030. 74–85 % of these expenses account for fuel costs, whereas the remaining expenses account for investments in residential heating systems and energy efficiency retrofits. Reducing the hurdle rate increases total heating costs in 2020. This cost increase is primarily driven by the additional investments in building retrofits. In 2025 and 2030 total residential heating costs remain approximately constant, as the expenses for investments in building retrofits and the direct rebound effect cancel out the fuel cost savings from the additional investments in building retrofits. At a hurdle rate of 25 %, investments in energy efficiency retrofits are limited to 0.02–0.05 billion Euro per year. Retrofit investments increase to 0.1–0.3 billion Euro as the hurdle rate reduces to 10 %. A further reduction from 10 % to 4 % leads to a more than 3-fold increase in retrofit investments. The substantial level of investments in the 4 % hurdle rate scenario gives rise to at least two policy considerations: First, the magnitude of the annual investments in 2020 under the 4 % hurdle rate scenario suggests that energy efficiency policies needs to be coordinated with the overall macroeconomic situation. That is, if the economy is at full employment, investments

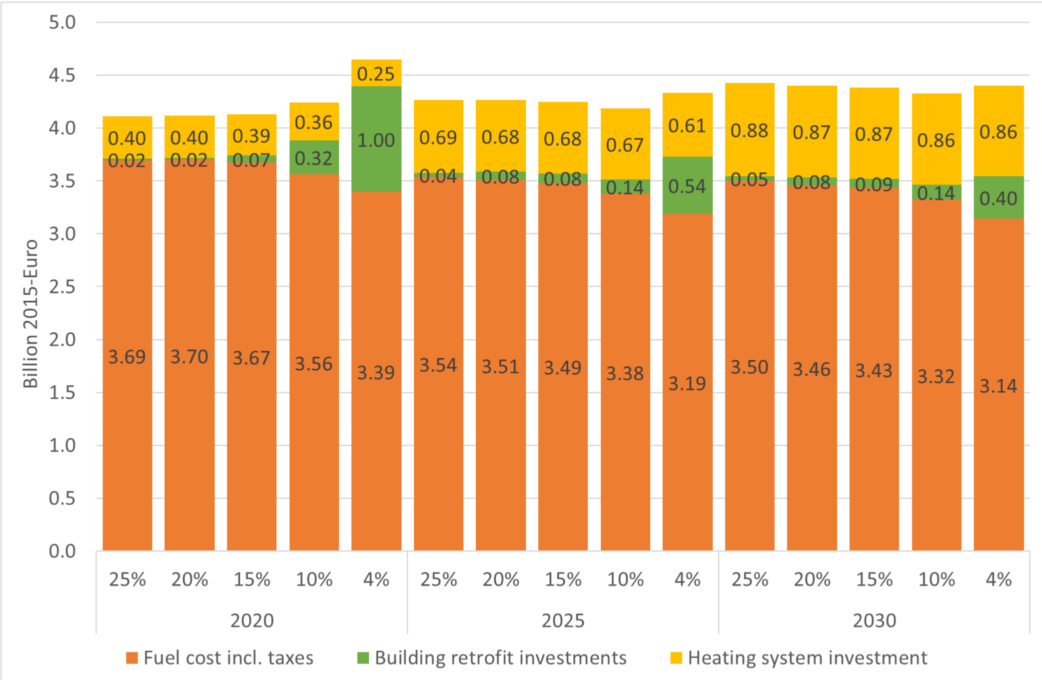


Figure 6: Composition of residential heating costs for the baseline and hurdle rate scenarios on an annual basis

of this magnitude could increase the risk for the economy to overheat. On the other side, if the economy suffers from recession, implementing energy efficiency policies could be a means to stimulate economic activity. The second key policy consideration relates to the questions whether the front loading of retrofit investments in the 4 % hurdle rate scenario is desirable from a policy perspective or whether a more gradual policy approach, which relies to a larger extent on marginal cost savings, would be more cost-efficient. Although this question is beyond the scope of this paper, the IntERACT model provides an ideal framework for providing insights on the impact of different energy efficiency policy pathways.

We report welfare effects from changing the hurdle rate in terms of Hicksian equivalent variation (HEV) in income, which can crudely be perceived as a measure of the change in real disposable income experienced by the representative household. Figure 7 highlights how reducing the hurdle rate from 25 % affects the disposable income of the representative household. Reducing the hurdle rate from 25 % to 20 %, we observe a positive effect on household income across all periods. Reducing the hurdle rate from 25 % to 15 % and lower, we see a clear trade-off in terms of higher upfront costs versus future benefits. A reduction in the hurdle rate from 25 % to 4 % reduces disposable household income by approximately 0.37 billion Euro in 2020, while the reduction increases income by more than 0.43 billion Euro in 2030. This result suggests that additional investments associated with a reduction in the hurdle rate from 25 % to 4 % have a simple payback time of less than 10 years (seen from the representative household).

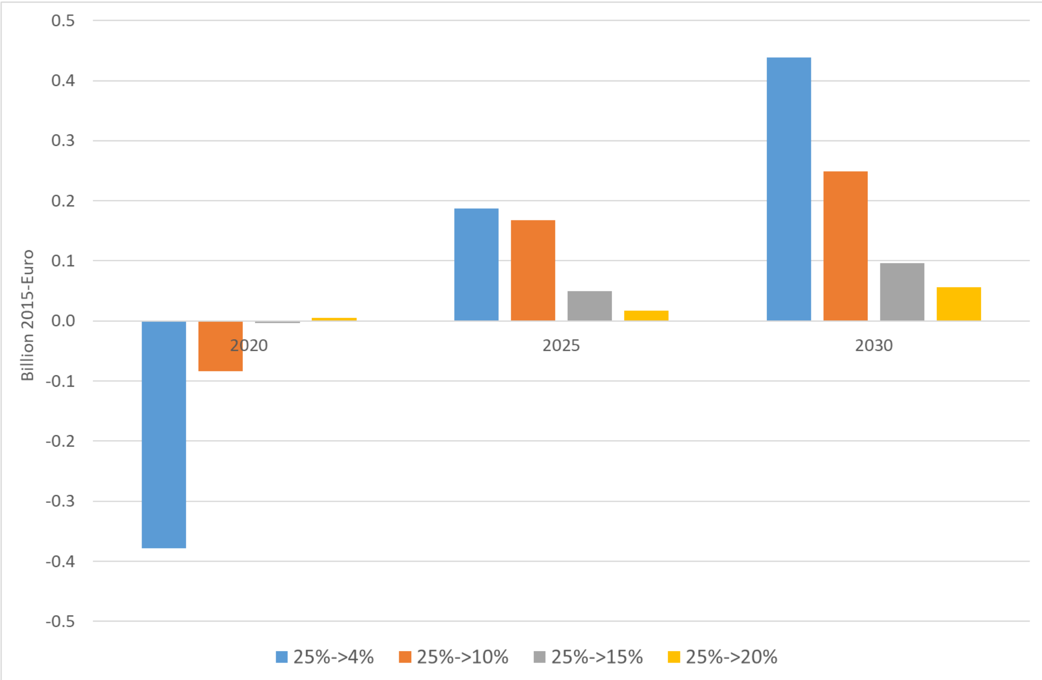


Figure 7: Effect on disposable income relative to the baseline scenario

### *5.5. Critical discussion*

This welfare effect can by itself be used to argue for the benefits of energy efficiency policies; however, it is important to stress a number of limitations of this paper. Attention is firstly drawn to two limitations of the general approach itself before additional weaknesses of the model instance as employed in this paper are addressed.

Firstly, the employed hybrid modelling approach focuses on new technology as a means to achieve energy and emissions savings. In particular, investment decisions for more efficient heat supply and heat saving measures are considered. But this overlooks the 'low hanging fruit' of behavioural change, which for example through lower internal temperatures, adjusted heating periods and shorter/cooler showers are relatively low cost options towards the same end. Indeed, such behavioural measures tend to be more economically attractive than investing measures, exactly because they have low or zero direct costs. The high indirect cost of these lifestyle changes is often cited as the main reason for not realizing this potential, as explained by barriers, failures and the rebound effect. The behavioural dimension of energy demand can be more significant in its ability to explain the variance in demand across households than technical characteristics (Huebner et al., 2015; Kelly et al., 2013), e.g. of the building and/or heating system. But it is extremely difficult to quantify and therefore model, which is why it is not considered here. We assume that, by employing average internal set temperatures and heating technologies, the representative household is accounted for. On the other hand, the IntERACT framework does not capture some of the multiple benefits of energy efficiency (IEA, 2014), which in the context of residential heating may be realized e.g. through improvements in indoor climate and comfort, and the potential for low-temperature district heating when considering heating system benefits. Hence, in some cases the behavioural effect would negate some of the implied savings obtained in the results, in others the savings would be increased, but these deviations are assumed to cancel each other out.

