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Exploring the role of households' hurdle rates and demand elasticities in meeting Danish energy-savings target

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ABSTRACT

The EU's Energy Efficiency Directive (EED) sets a binding target for energy-savings in EU member states. The EED further requires member states to perform ex-ante evaluations of energy efficiency policies implemented to achieve these savings. However, ex-ante evaluation of energy efficiency policies is difficult as it requires detailed modelling of end-users' investment and energy demand behaviour. This paper details the Danish IntERACT modelling approach for ex-ante evaluation of energy efficiency policies directed at residential heating. IntERACT integrates the energy system model TIMES-DK into a computable general equilibrium framework. The paper explores the potential for meeting Denmark's EED-target through a policy-induced increase in households' investments in energy efficiency retrofits. The paper considers the effect of energy efficiency policies on households' investment behaviour by applying different levels of hurdle rates on households' investments in energy efficiency retrofits. The paper shows that reducing the hurdle rate from 25% to 4% could meet more than a third of Danish energy-saving requirements for the period 2021–2030. This result includes a direct rebound effect of 31%. Finally, the paper demonstrates that reducing the hurdle below 10% has a substantial negative impact on households' disposable income, making such policy less viable from a policy perspective.

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 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 Danish residential building stock (e.g., Tommerup and Svendsen, 2006; Kragh and Wittchen, 2010; Wittchen and Kragh, 2014).

However, ex-ante evaluations of residential energy efficiency policies under Article 7 require detailed modelling of households' behaviour both in terms of energy efficiency investments and energy demand. Capturing households' energy demand behaviour 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 partially offset direct energy-savings (Greening et al., 2000; Sorrell et al., 2009; Sorrell, 2009). Within existing ex-ante evaluations of energy efficiency policies following Article 7 of the EED, considerable uncertainty exists as to what extent Member States account for rebound effects (Rosenow et al., 2016).

Capturing households' investment behaviour is crucial for determining the level of energy-savings, both within the BAU scenario and the policy scenario. Households' investment behaviour regarding 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

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

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market interest rate (e.g., Corum and O'Neal, 1982; Jaccard and Dennis, 2006; Burlinson et al., 2018; 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 behavioural 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 understand better the role of hurdle rates in model-based policy evaluations in Denmark and beyond.

Combining demand and investment behaviour requires the use of hybrid energy-economy models – over traditional bottom-up and top-down modelling – as hybrid models combine the advantages of a technologically explicit bottom-up model with the behavioural realism sought by top-down models (Hourcade et al., 2006). Top-down models further incorporate important equilibrium effects using empirically derived demand and trade elasticities. In this paper, we use a Danish hybrid model, IntERACT, to explore the potential for meeting Denmark's EED-target by reducing the high discount rate implicit in households' investment decisions. We consider the reduction in hurdle rate, within IntERACT, as a proxy for the effectiveness of a mix of energy efficiency policies applied over the period 2021–2030. Our goal is not to determine the effects of any specific energy efficiency measure, but rather to explore the potential for reducing final energy demand for residential heating from a mix of policies. The IntERACT model 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 level of realised 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 on equilibrium effects, like rebound effects and the overall impact on households' disposable income 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 general equilibrium feedback in terms of rebound effect and the effect on households' disposable income.

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 behaviour. 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, for 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 behaviour 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.

2.2. 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, several studies have analysed 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., Dubin, 1982; Meier and Whittier, 1983; Train, 1985; Ruderman et al., 1987; Min et al., 2014; Burlinson et al., 2018). 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.

As shown in Table 1, the literature finds estimates ranging from 2.1% to 127% when considering all types of heating investments. However, for energy efficiency retrofits the range of average implicit discount rate is more narrow, namely between 10% to 32%. The differences in discount rates among and within studies largely depend on different assumptions concerning energy prices and the expected useful life of an investment (Train, 1985). Nevertheless, estimates of implicit discount rates are generally high, and notably higher than the opportunity cost of capital or market interest rate. In other words, households 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.

2.3. 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 behavioural – failures as the main explanation for households' high implicit discount rates, specifically in the context of the energy efficiency gap discussion (Ruderman et al., 1987; Jaffe and Stavins, 1994; Howarth, 2004; Allcott and Greenstone, 2012). 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 behavioural biases, and (iii) external barriers. Preferences refer to individual time, risk, reference-dependent and pro-environmental preferences. Bounded rationality, limited attention, and behavioural biases represent household behaviour 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 (Stern, 2000; Ramos et al., 2016).

(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) (Schleich et al., 2016; Burlinson et al., 2018). 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.

2.4. 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 behaviour. In order to achieve a reduction in the discount rate implicit in households' investment decisions, policies need to address the three underlying factors (i.e., preferences, unbounded rationality and external barriers) and impact these factors in a way that stimulates investments in energy efficiency improvements.

Policies like taxes, subsidies and regulation affect household investment behaviour. However, the extent to which policy intervention can change households' preferences depends on the underlying assumptions on consumer behaviour. Neoclassical economic theory assumes that preferences are stable over time and that behaviour is influenced only by prices and income constraints. In contrast, research within behavioural economics and psychology (for an energy-related overview see Frederiks et al., 2015) suggests that policy interventions can take into account households' preferences and behavioural biases and thereby establish conditions that favour the decision to invest in energy efficiency improvements or nudge households towards a specific behaviour. If households exhibit bounded rationality, information provision may reduce the behavioural bias and increase awareness (Newell and Siikamäki, 2014), or minimum energy efficiency performance standards may enforce specific investment decisions by limiting the availability of the most inefficient technologies (Schleich et al., 2016; Gillingham and Palmer, 2014).

However, external barriers to energy efficiency investments remain the primary focus of policy interventions and academic research. 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 behaviour and find mixed, however, largely positive effects (Abrahamse et al., 2007; Barbetta et al., 2015; Newell et al., 1999; Newell and Siikamäki, 2014; Ek and Söderholm, 2010; 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 Gulati, 2014; Datta and Filippini, 2016; Markandya et al., 2009).

2.5. 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 are typically 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 behaviour by adopting technology-specific hurdle rates.

Many economists criticise the first perspective, particularly the use of social discount rates to convert the financial costs of technologies over different periods into present value (Jaccard and Dennis, 2006). In part, this is because the financial cost and the social discount rate alone may not capture the full social cost of technological change as seen from the perspective of businesses and consumers. Rational households, for example, would factor the likelihood of cost overruns, errors in equipment installation, and equipment under-performance into their retrofit decision. In addition to these considerations related to households' rationality, the use of technology-specific hurdle rates in energy system models also captures factors related to bounded rationality and external barriers.

Table 2 gives a summary of hurdle rates applied to investment decisions in the residential sector, referring to different models and

[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).

Table 1
Implicit discount rate estimates.

