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Adoption of energy efficient technologies by households – Barriers, policies and agent-based modelling studies

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ABSTRACT

Increasing the adoption of energy efficient technologies by households is one of the formulated strategies to reduce greenhouse gas emissions. This paper presents a systematic review of agent-based modelling studies on the adoption of energy efficiency by households. It starts with an overview of barriers for adoption, of energy efficiency policies, energy efficiency model types. Afterwards, an analysis is given of technologies modelled, policies simulated, decision-making theories included, and the use of empirical data. An overview is presented of how technologies, barriers and policies relate in the models. Furthermore, the core policy recommendations from existing models are presented. The analysis shows that the reviewed studies predominantly focus on a subset of barriers – a lack of capital, a lack of information, high upfront cost, ignorance, inertia and other priorities. So far, agent-based models have focused on how subsidies, technology bans and information campaigns influence energy efficiency adoption. There is ample opportunity for future agent-based modelling research on energy efficiency adoption policy by studying other residential technologies, other barriers, and other policies that fit the agent-based modelling paradigm well.

1. Introduction

Stimulating energy efficiency adoption is one of the strategies formulated by the international community to reduce greenhouse gas emissions and our contribution to climate change [1]. The European Union and national governments therefore seek to increase the adoption of energy efficiency in society [2]. The residential sector is marked as an important sector to contribute to the internationally set climate targets and the increased adoption of energy efficiency by households is needed to mitigate the effects of a globally growing population and increasing energy demand [1]. The desired level of energy efficiency in households has not been achieved yet and has been named the 'efficiency gap' [3].

Energy efficiency can be specified as: 'achieving the same services and performance while using a technology with less energy use'[2]. The increased adoption of energy efficient technologies should thus contribute to achieving the targets set. However, a still open question is: what are effective ways in which this adoption may be achieved in different EU member states? This paper focuses on energy efficiency in households. For the residential sector it is not clear which technologies should be adopted by households, why many people are not adopting the most efficient technologies and how policy makers should stimulate adoption? There are many types of barriers, i.e. structural, economic, social or behavioural barriers that stop households from adopting a new technology.

Policy makers need to design and implement policy that moves the residential sector to become more energy efficient by taking away these barriers. Modelling and simulation is done in order to gain an understanding of what policies can be expected to positively impact the energy efficiency of which households under what conditions. This understanding supports policy makers in their evaluation of policies and helps them to decide on possible interventions.

Mundaca et al. [4] identifies four main methodological categories to create bottom-up energy economy models: *simulation models*, *optimization models*, *accounting models* and *hybrid models*. Of these four there are two popular classes of modelling studies that provide a descriptive representation of household energy use and technology adoption: the ones using *simulation models* and those using *accounting models* [4]. Simulation models, in particular our focus on agent-based models (ABMs), give a quantitative depiction of technology adoption in the context of exogenous scenarios. Accounting models are equation-based and focus mainly on grasping empirical technology adoption data and composing an as accurate representation as possible of the inventory of technologies adopted under the influence of various policy interventions [4]. These accounting models are useful to explain the effects of policies on the adoption of energy efficient technologies, but are limited

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in how they take heterogeneity of households, household choices and communications into account. Accounting models can describe these aspects on an aggregated level for different types of households. It would dramatically increase the data requirements and computational complexity to explicitly capture interactions on an individual level [5].

Agent-based modelling (ABM) is a method that explicitly addresses the heterogeneous nature of households, diverse preferences and choices that households make, and communication between households [4–6]. It can provide insights regarding the effects energy efficiency policy may have on a heterogeneous set of households: by exploring the adoption of energy efficient technologies by households modelled with adoption decision-making on an individual level. ABM can, therefore, generate insights that complement the knowledge acquired from accounting models for the purpose of energy efficiency policy evaluation.

This paper presents a systematic literature review of ABM studies on the adoption of energy efficiency by households. The purpose of this review is to identify the policy recommendations that are produced by ABMs and learn what properties of ABMs contribute to formulation of concrete policy recommendations, in particular with respect to the adoption barriers known in the literature. Additionally this review identifies opportunities for future ABM research that can provide novel knowledge on energy efficiency adoption policies.

This paper is structured as follows: Section 2 explains the literature review methodology that has been applied. Section 3 discusses the energy efficiency adoption barriers, policies and modelling methods. Section 4 then reviews ABMs on the technologies, policies, theories and data they included. The paper ends in Section 5 with conclusions about the insights and opportunities ABM has for energy efficiency policy.

2. Methodology

In order to review the use of ABMs for energy efficiency policy evaluation, a systematic analysis of existing ABMs on the topic is presented. The review focuses on ABM studies that model energy efficient technology adoption. In order to make the review systematic and do an assessment of usefulness, an overview of the barriers to adoption and energy efficiency policies is presented first. Second, popular modelling methods for studying the adoption of energy efficiency are compared. This provides us with a perspective for the review of the ABMs which enables us to identify the insights that ABM studies provide and find opportunities for future research.

An important input is a previously conducted literature review on ABM studies that describe energy efficient technology diffusion, which concludes that ABMs are technology specific, suitable for representing heterogeneous households, supported by empirical data and decision making theories [5]. Our review is structured according to the study by Moglia et al.. However, our review focuses on the conclusions that can be drawn about policy interventions rather than on the elements of technology diffusion ABMs. Therefore, the content of the ABM studies is analysed to identify lessons learned about policy interventions for specific energy technologies.

The literature review consists of three steps, which are now described.

2.1. Step 1: overview of barriers, policies and modelling methods

Before conducting the literature review on ABM studies the problem space concerning the adoption of energy efficiency is explored and discussed. This is done by identifying the barriers that obstruct households from adopting a more energy efficient technology and by outlining the range of policy interventions that are available to policymakers. The barriers have been identified be studying literature that lists different types of barriers. The barriers literature has been searched in Scopus using search terms, amongst others *energy efficient technology, barrier, energy behaviour* and *energy efficiency gap*. To select the papers that were most relevant and listed barriers only a number of papers were handpicked that explicitly mentioned energy efficiency barriers and had numerous citations. For literature on energy efficiency policies, a similar procedure was followed. The main search terms user were *energy efficiency policy* or *policy instruments*, *households* or *residential*, *energy efficiency*, *energy behaviour* or *energy conservation*.

Creating this overview of barriers and policies provides us with the necessary context to judge and review the ABM studies on usefulness for policymakers. Also the use of accounting models and ABMs is discussed before conducting the review of ABM papers. This discussion highlights the aspects and insights that ABMs add to knowledge derived from energy efficiency adoption accounting models.

2.2. Step 2: definition of search terms and filters for collecting articles

The keywords that have been defined for this literature search have been selected to capture articles that describe ABM studies on the adoption of energy efficiency by households. The search has been conducted on the 17th of March 2017 using the advanced search option of the Scopus scientific library. The following search queries were used:

- (ABM OR “agent-based modeling” OR “agent-based modelling”) AND (“energy efficiency”) AND ((“household”) OR (“consumer”))
- (ABM OR “agent-based modeling” OR “agent-based modelling”) AND (“energy technology”) AND ((“household”) OR (“consumer”) OR (“residential”))
- (ABM OR “agent-based modeling” OR “agent-based modelling”) AND “energy efficiency” AND “barriers” AND (“household” OR “residential” OR “consumer”)

The literature review has only considered scientific research papers from peer-reviewed journals and conference papers published in English. The queries that were used for the literature search provided 83 results. With the later queries, the search term ‘residential’ was added as an alternative term for households. A check was made that no relevant papers were missing in the result set from the first query. From the list a final selection was handpicked by scanning the titles and abstracts of these papers to only include papers that described studies with results from an ABM (so conceptual articles and articles not discussing ABMs are excluded). A thorough scan of all the papers after this step was needed to sort out papers that referred to ABMs but did not present any model conceptualization or results in the paper. This produced a list of 23 papers that have been reviewed. All of these ABM studies have been published in established energy and/or sustainability related journals. One of the papers was part of a conference proceedings.

2.3. Step 3: evaluation of the papers

The 23 papers have been evaluated and analysed by making an overview using a framework of analysis that is similar to the review by [5] that includes modelled technologies, theories used to structure the model and the use of empirical data. The analysis framework therefore starts by discussing the technologies that have been modelled in each study and answering whether the study considers 1) the adoption of efficient energy technologies and/or 2) the more efficient use of technologies by households. The existing review framework is augmented with the policy interventions considered and the outcomes related to those policies in order to highlight the relevance of these ABM studies for the purpose of policy evaluation. The type of policies modelled are discussed together with the degree to which the ABMs are used to test and design policy alternatives and the effects they have on adoption barriers. Next, the theories used to describe the decision making logic of agents in the models are discussed and last the use of empirical data is considered.

