Adoption of Residential Energy Efficient Technologies: a Review on Agent Based Modeling Studies

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Abstract.
The improvement of energy efficiency has been marked as a key strategy to reduce greenhouse gas emissions. Policy makers see the residential sector as an important target to realize this energy efficiency improvement, because the residential sector is responsible for about 30% of the total energy use. However, the adoption of energy efficient technologies by households is a complex affair. Households have many complex attitudes and perceptions regarding energy efficient technology adoption. Agent-Based Modeling (ABM) is a modeling method that is suitable for modeling complex adaptive systems like the adoption of energy efficient technologies. In this paper 23 ABM studies are reviewed in order to create an overview of what energy efficient technologies have already been modelled using agent based modeling. With this overview new pathways to future research can be identified. Most of the reviewed ABMs focus on the adoption of one specific energy technology, therefore an interesting future study would be on a comparison of multiple energy efficient technologies. Subsidies and efficiency regulations are the most commonly explored energy efficiency policies in the ABM studies. This leaves many other interesting policies still unexplored. Lastly, the ABM studies use several different theories to describe the decision making logic of agents. Popular theories are the theory of planned behavior and the utility function.

Keywords.
Energy efficient technology, agent based modeling, adoption, households, literature review.

1) Introduction

The improvement of energy efficiency is one of the key strategies to realize the Paris climate conference goals (International Energy Agency, 2015) relating to the global reduction of greenhouse gas emissions. However, historically the adoption of energy efficiency has been slow (Pelenur & Cruickshank, 2012) and there is a discrepancy between our actual energy use and the potential energy savings. This difference between the energy conservation potential and the actual energy use, has been named the 'efficiency gap' by academics (Jaffe & Stavins, 1994). Policy makers are looking for effective policies that will aid in closing this efficiency gap. An important target for policy makers is the residential sector. Globally, the residential sector is responsible for approximately 30% of the total energy use (Swan & Ugursal, 2009) and in the OECD countries this percentage is estimated to be 20% (Fumo & Biswas, 2015). By targeting newly built houses and existing households with energy efficiency policies, policy makers try to steer people to a more energy efficient way of living. However, the degree of eventual energy efficiency adoption is up to residents themselves (Moglia, Cook, & Mcgregor, 2017). The decision making about residential energy technologies and efficiency measures is very complex. There are many different types of barriers that can obstruct households from adopting energy efficiency. Because of the complex nature of energy efficiency adoption and household decision making, modeling methods are needed that can describe and analyze this complexity (Moglia et al., 2017). Agent-Based Modeling (ABM) is a modeling method that can be applied to study and analyze the complex adoption process of energy efficiency.

In this article several conducted ABM studies on the adoption of energy efficient technologies by households are reviewed. This review is done in order to learn about the technologies, policies and adoption barriers modelled by state-of-the-art ABM studies. Observations on the decision making theories used for agent based modeling and the use of empirical data, may also be valuable to modelers of future agent based models. Moreover, by analyzing these ABM studies new directions for future work can be identified. This literature review has also been used for the Changing Energy Efficiency Technology Adoption in Households (CHEETAH) research project (É. J. L. Chappin et al., 2017).

Research Questions

A structured discussion is needed to get a clear overview of the aspects of residential energy efficient technology adoption that have been explored using agent based modeling. This structure will be provided by a number of research questions that need answering:

- What energy technologies have been modelled in the ABM studies?
- Which efficiency policies have been explored in the ABM studies?
- Which theories have been used to describe the decision making logic of agents in the ABM studies?
- Are the ABM studies based on empirical research?

In this paper, the reviewed ABM studies will be analyzed and discussed according to these research questions.

Outline of the paper

The remainder of this paper has the following structure: first, in paragraph 2, the literature review methodology is explained and the search queries used to find the ABM studies are discussed. Next, in paragraph 3, the results from the literature search are presented and the found ABM studies are reviewed based on the formulated research questions. Lastly, in paragraph 4, the discussion is concluded by answering the research questions and identifying pathways for further agent based modeling studies.