Estimates	Comments	Investment type	Reference
20.79%	Discount rate for an average homeowner based on data from a stated choice experiment	Energy efficiency retrofits	Jaccard and Dennis (2006)
10% for gas-heated, 14% for oil-heated, and 19%–21% for electricity-heated houses	Average discount rates based on historical data on residential construction practices, the assumption of no real energy price increases, and cash payment of upfront cost	Energy efficiency retrofits	Corum and O'Neal (1982)
26% for US, and 12% for Pacific Northwest	Average discount rates based on household survey data, the assumption of no real energy price increases, and 15 years useful life	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 based on data from general public utilities, the assumption of no real energy price increases, and infinite useful life	Energy efficiency retrofits	Little (1984) (as cited in Train, 1985)
36%	Discount rate based on data from a quasi-experimental survey, controlling for consumer inattention and heuristic decision-making	Connection to district heating	Burlinson et al. (2018)
9%	Discount rate for an average homeowner based on data from 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 discount rates based on data on historical efficiency choices, the assumption of no real energy price increases, and 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 based on household survey data, the assumption of no real energy price increases and infinite useful life	Heating system and fuel choice	Goett (1984)
2.1–9.3%	Discount rates based on household survey data, the assumption of no real energy price increases, and real-world data on useful life	Heating system and fuel choice	Dubin (1982)
7%–31%	Discount rates based on cross-sectional data for fuel choice in 48 US states, the assumption of no real energy price increases, and infinite useful life	Heating system and fuel choice	Lin et al. (1976)
36%	Average discount rate based on household survey data, the assumption of no real energy price increases, and infinite useful life	Heating system and fuel choice	Goett (1978) (as cited in Train, 1985)
6.5%–16%	Average discount rates based on household survey data, the assumption of no real energy price increases, and infinite useful life	Heating system and fuel choice	Goett and McFadden (1982) (as cited in Train, 1985)
25%	Average discount rates based on the assumption of no real energy price increases and infinite useful life	Heating system and fuel choice	Berkovec et al (1983) (as cited in Train, 1985)

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). Bozic (2007) uses a hurdle rate of 15% to model investment in home heating system. Both Kannan (2009) and Kannan and Strachan (2009) uses a baseline hurdle rate of 25% within a UK MARKAL model to capture investment in residential retrofit investments. Kannan (2009) further 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 external barriers and market imperfections (Mundaca, 2008;

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 (2008)
	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)
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)

European Commission, 2016). Mundaca (2008) 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 programmes, 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%).

2.6. Summary

Evidence on the level of the implicit discount rate and the effect of individual policies on its underlying factors is ambiguous. The use of hurdle rates in existing energy-economy models confirms this ambiguity. Our literature review suggests that a 20%–25% implicit discount rate may represent households' investment behaviour with respect to energy efficiency retrofits in the absence of additional policy measures in a Danish context. In particular, we consider Jaccard and Dennis (2006) as the most relevant study because, first, the authors conduct a carefully designed stated choice experiment with the main goal to elicit hurdle rates for use in a Canadian hybrid model. Second, we consider the hurdle rate transferable to a Danish context because Canada, like Denmark, has historically had public policies in place promoting retrofit investments (see, e.g., Hamilton et al., 2010).

When it comes to the impacts of energy efficiency policy measures on the choice of hurdle rate, the reviewed literature gives no clear direction. The European Commission provides the most concrete exercise, in which policy pressure reduces the hurdle rate applied to residential renovations and heating systems by close to 3 percentage points within the energy system model PRIMES. We address this uncertainty within the IntERACT model by exploring the effect of reducing the hurdle rate from 25% to 4%, which corresponds to the level of the Danish social discount rate (see Danish Ministry of Finance, 2013). We consider the social discount rate as a relevant lower bound because traditional bottom-up engineering assessments of the Danish residential energy-saving potential built on the social discount rate (see, e.g., Kragh and Wittchen, 2010; Wittchen and Kragh, 2014). Investigating the different energy-saving outcomes when applying different hurdle rates between the social discount rate and a 25% hurdle rate furthermore demonstrates in what way a model like IntERACT is capable of representing two opposing viewpoints. We believe that by representing both the traditional viewpoint of engineers and economists, this paper does further the cross-disciplinary dialogue on the role of energy efficiency policy.

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 minimising 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. Fig. 1 illustrates the supply of residential heating in TIMES-DK. The rectangles in Fig. 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, 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 categorise the residential building stock into 36 groups in total.[3] With respect to heat saving measures, TIMES-DK includes cost curves for the 24 groups of existing buildings (constructed 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 judgement.

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, relying on Danish Energy Agency (2018a). This choice also reflects the need better to validate the electricity and district heating sector within TIMES-DK. However, we note that preliminary research indicates that investment in residential energy efficiency retrofits reduce the need to invest in electric generation capacity. Whereas, increasing investment in renewable electricity, by reducing the price of electricity, reduces investment in residential energy efficiency retrofits. These potential significant interaction effects will be the 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.[4] 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 3.4.

3.2. 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 behaviour. Based on Section 2, we consider a hurdle rate of 25% as a low-effectiveness policy scenario. In contrast, we consider the Danish social discount rate of 4% as the lower bound for choice of hurdle, or as a possible highly effective policy scenario. To explore the role of the hurdle rate, we consider three additional magnitudes, namely 10%, 15% and 20%, and apply these to households' investment decisions for heat saving measures. 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 behavioural 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 minimising 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.[5] 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

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

[4] 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.

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

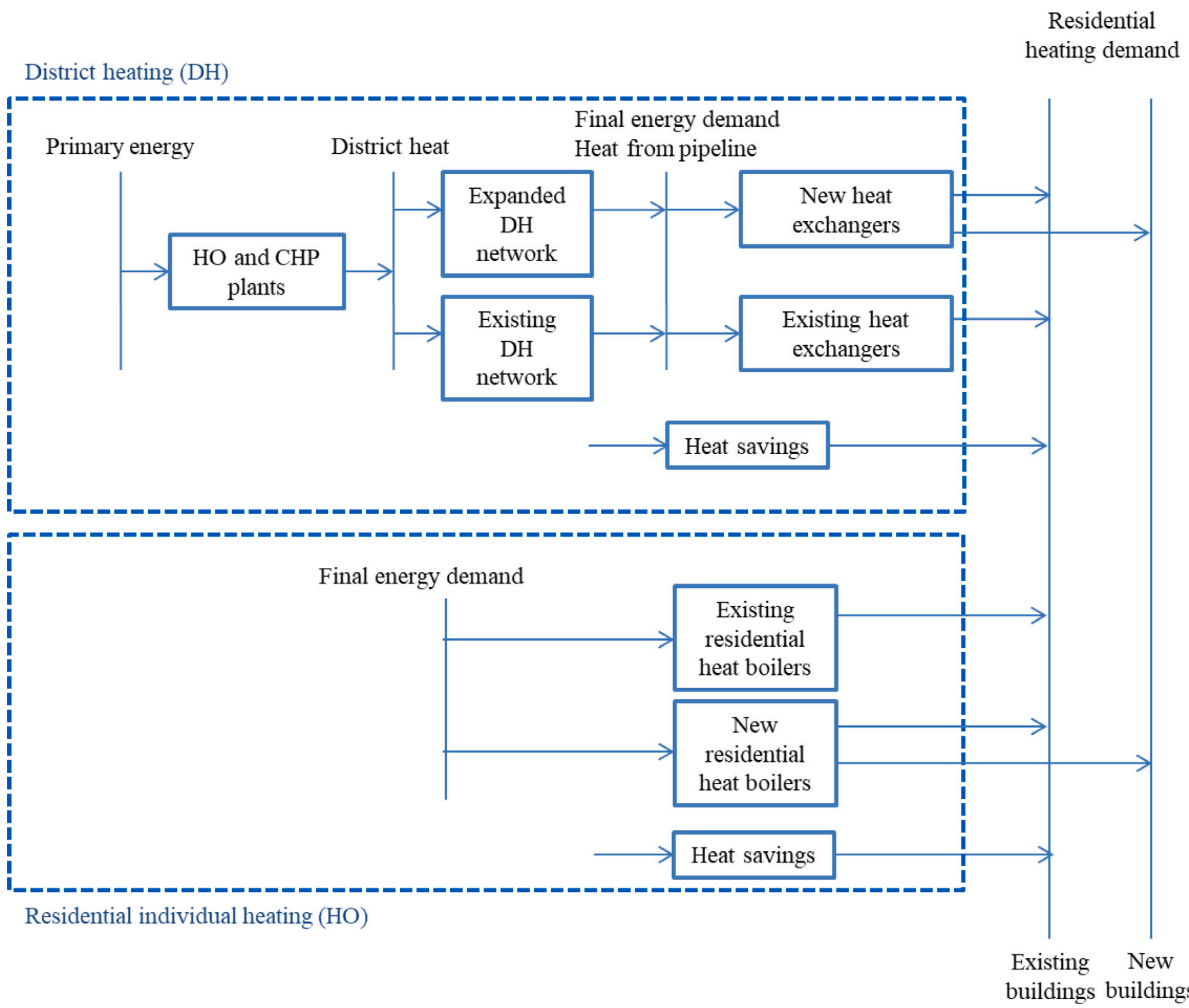

Fig. 1. Supply of residential heating in TIMES-DK.