Secondly, and relating to the previous point, the consideration of only a representative household can be seen as a weakness of this approach. This is done in order to simplify the two employed models and keep them computationally tractable. But this obviously overlooks socioeconomic heterogeneity between households, which has implications for investment behaviour and policy measures to address this. For example, tenure, employment status, income, age and households structure are all known to influence energy demand (Jones et al., 2015) as well as the disposition towards energy efficiency investments. In addition, not only the overall energy demand but also its timing in terms of profiles varies between households (McKenna et al., 2016). Both of these aspects mean that the representative household considered here should only be interpreted as an average. In reality, the baseline energy demand, its timing, and the investment behaviour will all differ greatly between households. Again, the implication is that the results will deviate in individual cases. The IntERACT framework therefore does not capture the distributional impacts of energy efficiency policies. Capturing the distributional impacts of policies may, however, be of key importance to policy makers and should therefore be the focus of future modelling development.

A third limitation relates to this paper itself and the narrow focus on residential heating. The required changes in the hurdle rates in order to achieve substantial efficiency savings are high, i.e. reducing from 25 % to 10 % or even 4 %. Considering the high implied costs associated with implementing policies to achieve this change, a question about the effectiveness of targeting energy efficiency improvement measures specifically in the residential heating sector arises. Given that the EED requires cumulative reductions in energy demand for the whole economy, it might be more economically efficient to target energy efficiency policies in other sectors. However, as IntERACT aims at modelling the whole energy system and already includes a rich representation of potential energy saving measures in industry sectors, it is ideally suited for this type of cross sector comparison related to energy efficiency policy. In fact, the savings seen in 2030 in the industrial sector with an assumed hurdle rate of 20 % are of around 6 PJ, that is, the same order of magnitude as the realized marginal cost savings in households (see Figure 5). Hence, for the Danish energy system at least and based on the assumptions made for this paper, the relative cost of energy savings in residential heating and industry are broadly comparable.

All of these previous points lie at the root of the one further limitation, which is that this paper does not identify or assess specific energy efficiency policies. Instead, we consider the level of hurdle rates as a proxy for the effectiveness of energy efficiency policies within the existing residential building stock. The key assumptions that (i) the hurdle rate only reflects non-monetary costs and (ii) that energy efficiency policies are capable of removing these costs likely leads to an underestimation of the cost to households from a policy-induced reduction in the hurdle rate; as already stated in Section 3.1.1. However, at the same time, IntERACT likely overestimates the welfare impacts on households within any given period because the representative household cannot smooth its consumption across periods. Future model developments could address this issue, for example by modelling the representative household using an intertemporal budget constraint following a Ramsey model framework (e.g., Barro and Sala-i Martin, 1995). Future research will focus on assessing the impact of specific policy measures, e.g. subsidies, fuel taxes, regulation, and information provision. A particular focus of this research should be on assessing potential interactions between combinations of energy efficiency policies, i.e. the extent to which the different instruments counteract or support one another (Wiese et al., 2018). The comprehensiveness of the IntERACT model could provide novel insights, as it captures important effects of energy policies, e.g. in terms of government revenue, competitiveness of businesses and disposable income of households.

## 6. Conclusion and policy implications

This paper analyzes the potential for meeting Denmark's EED target by reducing the high discount rate implicit in households' investment decisions. Based on a literature review, we determine that a hurdle rate of 25 % is a reasonable upper bound for capturing the investment decision of Danish households in the absence of energy efficiency policies. We consider the Danish social discount rate at 4 % as a reasonable lower bound, taking the perspective of policy makers.

Using the IntERACT model, the paper concludes that a policy-induced hurdle rate reduction from 25 % to 4 % could deliver half of Denmark's cumulative energy saving requirement of the EED for the period 2021–2030. This level of cumulative reduction includes a 37 % direct rebound effect. Although the rebound effect represents a welfare improvement as seen from a household's perspective, policy makers could consider additional instruments, e.g. fuel taxes, to reduce the demand rebound and increase the size of realized savings. Reducing the hurdle rate from 25 % to 4 % leads to a substantial shift in disposable income across periods. This result is driven by the front loading of investments in energy efficiency retrofits in the 4 % hurdle rate scenario. In particular, moving retrofit investments ahead in time increases costs in the early period due to an increased reliance on full cost saving measures.

From a policy perspective, it is important to note that the largest energy saving potential is realized when the hurdle rate reduces to well below 15 %. Such a substantial reduction in the level of hurdle rate requires policies that address multiple of the factors behind households' high implicit discount rates, which implies the need for a broad mix of energy efficiency policies. For example, in a lab experiment, informational policy measures reduce the hurdle rate by 5–10 % (Coller and Williams, 1999). In reality, however, the impact of informational policy measures may be even smaller due to the difficulty of getting the information to the target group (e.g. a certain type of home owners). A policy mix could therefore include information provision to increase overall awareness and thereby stimulate energy efficiency investments, combined with a subsidy for investments in energy efficiency retrofits to overcome liquidity constraints and address risk averse households. Policy measures will almost certainly have to differ by types of dwellings and households, and it would seem appropriate, based on the way in which this paper demonstrates marginal and full cost savings being realized in that order, to develop targeted policy for these separately. So, for example, the relatively high proportion of multi-family, social (21 %) and community (7 %) housing in Denmark (Kristensen, 2007) with a higher access to capital and ease of implementation of measures should perhaps be incentivized to implement more marginal measures, whilst addressing regulatory constraints for social housing could also increase the the scope for energy efficiency improvements. On the other hand, other types, such as owner-occupied detached housing, will require a different approach: in the case that these buildings actually have a lower renovation rate, they might be encouraged to implement full cost savings by an appropriate subsidy or tax. Overall, further research is needed, particular when it comes to how these different policies should affect the choice of hurdle rate in energy-economic models.

Despite the holistic nature of the modelling framework presented and applied in this paper, several limitations were identified and should be the focus of future work. For example, a finer differentiation between types of households and buildings would enable more specific policy insights, e.g. in terms of the distributional impact of energy efficiency policy. Another point concerns the modelling of different energy efficiency policy mixes and their interactions with other policies for carbon abatement and/or renewable energy development. The IntERACT model and its comprehensiveness make it particularly suitable for capturing both the impact of individual energy efficiency policies and the interaction effects among different policy combinations.

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## 8. Declaration of interests

None.

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## Appendix A. The residential building stock in TIMES-DK

Table A.1: Residential building stock in TIMES-DK

| **Classification** | **Categories** |
|---|---|
| Building type | Single-family |
| | Multi-family |
| Construction period | Before 1972 |
| | After 1972 |
| | New buildings |
| Type of supply area | Central district heating |
| | Decentral district heating |
| | Individual |
| Region | East Denmark |
| | West Denmark |

## Appendix B. Calculation of the investment premium in TIMES-DK

This appendix highlights how hurdle rates (technology specific discount rates) are modelled within the TIMES modelling framework. In case the technology specific discount rate is equal to the general discount rate used in TIMES, the stream of annual payments over the economic lifetime of the technology is equivalent to the initial lump sum investment, as both have the same discounted present value. If, however, the technologys discount rate is chosen different from the general discount rate, the stream of annual payments has a different present value than the lump sum investment. The TIMES modelling framework accounts for this difference by multiplying the investment with a correction factor presented in the following equation (from Loulou et al., 2016, p. 166).

$$1 + P = \frac{CRF_s}{CRF} = \frac{\left(1 - \frac{1}{1+i_s}\right)\left(1 - \frac{1}{(1+i)^{\text{Elife}}}\right)}{\left(1 - \frac{1}{1+i}\right)\left(1 - \frac{1}{(1+i_s)^{\text{Elife}}}\right)}, \tag{B.1}$$

where we have used the following abbreviations.

| | |
|---|---|
| $CRF_s$ | Capital recovery factor for the technology specific discount rate |
| $CRF$ | Capital recovery factor for the general discount rate |
| $P$ | Technology specific investment premium |
| $i_s$ | Technology specific discount rate |
| $i$ | General discount rate |
| Elife | Economic life of the investment |

The capital recovery factor is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time. Equation B.1 captures the difference in capital recovery factor between the technology specific discount rate and the general discount rate, i.e. (in essence) the difference in net present value between applying the general discount rate and the technology specific discount rate to a future payment stream. Hence, applying a technology specific hurdle rate within the TIMES modelling framework corresponds to adding a premium on top of the lump-sum investment of a technology before the investment is annualized using the general discount rate.