2) Methodology

To examine the state of the scientific literature on previously conducted energy efficient technology adoption ABM studies, a literature review is used. A selection of relevant ABM studies was made for this literature review. To come to this selection of literature, a number of search terms were used. The search queries used contained terms like: *ABM*, *agent-based modelling* or *agent-based modeling*, *energy efficiency*, *household*, *consumer* or *residential*. The term *barriers* was also added in some searches to find ABM studies that specifically dealt with energy efficiency barriers.

To find the reviewed ABM studies Google Scholar and the Scopus search database have been used. Within these search libraries papers were filtered on relevance and most citations. Using the above stated search queries and filters 83 search results were found. The final selection of papers has been done by handpicking. Only papers that described an agent based modeling study have been reviewed. To increase the number of ABM studies to review, studies that describe the adoption of Solar PV systems and electrical vehicles have been included.

3) Energy efficient technology adoption agent based models

The literature search on energy efficient technology adoption ABMs resulted in a list of 23 agent based modeling studies.

Table *1* presents the full list of reviewed agent based modeling studies and describes the technologies that have been modeled and the policies that have been explored.

Table *2* shows the same list of ABM studies but gives an overview of the theories that have been applied and the type of data that has been used.

A first thing that is striking about the search results is that all agent based modeling studies have been published in recent years. The earliest conducted agent based modeling study in this review was by Faber et al (2010). Almost all other studies are less than five years old, with most of them conducted after 2015. This indicates that the use of agent based models to explore the complex nature of energy technology adoption is a novel research approach that is becoming increasingly popular.

3.1. Energy efficient technologies studied

Many of the agent based modeling studies focus on technologies that are relatively novel and in the early stages of the adoption curve. Alyousef et al. (2017), Palmer et al. (2015), Rai and Robinson (2015) and Zhang et al. (2014) model the adoption of solar PV systems in residences. Another technology that is relatively novel, is the electric vehicle modelled by Noori and Tatari (2016), Silvia and Krause (2016) and Wolf et al. (2015). These technologies are not directly linked to the theme of energy efficiency, but are seen as technologies that can significantly contribute to the reduction of greenhouse gas emissions and a sustainable future. It is curious to see that a large portion of the search results do not specifically consider energy efficiency, when searching for energy efficiency adoption ABMs. This indicates that energy efficiency is rarely regarded as main topic in agent based modeling studies, but rather as an additional aspect. Other residential technologies that are often modelled are lighting technologies and heating systems. ABM studies on lighting technologies like by Cao et al. (2017), Chappin and Afman (2013), Hicks and Theis (2014) and Hicks et al. (2015), compare between different types of lighting technologies: incandescent lighting, CFL, LED and halogen lighting. Faber et al. (2010) studies a specific heating technology, namely the Micro-CHP. Snape et al. (2015) also models only one specific heating technology: the heat pump. Maya Sopha et al. (2011) and Sopha et al. (2013) take into account multiple heating technologies like: direct electric heating, wood pellet heating stoves and heat pumps.

Striking about this analysis on the modelled energy efficient technologies, is that most ABM models focus on the adoption of one specific technology. Comparing different technologies that perform the same function is done in some of the ABM studies. Comparisons between different commercial models of the same type of technology are also absent. From this comparison we can thus conclude that the reviewed ABM studies focus on technologies that are novel, have a significant efficiency improvement potential and a great potential to disrupt established technologies. More established technologies are mostly modeled for the sake of comparison, but exploring how more energy efficiency can be accomplished with these technologies is a research pathway that still needs to be taken.

3.2. Efficiency policies explored

Two different types of ABMs can be identified when studying the ways these ABMs deal with efficiency policies: studies that do include policies and studies that do not explore the effects of policies. When examining the results on policies modeled in

Table *1*, the amount of studies that consider financial incentives such as subsidies, stands out. 12 out of the 23 studies explore the effects of subsidies on the adoption of technologies, which may be because of the focus on novel technology adoption in a large portion of the ABM studies. Another type of policy that is regularly explored is the use of regulations, like a ban or obligation. These are simulated by for instance Cao et al. (2017), Chappin and Afman (2013), Friege (2016) and Maya Sopha et al. (2011). There is also a number of studies that do not take policies into account. Within this group there are papers that do not focus on energy technology adoption, but rather on the adoption of energy efficient behaviors. Examples of these studies are Kowalska-Pyzalska et al. (2014) and Chen et al. (2012).