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; social discount rate: 4%.

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.

3.3. 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 (labour and capital) to firms. The utility function 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. Fig. 2 illustrates the nesting structure of the Stone Geary utility function that we use. The Stone Geary specification allows specifying 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. In contrast, 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

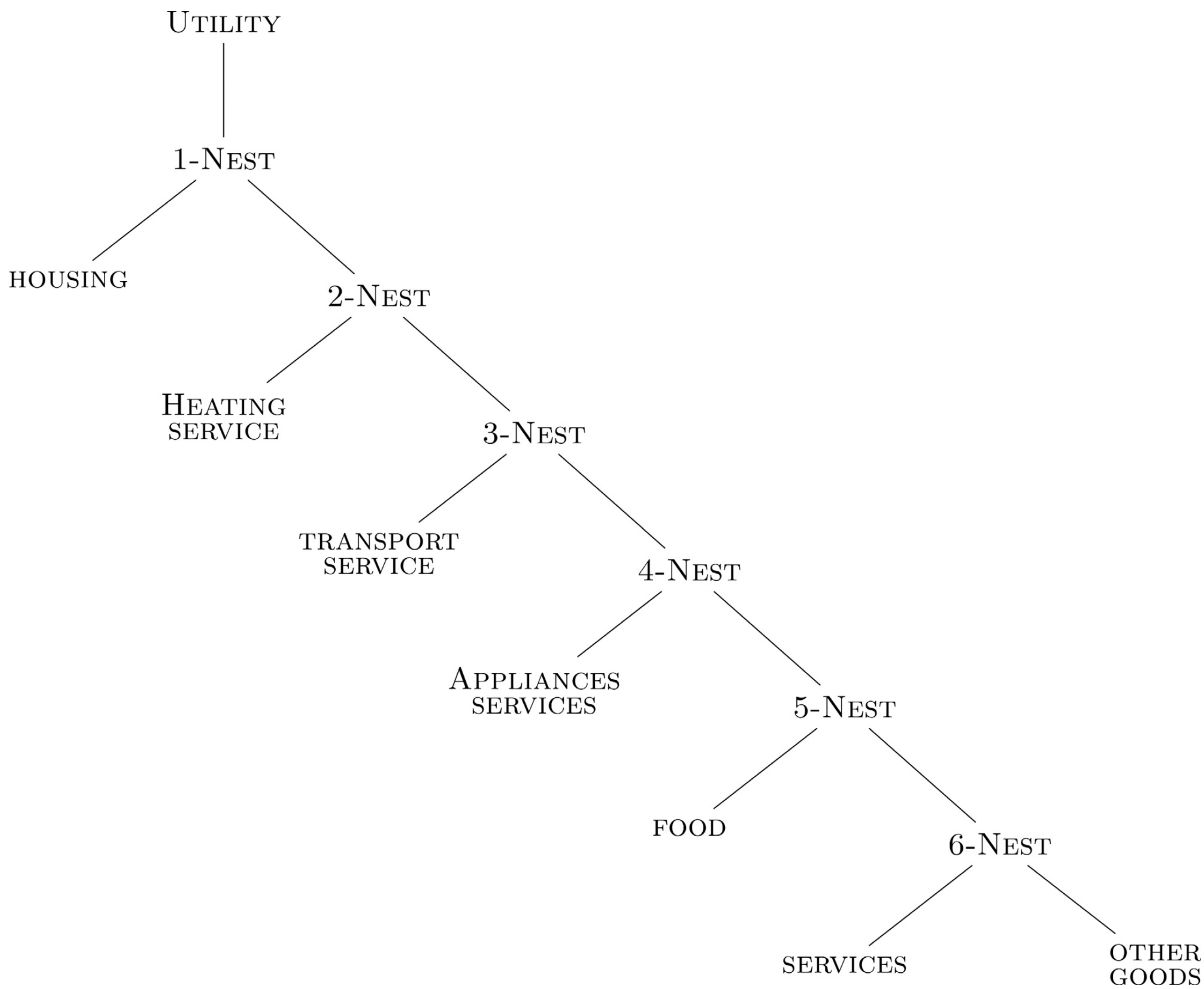

Fig. 2. Nesting utility function of the representative household.

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.

3.4. Iterations between residential heating supply and demand

Fig. 3 illustrates the automated iterative soft-linking routine used to balance heating service supply and demand within IntERACT. We initialise the iterative routine by running TIMES-DK (1* in Fig. 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.

Eq. (1) expresses how the future heating supply function in the CGE model is adjusted based on the TIMES-DK solution. Eq. (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 the cost of heating services (the left hand side of equation).[6]

We update the cost side of Eq. (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.

[6] See Andersen et al. (2019) for a complete discussion of the IntERACT linking method.

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.

Eq. (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).

Equations for soft-linking routine within IntERACT

$$\underbrace{\left[\frac{\frac{\sum_f x^{\text{TIMES-DK}}_{f,\text{year}}}{\sum_f x^{\overline{\text{CGE}}}_{f,2015}}}{\frac{\sum_{b,s,r} d^{\text{TIMES-DK}}_{b,s,r,\text{year}}}{\sum_{b,s,r} d^{\text{TIMES-DK}}_{b,s,r,2015}}}\right]}_{\substack{\text{Change in conversion efficiency}\\ \text{relative to CGE benchmark}}} \cdot \underbrace{\sum_f \left[\frac{x^{\text{TIMES-DK}}_{f,\text{year}}}{\sum_f x^{\text{TIMES-DK}}_{f,\text{year}}} \cdot pf_{f,\text{year}} \cdot (1+\text{tax}_{f,\text{year}})\right]}_{\text{Updated fixed cost shares}}$$

$$\geq pces_{\text{year}}, \quad \underbrace{ces_{\text{year}}}_{\substack{\text{Complementary}\\ \text{variable}}} \tag{1}$$

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

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_{year}	Heating demand (CGE model)
$pf_{f,\text{year}}$	Fuel price (harmonised across the CGE and TIMES-DK model)

Parameters

$d^{\text{TIMES-DK}}_{b,s,r,\text{year}}$	TIMES-DK heating demand by building type, supply area and region
$x^{\text{CGE}}_{f,2015}$	CGE benchmark fuel input quantity (in monetary units, real 2015 prices)
$x^{\text{TIMES-DK}}_{f,\text{year}}$	TIMES-DK fuel input quantities (in monetary units, real 2015 prices)
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)

Table 4
Cost of energy efficiency retrofits for each type of building component (2015-Euro/m^2 by building area).
Source: Petrović and Karlsson (2014).

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

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 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 realised 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. Fig. 4 illustrates these steps and shows the full and marginal cost curves for residential heat saving measures. The supplementary material accompanying this paper includes 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 100 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, to represent the heterogeneity of the energy-saving potential.