3. Energy efficiency adoption barriers, policies and modelling methods

3.1. Energy efficiency adoption barriers

The 'efficiency gap' is a phenomenon that has been discussed by academia for decades. It can be defined as the slower than optimal adoption of energy efficient technologies [7]. Jaffe and Stavins [7] define optimal adoption in a number of different ways. This paper define the efficiency gap as the hypothetical energy efficiency level that can be achieved by overcoming all barriers that obstruct energy efficiency adoption. In scientific literature a diverse set of barriers have been identified, which all can manifest as cause of obstruction to the adoption of energy efficient technologies by households.

The energy efficiency adoption barriers differ in type and occur to households in varying degrees. Barriers such as split incentives, supply infrastructure limitations and codes and standards are *structural* in nature and largely outside the sphere of influence of households [9]. Other barriers are *economic* in nature: Households may lack the capital to invest in a new energy technology or find the upfront cost too high [3,8,9,12]. There are many *behavioural* barriers that have been identified in literature. House owners can have other priorities than energy efficiency when making a choice, be ignorant about energy efficiency or simply unwilling to change [5,8]. Last, there are barriers that occur due to *social behaviour*. People may weigh the actions by their social peers when making a decision about adopting a new energy technology or have trust issues with the novel technology [5].

This diversity in adoption barriers and household situations makes the adoption of energy efficient technologies a hard to capture process. Extensive empirical data and modelling is needed to describe all the barriers and complex interactions between households.

3.2. Energy efficiency policies

To address the 'efficiency gap' and overcome the barriers to energy efficiency adoption, policies are implemented. Table 2 presents a list of energy efficiency policies that have been discussed in literature. Most of these policies are directed at the adoption decision of individual households. Tax reductions, subsidies, discounts, prohibitions, promotions and awareness raising campaigns are all examples of policies that influence the adoption decision of the household directly. Some regulatory approaches like performance standards, building codes and trade restrictions narrow the available choices of households to more efficient technologies. There are also relatively novel policies, like the energy efficiency tender, tradable white certificates and energy efficiency obligations which are not directed at households but at intermediary parties. Intermediary parties play a significant role in the adoption decision process of households and can be specified as: a party that enables others to adopt energy efficient technologies. Examples of intermediaries are utility companies, electronics stores, web shops or energy service companies. Through policy these intermediary parties can be stimulated to push energy efficient technologies to households.

3.3. Descriptive modelling methods

The 'efficiency gap' from the perspective of the policy maker is a particularly interesting avenue for modelling research: the fit of policy alternatives to different adoption barriers may be specific to particular conditions, such as technologies/societal functions, countries, consumer groups, etc. Modelling and simulation can be used to describe and explain the effects of policy alternatives and design promising energy efficiency policies.

An established way of modelling energy demand and the adoption of energy efficient technologies by households is the use of accounting models [4,26,27]. Accounting based models usually focus on the management and use of large amounts of data and have a number of general characteristics: 1) Accounting models provide a detailed representation of energy end-uses, 2) Calculation of energy demand is done on basis of economic, social and technical factors, 3) A scenario approach is used to account the development of adoption under the influence of policy [26]. Taking many factors into account the energy demand is then determined by means of aggregation. The decision frameworks in accounting models are relatively elegant compared to other model types such as optimization and simulation models. The decision framework in accounting models commonly follow the following steps: 1) selection of policy measure, 2) selection of efficient technology, 3) definition of technical performance of the technology and 4) definition of the particular market penetration rate [4]. An example of a decision making framework used in accounting models is the use of net present value calculations. In models using net present value, like some models discussed in [28], the adoption decision of a household is reduced to an investment decision, based on a net present value calculation. At the core of modelling these investment decisions are discount rates. The discount rate helps to represent the perceived value of an investment and expresses this value in monetary form. To capture the influence of other, non-financial, factors and barriers on the investment decision, the implicit discount rate is added to the calculation. The implicit discount rate covers aspects such as preferences in risk and time, personality, habits and biases on top of the regular discount rate [8]. When based on profound empirical data this method is very powerful in explaining the investment decisions households take.

The predictive strength of accounting models also has limitations. Due to the need to aggregate data a substantial amount of data is lost in accounting models and the decision making frameworks are usually more simplified than in other model types. In the case of a model based on net present value calculations the barriers and factors are all reduced to a unidimensional unit: money and captured in an implicit discount rate [8]. In the process of this reduction to unidimensional unit some fundamental aspects of the barriers discussed are neglected. Accounting models can describe barriers on an aggregated level for different types of households, but describing barriers on an individual level would dramatically increase the data requirements and computational complexity [5].

ABM can complement these limitations of accounting models by offering flexibility and the possibility to use a more elaborate decision making framework. Households can be modelled as heterogeneous agents in ABMs and therefore can take into account the large variability in preference of households and also the diverse set of adoption barriers. In ABM the complex relations and interactions between households and household behaviour can also be explicitly addressed and the decision nature of technology choice modelled more specifically and elaborately. This can provide policy makers with knowledge about policy design and analysis that is complementary to the use of accounting models. To learn about what insights ABMs produce about energy efficiency policies the reviewed papers are discussed.

Fig. 1 shows that the ABM efforts on energy efficiency studies are

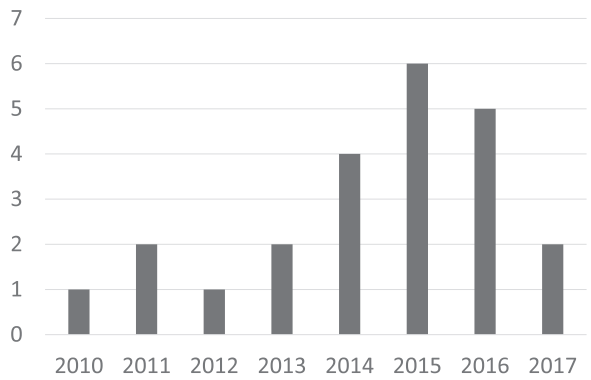

Fig. 1. Year of publication of the ABMs reviewed.

relatively young. The earliest published ABM study on the adoption of energy efficient technologies was published in 2010. As can be seen in the figure ABM has gained popularity over the years, with more ABM studies being published in recent years. This fits in the popularity of ABM for studying diffusing in general.

This also suggests that energy efficiency adoption by households has mostly been addressed using other modelling methods (i.e. the accounting models discussed before). The review is used to explore where added value of ABM may lie.

4. Energy efficient technology adoption agent based models

In this section the reviewed ABM studies will be discussed on the technologies that are studied in the paper, policy measures that are explored using the ABMs, theories used to describe decision making of households and the use of empirical data. These angles are used to find what the literature has focused on so far and where opportunities lie for further research. An complete overview of the results is found in Table 5 in the appendix.

4.1. Technologies

From the 23 reviewed studies, 16 study specific adoption of energy technologies, the remaining seven studies focus on the efficient use of energy. 20 papers fixate their ABM around a specific energy technology and this technology specificity seems to pertain to energy efficiency adoption ABMs. Therefore the analysis discusses the technologies that are typically modelled using ABMs and their relation to energy efficiency adoption.

ABMs are suitable for describing and simulating the adoption or diffusion of a technology by a population of household agents over time. A first remark to be made about the modelled technologies is that there are 11 different technologies and/or behaviours modelled (Table 3), despite the small number of papers that have been reviewed. ABMs are thus created to model a comparatively broad set of technologies. Most of the reviewed paper have as primary purpose to gain diffusion or policy insights pertaining a particular technology.

Another general observation is that these models are forward looking and exploring the increase in energy efficiency in the future. A large portion of the ABMs describe technologies that are relatively novel and which have not established themselves as dominant technologies yet. This suggests that these studies focus on the efficiency gains of new technologies. Examples of these are the modelling studies on electric vehicles, solar PV and battery systems and micro CHP units.

In [43–46] the diffusion of electric or plug-in electric vehicles is explored. Electric vehicles are as a technology not directly linked to the subject of energy efficiency, only for households that produce their own electricity it can be said to be explicitly the case. However, the increase of the electric vehicle fleet can in any case be regarded as a move towards a more sustainable society. By substituting gasoline fuel cars by electric vehicles the possibility of having a fleet run on renewable energy increases. Energy efficiency is thus just regarded as a motive or reason, together with sustainability, to push the diffusion of this technology. This push for electric vehicle diffusion is based on the hypothesis that electric vehicles are a more sustainable technology than gasoline powered vehicles.