## Appendix C. Details regarding the distribution of energy savings

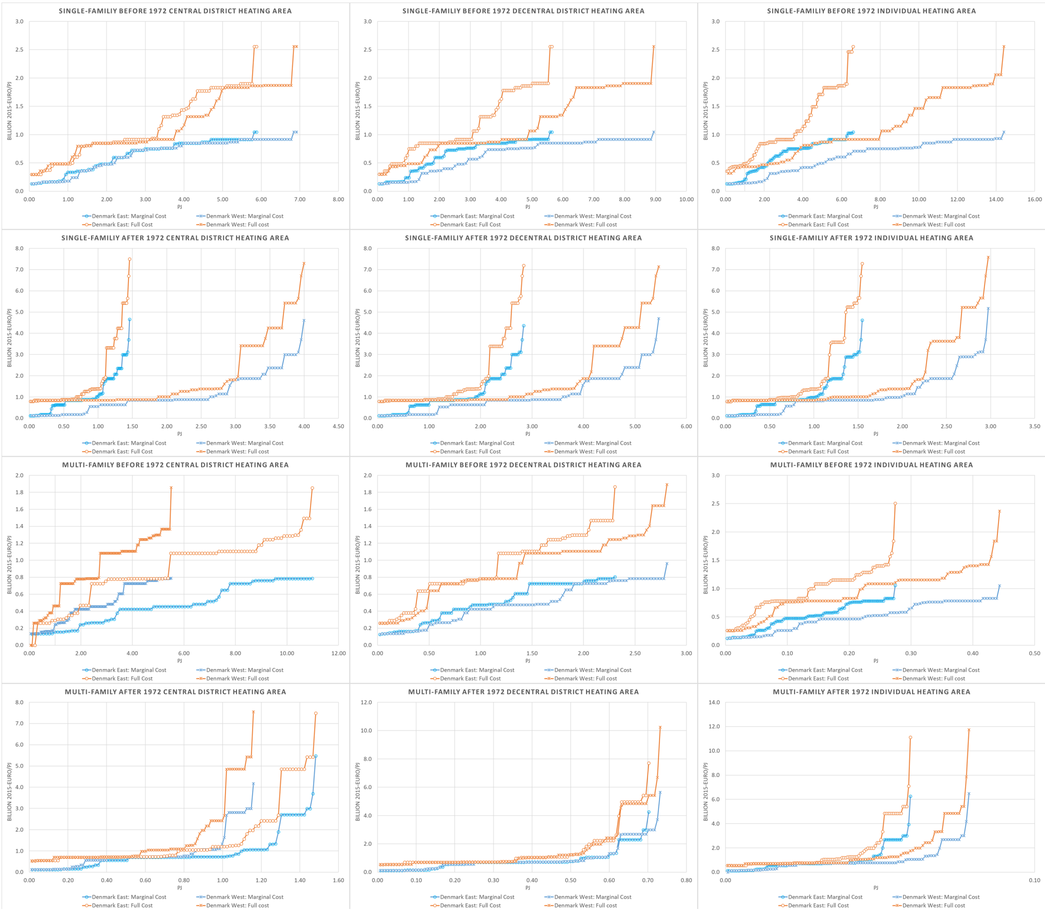


Figure C.1: Full and marginal cost curves for residential energy efficiency retrofit measures by 24 groups of existing buildings

*Detailed description of residential energy saving potential*

Figure C.1 illustrates 24 marginal and full cost curves and the associated technical potential. Single family houses, see first and second row, show the largest energy saving potential (73.3 PJ). For houses built before 1972 the energy saving costs (both full and marginal) are significantly lower compared to houses built after 1972 (first and third row). Thus, older houses have both the largest saving potential and the lowest (marginal and full) costs.

*Realized residential energy savings*

Figure C.2 shows how the level of hurdle rate affects the share of the technical potential realized for each of the 24 groups of existing buildings in 2030. Generally, the saving potential for single-

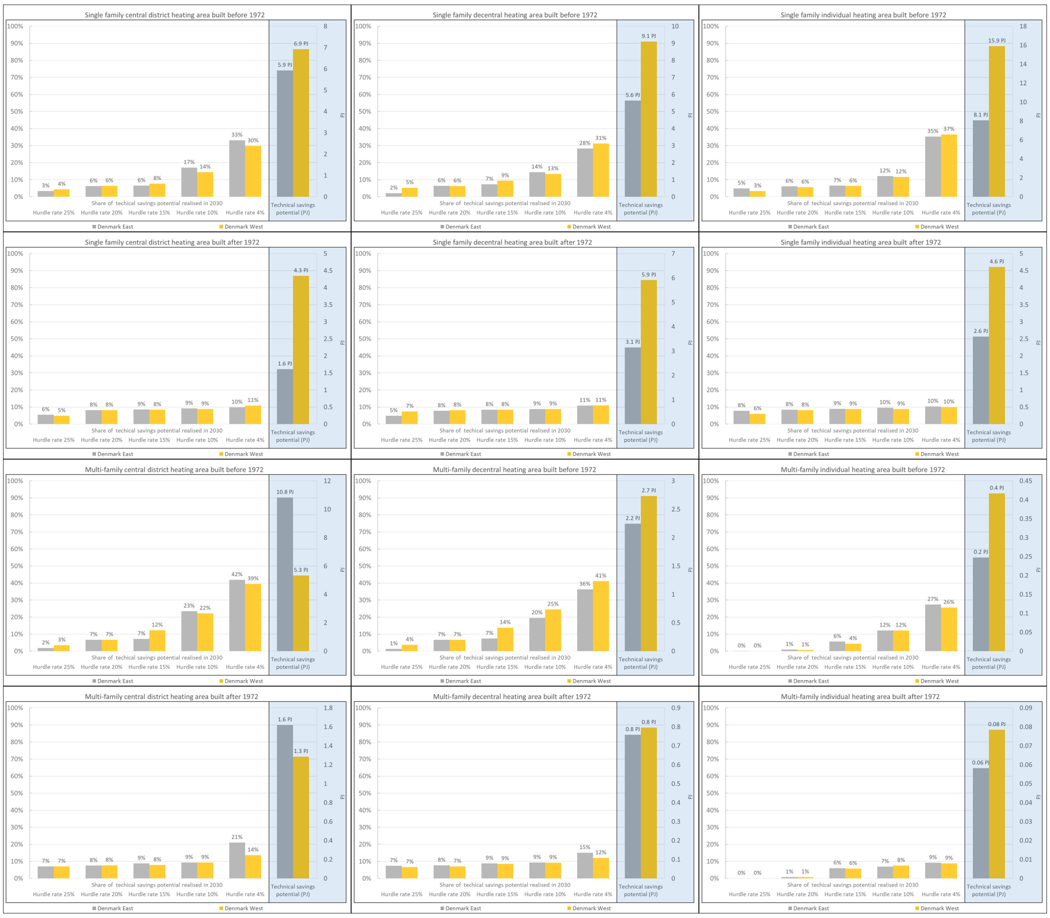


Figure C.2: Realized energy savings as a share of technical potential by 24 groups of existing buildings and multi-family houses built before 1972 are realized to the highest degree, reflecting that the cost of energy saving measures for these buildings are relatively low, see Figure C.1.