First, within any given year, the age distribution of building determines the marginal cost potential, i.e. the share of end-of-life building components. We assume that 5% of the total savings potential for each step is available in 2020 at marginal cost. We further assume that all building components will need replacement between 2018 and

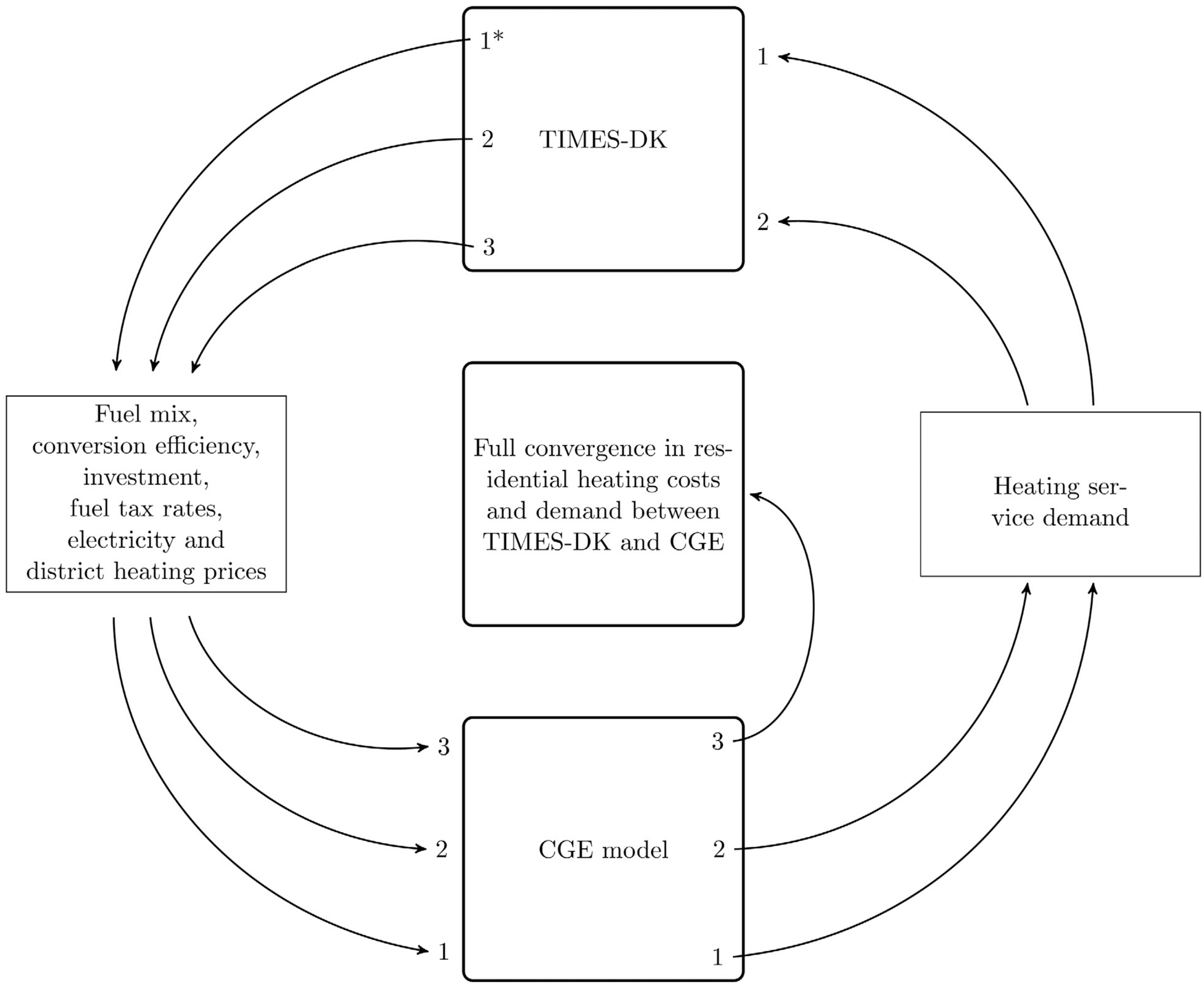

Fig. 3. Iterations between heating supply and heating demand within the IntERACT model.

2050. We translate this into an assumption that annually 3% (one divided by 32 years) of each of the 2400 cost steps become available at marginal cost. Information on the age distribution associated with the building component of different building stocks could potentially improve the representation of marginal cost potentials to something more advanced.

Second, each of the 2400 cost steps is heterogeneous in the sense that each represents hundreds of different buildings with individual owners. Realising the full potential of any cost step in the short term is not likely; even if cost-effective seen from the perspective of the TIMES-DK. For example, it is unlikely that elderly persons will spend their last years on earth investing in an energy retrofit. To capture this heterogeneity within TIMES-DK, we introduce a constraint that limits the sum of realised marginal and full cost potentials in 2020 to 30% of the total technical potential for each cost steps. This constraint increases linearly to 100% in 2030, ensuring that the sum of marginal and full cost potential cannot exceed the total cumulative savings potential for each step.

We consider these two types of constraints as a reasonable initial attempt at capturing some of the barriers not directly related to the choice of the hurdle rate. Due to the significance of these constraints, Appendix C show how the constraints help to shape the level of realised savings within the paper.

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% as a low-effectiveness policy scenario, whereas a hurdle rate of 4% reflects a highly effective mix of policies. The section highlights how the level of hurdle rate impacts final energy demand and realised energy-savings; further discussing how behavioural assumptions related to residential heating demand influence the rebound effect associated with a reduction in the applied hurdle rate. The section then examines 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. Next, the section considers what level of subsidy would be required to overcome the impact of the hurdle rate. Finally, the section concludes by discussing 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

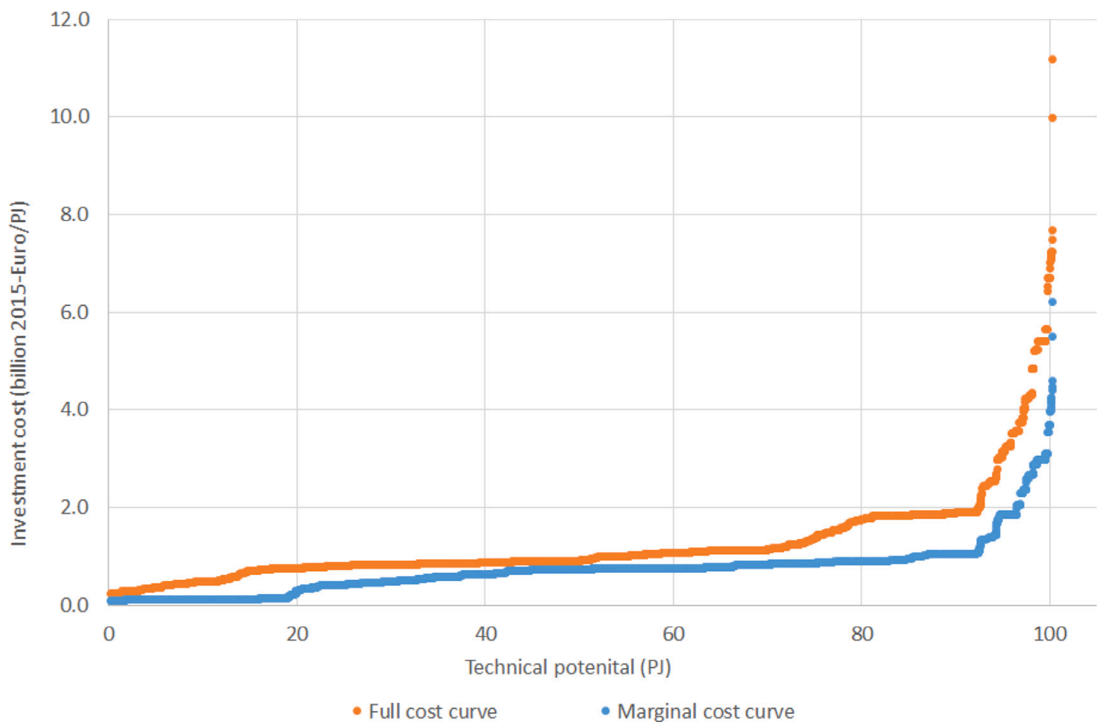

Fig. 4. Full and marginal cost curves for residential energy efficiency retrofits.