Another technology diffusion that is being explored using ABM is the adoption of residential solar PV systems and solar PV with battery systems. In [39,40,42,52] the adoption of these solar PV systems is researched. Solar PV systems are likely to play an increasingly significant role in the energy system as it allows households to produce their own electricity. Solar PV fits in the electrification process and can be seen as an important condition for households to adopt technologies (for instance electrical heating technologies) that use electricity and contribute to a better and more efficient use of energy.

The adoption of different lighting technologies are also explored by multiple ABM studies [29,30]. These ABM studies differentiate themselves from other studies because a variety of lighting technologies are being modelled within the same study. So rather than having a dichotomous model where it is either: adopt or not adopt the technology, multiple technologies that fulfil the same function are compared and judged on their energy efficiency performance. The lighting technologies that are modelled in these studies are: incandescent lighting, light emitting diodes (LED), compact fluorescent lighting (CFL) and halogen lighting. In [31,32] these lighting technologies are modelled as well. However the focus of these studies is on the use of these lighting technologies rather than on the adoption. Hicks and Theis [32] and Hicks, Theis and Zellner [31] conclude that the energy savings accomplished by efficient lighting technology adoption can be diminished and eroded by a rebound effect.

Other residential technologies that have been modelled are: Micro-CHP units [37], wall insulation [38], residential heating technologies like direct electric heating, wood pellet heating stoves and heat pumps [33–35]. These papers are exemplar of studies that describe the diffusion of a technology that improves the energy efficiency of a household compared to the current installed technology.

Lastly, in [47,48] the effect of a CO_2 meter and a behaviour-changing feedback device on the energy consumption behaviour of households is explored. These studies differ from the studies that model technology diffusion because the focus is put on the adoption of energy efficient behaviour through these technologies. In [49–51] the focus is also not on energy efficiency improvement through technology adoption but rather on more energy efficient behaviour of households and adoption of green eco-innovations.

The reviewed papers study a broad set of energy efficient technologies and behaviours. The majority of studies focus on improvement of energy efficiency and sustainability through technology adoption and therefore use energy efficiency as a reason or motive to push these more efficient technologies. Most of the studies are dichotomous, they compare households that do or do not adopt a new technology. There are some cases where different technologies that fulfil the same function are compared, this is the case for the papers that study lighting technologies. These studies show that ABMs can both explore dichotomous adoption decisions and adoption of multiple competing technologies. The latter option can be identified as an opportunity provided by the ABM method that needs further exploration, since there are other household technologies besides lighting technologies that fulfil a specific function for households. Some examples of household functions that have not been explored are refrigeration, cooking or washing. The adoption of different appliances that fulfil household functions can be compared and studied using ABM.

4.2. Energy efficiency barriers and policies

The main interest in ABM for policy makers lies in ABM's capability to assist the design and evaluation of energy efficiency policies. This section shows the policies that are included in the studies, the degree to which the studies contribute to policy design and evaluation and the barriers they tackle. This will provide us with insights on the usefulness of ABM for policymakers, the current knowledge derived from ABMs and possible opportunities for further policy exploration and evaluation.

The range of barriers and policies included in the reviewed studies is narrow, compared to the list of identified barriers in Table 1 and policies in Table 2. An overview of the policies that are included, the barriers that are targeted and the policy conclusions is shown in

Table 1
Barriers to energy efficient technology adoption by households.

Barriers	Definition	References
Structural barriers		
Split incentives	A circumstance in which the flow of investments and benefits are not properly rationed among the parties to a transaction, impairing investment decisions	[3,8–11]
Uncertainty of prices of energy carriers and other resources	Uncertainty about the price of fuels, electricity or other resources defining the production cost of technologies in the future	[9,12,13]
Supply infrastructure limitations	Limitations of the supply infrastructure of energy efficient technologies	[3,9]
Lack of codes and standards	Codes and standards for existing energy efficient technologies, in the field of EE but also other kinds of codes and standards (safety).	[9,13]
Economic barriers		
Lack of capital	Insufficient capital available to do an investment	[8,9,12]
High upfront costs	High upfront investment cost of energy efficient technologies	[3,12]
Lack of information	Insufficient information available to make an investment decision	[8–14]
Transaction costs	Cost incurred in making an economic exchange of some sort/the cost of participating in a market (search and information costs, bargaining costs, policing and enforcement costs)	[8,11]
Behavioural barriers		
Bounded rationality	Decision maker's rationality is limited by the tractability of the decision problem, the cognitive limitations of their mind and the time available to make the decision	[8]
Satisficing	People do not tend to optimize their decision but rather aim to satisfy a small set of criteria, i.e. the minimum requirements	[5]
Availability bias	People primarily draw on knowledge and information that is easily accessible. Lack of information may mean that some opportunities are missed	[5]
Other priorities	Other priorities than energy efficiency when purchasing an energy technology	[5,12,13]
Ignorance	Lack of knowledge, understanding or education about energy efficiency	[5,12]
Inertia	People have a tendency to want to stick with the status quo rather than having to change for practical reasons and for convenience; as they like to avoid hidden costs associated with a switch	[5,12,13]
Persisting with sunk costs	Once people have invested in something, in terms of time and/or money, they tend to become fixated on 'recovering losses'	[5]
Being loss and risk averse	People weight losses more than gains when making decisions and people tend to avoid the prospect of a loss even with the prospect of certain gains, and tend to accept a gamble in order to avoid a loss	[5,8,9]
Irrational response to monetary incentives	People's response to incentives are often short-lived and unpredictable and may crowd out intrinsic motivations	[5]
Free-riding effect	People tend to look for ways that they can gain benefits without paying for them	[5]
Social behavioural barriers		
Social comparisons	People tend to follow the behaviour of others, i.e. following the norm	[3,5,13]
Trust	People seek information and judgement from those that they trust. People may also trust information from specific people or institutions more than others.	[3,5,13]

Table 4. Fig. 2 shows two graphs of the policies (left) and the barriers (right) that occur together. Fig. 3 shows links between policies and barriers (left) and technologies and barriers (right). The *barriers addressed* primarily deal with economic aspects (high upfront cost, lack of capital, uncertainty in fuel prices) and behavioural aspects (inertia, lack of information, ignorance, other priorities). A clear clustering is also formed that link economic and behavioural aspects, which appears to be at the heart of the ABM approach. The explored *policy options* are limited to a few forms of financial support, regulation and information campaigns. Most of the studies modelled financial support as policy to

Table 2
Energy efficiency policies - policy instrument types taken from [4].

Type of policy instrument	Policy instrument	Policy directed at	References
Economic, financial and market based instruments	Taxes (reductions, credits, exemptions, energy tax)	Households	[4,15]
	Subsidies and grants	Households	[4,15–17]
	Tradable white certificates	Intermediary parties	[4,15,18–21]
	Soft loans	Households	[4]
	Rebates	Households	[4,22]
	Third-party financing	Households and other parties	[4]
	Pricing	Households	[15]
	Discounts	Households	[15]
	Reducing interest rates	Households	[15]
	Energy efficiency tender	Intermediary parties	[23,24]
Regulatory approaches	Performance standards / House energy labels	Households and producers of energy technologies	[4,15,16]
	Building codes	Construction companies and households	[4]
	Trade restrictions	Intermediary parties	[15]
	Permits and warranties	Households and other parties	[15]
	Prohibitions	Households and other parties	[15]
	Energy efficiency obligations	Intermediary parties	[18,20,25]
Informative and voluntary schemes	Awareness-raising campaigns	Households	[4,15]
	Energy (audit) management	Households	[4]
	Voluntary certification and labelling	Households	[4]
	Voluntary agreements	Intermediary parties	[4]
	Environmental awards	Intermediary parties	[15]
	R&D programs	Producers of energy technologies	[16]
	Promotion	Households	[16]

Table 3
Technologies studied in papers.

Technologies studied	Number of studies	Reference
Lighting technologies: Incandescent, light emitting diode (LED), compact fluorescent lamp (CFL), Halogen	4	[29–32]
Residential heating systems: Direct electric heating, Wood pellet heating stoves, Heat pump	2	[33,34]
Heat pump	1	[35]
Heating, Ventilation and Airco (HVAC) heating, HVAC cooling, Area lighting, Task lighting, Equipment (computers), Hot water supply	1	[36]
Micro-CHP	1	[37]
Wall insulation	1	[38]
Solar PV systems	4	[39–42]
Electric Vehicles	4	[43–46]
CO_2 meter	1	[47]
Behaviour changing feedback device	1	[48]
No specific appliances or technologies modelled	2	[49,50]
(Green) eco-innovations	1	[51]

stimulate the adoption of a technology. Twelve studies did this by including a subsidy or tax exemption policy in their models. Five studies modelled a form of regulation such as a technology ban or adoption obligation. Five studies considered informational instruments such as a campaign or promotion in their modelling studies. Last, nine studies did not examine any policies.