# Appendix D.

# Auctioning revenues to foster energy efficiency: status quo and future potential within the European Emissions Trading System

# Auctioning revenues to foster energy efficiency: status quo and future potential within the European emissions trading system

Catharina Wiese
Technical University of Denmark
Produktionstorvet 424
DK-2800 Kongens Lyngby
Denmark
catwi@dtu.dk

Jan Rosenow
The Regulatory Assistance Project
Rue de la Science 23
B-1040 Brussels
Belgium
jrosenow@raponline.org

Richard Cowart
The Regulatory Assistance Project
Rue de la Science 23
B-1040 Brussels
Belgium
rcowart@raponline.org

## Keywords
EU Emission Trading Scheme (EU ETS), auctioning revenue use, energy efficiency programme

## Abstract
Auctioning revenues in the European Union's Emissions Trading System (EU ETS) are likely to increase in the future. This projection is driven by recent changes within the system's framework, addressing the current surplus of emission allowances and reducing the overall cap. More specifically, the Market Stability Reserve starts operating in 2019 and the linear reduction factor increases from 1.74 percent to 2.2 percent annually from 2021, increasing scarcity and allowance prices. Considering the growing amount of auctioning revenues projected, it becomes ever more important to assess the use of these revenues and their potential contribution to accelerate decarbonisation efforts. While there are various opportunities to invest auctioning revenues to drive emission reductions, we argue that strategic investments in energy efficiency programmes provide opportunities for realising multiple dividends: additional emission reductions from both ETS and non-ETS sectors, lower economic and societal decarbonisation costs, and support for the political process to further tighten the ETS cap. Our assessment of the status of auctioning revenue use at EU Member State level shows that Member States have made only limited use of these multiple dividends in recent years. In 2017, no more than 22.4 percent of total revenues have been strategically invested in energy efficiency programmes, as Member States have officially reported to the European Environment Agency's reporting obligations database. However, evidence from efficiency programmes funded by auctioning revenues in Ireland, Germany and Czech Republic illustrate that these programmes deliver energy savings and emission reductions, cost savings to consumers, tax revenue to the national budgets, employment and economic growth. We conclude that the EU carbon price can provide important signals to investors and energy users, but auctioning revenues can also be a powerful tool in the energy transition and the strategic use of revenues needs to be accelerated in all Member States.

## Introduction
Without ambitious energy efficiency targets and a significant increase in energy efficiency investments, the EU will most likely miss even its current 2030 climate target of reducing greenhouse gas (GHG) emissions by 40 percent based on 1990 levels, let alone deliver on the commitments made in Paris (Rosenow et al. 2018). On a global scale, the International Energy Agency (IEA) recently concluded that improvements in end-use energy efficiency could deliver at least 35 percent of the total emission reductions needed by 2050 to avoid drastic global climate disruption (IEA 2018). Thus, capturing the existing untapped and cost-effective potential for end-use energy efficiency improvements (IEA 2018, Thema et al. 2018) should logically be a major goal of climate policy. However, the EU ETS, Europe's key tool to reduce GHG emissions, is not able to overcome the various non-price barriers to energy efficiency because a carbon pricing instrument alone does not address lack of information, behavioural failures and liquidity constraints (e.g. Cowart 2011). These barriers are commonly considered a major reason why households and businesses largely fail to invest in cost-effective energy efficiency improvements (Jaffe and Stavins 1994; Gillingham et al. 2009).

The political discussion on the EU ETS still puts a larger emphasise on the carbon price and its potential to incentivise low-carbon investments, with less focus on how the revenues generated through the auctioning of EU allowances are spent. Considering that auctioning revenues are an increasing source of income for EU Member States, we propose that now is the time to assess the potential contribution of strategic revenue investments to accelerate decarbonisation efforts and to align the EU ETS with the most cost-effective opportunity to deliver emission reductions through energy efficiency.[1]

Total auctioning revenues have increased by around 46 % from 2016 to 2017.[2] This increase is driven by recent changes within the ETS framework and the revision of the EU ETS Directive (Directive (EU) 2018/410)[3]:

- The ETS *Market Stability Reserve* (MSR) starts operating in January 2019 and the *linear reduction factor* (LRF) will increase from 1.74 to 2.2 percent annually from 2021. Addressing the surplus of emission allowances in the EU carbon market and reducing the cap respectively, both the MSR and the LRF will have an increasing effect on the EU carbon price. Indeed, already in anticipation of the future changes, allowance prices have increased by around 180 percent from as low as 5 Euros per tonne in 2017 to around 20 Euros per tonne at the end of 2018.[4]
- The *share of free allocations* will reduce to 30 percent until 2026 and reduce to 0 percent by 2030 (for sectors not at risk for carbon leakage). A reduction in the number of allowances allocated for free increases the number being auctioned and, thus, has a positive effect on revenues generated through auctioning.
- Discussions on introducing a *carbon floor price* (CFP) in some Member States (see e.g. Simon 2018) – The direct price control mechanism of a CFP would ensure a certain price level and increase ETS revenues in the implementing states.

All of the above affects the volume of auctioning revenues that EU Member States receive. The exact effect depends on the price increase opposed to the reduction in allowances available. Yet, projected auctioning revenue developments show a future increase up to 20 billion Euros per year before 2030 (Ecologic Institute and WWF 2016), which also the most recent trends of prices and revenues from 2016 to 2017 confirm. Strategically investing this growing opportunity into energy efficiency programmes would reinforce the ETS and deliver multiple dividends:

- Additional emission reductions from sectors both covered by, and outside, the ETS;
- Lower economic and societal decarbonisation costs, capturing a larger fraction of cost-effective emission reduction potential, which may remain untapped if not additional funding for energy efficiency (from auctioning revenues) is made available, and reducing energy bills for end-users.
- A wide range of non-energy benefits from energy efficiency improvements and the resulting demand reduction. Among those benefits are improvements in health, comfort, air quality, public housing and welfare costs, job creation, and economic growth; and
- Support for the political process to further tighten the EU ETS cap. An increase in the political will and social acceptance, as a result of the previous benefits, can enable more ambitious long-term decarbonisation targets.

The paper is structured as follows: Section 2 introduces why investing auctioning revenues in energy efficiency would further reduce emissions at lower economic and societal costs. In Section 3, we present our assessment of auctioning revenue use at the EU Member State level and show promising examples of Member States that have used their auctioning revenues for energy efficiency in recent years. Section 4 discusses interactions between energy efficiency improvements and the EU ETS, and Section 5 concludes.

## The economic case for investing auctioning revenues in energy efficiency

Strategically investing auctioning revenues in energy efficiency measures can make a relevant contribution to achieve emission reductions at the lowest economic and societal costs.[5] Some economists would strictly disagree with this proposition; defining external costs of GHG emissions as the only market failure to address. In a first-best setting, a single carbon pricing instrument as the EU ETS would, in theory, internalise the externality and effectively incentivise emission reductions, while any policy on top, would distort market forces (e.g. Baranzini et al. 2017).

However, others acknowledge the existence of second-best problems, e.g. market failures and/or exogenous real-world constraints, which rationalise the use of multiple policies with a common policy target (e.g. Bennear and Stavins 2007). Also the EU has taken a different position, adopting mandates for renewable energy and efficiency in addition to the EU ETS. Investing auctioning revenues to further strengthen EU energy efficiency policy would reinforce the ETS and reduce the economic and societal costs of GHG emission reductions, because:

1. **Investing auctioning revenues in energy efficiency can help to realise a larger fraction of cost-effective emissions reduction potential**. Recent evidence shows that in all EU Member States there exists a large and untapped potential for cost-effective energy efficiency improvements (Thema

1. The policy mix for reaching decarbonisation targets cost effectively is not limited to energy efficiency policies but also includes, e.g., renewable energy support, research and development for clean technologies, and others, which also overcome some of the limits to carbon pricing and the reliance on a single pricing instrument. However, the economic and societal cost advantages of energy efficiency and the need for funding to stimulate efficiency investments among a large number of end-users make it a particularly important resource to utilise. These are principal justifications for the policies adopted by the EU and many other jurisdictions that call for implementing the "energy efficiency first principle".

2. This increase compares the total auctioning revenues in 2016 and 2017 for all EU Member States but France, which has not reported revenues for 2017 yet, and Bulgaria, which has locked its report for public view in 2016 and 2017. 2016 total revenues without France and Bulgaria amount to 3.47 billion éuros. 2017 total revenues amount to 5.09 billion Euros.

3. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0410&from=EN (Accessed 18/12/2018).

4. E.g.: https://markets.businessinsider.com/commodities/co2-emissionsrechte/euro (Accessed 18/12/2018).

5. The strategic use of revenues from carbon cap-and trade schemes to achieve emission reductions at lowest economic and societal cost has also been named 'carbon revenue recycling' by e.g. Cowart (2011).

et al. 2018). Realising this potential would accelerate GHG emission reductions and, because it is cost-effective and would save more than it would cost in many instances, reduce the economic cost of reaching decarbonisation targets. The potential remains untapped due to various barriers to energy efficiency, which include imperfect and asymmetric information, principal agent problems, behavioural failures, and limited access to capital. It is well established that in the markets for energy efficiency, market failures and barriers beyond the negative externality of energy production and consumption exist. These barriers keep energy end-users from investing in cost-effective energy efficiency improvements and are a major justification for public policy interventions implementing multiple policies (Jaffe and Stavins 1994; Gillingham et al. 2009). By definition, non-price barriers to energy efficiency cannot be overcome by a pricing policy alone; i.e., due to other real-world constraints, a carbon price cannot unlock all long-term, cost-effective energy saving and thus GHG emissions reduction potential. Therefore, energy efficiency programmes that address the behavioural, financial, and legal barriers to energy efficiency are needed in order to make use of a greater fraction of the cost-effective emissions reduction potential. While there are many opportunities to invest auctioning revenues to accelerate decarbonisation, energy efficiency investments provide opportunities that save more than they cost and therefore should be used first (see footnote 1).