hurdle rate scenario. The baseline scenario shows a reduction in final energy demand from 163 PJ to 151 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 14 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 13 PJ and 104 PJ over the period 2021–2030. Thus, a policy mix, which effectively reduces the baseline hurdle rate to 4%, could potentially deliver more than a third of the 275 PJ Danish cumulative energy-saving requirement under the EED (i.e. see Section 1). This substantial contribution to cumulative energy-savings reflects that the 4% hurdle rate scenario leads to front loading of savings; i.e. in the 4% hurdle rate scenario final energy demand reduces by 4.5 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 2.4 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.

5.2. Realised energy-savings full and marginal cost

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., Tommerup and Svendsen, 2006; Kragh and Wittchen, 2010; 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.

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	160.9	0.0	−0.2	−1.3	−4.5
2025	155.4	−1.2	−1.6	−4.0	−10.5
2030	150.5	−2.0	−2.4	−5.7	−14.3
Cumulative change 2021–2030		−13	−16	−40	−104
Contribution to Danish EED-target		4%	6%	14%	38%

Fig. 5 illustrates the level of realised 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 realised in 2030; i.e. less than 5% of the total technical saving potential (100 PJ). At a hurdle rate of 4%, realised energy-savings increase to 24.3 PJ in 2030. However, this magnitude of energy-savings still corresponds to less than one fourth of the total technical potential.[7]

Fig. 5 is mainly the results of the two constraints discussed in Section 4, namely the limited potential of marginal cost savings and the representation of the heterogeneity of the savings potential. The 25% and 20% hurdle rate scenarios only realise the cheapest marginal cost savings steps. The assumption that only 3% of each marginal cost step becomes available each year limits the potential for realising marginal savings. Reducing the hurdle rate towards 15%, we begin to

[7] Supplementary material accompanying this paper contains more details regarding the distribution of energy-savings for the 24 groups of existing buildings.

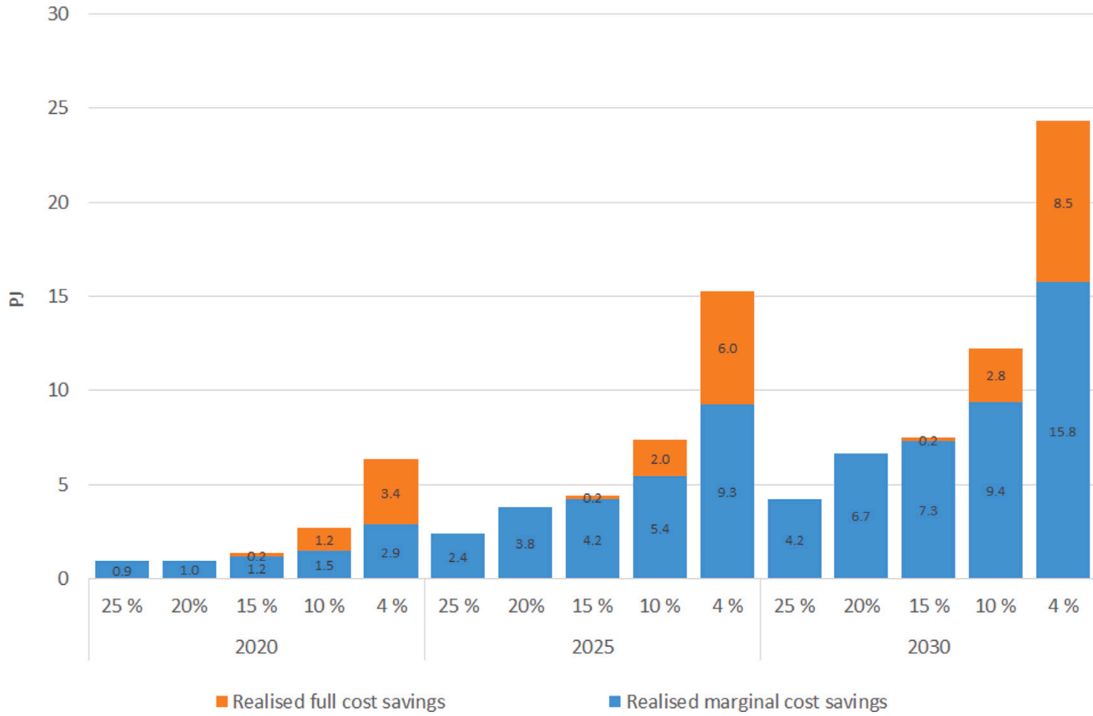

Fig. 5. Realised full and marginal cost energy-savings in 2020, 2025 and 2030.

see investment in full cost-savings; as these are no longer prohibitively expensive. Hence from the perspective of cost minimisation, it makes sense to front-load investments in full cost-savings, instead of investing in marginal cost-savings at a later point in time.[8]

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 realised full cost potential.

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. This section discusses the scale of the direct rebound within IntERACT for residential heating demand, thereby underlining the importance of demand behaviour for ex-ante evaluations.

We consider 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 3.3 (lower, central and upper estimate) where each estimate reflects a certain implicit heating price elasticity. We include 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 realised 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 146.5–153.1 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 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 125.8–143.4 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 20.7 PJ in 2030. When assuming an upper estimate of substitution elasticity, the final energy demand is only reduced by 9.7 PJ. This result underscores the necessity to take into account demand behaviour when implementing ex-ante evaluations of energy efficiency policies.

Table 6 range regarding the direct rebound effect, which varies between 19%–53%. The central estimate of substitution elasticity used in this paper results in a direct rebound effect of 31%. 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 realise 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 behavioural economics perspective, moralisation may convince households that their contribution to

[8] We note that the shape of the realised full cost-savings over time depends critically on the representation heterogeneity with respect to each savings step, i.e. the assumption that only 30% of the saving potential is available in the year 2020 for each cost step. For a further discussion see Appendix C.2

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	125.8	−20.7	0%
Lower estimate	−0.25	148.7	132.0	−16.7	19%
Central estimate	−0.38	150.5	136.2	−14.3	31%
Upper estimate	−0.50	153.1	143.4	−9.7	53%

energy-savings is socially beneficial and thereby reduce the rebound effect (Oikonomou et al., 2009).

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).

Fig. 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. Between 74%–89% of these expenses account for fuel costs including taxes, 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 0.12–0.19 billion Euro as the hurdle rate reduces to 10%. A further reduction from 10% to 4% leads to a 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 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.

We report welfare effects from changing the hurdle rate in terms of Hicksian equivalent variation (HEV) in income, which we here interpret as a measure of the change in real disposable income experienced by the representative household. Fig. 7 highlights how reducing the hurdle rate from 25% affects the disposable income of the representative household. Reducing the hurdle rate from 25% to 15%, we observe an improvement in household disposable income across all periods as the effect of the reduces heating cost dominates the increase in retrofit investment. In 2030 the representative households disposable income increase by 58 million euro (or 60 euro per for each Dane).

A hurdle rate reduction from 25% to 10%, we see a minor trade-off in terms of higher upfront costs in 2020 versus significant future benefits. However, over the period, the representative household experiences a net increase in disposable income; suggesting that the level of energy efficiency policy represented by the hurdle rate 10% scenario offers an improving.