The most modelled policies are the *economic, financial and market based instruments* (Table 2), typically in the form of a *subsidy or tax exemption*. They aim to tackle a variety of barriers with a focus on high upfront costs and a lack of capital. The conclusions about the effectiveness of these policies is found to differ across the studies as is shown in Table 4. In the studies about lighting technologies subsidies are found to be less effective at increasing energy efficiency adoption than other policies. Chappin and Afman [30] find this to be the case and Hicks et al. [32] conclude that a subsidy in combination with other policies can be beneficial as long as households do not increase their energy consumption due to lowered electricity cost caused by having more efficient lighting technologies. These results suggest that for lighting technologies the barriers of high upfront cost and lack of capital do not apply. Studies on heating technologies are more optimistic about the benefits of financial incentives in the form of subsidies. Snape et al. [35] finds that the UK Renewable Heat incentive has already been effective in increasing the adoption of heat pumps and that more policy action is needed to keep this adoption rate from falling. Faber et al. [37] researched the adoption of micro-CHP units and found subsidies based on decreasing price differences between technologies to be much more effective than applying a purchase subsidy. Sopha et al. [33] and Sopha et al. [34] conclude that support for technical development in heating technologies such as wood-pellet stoves are, in combination with other policies, necessary to increase the adoption of these technologies. Palmer et al. [39] finds that current solar PV scheme of Italy is already effective and that at the current level of subsidies the adoption rate will probably slow down. Zhang et al. [41] states that incentives have little effect on increased solar PV adoption and instead suggests another policy to increase adoption: seeding, which is providing a number of households with free solar PV systems and then relying on peer effects to increase adoption. Alyousef et al. [42] concludes that support for battery efficiency research is needed together with a higher electricity price to increase adoption, which can be seen as a subsidy to electricity producers and battery owners. For the solar PV technology high upfront cost and a lack of capital are thus considered adoption barriers that can be addressed with different sorts of subsidies. The studies on electric vehicle adoption see subsidies for electric vehicles as a necessity to stimulate adoption. Noori and Tatari [44] and Silvia and Krause [46] suggest a combination with information instruments and Wolf et al. [45] conclude that an exclusive zone for electric vehicles in cities boost adoption more effectively as opposed to financial incentives alone. For the adoption of electric vehicles these studies see as most prevalent barriers high upfront cost, lack of capital and a lack of information about electric vehicles. Subsidies are modelled most often of all policy alternatives. A possible explanation for this popularity is the flexibility of this policy. Governments can incentivize adoption with different types of subsidies, like subsidizing technology use, technology adoption or the fuel of a technology. Moreover, in these studies subsidies are combined with other policy alternatives to address a multitude of adoption barriers, as Fig. 2 and Fig. 3 suggest. Subsidies seem most effective in the studies on technologies where high upfront cost and a lack of capital are the main adoption barriers, such as the studies on electric vehicles and the heat pump [35,44–46]. In the studies on solar PV, lighting technologies and Micro-CHP's [30,32,39,41,42] subsidies seem less effective. This suggests that for these technologies other barriers, like inertia and social comparisons are more relevant than the high upfront cost or lack of capital barriers.

Five studies investigate *regulatory approaches* (Table 2) in the form of a ban, obligation or price regulation. These policies are in all cases found to be effective at increasing the adoption of more energy efficient technologies. Cao et al. [29] and Chappin and Afman [30] both conclude that banning incandescent lamps is a most effective policy to increase the uptake of more energy efficient lighting technologies and note that increasing the share of high-efficient lighting technologies is essential. These results suggests that household's inertia and having other priorities are important barriers that block adoption of efficient lighting technologies. Chappin and Afman [30] also note that a tax at a sufficiently high level can be effective, Hicks et al. [32] also find this but warn about a rebound effect. Friege [38] researches the adoption of wall insulation and finds that obligating new homeowners to insulate the walls has a great potential to increase the insulation rate. Sopha et al. [33] find that establishing a stable price for fuel for wood-pellet stoves and other heating technologies, is one of the requirements to stimulate adoption. This can be accomplished through a price regulation or other policy forms. Fig. 3 shows that regulation and taxation address adoption barriers like inertia, other priorities and ignorance. In the studies where they are researched they seem have a positive effect on the adoption of energy efficient technologies by households. Regulation also seems more effective at overcoming inertia and other priorities than the use of subsidies in these studies.

Last, five studies examined the effects of *informative and voluntary schemes* (Table 2) on the adoption of energy efficient technologies. These instruments were either an information campaign or promotion in the reviewed studies. These policies aim at barriers such as a lack of information, inertia, ignorance and other priorities, as indicated in Fig. 3. Cao et al. [29] (lighting technologies), Sopha et al. [33] (heating technologies) and Friege [38] (wall insulation) all found these information campaigns not to be as effective as other available policies. This indicates that the barrier of lack of information may be high or that there are other barriers that obstruct the adoption of energy efficient technologies by households. Only in studies about electric vehicle adoption were information campaigns found to be effective, given that these were combined with a subsidy policy [44,46].

The *limited diversity* in policy measures explored in the reviewed studies is noteworthy, compared to the relatively diverse set of technologies and behaviours modelled. There are more types of financial, regulatory and informational instruments available that could be explored. Also policies that include the role of the intermediary have not been found in the reviewed studies, which is a clear opportunity for future ABM studies. Policies, such as tradable white certificates, energy efficiency obligations and energy efficiency tenders, include different

Table 4
Policy conclusions and barriers.

Paper	Technology modelled	Policies included	Barriers targeted	Policy conclusion
Economic, financial and market based instruments				
[30]	Lighting technologies	a)Subsidy b)Tax c)Lamp ban	a) High upfront cost b, c) Lack of information, Other priorities, Ignorance, Inertia	Subsidies not as effective as other policy types
[32]	Lighting technologies	a) Subsidy b) Tax	a) High upfront cost, Social comparisons, b) Ignorance, Other priorities,	Subsidy in combination with other policies can be beneficial but rebound effect diminishes savings
[35]	Heat pumps	a) Subsidy for high energy standard (UK Renewable Heat incentive)	a) Lack of capital, High upfront cost	Incentives and standards program has already pushed heat pump diffusion beyond a certain point and more policy stimulation is needed
[37]	Micro-CHP	a) Subsidy	a) Lack of capital, High upfront cost, Uncertainty of fuel prices	Subsidy is only effective in certain price range and subsidies based on decreasing price difference between competing technologies are much more cost effective than fixed purchase subsidies
[33]	Residential heating technologies	a) Subsidy b) Regulation (price) c) Technical development stimulation d) Promotion and Education	a, c) High upfront cost, a) Lack of Capital, b) Uncertainty of fuel prices, d) Lack of information, Inertia	Technical development and financial support in combination with other policies are required
[34]	Residential heating technologies	a) Subsidy b) Regulation c) Technical development stimulation d) Promotion and Education	a, c) High upfront cost, a) Lack of Capital, b) Uncertainty of fuel prices, d) Lack of information, Inertia	Technical development and financial support in combination with other policies are required
[39]	Solar PV	a) Subsidy (Italian solar PV support scheme)	a) Lack of capital, High upfront cost	Current support scheme is already effective and diffusion will slow down in the future
[41]	Solar PV	a) Subsidy b) Seeding (providing for free)	a, b) Lack of capital, High upfront cost	Subsidies have a very poor effect on increasing adoption
[42]	Solar PV	a) Subsidy Price effect scenario	a) Lack of capital, High upfront cost, Uncertainty of fuel prices	Price increase in electricity (subsidy for production and storing) is more effective than subsidizing purchase
[44]	Electric vehicles	a) Subsidy b) Information campaign	a) Lack of capital, High upfront cost, b) Lack of information, Ignorance, Inertia	Subsidies are vital to boost adoption of electric vehicles
[46]	Electric vehicles	a) Subsidy b) Awareness campaign	a) Lack of capital, High upfront cost, b) Lack of information, Ignorance, Inertia	Subsidies in combination with information campaigns are most effective at stimulating adoption
[45]	Electric vehicles	a) Subsidy b) Tax exemption c) Exclusive EV zone	a, b) Lack of capital, High upfront cost, Codes and standards, Inertia	Exclusive electric vehicle zone is more effective than subsidizing
Regulatory approaches				
[29]	Lighting technologies	a) Lamp ban b) Information campaigns	a) Other priorities, Ignorance, b) Lack of information, Inertia	Banning incandescent light bulbs is most effective policy to increase energy efficiency from lighting.
[30]	Lighting technologies	a) Subsidy b) Tax c) Lamp ban	a) High upfront cost b, c) Lack of information, Other priorities, Ignorance, Inertia	Banning incandescent light bulbs is most effective policy to increase energy efficiency from lighting.
[32]	Lighting technologies	a) Subsidy b) Tax	a) High upfront cost, Social comparisons, b) Ignorance, Other priorities,	Banning incandescent light bulbs is an effective policy but a rebound effect diminishes savings
[38]	Wall insulation	a) Homeowner adoption obligation b) Information campaign	a) Other priorities, Ignorance, Inertia b) Lack of information	Obligating new home-owners to adopt improved wall insulation is the most effective policy
[33]	Residential heating technologies	a) Subsidy b) Regulation (price) c) Technical development stimulation d) Promotion and Education	a, c) High upfront cost, a) Lack of Capital, b) Uncertainty of fuel prices, d) Lack of information, Inertia	A stable price for fuel for wood pellet stoves is one of the conditions needed to stimulate adoption