2. **Investing auctioning revenues in energy efficiency would reduce the energy bill impacts of carbon pricing on energy end-users**. The EU allowance price paid by power and heat generators has a disproportionate and negative effect on consumer energy bills. A calculation of the consumer cost per tonne of abatement in competitive power markets shows that the cost to consumers per tonne of carbon reduced can be several times larger than the market price of carbon allowances (Cowart 2011). According to a study from Cambridge Econometrics and the Energy Centre of the Netherlands (2013), at a carbon price of 20 Euros per tonne, the impact on the merit order of dispatch in wholesale power markets yields a cost to power consumers amounting to 248 Euros per tonne avoided, assuming nil price elasticity.[6] The study furthermore shows that greater support for investments in end-use energy efficiency would reduce energy demand, which a pricing instrument alone would only achieve to a limited degree considering low energy price elasticities, specifically in the short run. These elasticities have been found to be larger in the long run, and, considering both time horizons, heterogeneous across end-use sectors, however, overall results show an inelastic response to price changes (e.g. Gillingham et al. 2009, Labandeira et al. 2017). The reduction in energy demand due to greater support for investments in end-use energy efficiency would further reduce GHG emissions, and consumer energy bills due to reduced prices on wholesale power markets.[7]

Both rationales make clear why using auctioning revenues to support energy efficiency measures complementary to the EU ETS would reduce the economic and societal costs of decarbonisation. Considering that the major goal of carbon pricing is to achieve emission reductions at the lowest costs, it is logical to use the ETS carbon price and the resultant auctioning revenues to incentivise end-use energy efficiency. Energy efficiency is a key to capturing the most cost-effective energy and emission reduction potential, while minimising rate and cost impacts.

## Status quo of auctioning revenue use at the EU Member State level

Article 10(3) of the EU ETS Directive 2003/87/EC recommends that Member States should use at least 50 percent of auctioning revenues or the equivalent in financial value of these revenues for energy- and climate-related purposes. These purposes are specified in Art. 10(3) and Art. 3d(4) (for aviation allowances) and include a range of options: further GHG emission reductions in EU and third countries, the development of renewable energies, measures to increase energy efficiency, shift to low emission and public forms of transport, and administrative policy expenses.[8]

Since 2013, a mechanism for reporting on the use of auctioning revenues[9] requires Member States to report annually (for the first time by July 2014) on the amounts of revenue generated through the auctioning of allowances and the use of these revenues, or the equivalent in financial value. Member States shall specifically report the purpose and type of revenue use for energy- and climate-related programmes, domestic and international.[10] The following section assesses the national reports submitted by 31 July 2018, reporting the use of auctioning revenue for 2017.[11]

6. Considering the following effects of carbon pricing on wholesale power markets adds further clarification to this point: First, a carbon price increases the marginal cost of fossil-based generation. This cost increase may change the merit order of power markets, which ranks generation units and determines the order of dispatch based on short run marginal generation cost from cheapest to most expensive. Thus, generators that emit most GHG emissions and consequently have the highest cost increase may not be dispatched in order to meet electricity demand, when they are required to pay a carbon price. This potential change in the merit order of dispatch would lead to a reduction in GHG emissions from power generation. However second, a carbon price also increases the price paid by consumers, whenever the marginal generation unit, i.e. the last unit dispatched, is fossil-based. In that case, the clearing price on wholesale power markets increases and finally this price increase is passed through to consumers. Calculations based on power price increases, i.e. the extra cost to consumers, and the avoided tonnes of GHG emissions due to the impact on the merit order of dispatch yield the cost to consumers of 248 Euros per tonne avoided emissions (Cowart 2011). Note: Although the modelling timeframe in the study from Cambridge Econometrics and the Energy Centre of the Netherlands (2013) was set to 2020, the analysis of interactions between cap reductions, carbon prices, emissions and end-use energy efficiency are still relevant and provide meaningful results at all timescales.

7. The wholesale power price is lower due to the demand reduction for energy and EU allowances. Both demand reductions have a lowering effect on the clearing price on competitive power markets.

8. Art. 10(3) and Art. 3d(4) of Directive 2003/87/EC provide a more detailed list of eligible purposes. Retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02003L0087-20140430&from=EN.

9. Specified in Art. 17 of Regulation (EU) No 525/2013. Retrieved from: https://publications.europa.eu/en/publication-detail/-/publication/4bf8306c-dab2-4fa0-8c83-8d44d760b31f/language-en.

10. International use comprises funding of multilateral (e.g., United Nations Framework Convention on Climate Change (UNFCCC) Green Climate Fund) or bilateral programme support.

11. Member states submit their reports to the European Environment Agency's reporting obligations database (ROD), part of the European Environment Information and Observation Network (EIONET). Deliveries are available at: http://rod.eionet.europa.eu/obligations/698/deliveries (Accessed at 09/01/2019).

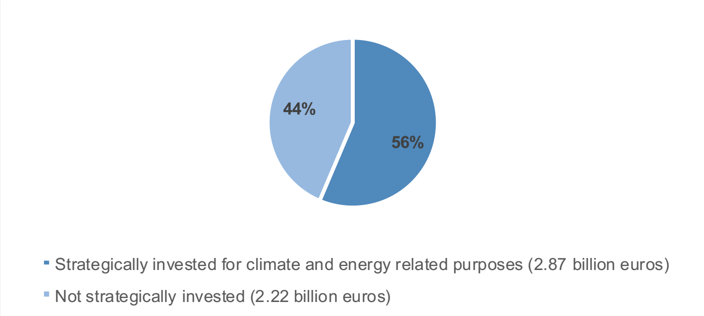


*Figure 1. Use of 2017 auctioning revenues as a share of total revenues: 5.09 billion Euros.*

**ASSESSMENT OF THE MEMBER STATES' REPORTING ON THE USE OF 2017 AUCTIONING REVENUES**

In 2017, EU Member States received 5.09 billion Euros through the auctioning of emission allowances in the EU ETS.[12] Altogether, the reporting reveals that Member States used or plan to use 4.07 billion Euros (80.0 percent) of the total amount of 2017 revenues or the equivalent in financial value for energy- and climate-related purposes. This relatively high share is consistent with the findings of reports on the use of auctioning revenues from previous years (Ecologic Institute and WWF 2016; Le Den et al. 2017; Wiese et al. 2018). However, it is worth noting that the calculation *includes Member States that do not earmark auctioning revenues for specific uses* but still report the equivalent in financial value used for energy and climate purposes from their national budgets.

Strictly speaking, these Member States do not *strategically invest* their auctioning revenues, i.e., they do not *directly use* them for energy and climate purposes. Excluding Member States that do not earmark auctioning revenues for specific uses, the reported strategic investments reduce to 2.87 billion Euros, equivalent to 56.4 percent of total 2017 revenues, shown in Figure 1. The share of revenues not strategically invested in energy and climate purposes includes the use of auctioning revenues that Member States do not specify (0.60 billion Euros) and all revenues from Member States that do not earmark (1.62 billion Euros). These amounts are not strategically reinvested, but allocated to the national budgets. The further assessment of auctioning revenue use therefore excludes Member States that do not earmark. For 2017 revenues, the national reports submitted by 31 July 2018 from Austria, Denmark, Finland, Luxembourg, the Netherlands, Poland, Sweden, and the United Kingdom indicate that these Member States do not earmark auctioning revenues for specific uses.

All other Member States, except Romania, report to invest some share of their total revenues for domestic or international energy- and climate-related purposes ranging from 12 percent in Cyprus to 116 percent in Malta.[13] Assessing the Member States' official reporting, a significantly larger share of strategically invested revenues is used domestically (126.4 percent), while only a smaller share is spent for international use (6.1 percent). The assessment of domestically invested revenues reveals the challenge of heterogeneity among Member States' way of reporting auctioning revenues use: Germany indicates to use 100 percent of its total 2017 revenues for energy- and climate-related purposes (1.15 billion Euros). However, it reports the total spending of its national energy and climate fund for different domestic types of use (2.05 billion Euros). Thus, only 56 percent of the fund's total spending is financed through auctioning revenues. Germany's way of reporting largely explains why more than 100 percent of total auctioning revenues are reported to be used domestically (126.4 percent). In order to make Germany's domestic use of auctioning revenues comparable to the other Member States' reporting and to total auctioning revenues, we adjusted its domestic use, setting it equal to 100 percent total revenue in 2017, and applied the ratios of domestic types of use to this amount.[14] Also Lithuania reports a higher amount as domestic use than the amount indicated to be used for energy- and climate-related purposes. However, the difference is small and the associated impact on comparability is limited.