Reducing the hurdle rate from 25% to 4% is associated with a substantial increase in investment, driven by the reliance on full cost measures. As a consequence, disposable income is reduced in both 2020 as well as 2025; suggesting, that the highly effective policy scenario would not improve welfare in the short-run. Whereas, the increase in disposable income in 2030 is not enough to compensate for the reduction in disposable income in 2020 and 2025.

5.5. Level of subsidy to overcome the hurdle rate

Until this point, the paper has not identified or assessed specific energy efficiency policies. Instead, we have purely used the hurdle rates as a proxy for the effectiveness of energy efficiency policies within the existing residential building stock. However, an essential focus of contemporary research is on understanding the 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). Within this section, we approach this discussion by considering the level of investment subsidy required to realise the level savings associated with the 10% hurdle rate scenario (i.e., 12.2 PJ cf. Fig. 5). We focus on the 10% rather than the 4% hurdle rate scenario since the previous section has demonstrated that the 4% scenario would not improve households' welfare in the short run.

Table 7 reports the marginal investment subsidy (i.e., formally the shadow price of the constraints) needed in a future year to ensure investment in building retrofit (corresponding to 12.2 PJ) for the hurdle rate 15%, 20% and 25% scenarios. Within the 25% hurdle rate scenario realising 12.2 PJ of savings in 2030 requires a marginal investment subsidy around 201 Euro per GJ, whereas the 15% hurdle rate scenario requires a subsidy of 69 Euro per GJ. Government outlays to such levels of subsidies would be substantial. Simply multiplying the 12.2 PJ with the level of marginal subsidies suggest annual government outlays ranging from 85–245 billion Euro, cf. Table 7.

We note that the size of the subsidy outlays depend critically on whether the subsidy scheme can discriminate across individual energy retrofit measures. Partly, since it is only the marginal retrofit measure which requires the marginal investment subsidy, and partly since households already investing in retrofit measures should ideally not get the subsidy (free rider problem). Because of this, subsidy outlays may be substantially (perhaps 25%–75%) smaller depending on the specific policy design. Nevertheless, to put these numbers into context, the budget for the current Danish subsidy scheme for residential building retrofit investments is much lower, at around 26 million Euro for the whole period 2021–2024.[9]

Given the prohibitive size of the required subsidy to incentive investment in energy retrofit – prohibitive from a policy perspective – it should come as no surprise that much energy efficiency policy

[9] Danish Energy Agreement 2018

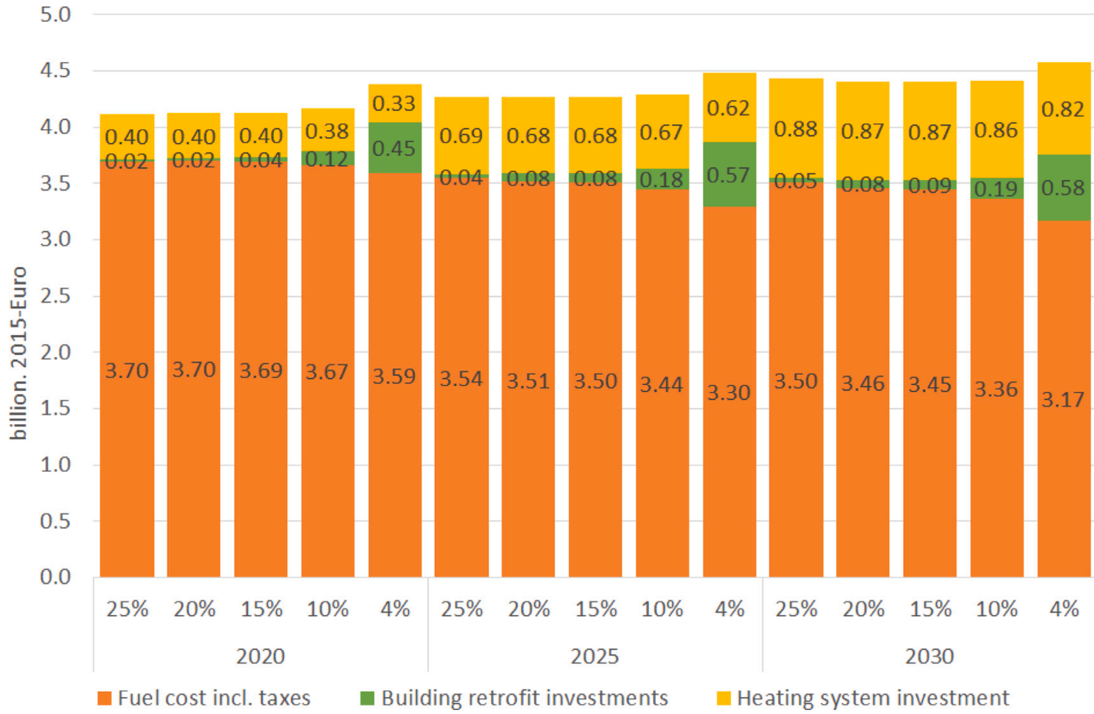

Fig. 6. Composition of residential heating costs for the baseline and hurdle rate scenarios on an annual basis.

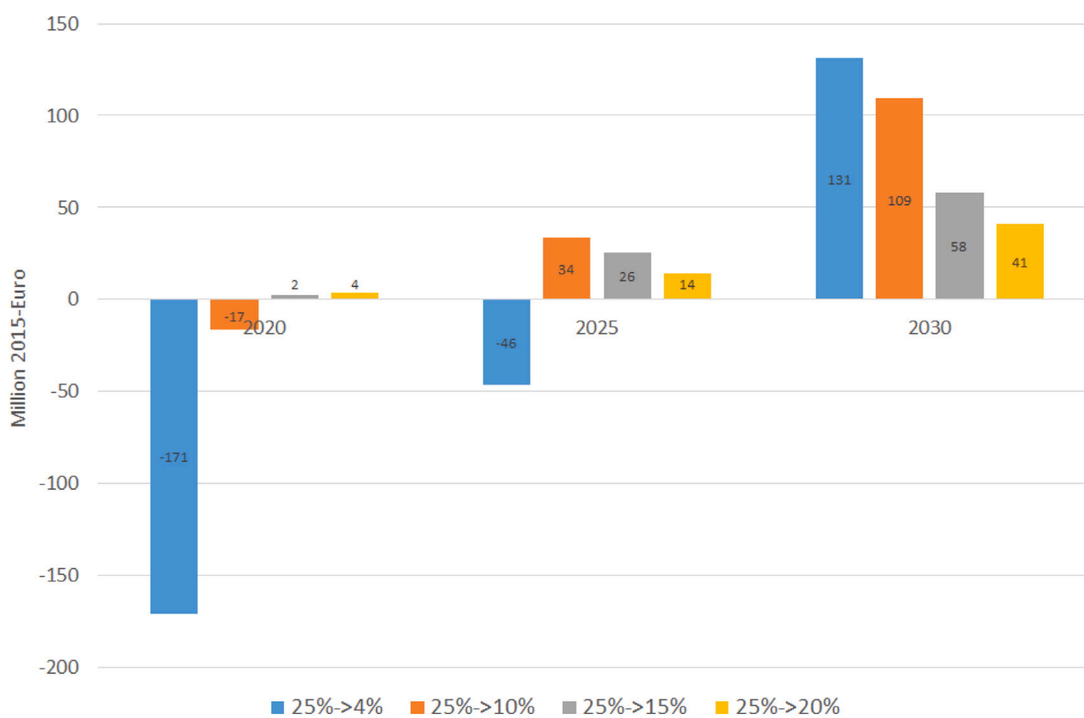

Fig. 7. Effect on disposable income relative to the baseline scenario.

focuses on regulation rather than using financial instruments such as subsidies or taxes. However, returning to the theme of the interactions across different energy efficiency policies, the critical consideration becomes how a policy (e.g. a subsidy) should impact the choice of hurdle rate within a model like IntERACT. A subsidy may, for example, reduce the information barrier, as the government would typically spend resources informing the households about the subsidy and the potential for energy-savings. One may further speculate that the subsidy by increasing the cost of staying uninformed, can address issues related to bounded rationality. Whereas, a subsidy may further provide funds to liquidity-constrained households.