(*continued on next page*)

Table 4 (*continued*)

Paper	Technology modelled	Policies included	Barriers targeted	Policy conclusion
Informative and voluntary schemes				
[29]	Lighting technologies	a) Lamp ban b) Information campaigns	a) Other priorities, Ignorance, b) Lack of information, Inertia	An information campaign can be effective but the effect is small compared to banning incandescent light bulbs
[33]	Residential heating technologies	a) Subsidy b) Regulation (price) c) Technical development stimulation d) Promotion and Education	a, c) High upfront cost, a) Lack of Capital, b) Uncertainty of fuel prices, d) Lack of information, Inertia	The effect of an information campaign is not significant, only in combination with other policies
[38]	Wall insulation	a) Homeowner adoption obligation b) Information campaign	a) Other priorities, Ignorance, Inertia b) Lack of information	Information instruments have relatively small impact on adoption
[44]	Electric vehicles	a) Subsidy b) Information campaign	a) Lack of capital, High upfront cost, b) Lack of information, Ignorance, Inertia	Information campaign only effective when combined with a subsidy scheme
[46]	Electric vehicles	a) Subsidy b) Awareness campaign	a) Lack of capital, High upfront cost, b) Lack of information, Ignorance, Inertia	Information campaign only effective when combined with a subsidy scheme

actors in the diffusion process of energy efficiency. Since these are relatively novel policies the data on interactions between intermediaries, households and policy is not as readily available, which can be marked as one of the explanations why it has not been done before. The effectiveness of these policies has not been explored yet and ABM is a suitable method to do this because it allows the modelling of complex relationships and interactions between multiple and heterogeneous agents [5].

A substantial number of studies *do not take policies or policy scenarios into account* at all. Azar and Menassa [36] and Rai and Robinson [40], aim to illustrate that the use of ABM is useful to model dynamics and heterogeneous agents. Other studies that do not include policies are by Chen et al. [49], Kowalska-Pyzalska et al. [50] and Byrka et al. [51], operationalize theories using an ABM to illustrate how these theories explain a phenomenon. For instance in Kowalska-Pyzalska et al. [50] the ABM offers a hypothetical explanation for the evaluated discrepancy between consumer opinions in surveys and the actual participation in pilot programs and the adoption of dynamic tariffs.

Ten of the reviewed studies analyse the adoption of energy efficient technologies, these studies *do not specifically test different policies and policy scenarios*, but rather study the diffusion of a particular technology. The effects of policy are included in these studies, among other external factors that influence diffusion, but are not the central focus of the ABM study. Examples of these studies are Hicks and Theis [31] and Hicks et al. [32] who study the adoption of efficient lighting technologies in different scenarios of consumer light consumption. They conclude that all savings acquired through policy can be eroded and negated by a rebound effect. Other examples are Snape et al. [35], who conclude that the current incentives program for heat pumps is successful but insufficient for the future and Palmer et al. [39] who find that the current subsidies in Italy have already accomplished a significant adoption rate. These conclusions are certainly relevant to policymakers, but policy testing is not the focus of these studies. Seven studies conduct more focused policy testing. Examples of these are: Cao et al. [29] and Chappin and Afman [30] who test different policies for efficient lighting technology adoption. Sopha et al. [33] do a policy scenario analysis for a few heating technologies and compare how different combinations of these policies affect adoption. Friege [38] compares policies like new homeowner obligations for wall insulation and the effect of information campaigns on wall insulation adoption.

What we can conclude from this review from a policy perspective, is that the majority of studies aims to analyse the adoption of energy efficiency and policy testing and is therefore of interest to policy makers. The explored policies are however, limited in scope. Mostly financial incentives are modelled in these ABMs, whilst more policies constructs have been identified in literature, like policies that include an intermediary. To gain insight on what aspects of ABMs allow modellers to do policy testing and design, the decision making theories and input data used need to be examined.

4.3. Decision theories

The decision making logic of agents in ABMs are often rooted in theory, i.e. a particular decision making theory is explicitly used to describe the adoption decision of a household in the model and we explored how the choice of theory affects the barriers modelled.

The most often applied theory is the *Theory of Planned Behaviour* by Ajzen [53]. This theory states that the behaviour of an individual is determined by the intention and perceived behavioural control of this individual. The intention in turn is influenced by the attitude and subjective norm of the individual. This provides a basis for where barriers come from and how they may be taken away at the individual level and therefore fits well with ABM in general and in particular those that focus on energy efficiency. Seven of the studies use this decision-making theory to describe the decision making of households [33,34,40,47,48,50,51]. A reason for the popularity of the Theory of

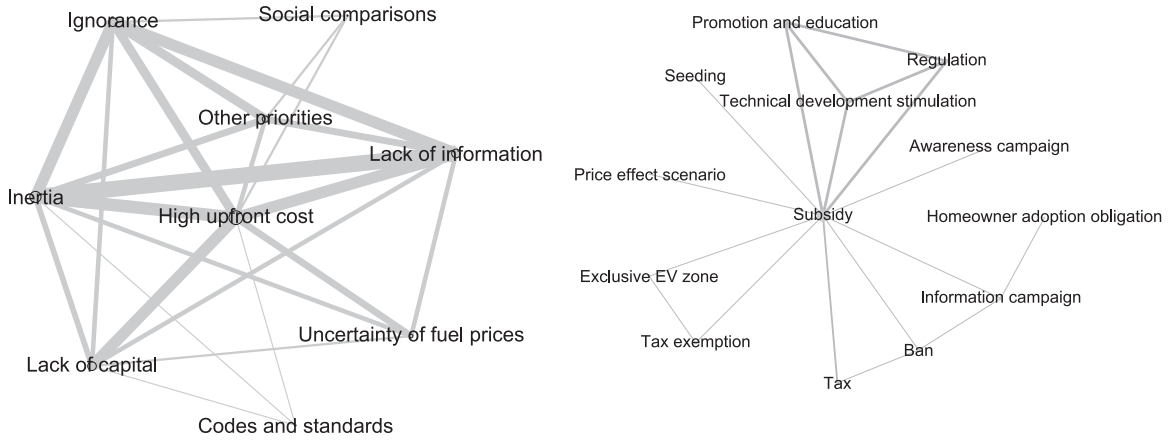

Fig. 2. Barriers (left) and policies (right) that co-occur in the reviewed ABMs. Nodes in these graphs are barriers and policies. Node size reflects how often they occur with other barriers and policies. Edges thickness reflects the number of times that barriers and policies are modelled together.

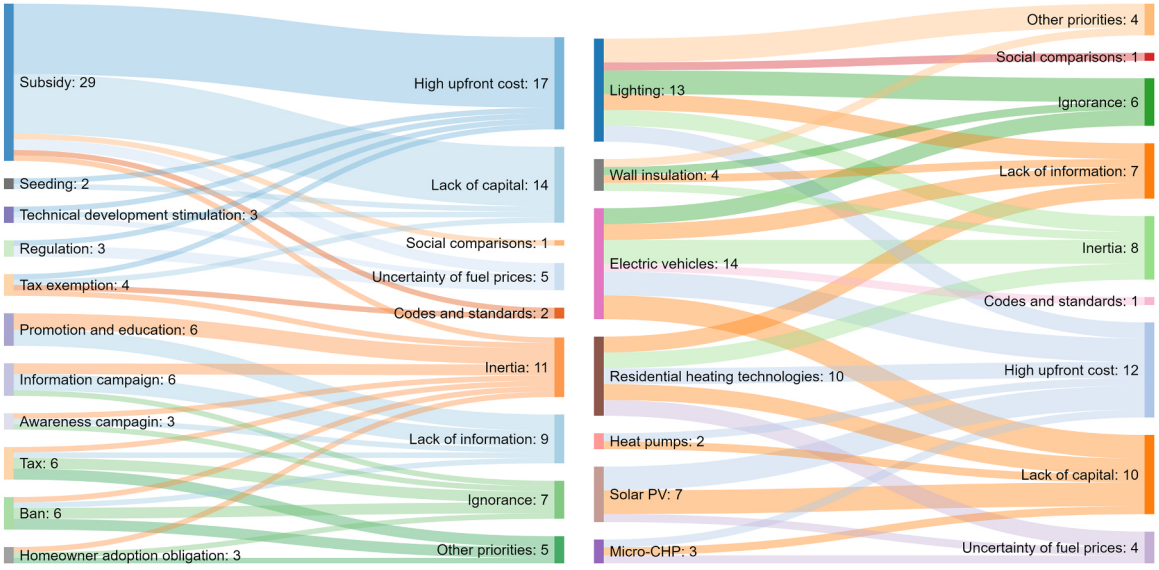

Fig. 3. Connections between policies, technologies and barriers visualized in Sankey diagrams. The graph on the left shows links between policies and barriers. The graph on the right shows links between technologies and barriers.