Figure 2 shows, on an aggregate level, how Member States use their auctioning revenues domestically as a share of the Member States' total domestic use, distinguishing different types of use.

The largest share of total domestic use (41.9 percent = 1.14 billion Euros) finances energy efficiency measures, followed by the promotion of renewable energy (31.2 percent = 0.85 billion Euros), other domestic/EU uses (9.2 percent = 0.25 billion Euros), and the shift to low-emission and public forms of transport (7.9 percent = 0.22 billion Euros). Putting it into perspective with total auctioning revenues, these shares correspond to 22.4 per-

12. This amount of 2017 auctioning revenues and the further assessment of the Member States' reporting does not include France, which has not reported its revenues for 2017 yet, and Bulgaria, which has locked its report for public view.

13. Romania reports to use zero percent of their 2017 auctioning revenue for energy- and climate-related purposes, while Malta reports to use a higher amount for energy- and climate-related purposes than their total auctioning revenue. This difference might occur due to the use of carryover revenues from years before 2017. However, the reported data provides no further explanation.

14. We are aware that this approach only gives an approximation of Germany's auctioning revenue use, however, the available data does not allow for more detailed conclusions. The analysis of domestic use required the following additional data processing: (1) Interpretation of committed versus disbursed spending on a country-by-country basis. Some Member States report both committed and disbursed amounts, with the disbursed amounts being included in the committed amounts, while other Member States report both amounts separately. (2) Where Member States report ambiguous domestic types of use or the reported type does not match the purpose of revenue use (i.e., specific programme support), we took a further look at the individual programmes, if provided, to categorise the Member States' domestic use.

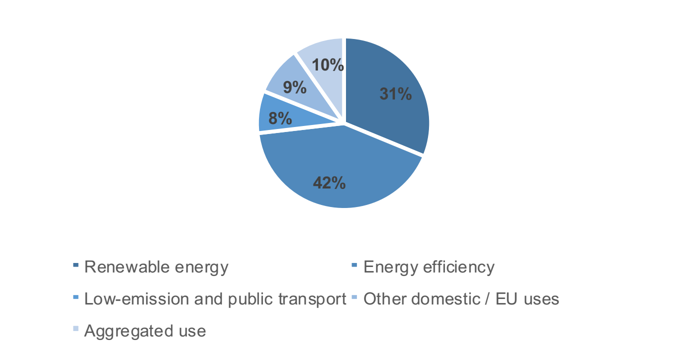


*Figure 2. Domestic types of use as a share of total domestic use.*

**Table 1. The use of auctioning revenues for energy efficiency in Ireland, Germany and Czech Republic.**

| Member State | Domestically invested revenues for energy efficiency | Energy efficiency investment |
|---|---|---|
| Ireland | 52,298,000 Euros;<br>98 percent of total domestic use | **Better Energy Homes Scheme**: provides grants to all homeowners, including property owners of dwellings built prior to 2006, to improve the energy efficiency of their homes through insulation measures, heating upgrades and solar thermal. |
| Germany | 0.64 billion Euros (adjusted);<br>56 percent of adjusted domestic use | **Energy and Climate Fund**: supports various energy efficiency programmes, such as the KfW support scheme in the building sector, energy-saving measures implemented through the *Energieeffizienzfond* (energy efficiency fund), the tender scheme STEPup! for industrial energy-saving investments, and the *Anreizprogramm Energieeffizienz* (energy efficiency incentive programme) for the replacement of heating and ventilation systems. |
| Czech Republic | 99,888,000 Euros;<br>50 percent of total domestic use | **New Green Savings Programme**: a financial support scheme designed to promote energy savings in single-family and multifamily buildings (only in November 2016 the Czech government approved to also include public sectors buildings), focusing on the renovation of existing buildings, construction of new buildings with low-energy standard, and utilisation of low-emission or renewable sources for heating.<br>**EFEKT Programme**: a financial support scheme designed to promote energy-saving measures and renewable energy sources among small customers, focusing on energy efficiency improvements, energy management, and awareness raising through education. |

cent, 16.7 percent, 4.9 percent and 4.2 percent, respectively. The aggregated use category includes: Funding of research and development (R&D) for clean technologies and energy efficiency (1.0 percent), of R&D and demonstration projects for reducing emissions and for adaptation (0.1 percent), other reductions of GHG emissions (0.2 percent), forestry sequestration in the Union (0.1 percent), adaptation to the impacts of climate change (1.0 percent), cross-cutting measures (2.0 percent), and coverage of administrative expenses of the management of the ETS scheme (0.3 percent).[15]

15. These investment categories are officially listed as energy- and climate-related purposes in the EU ETS Directive. We have added the category "cross-cutting measures", in case multiple purposes have been reported for the same amount of spending, and aggregated the categories for which only a small share of domestic revenues is used in order to ensure a clearer presentation in Figure 2.

56.5 percent of the total domestic use for energy efficiency comes from German auctioning revenues (with adjustment). Yet, Germany is not the only country devoting a large share of their domestically reinvested revenues to increase energy efficiency. Belgium, Czech Republic, Croatia, Germany, Hungary, Ireland, Italy and Latvia report to strategically invest between 50 and 100 percent of their domestic use of auctioning revenues in energy efficiency.

Ireland has, in 2017, devoted the largest share of auctioning revenues to energy efficiency, with 98 percent funding the country's Better Energy Homes Scheme. Germany reports the highest 2017 auctioning revenue of all EU Member States, 1.15 billion Euros, and thus with a high share supporting energy efficiency measures, it contributes significantly to the total reported use for energy efficiency. In the Czech Republic, the strategic use of auctioning revenues is a well-established practice. The Czech New Green Savings Programme has been funded by auctioning revenues since its programme launch in 2013, and auctioning revenues are considered a major source for energy efficiency finance in the Czech Republic. Drawing on these exceptional cases and the availability of evaluations of the Member States' funded energy efficiency programmes, we provide further insights for Ireland, Germany, and the Czech Republic in Table 1 and the following paragraphs.

## THE USE OF AUCTIONING REVENUES FOR ENERGY EFFICIENCY IN IRELAND, GERMANY AND CZECH REPUBLIC

### Ireland's Better Energy Homes Scheme

Better Energy Homes is a financial support scheme that provides grants (covering around 30 percent of the total investment costs) to homeowners, including landlords of dwellings, to invest in energy efficiency actions, e.g. attic and wall insulation, renewable heating technology upgrades and installations of heat pumps. Since 2016, special grants for deep retrofits are available within the Deep Retrofit multi-annual pilot programme.[16] All actions must be installed by contractors registered by the Sustainable Energy Authority of Ireland (Broc 2017). In 2016, the scheme spent 17 million Euros in grants, which resulted in over 15,000 homeowners undertaking 36,000 energy efficiency measures in their homes. The measures installed in 2016 are estimated to deliver new annual energy savings of 84.26 GWh and 2877 kilo tonnes of $CO_2$ per year. Since the start of the scheme, over 202.4 million Euros worth of grants has been paid to homeowners. These funds have supported the upgrade of 191,338 homes, with a total 475,190 individual energy efficiency measures undertaken (Department of Communications, Climate Action & Environment 2017).[17]

### Germany's Energy and Climate Fund

The largest proportion of financial resources allocated to the Energy and Climate Fund and invested in energy efficiency programmes in Germany contributes to the KfW support programme Energy-efficient Refurbishment.[18] In 2017, the refurbishment programme allocated financial support to modernise around 275,000 dwellings. The supported refurbishment projects delivered 1,441 GWh annual end-use energy savings[19] and GHG emission reductions amounting to 479,804 tonnes of $CO_2$ equivalent per year. Annual heating costs to consumers will be reduced by approximately 136 million Euros; considering total lifetime energy savings, heating cost savings are expected to reach approximately 4.8 billion Euros (discounted net present value over 30 years assumed average lifetime for the applied energy savings measures). The total investment stimulated by the programme – 10.9 billion Euros, including value-added tax—are estimated to deliver 118,000 person-years of employment[20] and, taking into account second order investment effects outside the building industry, a net turnover of 16.1 billion Euros. Of the total investment sum, 1.8 billion Euros return directly back to the national budget through value-added tax (Diefenbach et al. 2018).[21]