However, the question for future research remains, namely, how should different policy instruments affect the choice of hurdle rate in a model like IntERACT. In a study focusing on the industrial sector in the USA, Qiu et al. (2015) find that increasing energy efficiency policy pressure in the form of recommended energy-saving measures lowers the implied discount rate (or hurdle rate) by around nine percentage points. Whereas the European Commission, as discussed in Section 2.5,

Table 7
Marginal subsidy needed to realise energy-savings associated with 10% hurdle rate scenario.

Hurdle rate scenario	Marginal investment subsidy (Euro/GJ)	Average annual subsidy outlay (Million Euro)
Hurdle rate 25%	201	245
Hurdle rate 20%	135	165
Hurdle rate 15%	69	85

assumes that energy efficiency policy pressure reduces the residential hurdle rate by close to three percentage points. Future research therefore needs to validate the choice of hurdle rates in a Danish context, for example, by conducting surveys to elicit preferences and investment behaviour for Danish households.

5.6. Critical discussion

The effect on households' disposable income from a policy-induced hurdle rate reduction within this paper points to societal benefits of a moderate level of energy efficiency policy (i.e. the 10% hurdle rate scenario). However, several limitations apply to the modelling results. We first draw attention 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 realising 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 realised 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 realised marginal cost savings in households (see Fig. 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.

A fourth limitation of this approach relates to the ability of the hurdle rate to account for all factors relating to energy efficiency investments. Some factors reflects a shorter time preference (high discount rates), such as a belief that long-payback investments are likely to be riskier and thus costlier. In contrast, others may relate to qualitative concerns about energy services provided by more efficient technologies (Gillingham and Palmer, 2014; Wada et al., 2012). The latter is almost certainly not well captured by one assumed value for a hurdle rate. However, this limitation further underscores the need to explore the role of the hurdle rate within a modelling context.

All of these previous points lie at the root of the one further limitation the identification and assessment of specific energy efficiency policies; which the paper has only hinted at in Section 5.5. 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 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 welfare impact on households (cf. discussion in Section 3.2). 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 further important focus of this research should be on assessing the interactions between different energy efficiency policies. In particular, this would enable insights relating to the quantitative effects, in terms of additional energy efficiency investments, of specific policy measures. Future work should also attempt to extend this methodological framework to the whole energy system and explore interactions between sectors in the context of decarbonisation scenarios.

6. Conclusion and policy implications

This paper has explored 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 estimate of a low-effectiveness energy efficiency policy scenario. In contrast, we consider the Danish social discount rate of 4% as the lower bound on the hurdle rate or as a proxy for a highly effective energy efficiency policy scenario. The paper concludes, based on the IntERACT model, that a policy-induced hurdle rate reduction from 25% to 4% could deliver more than a third of Denmark's cumulative energy-saving requirement under the EED for the period 2021–2030. From a policy perspective, it is worth noting that a substantial increase in energy-saving requires a reduction in the hurdle rate to well below 15%. Such a substantial hurdle rate reduction requires policies that address multiple of the factors behind households' high implicit discount rates, which implies the need for a 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 maybe even smaller due to the difficulty of getting the information to the target group (e.g. a particular type of homeowners). We further underscore the need for a mix of policies by highlighting the size of the retrofit investment subsidy needed to realise savings associated with the 10% hurdle rate scenario. The size of such a subsidy makes it prohibitive from a policy perspective. Regulatory measures will hence likely need to play a central role in achieving ambitious energy-saving targets. Policy measures will likely also have to differ by types of dwellings and households to reflect the underlining heterogeneity. So, for example, the relatively high proportion of multi-family, social (21%) and community (7%) housing, in Denmark (Kristensen, 2007) with easy access to capital and ease of implementation of measures should perhaps be incentivised to implement more marginal measures. Addressing regulatory constraints for social housing could also increase the scope for energy efficiency improvements. Owner-occupied detached housing may require a different approach: in the case that these buildings have a lower renovation rate, they might be encouraged to implement savings measures by appropriate regulation, tax or subsidy. However, more research is needed, particular, on how the choices of different policy instruments should affect the choice of hurdle rate in a model like IntERACT.

Finally, the paper has shown the importance of modelling the general equilibrium feedback associated with energy efficiency policy. The paper has detailed how to incorporate a rich representation of income and substitution elasticities within a hybrid modelling framework — thereby capturing a rebound effect around 31% associated with a hurdle rate reduction from 25% to 4%. The application of a general equilibrium framework further allows us to conclude that reducing the hurdle rate to 4% leads to a reduction in the disposable income in 2020 and 2025. This reduction in disposable income is due to the substantial investment in full cost retrofit measures within the 4% hurdle rate scenario. A more moderate energy efficiency policy, like the 10% hurdle rate, which relies less on full cost measures, would be preferably seen from the perspective of policymakers. Notably, as the 10% hurdle rates scenario involves a more advantageous trade-off in terms of a minor reduction in disposable income in 2020 versus a significant increase in disposable income in 2025 and 2030.

CRediT authorship contribution statement

Kristoffer Steen Andersen: Conceptualization, Methodology, Software, Validation, Visualization, Investigation, Writing - review & editing. **Catharina Wiese:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Stefan Petrovic:** Data curation, Writing, Reviewing. **Russell McKenna:** Writing, Reviewing, Supervision and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. The residential building stock in TIMES-DK

See Table A.1.

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 technology's 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).

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

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. Eq. (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 for a specific technology before annualising the investment using the general discount rate.

Appendix C. Sensitivity analysis: significance of annual availability of marginal cost savings and heterogeneity assumptions

This appendix explores how the level of realised full and marginal cost savings depends on the two energy-saving constraints discussed in Section 5.2, i.e., the annual availability of marginal cost savings and the representation of heterogeneity of the energy-saving potential.