Planned Behaviour could be its flexibility and elegance. The theory is relatively easy to operationalize. Household intentions can be modelled as threshold values for different behaviours. Moreover, the attitudes, norms and intentions of individual households can be broken down into more specific attitudes, norms and intentions. This makes it very suitable for including multiple barriers in the ABM. Households can for instance have a certain attitude towards a new technology and a certain preference for known technologies, making it possible to include the inertia barrier in the ABM. The Theory of Planned Behaviour is used to model a variety of barriers (high upfront cost, lack of capital, uncertainty of fuel prices, lack of information, and inertia, and other priorities as barriers) and a range of policies (economic such as subsidies, but also targeted at providing information). This theory may also fit a variety of other barriers affecting intentions and perceived behavioural control and policies that may be used to overcome these barriers.

A number of studies make use of *utility functions* to structure the decision making logic of agents and form the agent theory. Five studies describe the decision of households to adapt a technology by calculating the maximum utility [31,32,39,43,44]. The use of a utility function is also common in other economic models [27] and allows multiple aspects of the adoption decision to be expressed as utility for the household. This implies that using utility functions enables ABMs to be connected to other types of models. Though utility functions can represent different types of aspects, they are used to model economic barriers such as high upfront cost and lack of capital, essentially focussing on economic aspects of the household decisions. This also translates to economic policies (with a focus on subsidies).

Other theories that are regularly used in these ABMs are network or social network theory [30,33,38,49,51] and the diffusion of innovations theory [45,46]. These theories do not necessarily describe the decision making of households but rather how information, perceptions or innovations spread through a network or population of households. It is possible to combine these theories with others that describe different aspects of the household adoption process. The diversity of theoretical angles and the diversity in purposes (The ranging from exploring the usefulness of ABMs to the tests of particular policy instruments) shows that ABM is a versatile method. It also suggests there still are many opportunities for improving the understanding of energy efficiency policies.

4.4. Empirical data

There are two main uses of empirical data in agent-based models: 1) to structure the decision making logic of agents and 2) to provide specific data on properties of barriers, technologies, households and policies. Models that use empirical data to structure decision making logic are different from models that use a theory because the particulars in the dataset make the modelling study highly specific to a technology, arising barriers, and a population of households (and this effect is less prominent when a theoretical basis is used). There are five studies that do not mention the use of a theory to structure the decision making rules [29,35–37,52]. These studies either make their own assumptions about the decision making behaviour of households or base the decision making purely on *empirical data*.

The use of empirical data to determine the specific properties of households, technologies and policies seems to lead to concrete results about energy efficiency adoption and policy testing. Fourteen of the studies use data from a complementary survey or empirical research for this purpose and eight of the studies extract data from an available dataset. The studies that draw policy conclusions all use data from a survey or statistical study to substantiate their ABMs and results. For instance [30,33,38] all make use of survey data and can compare the effectiveness of different policies on the adoption of lighting technologies, residential heating technologies and wall insulation. Chappin and Afman [30] point out that a ban of incandescent lighting is much more effective than subsidies and Sopha et al. [33] propose a package of policies to stimulate wood pellet stoves and recognize that information campaigns are only effective when combined with subsidies and regulation on wood-pellet fuel prices. Other studies [39,41,42,44,46] use survey or statistical data test the effectiveness of policies in different scenarios. Palmer et al. [39] for instance conclude that the current subsidy scheme is already effective at stimulating the diffusion of solar PV and will need to be extended to push adoption further.

There are also studies in this review that do not make use of empirical data at all. Kowalska-Pyzalska et al. [50] and Byrka et al. [51] do not make use of empirical data and focus on generating insight in how the theory can be translated into an ABM. Rather than focussing on generating insights in the effectiveness of particular energy efficiency policies, these models have as goal to operationalize certain theories. This operationalization of the theory can then be used for academic discussion.

These findings suggest a variety in modelling purposes and that the studies are set up differently according to their purpose. We observe that only papers with empirical data (through a survey) provide concrete suggestions for policy interventions. Decision making theories can be used to shape the structure of the model and also helps focus the relevant empirical data for the issue that is modelled. Using decision theories also enables the reuse of models or model pieces and a comparison of different modelling studies.

5. Conclusion

In this paper, barriers to the adoption of energy efficiency by households are identified and four clusters have been identified: structural, economic, behaviour, and social barriers. Accounting models and agent-based models (ABMs) are models used to describe the effects of different policy alternatives that address these adoption barriers. ABMs complement accounting models by offering the possibility to model more elaborate decision making logic of households. The literature review resulted in 23 studies on energy efficiency adoption using ABM. The following barriers were addressed in existing modelling studies: a lack of capital, a lack of information, high upfront cost, inertia, ignorance, uncertainty of fuel prices, and other priorities. The set of modelled policies is restricted to subsidies, regulation and taxation, technology ban, household adoption obligation and various information campaigns. These policies directly influence the adoption decision of households and are therefore effectively operationalized in the studied ABMs. Policies that indirectly influence the adoption decision of households, such as policies affecting intermediary parties, have not been modelled before. Many of the models are rooted in the Theory of Planned Behaviour, use utility functions, and/or use empirical data. Overall, the studies show that subsidies help to stimulate the adoption of electric vehicles and alternative heating technologies. Banning incandescent lamps is the most effective policy to increase the adoption of efficient lighting. An obligation for new homeowners to insulate their houses effectively helps to increase the adoption of wall insulation. And informational instruments are not as effective as other policies to stimulate electric vehicle adoption unless combined with a subsidy scheme. These conclusions translate into concrete policy advice specific to a particular technology. Many of the adoption barriers, of the energy efficient technologies and of the energy efficiency policies have not been researched yet with ABM. This seems to be the case because the decision making theories used in the reviewed ABM studies are best suited to describe economic or behavioural barriers. ABM has the potential to provide insight in many more energy efficiency policy questions.

The literature review shows that most of the ABMs on energy efficiency in households rely on empirical data from public databases or survey studies to use as input for the model parameters and agents. Decision making and network theories structure the model logic and directs and focuses the empirical data needed. Models that have a theoretical basis and use empirical data show the strongest ability to test policies on a complex population of heterogeneous households. The value of ABM, for energy efficiency policy making, constitutes of its capacity to produce policy recommendations specific to the adoption of particular energy efficient technologies in the context of heterogeneous populations and specific energy efficiency policies. This capacity complements the policy recommendations that are derived from other types of models like accounting models. Both accounting models and ABMs are founded in extensive empirical data and are therefore suitable to complement each other for the purpose of policy testing and design. In this collaboration, ABMs can specifically contribute to the policy research by focusing on elaborate decision making modelling and the heterogeneity of households.

One pathway for further ABM research is evaluating policies with a more elaborate institutional setting, such as policies that involve multiple stakeholders. Prime examples are policies aimed at intermediary parties, like tradable white certificates, energy efficiency obligations and energy efficiency tenders. By including the complex interactions between intermediary and households in these models, novel and distinctive policy insights about these policies can be derived. Another research opportunity pertains the modelling of other household energy technologies and other adoption barriers than the ones already studied.

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Appendix

See appendix Table 5

Table 5
Energy Efficiency Adoption ABMs.