### The Czech Republic's New Green Savings and EFEKT Programme

The Czech New Green Savings Programme, which is estimated to provide 700 million Euros in funds to owners of single-family or multifamily houses, is in its entirety financed through auctioning revenues (phase 3 auctions, 2013–2020). The financial support scheme for investments in energy-efficient building infrastructure is estimated to deliver 650 TJ energy savings for every 38 million Euros invested (Hrbek 2018). Referring to the programme's subsidy rate, it is expected that every Czech crown (CZK) spent in the programme initiates an additional investment of two to three crowns by building owners. Thus, the public investment returns to the national budget through value-added tax, income tax, and social and health insurance of the workers. Indeed, a 1 million CZK (approximately 40,000 Euros) public investment in enhanced energy efficiency in buildings is expected to induce 2.13 to 3.59 million CZK (83,000 to 140,000 Euros) growth of gross domestic product, on average 2.06 additional persons employed, mainly in small- and medium-sized enterprises in the construction sector, and 720,000 CZK (28,000 Euros) in total tax revenues (Zámečník and Lhoták 2012).

In 2016, the EFEKT Programme paid out 81.55 million CZK (3.2 million Euros) in subsidies (50 million CZK, 2.0 million Euros, financed through auctioning revenues) supporting 188 energy-saving projects for increasing the energy performance of public lighting, replacing heating systems, providing energy audits, introducing energy management systems (ISO 50001), and supporting education- and awareness-raising measures. The payments initiated a total investment sum of 146.28 million CZK (5.7 million Euros). The improved energy performance of public lighting and the replacement of heating systems delivered direct energy savings of 13,896 GJ per year and an annual reduction of 3,596 tonnes of $CO_2$. The average cost per GJ saved amounts to 7870 CZK[22] (307 Euros), 3880 CZK supported through state subsidies (Ministry of Industry and Trade 2017).

16. Further information available at: https://www.seai.ie/grants/home-energy-grants/ (Accessed 09/01/2019).

17. According to Ireland's National Energy Efficiency Action Plan 2017, the budget allocation for the Better Energy Homes Scheme changes from year to year. 2017 is the first year that Ireland reports to have allocated auctioning revenues to the scheme (Department of Communications, Climate Action & Environment 2017).

18. According to Germany's official reporting, auctioning revenues largely support building refurbishments. Within the programme Energy-efficient Construction, KfW also supports the energy-efficient construction of new dwellings. This programme supported approximately 54,000 building projects in 2017. With that number of supported construction projects, the programme reached a share of around 39 percent of all new residential constructions in Germany. The end-use energy savings of the supported construction projects in 2017 amount to 295 GWh per year and GHG emissions reductions are estimated to add up to 138,522 tonnes of $CO_2$ equivalent annually (Diefenbach et al.2018).

19. Because building renovation programmes deliver savings across multiple fuel types, the assessment converts all savings to a common metric (GWh/yr) using each fuel's energy content.

20. Person-year = Employment of one person for one year with the average weekly working hours of the respective industry.

21. It is worth noting that this tax revenue is close to the total amount allocated to the Energy and Climate Fund from all sources in 2017. The German experience thus reveals that, although treasury departments might be reluctant to "lose" income by dedicating auctioning revenues to efficiency programmes instead of to general funds, in relatively short order those auctioning revenues could well be replaced by taxes received due to the positive economic activity stimulated by the efficiency programme.

22. These costs are expected to decrease in the future of the programme, due to changes in the programme design. Until 2016, structural investments related to public lighting improvements were eligible for programme support, which will not be the case from 2017. In general, the programme aims to focus on information, education and awareness raising measures, for which the energy saving impact is difficult to measure.

#### CRITICAL REVIEW OF MEMBER STATES' AUCTIONING REVENUE DATA

Our assessment uses the EU Member States' official reporting on the use of 2017 auctioning revenues. As mentioned before, the reporting is mandatory; however, it is the Member States' own responsibility to report, and there is no external verification of the reported numbers. Thus, the assessment requires some degree of reliance on the Member States' submissions. For Ireland, Germany, and the Czech Republic, we could find and use further information on their use of auctioning revenues, while for other Member States that reinvest revenues for energy efficiency, only limited information on the exact use and/or the effectiveness of the support is available.

Overall, the quality of reporting improved since the introduction of the mandatory reporting scheme, with more Member States specifying their use of auctioning revenues. The following points should still be discussed:

- Although the level of detail has improved over time, it still varies among Member States. Different inconsistencies exist, most often the summation of reported domestic and international use yields an amount higher or lower than the amount reported to be used for energy- and climate-related purposes. Furthermore, for both domestic and international use, Member States shall distinguish between committed funds and funds actually disbursed for use and provide a definition for both. However, many Member States do not provide the required definition and different Member States apply it differently. There is a clear need for more transparent and granular reporting, which should ideally also include a requirement for independent monitoring and verification of the reported uses.
- Ireland, Germany, and the Czech Republic strategically invest their auctioning revenues in energy efficiency programmes and thus realise some of the potential multiple dividends of the EU ETS to further abate GHG emissions, achieve cost savings and non-energy benefits. However, the official reporting does not allow to draw conclusions whether the use of auctioning revenues for energy efficiency in these countries and other Member States has led to *additional* programme support and incremental energy efficiency investments, as it would require a counterfactual without the revenue income stream. Future research could estimate the additional impact of auctioning revenues on efficiency programmes by comparing trends in funding levels before and after the revenues were assigned to certain programmes and by studying their political and administrative histories. There are two important issues to consider. First, auctioning revenues will not be reducing emissions if they are merely replacing other funding sources for efficiency programmes. Second, decision-makers should not assume that auctioning revenues alone will be adequate to finance all of the cost-effective efficiency investments that will need to be undertaken to meet Europe's climate and energy targets. In fact, total investments in programmatic efficiency measures should often be higher than the auctioning revenues in a particular state.
- Slovakia, Belgium, Greece and Germany report to use a substantial share of total domestic use for electricity price compensation to energy-intensive industry at risk for carbon leakage (48.9 percent, 29.6 percent, 15.0 percent and 14.1 percent, respectively). This use counts as an energy- and climate-related purpose, although certainly decreasing the beneficiaries' motivation to reduce their energy consumption. Using these revenues to improve energy efficiency at such industries would improve their competitiveness, while also reducing emissions, and should therefore be preferred. Unless process improvements are not feasible, and even in that case revenues could be used to fund energy- and climate-related R&D for process innovation to make them feasible in the future, using auctioning revenues to subsidise continued emissions, rather than reducing emissions, should not be eligible to count as use for climate and energy purposes.
- The recently released economic report of Germany's energy and climate fund (for 2017) shows that a large fraction of money (approximately 40 percent) committed to support energy and climate programmes was not disbursed for actual use (Zeitung für Kommunale Wirtschaft 2018). This case shows that the use of auctioning revenues for energy efficiency programmes faces the common barriers for a successful implementation, not only in Germany. The provision of financial resources is one important step; however, it does not solve the challenge to overcome all other barriers to energy efficiency. Strategically investing revenues is a means to an end, not an end in itself, and requires further engagement to achieve energy demand reductions cost effectively.

### Discussion on interactions among the EU ETS, auctioning revenue use, and energy efficiency improvements

The recent changes within the ETS framework and the revision of the EU ETS Directive are addressing the current surplus of emission allowances and reducing the overall cap (MSR and LRF, respectively). These changes are intended to increase future EU allowance prices and the incentive to reduce emissions. The impact on auctioning revenues is not straightforward: In the first instance, lowering the number of allowances available in the system would, all else equal, lower total available revenues. On the other hand, a tighter market should increase the carbon price, and the gradual elimination of free allocations will also tend to drive up total auctioning revenues. Indeed, projections indicate that total auctioning revenues across the EU might increase up to 20 billion Euros per year before 2030 (Ecologic Institute and WWF 2016), as mentioned before. If Member States were to continue to devote the same fraction of auctioning revenues to efficiency programmes as reported in 2017, higher revenues would increase the amount of revenues used for energy- and climate-related purposes and increase the income stream available for energy efficiency programme support.