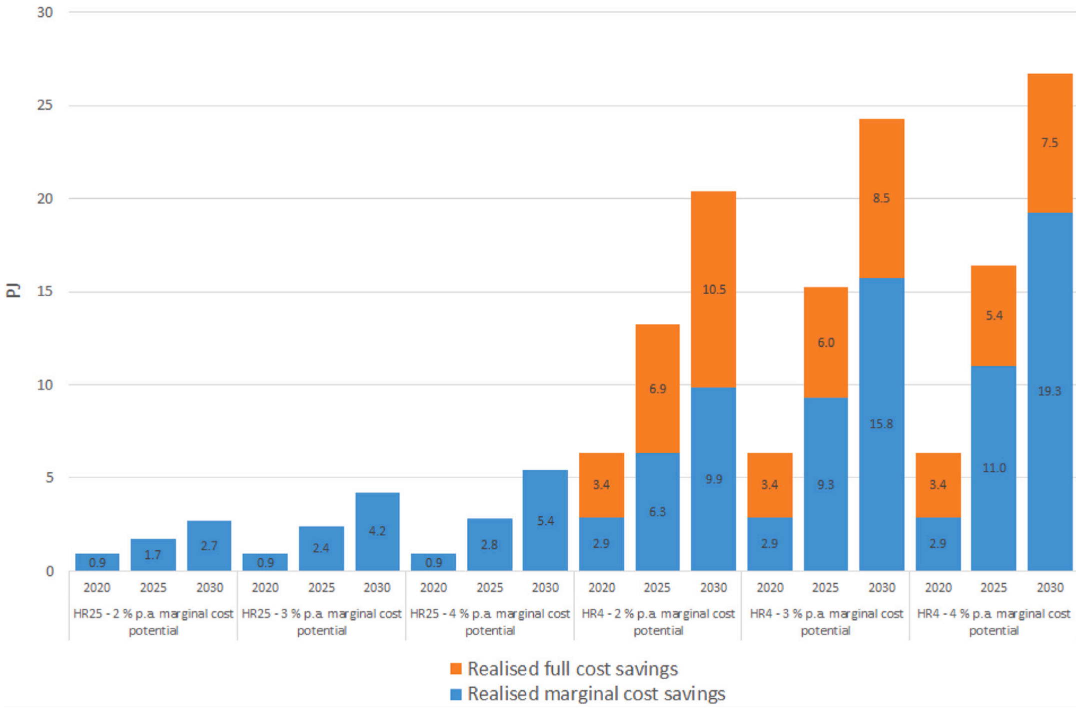

Fig. C.1. Sensitivity of realised residential savings to the annual increase in marginal cost potential for hurdle rate 4% and hurdle rate 25% scenarios respectively.

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

C.1. Annual availability of marginal cost savings

Within this paper, we have assumed that on average, 3% of total savings potential for each of the 2400 steps becomes available at marginal cost. Fig. C.1 highlights the impact on realised savings from alternative growth rate assumptions (2% and 4% respectively) within the 4% and 25% hurdle rate scenarios. Within the 25% hurdle rate scenario, changing the growth rate by one percentage point changes the level of realised savings 2030 by one third; reducing the growth rate from 3% to 2% decreases the level of realised savings from 4.2 PJ to 2.7 PJ in 2030. While increasing the growth rate to 4% leads to an increase in realised savings from 4.2 to 5.4 PJ in 2030. Within the 4% hurdle rate scenario, changing the availability of the marginal savings potential affects not only the total level of realised savings but also the composition of realised marginal and full cost potential. When the growth rate of marginal potential is reduced by one percent, the total realised saving in 2030 is reduced by 3.9 PJ. However, we also observe a shift towards full cost savings. So that the share of full cost savings in 2030 increases from 35% to 52%. When the growth rate applied to the marginal cost potential increases form 3% to 4% we see an increase in total realised savings by 2.4 PJ in 2030; simultaneously the share of full cost savings is reduced from 35% to 28%.

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This sensitivity analysis has underscored the importance of the assumptions related to the marginal cost potential for the level of realised savings in 2030 within the IntERACT model; underlining the need for future research to improve the representation of marginal cost potentials within the model.

C.2. Heterogeneity of the energy-saving potential

Within the paper, we argue that due to household heterogeneity, only a limited share of each savings step will be available in the period 2020 and 2025. We assume that the sum of realised marginal and full cost potential cannot exceed 30% of the total technical potential for each of the 2400 savings steps in 2020; increasing to 100% of the total potential for each step in 2030. Fig. C.2 highlights how these heterogeneity constraints shape the level of realised savings by considering two alternative scenarios: (i) a scenario in which only 15% of the total potential for each step is available in 2020, increasing to

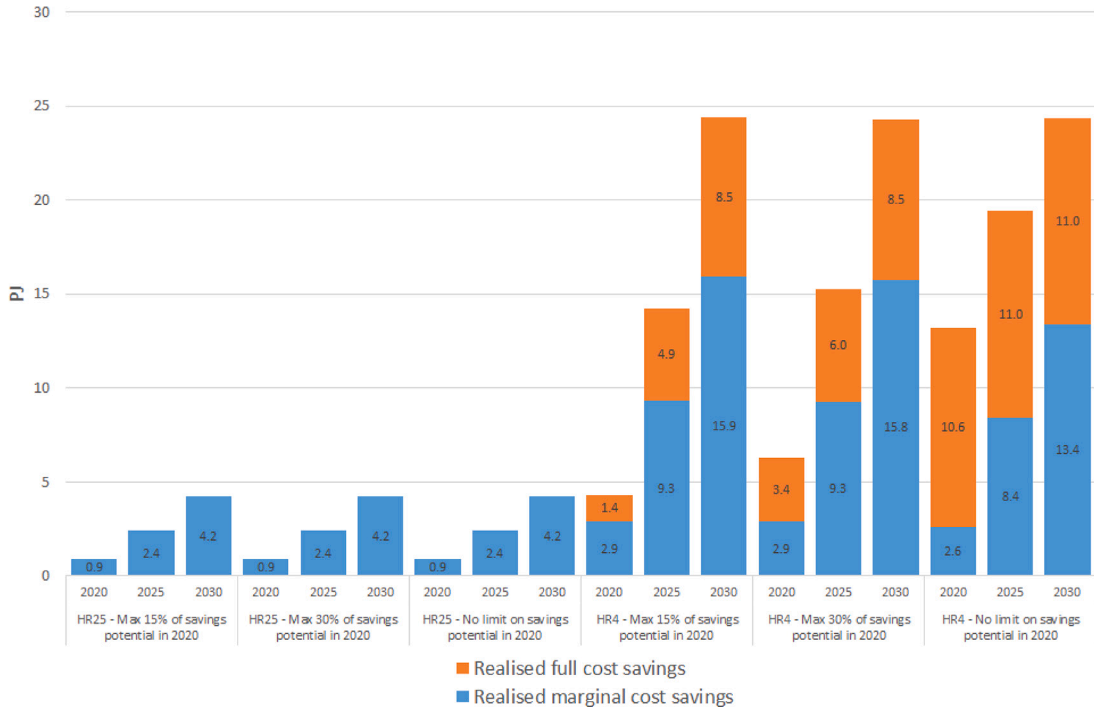

Fig. C.2. Sensitivity of realised savings to short term availability of savings potential for each step for the hurdle rate 4% and hurdle rate 25% scenarios respectively.

100% in 2030 and (ii) a scenario that allows 100% of each savings step to be available in already 2020.

First of all, we note that the heterogeneity constraints do not affect scenarios with only marginal savings; since, without full cost savings, it is the limited availability of marginal cost savings which imposes the binding constraints on the level of realised savings. Fig. C.2 illustrates this result for the 25% hurdle rate scenario. Tightening the heterogeneity constraint within the 4% hurdle rate scenario reduces the realised full cost savings by 2 PJ in 2020 and 2025. The level of realised savings in 2030 is unaffected due to the assumption that 100% of the total savings potential for each saving step will be available in 2030. If we remove the heterogeneity constraints within the 4% hurdle rate scenario – assuming that it is possible to realise 100% of the total savings potential in 2020 – we see a three-fold increase in the level of realised full cost savings and a small reduction in marginal cost savings. The reason is that it is cheaper for the model to realise all of the cheapest full cost savings steps. Simultaneously the model no longer needs the most expensive marginal cost savings steps; hence the reduction in realised marginal cost savings by 0.3 PJ in 2020.

This sensitivity analysis has underlined that removing the heterogeneity constraint within the 4% hurdle rate scenario does not change the level realised saving in 2030. Instead, we see an unrealistic level of front-loading in investments in full cost savings; underscoring the need to include the heterogeneity constraint to moderate investment behaviour within low hurdle rate scenarios.

Appendix D. Supplementary data: technical savings potential and realised savings by region, building type, building area and building age

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.enpol.2020.111785.

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