Technology modelled	Adoption vs. use	Policies included	Degree of policy design	Theories used	Data	Modelling logic	Reference and Authors (year)	Journal
Lighting technologies: Incandescent, LED, CFL, Halogen	Adoption	Policy scenarios (lamp ban, campaign, etc.)	Policy testing	No theory used as basis defined	Data from US institutions	Empirical – Model - Analysis	[29] (Cao et al., 2017)	Sustainable Energy Technology and Assessments
Lighting technologies: Incandescent, LED, CFL, Halogen	Adoption	Policy scenarios (lamp ban, tax and subsidy)	Policy testing	Social network theory	Survey data and internet sources	Theory – Empirical – Model - Analysis	[30] (Chappin and Afman, 2013)	Environmental Innovation and Societal Transitions
Lighting technologies: Incandescent, LED, CFL, Halogen	Use	Light consumption scenarios	Analysis	Multiplicative utility function Probabilistic choice mechanism	Survey data	Theory – Empirical – Model – Analysis	[31] (Hicks and Theis, 2014)	International Journal of Life Cycle Assessment
Lighting technologies: Incandescent, LED, CFL, Halogen	Use	Subsidy, tax and other scenarios	Analysis	Multiplicative utility function	Survey data	Theory – Empirical – Model – Analysis	[32] (Hicks et al., 2015)	Journal of Industrial Ecology
Residential heating systems: - Direct electric heating - Wood pellet heating stoves - Heat pump	Adoption	Regulation, subsidies, technical development, promotion and education	Policy testing	Theory of planned behaviour Social network theory Meta-theory of consumer behaviour	Survey data	Theory – Empirical – Model – Analysis	[33] (Sopha et al., 2011)	Energy Policy
Residential heating systems: - Direct electric heating - Wood pellet heating stoves - Heat pump	Adoption	Regulations, subsidies, Technical development, Promotion and education	Analysis	Theory of planned behaviour Meta theory of consumer behaviour	Survey data, National statistics data	Theory – Empirical – Model – Analysis	[34] (Sopha et al., 2013)	Environmental Innovation and Societal Transitions
- HVAC heating - HVAC cooling - Area lighting - Task lighting - Equipment (computers) - Hot water supply	Use	No policies studied	Show use	No theory as basis defined	No empirical data used	Model - Analysis	[36] (Azar and Menassa, 2011)	Journal of Computing in Civil Engineering
Heat pump	Adoption	UK Renewable Heat incentive	Analysis	No theory as basis defined	Predictions from other studies	Model - Analysis	[35] (Snape et al., 2015)	Energy Policy
Micro-CHP	Adoption	Subsidy	Policy testing	No theory as basis defined	No empirical data used, publicly available data	Model - Analysis	[37] (Faber et al., 2010)	Energy Policy
Wall insulation	Adoption	Homeowner obligation and information instruments	Policy testing	Social impact theory	Survey data, publicly available data	Empirical – Model - Analysis	[38] (Friege, 2016)	Energy and Buildings
Solar PV systems	Adoption	Italian solar PV support scheme	Analysis	Multi-attribute utility function	Statistical data	Empirical – Model - Analysis	[39] (Palmer et al., 2015)	Technological Forecasting & Social Change
Solar PV systems	Adoption	No policies studied	Show Use	Theory of planned behaviour Relative agreement algorithm	Survey data	Theory – Empirical - Model	[40] (Rai and Robinson, 2015)	Environmental Modelling & Software
Solar PV systems	Adoption	Financial incentives and seeding (give away)	Analysis	No theory as basis defined	Dataset from the California Solar Initiative	Empirical – Model - Analysis	[41] (Zhang et al., 2014)	AAAI Fall Symposium
Solar PV systems	Adoption	Price and subsidy scenarios	Policy testing	Affect control theory	Survey data and official reports	Theory – Empirical – Model- Analysis	[42] (Alyousef et al., 2017)	Computer Science Research and Development
Electric Vehicles	Adoption	No policies studies	Analysis	Utility function	Survey data	Empirical – Model-Analysis	[43] (McCoy and Lyons, 2014)	Energy Research & Social Science
Electric Vehicles	Adoption	Information campaigns, subsidies	Analysis	Utility function	Data from previous studies	Model - Analysis	[44] (Noori and Tatari, 2016)	Energy

(*continued on next page*)

Table 5 (*continued*)

Technology modelled	Adoption vs. use	Policies included	Degree of policy design	Theories used	Data	Modelling logic	Reference and Authors (year)	Journal
Electric Vehicles	Adoption	Tax exemption and subsidy	Analysis	Theory of innovation adoption Homophily in social networks	Survey data	Theory – Empirical – Model - Analysis	[45] (Wolf et al., 2015)	Technological Forecasting & Social Change
Electric Vehicles	Adoption	Subsidies and awareness campaign	Policy testing	Diffusion of innovations	Empirical data and probabilities	Theory – Empirical – Model - Analysis	[46] (Silvia and Krause, 2016)	Energy Policy
CO_2 meter	Adoption	No policies studied (diffusion scenarios)	Analysis	Theory of planned behaviour	Empirical data used	Theory – Empirical – Model - Analysis	[47] (Jensen, Holtz, Baedeker, and Chappin, 2016)	Energy and Buildings
Behaviour changing feedback device	Use	No policies studied (diffusion scenarios)	Analysis	Theory of planned behaviour	Commercial data used	Theory – Empirical – Model – Analysis	[48] (Jensen, Holtz, and Chappin, 2015)	Technological Forecasting & Social Change
No specific appliances or technologies modelled	Use	No policies studied	Theoretical	Network theory	Data from empirical experiment	Theory – Model - Theory	[49] (Chen et al., 2012)	Energy and Buildings
No specific appliances or technologies modelled	Use	No policies studied	Theoretical	Theory of planned behaviour Value-belief-norm model	No empirical data used (theoretical model)	Theory – Model – Analysis	[50] (Kowalska-Pyzalska et al., 2014)	Energy Policy
(Green) eco-innovations	Use	No policies studied	Theoretical	Theory of planned behaviour Network theory	No empirical data used (theoretical model)	Theory – Model - Analysis	[51] (Byrka, Jedrzejewski, Sznajd-Weron, and Weron, 2016)	Renewable and Sustainable Energy Reviews