The interaction between the EU ETS and improved energy efficiency, expecting higher (and ideally incremental) support for complementary energy efficiency measures funded by auctioning revenues, is more complex and often debated among researchers and policy advisers.[23] If energy efficiency

23. This debate is not limited to energy efficiency improvements, but even more established with respect to increased adoption of renewable energy sources (e.g. Del Río González 2007) and starts to include policy changes on the national level, e.g. coal-phase out proposals (Ecofys 2016).

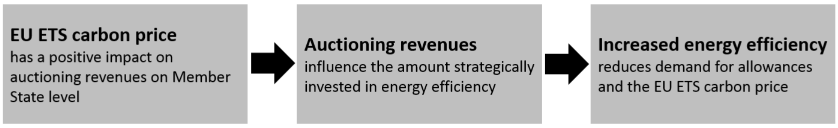


*Figure 3. Linkage among the EU ETS carbon price, auctioning revenues and energy efficiency within the ETS sectors. Source: authors' illustration.*


*Figure 4. End-use efficiency improvements outside the EU ETS. Source: authors' illustration.*

programmes have the effect of lowering demand for allowances by reducing energy consumption and generation (covered by the ETS, i.e. electricity), the carbon price would reduce, illustrated in Figure 3. Freed-up allowances would be banked for later use or sold to other emitters, meaning that the efficiency programmes would not achieve emission reductions under the cap-and-trade system but only reduce the price and thus the cost to businesses and consumers of complying with the cap. The carbon price reduction would furthermore hamper the capacity of the EU ETS to incentivise low-carbon investments.

While critics have frequently used this "waterbed effect" to argue against the implementation of measures that would reduce emissions additional to the EU ETS, we start with the argument that the overriding rationale of carbon cap-and-trade systems is, indeed, to uncover the lowest-cost opportunities to reduce emissions and therefore to reduce the price of carbon. Thus, any action to reduce emissions within a cap-and-trade system will intentionally release emissions allowances into the market and reduce pressure on the carbon price without directly reducing the cap. In other words, the "waterbed effect" is an essential design element of cap-and-trade systems. It is therefore inconsistent with cap-and-trade theory to criticise additional policies, such as efficiency programmes, merely because they may reduce carbon prices under a cap.

We emphasise three further interactions between energy efficiency improvements and the EU ETS, taking into account where revenues are currently invested, why the revised ETS framework "punctures the waterbed" and how future revisions could further reinforce the major objective of the EU ETS to reduce emissions cost effectively:

- Some Member States use their auctioning revenues to improve the thermal efficiency in buildings and add insulation to homes, reducing energy consumption of natural gas, fuel oil, or district heat systems that are largely outside the ETS. E.g., both the German KfW support schemes and the Czech New Green Savings Programme incentivise building efficiency improvements, to name just two EU examples. In this way, the cap-and-trade scheme can drive reductions even outside, and in addition to, the reductions mandated by the cap, as shown in Figure 4. This approach is especially useful when it would be impracticable or politically infeasible to bring those sectors into the cap regime.
- Considering the large amount of surplus allowances built-up in the EU ETS and the new implementation of the MSR, the "waterbed effect" argument is punctured (Sandbag 2017; Perino 2018). From 2019 to 2028, the MSR is expected to take in approximately 1.8 billion allowances (additional to the initial transfer of unallocated and back-loaded allowances from phase 3). Moreover, the latest EU ETS reform implemented that these allowances are limited in their validity and a substantial number of allowances, up to 2.4 billion, is expected to be cancelled in 2023 (Marcu et al. 2018). With the MSR in operation, complementary measures, which reduce the demand for allowances, increase the current surplus, of which a large proportion will eventually be cancelled, which is taken into account in Figure 5. Thus, freed-up allowances and finally emissions are not simply shifted in space and time, as supposed by the "waterbed effect" argument, but added to the existing surplus of allowances on the EU carbon market. The cancellation mechanism and the MSR in general are intended to increase the carbon price, and reduce overall emissions.[24]
- With respect to future revisions of the ETS framework, another approach is to use success in the strategic use of auctioning revenues for energy efficiency, which lowers energy bills along with emissions, to support the political process to tighten the cap further in later rounds of cap administration. This approach has notably succeeded in the nine states comprising the RGGI cap-and-trade scheme in the northeastern United States (Acadia Center 2017), and it could help to drive lower cap levels in Europe and elsewhere, as well. The recent ETS reform, increasing the LRF and introducing the MSR, are both long-needed improvements to the system, but they are only a starting point. Ideally, the cap should reflect changing circumstances and market conditions.[25] Suc-

24. The ability of the MSR to absorb the impact of complementary policies on the supply and demand imbalance, and the carbon price effect are however still uncertain and rely on potential adjustments after the MSR reviews scheduled for 2021 and 2026. The opposite MSR mechanism to release allowances to the market when a lower threshold of allowances in circulation is reached is not expected to be utilised before 2030 (Marcu et al. 2018).

25. For a detailed discussion on options for dynamic cap adjustments and its benefits, see Cowart et al. (2017), who refer to this opportunity as "A "virtuous cycle" of emissions reductions and allowance retirements".

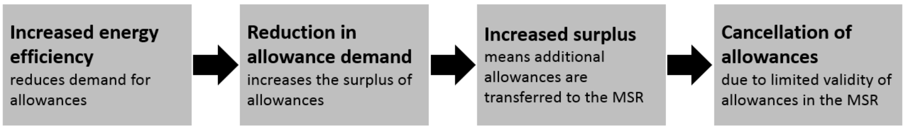


*Figure 5. Interaction between the EU ETS and complementary energy efficiency measures, taking into account the MSR mechanisms. Source: authors' illustration, adapted from Whitmore (2017).*

cessfully investing auctioning revenues in end-use energy efficiency could increase the political will and wider social acceptance for more ambitious, long-term decarbonisation targets within the ETS.

These three interactions show that the strategic use of auctioning revenues for energy efficiency has the potential to reinforce the EU ETS. Complementary, energy efficiency programmes funded by ETS revenues, additional to the main carbon pricing instrument, can lead to further emission reductions in ETS and non-ETS sectors, at lower costs for consumers and society. Beyond that, energy efficiency improvements provide multiple non-energy benefits and, finally, the opportunity for tighter cap regulation. Thus, the EU ETS can yield multiple dividends, but in order to realise them, the strategic use of auctioning revenues needs to be accelerated in all Member States.

## Concluding remarks

Strategically investing auctioning revenues in end-use energy efficiency provides an increasing opportunity for Member States to reinforce the EU ETS. Support for complementary energy efficiency programmes can yield multiple dividends because energy efficiency improvements help to deliver cost savings and emissions reductions, reduce the upward pressure on consumer energy bills, and realise the energy and non-energy benefits of end-use efficiency. Furthermore, in practical political terms, the multiple dividends can be substantial. To achieve the targets of the Paris agreement and avoid drastic global climate disruption, climate policies must deliver GHG emission reductions sustainably over decades of progress, which, in modern democratic societies, requires sustained political support. Public support for climate policies will be easier to maintain when the consumer costs of carbon pricing are moderate, and the policy is seen to deliver costs savings to end-users, not primarily higher prices across the board.

In the EU ETS, the potential to use these benefits is to a large extend still untapped. Some Member States strategically invest their auctioning revenues for energy- and climate-related programmes. However, the fundamental understanding that both the carbon price and the strategic use of revenues can help to achieve the EU's decarbonisation targets cost effectively is limited. The analysis of the Member States' use of auctioning revenues shows that in 2017, 43.6 percent of total revenues are strategically invested for energy- and climate-related purposes and no more than 22.4 percent in energy efficiency programmes. To further establish the strategic use of auctioning revenues, EU Member States need to become aware of the multiple dividends they could achieve. The energy efficiency programmes partially funded by auctioning revenues in Ireland, Germany, and the Czech Republic directly illustrate that these programmes deliver energy savings and GHG emissions reductions, cost savings to consumers, tax revenue to the national budgets, employment, and economic growth. Thus, in expectation of a future increase in EU ETS auctioning revenues, making the case for their strategic use becomes ever more relevant.

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## Endnotes

Some parts of this paper build on the non-peer reviewed work by Wiese et al. (2018).

After the paper deadline, personal communication with the Department of Communications, Climate Action and Environment in Ireland revealed that Ireland does not earmark auctioning revenues for specific uses. Thus, the reported investment in the Better Energy Homes Schemes does not represent a strategic use of auctioning revenues but only serves to accord with the Commission's recommendation to use at least 50 percent of auctioning revenues or the equivalent in financial value of these revenues for energy- and climate-related purposes.

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