References

[1] IEA. Energy Efficiency Market Report 2016; 2016.
[2] European Commission. Energy Efficiency Plan 2011. Brussels; 2011.
[3] Pelenur MJ, Cruickshank HJ. Closing the energy efficiency gap: a study linking demographics with barriers to adopting energy efficiency measures in the home. Energy 2012;47:348–57. https://doi.org/10.1016/j.energy.2012.09.058.
[4] Mundaca L, Neij L, Worrell E, Mcneil M. Evaluating energy efficiency policies with energy-economy models. Annu Rev Environ Resour 2010;35:305–44. https://doi.org/10.1146/annurev-environ-052810-164840.
[5] Moglia M, Cook S, Mcgregor J. Engineering advance a review of agent-based modelling of technology diffusion with special reference to residential energy efficiency. Sustain Cities Soc 2017;31:173–82. https://doi.org/10.1016/j.scs.2017.03.006.
[6] van Dam KH, Nikolic I, Lukszo Z. Agent-based modeling of socio-technical systems; 2013.
[7] Jaffe AB, Stavins RN. The energy-effincency gap what does it mean? Energy Policy 1994;22:804–10. https://doi.org/10.1016/0301-4215(94)90138-4.
[8] Schleich J, Gassmann X, Faure C, Meissner T. Making the implicit explicit: a look inside the implicit discount rate. Energy Policy 2016;97:321–31. https://doi.org/10.1016/j.enpol.2016.07.044.
[9] Hirst E, Brown M. Closing the efficiency gap: barriers to the efficient use of energy. Resour Conserv Recycl 1990;3:267–81. https://doi.org/10.1016/0921-3449(90)90023-W.
[10] Gillingham K, Palmery K. Bridging the energy efficiency gap: policy insights from economic theory and empirical evidence. Rev Environ Econ Policy 2014;8:18–38. https://doi.org/10.1093/reep/ret021.
[11] Howarth RB, Andersson B. Market barriers to energy efficiency. Energy Econ 1993;15:262–72. https://doi.org/10.1016/0140-9883(93)90016-K.
[12] Cagno E, Worrell E, Trianni A, Pugliese G. A novel approach for barriers to industrial energy efficiency. Renew Sustain Energy Rev 2013;19:290–308. https://doi.org/10.1016/j.rser.2012.11.007.
[13] Lorenzoni I, Nicholson-Cole S, Whitmarsh L. Barriers perceived to engaging with climate change among the UK public and their policy implications. Glob Environ Change 2007;17:445–59. https://doi.org/10.1016/j.gloenvcha.2007.01.004.
[14] Allcott H, Micheal G. Is there an 'energy gap'? J Econ Perspect 2008;161:145–57. https://doi.org/10.1680/ener.2008.161.4.145.
[15] Lindén AL, Carlsson-Kanyama A, Eriksson B. Efficient and inefficient aspects of residential energy behaviour: what are the policy instruments for change? Energy Policy 2006;34:1918–27. https://doi.org/10.1016/j.enpol.2005.01.015.
[16] Geller H, Harrington P, Rosenfeld AH. Polices for increasing energy efficiency: thirty years of experience in OECD countries. Energy Policy 2006;34:556–73. https://doi.org/10.1016/j.enpol.2005.11.010.
[17] Houde S, Aldy JE. Belt and Suspenders and more: the incremental impact of energy efficiency subsides in the presence of existing policy instruments; 2014.
[18] Stede J. Bridging the industrial energy efficiency gap – assessing the evidence from the Italian white certificate scheme. Energy Policy 2017;104:112–23. https://doi.org/10.1016/j.enpol.2017.01.031.
[19] Bertoldi P, Rezessy S. Tradable white certificate schemes: fundamental concepts. Energy Effic 2008:237–55. https://doi.org/10.1007/s12053-008-9021-y.
[20] Bertoldi P, Rezessy S, Lees E, Baudry P, Jeandel A, Labanca N. Energy supplier obligations and white certificate schemes: comparative analysis of experiences in the European Union. Energy Policy 2010;38:1455–69. https://doi.org/10.1016/j.enpol.2009.11.027.
[21] Langniss O, Praetorius B. How much market do market-based instruments create ? An analysis for the case of '"white"' certificates $. Energy Policy 2006;34:200–11. https://doi.org/10.1016/j.enpol.2004.08.025.
[22] Datta S, Gulati S. Utility rebates for energy star appliances: are they effective? J Environ Econ Manag 2014;68:480–506. https://doi.org/10.1016/j.jeem.2014.09.003.
[23] Iimi A. Multidimensional auctions for public energy efficiency projects: evidence from Japanese Esco Market. Rev Ind Organ 2016;49:491–514. https://doi.org/10.1007/s11151-016-9510-7.
[24] Seefeldt F, Bornholdt M. From theory to practice : the development of the 'competitive efficiency tender' in Germany. In: Proceedings of the ECEEE summer study; 2012, p. 433–44.
[25] Rosenow J. Energy savings obligations in the UK — a history of change. Energy Policy 2012;49:373–82. https://doi.org/10.1016/j.enpol.2012.06.052.
[26] Chateau B, Lapillone B. Accounting and end-use models. Energy 1990;15:261–78.
[27] Bhattacharyya SC, Timilsina GR. Modelling energy demand of developing countries: are the specific features adequately captured? Energy Policy 2010;38:1979–90. https://doi.org/10.1016/j.enpol.2009.11.079.
[28] Chappin ÉJL, Hesselink LXW, Blok K, Mueller A, Forthuber S, Braungardt S. et al. Working paper on modelling and survey - changing energy efficiency technology adoption in households; 2017.
[29] Cao J, Choi CH, Zhao F. Agent-based modeling of the adoption of high-efficiency lighting in the residential sector. Sustain Energy Technol Assess 2017;19:70–8. https://doi.org/10.1016/j.seta.2016.12.003.
[30] Chappin EJL, Afman MR. An agent-based model of transitions in consumer lighting: policy impacts from the E.U. phase-out of incandescents. Environ Innov Soc Transit 2013;7:16–36. https://doi.org/10.1016/j.eist.2012.11.005.
[31] Hicks AL, Theis TL. An agent based approach to the potential for rebound resulting from evolution of residential lighting technologies. Int J Life Cycle Assess 2014;19:370–6. https://doi.org/10.1007/s11367-013-0643-8.
[32] Hicks AL, Theis TL, Zellner ML. Emergent effects of residential lighting choices:

prospects for energy savings. J Ind Ecol 2015;19:285–95. https://doi.org/10.1111/jiec.12281.
[33] Sopha BM, Klöckner CA, Hertwich EG. Exploring policy options for a transition to sustainable heating system diffusion using an agent-based simulation. Energy Policy 2011;39:2722–9. https://doi.org/10.1016/j.enpol.2011.02.041.
[34] Sopha BM, Klöckner CA, Hertwich EG. Adoption and diffusion of heating systems in Norway: coupling agent-based modeling with empirical research. Environ Innov Soc Transit 2013;8:42–61. https://doi.org/10.1016/j.eist.2013.06.001.
[35] Snape JR, Boait PJ, Rylatt RM. Will domestic consumers take up the renewable heat incentive? An analysis of the barriers to heat pump adoption using agent-based modelling. Energy Policy 2015;85:32–8. https://doi.org/10.1016/j.enpol.2015.05.008.
[36] Azar E, Menassa C. Agent-based modeling of occupants and their impact on energy use in commercial buildings. J Comput Civ Eng 2011;26:506–18. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000158.
[37] Faber A, Valente M, Janssen P. Exploring domestic micro-cogeneration in the Netherlands: an agent-based demand model for technology diffusion. Energy Policy 2010;38:2763–75. https://doi.org/10.1016/j.enpol.2010.01.008.
[38] Friege J. Increasing homeowners' insulation activity in Germany: an empirically grounded agent-based model analysis. Energy Build 2016;128:756–71. https://doi.org/10.1016/j.enbuild.2016.07.042.
[39] Palmer J, Sorda G, Madlener R. Modeling the diffusion of residential photovoltaic systems in Italy: an agent-based simulation. Technol Forecast Soc Change 2015;99:106–31. https://doi.org/10.1016/j.techfore.2015.06.011.
[40] Rai V, Robinson SA. Agent-based modeling of energy technology adoption: empirical integration of social, behavioral, economic, and environmental factors. Environ Model Softw 2015;70:163–77. https://doi.org/10.1016/j.envsoft.2015.04.014.
[41] Zhang H, Vorobeychik Y, Letchford J, Lakkaraju K. Predicting rooftop solar adoption using agent-based modeling. In: Proceedings of the AAAI fall symposium; 2014, p. 44–51.
[42] Alyousef A, Adepetu A, de Meer H. Analysis and model-based predictions of solar PV and battery adoption in Germany: an agent-based approach. Comput Sci - Res Dev 2017;32:211–23. https://doi.org/10.1007/s00450-016-0304-9.
[43] McCoy D, Lyons S. Consumer preferences and the influence of networks in electric vehicle diffusion: an agent-based microsimulation in Ireland. Energy Res Soc Sci 2014;3:89–101. https://doi.org/10.1016/j.erss.2014.07.008.
[44] Noori M, Tatari O. Development of an agent-based model for regional market penetration projections of electric vehicles in the United States. Energy 2016;96:215–30. https://doi.org/10.1016/j.energy.2015.12.018.
[45] Wolf I, Schroder T, Neumann J, de Haan G. Changing minds about electric cars: an empirically grounded agent-based modeling approach. Technol Forecast Soc Change 2015;94:269–85. https://doi.org/10.1016/j.techfore.2014.10.010.
[46] Silvia C, Krause RM. Assessing the impact of policy interventions on the adoption of plug-in electric vehicles: an agent-based model. Energy Policy 2016;96:105–18. https://doi.org/10.1016/j.enpol.2016.05.039.
[47] Jensen T, Holtz G, Baedeker C, Chappin ÉJL. Energy-efficiency impacts of an air-quality feedback device in residential buildings: an agent-based modeling assessment. Energy Build 2016;116:151–63. https://doi.org/10.1016/j.enbuild.2015.11.067.
[48] Jensen T, Holtz G, Chappin ÉJL. Agent-based assessment framework for behavior-changing feedback devices: spreading of devices and heating behavior. Technol Forecast Soc Change 2015;98:105–19. https://doi.org/10.1016/j.techfore.2015.06.006.
[49] Chen J, Taylor JE, Wei HH. Modeling building occupant network energy consumption decision-making: the interplay between network structure and conservation. Energy Build 2012;47:515–24. https://doi.org/10.1016/j.enbuild.2011.12.026.
[50] Kowalska-Pyzalska A, Maciejowska K, Suszczyński K, Sznajd-Weron K, Weron R. Turning green: agent-based modeling of the adoption of dynamic electricity tariffs. Energy Policy 2014;72:164–74. https://doi.org/10.1016/j.enpol.2014.04.021.
[51] Byrka K, Jedrzejewski A, Sznajd-Weron K, Weron R. Difficulty is critical: the importance of social factors in modeling diffusion of green products and practices. Renew Sustain Energy Rev 2016;62:723–35. https://doi.org/10.1016/j.rser.2016.04.063.
[52] Zhang H, Vorobeychik Y, Letchford J, Lakkaraju K. Data-driven agent-based modeling, with application to rooftop solar adoption. Auton Agent Multi Agent Syst 2016;30:1023–49. https://doi.org/10.1007/s10458-016-9326-8.
[53] Ajzen I. The theory of planned behavior. Organ Behav Hum Decis Process 1991;50:179–211.