Policies seem to have a limited role in the reviewed agent based modeling studies. A sizable portion of the studies do not take policies into account, the focus of these studies is more often on the adoption of a technology or behavior that contributes to energy efficiency. The studies that do include policies, often in the form of policy scenarios, mostly include financial incentives or regulatory policies. Therefore we can conclude that the exploration of the effects of efficiency policies on the adoption of energy efficient technologies is insufficiently featured in these ABM studies.

Table 1 - Technologies and Policies modelled in reviewed ABM studies

Reference	**Technology modelled**	**Policies modelled**
(Alyousef et al., 2017)	• PV and battery systems	• Price and subsidy scenarios
(Cao et al., 2017)	• Lighting technologies	• Policy scenarios (lamp ban, campaign, etc.)
(E. J. L. Chappin & Afman, 2013)	• Lighting technologies	• Policy scenarios (lamp ban, tax and subsidy)
(Faber et al., 2010)	• Micro – CHP (combined heat and power)	• Subsidy
(Friege, 2016)	• Wall insulation	• Homeowner obligation
(Hicks & Theis, 2014)	• Lighting technologies	• Light consumption scenarios
(Hicks et al., 2015)	• Lighting technologies	• Subsidy, tax and other scenarios
(Maya Sopha et al., 2011)	• Residential heating systems	• Regulation, subsidies, technical development, promotion and education
(McCoy & Lyons, 2014)	• Electric vehicles	• No policies studied

(Sopha et al., 2013)	• Residential heating systems	• Regulations and subsidies
(Noori & Tatari, 2016)	• Electric vehicles	• Subsidies
(Palmer et al., 2015)	• Solar PV systems	• Italian solar PV support scheme
(Rai & Robinson, 2015)	• Solar PV technology	• No policies studied
(Silvia & Krause, 2016)	• Plug-in electric vehicles	• Subsidies
(Snape et al., 2015)	• Heat pump	• UK Renewable Heat incentive
(Wolf et al., 2015)	• Electric vehicles	• Tax exemption and subsidy
(Zhang et al., 2014)	• Rooftop solar systems	• Financial incentives and seeding (give away)
(Azar & Menassa, 2011)	• HVAC heating and cooling technology	• No policies studied
(Chen et al., 2012)	• No technology modelled	• No policies studied
(Kowalska-Pyzalska et al., 2014)	• No technology modelled	• No policies studied
(Byrka, Jedrzejewski, Sznajd-Weron, & Weron, 2016)	• Green eco-innovations	• No policies studied
(Jensen, Holtz, Baedeker, & Chappin, 2016)	• CO_2 meter	• No policies studied (diffusion scenarios)
(Jensen, Holtz, & Chappin, 2015)	• Behavior-changing feedback device	• No policies studied (diffusion scenarios)

3.4. Decision making theories applied

Moglia et al. (2017) identify three different decision making models that can be used to describe the adoption of energy efficient technologies. These decision making models are: the Theory of planned behavior, the Consumat approach and the use of a utility function. The Consumat approach is a theoretical framework that describes agent decision making based on behavioral science. However none of the reviewed ABM studies seems to have adopted this approach. The theory of planned behavior on the other hand is quite a popular behavioral theory applied. It is used in seven out of the 23 reviewed studies. Last, Moglia et al. (2017) name utility functions as a way to describe agent decision making. Five out of the 23 studies make use of a utility function in their agent based model. By using a utility function to describe the behavior of agents the decision making is not really based on a behavioral sciences, but rather on the assumption that agents maximize their economic utility. These models are therefore significantly influenced by economics. Some of the reviewed agent based models do not use any specific theory to describe the behavior of agents. Examples of these studies are Cao et al. (2017), Faber et al. (2010), Snape et al. (2015), Zhang et al. (2014) and Azar and Menassa (2011). These ABM studies are typically grounded in detailed data from empirical research. The decision making logic in these studies is then based on a number of equations that describe thresholds or factors influencing the adoption of energy efficient technologies by households.

Table 2 - Theories and Data used in ABM studies

Reference	**Agent decision theory used**	**Type of Data**
(Alyousef et al., 2017)	• Affect control theory	• Survey data and official reports
(Cao et al., 2017)	• No theory as basis defined	• Data from US institutions
(E. J. L. Chappin & Afman, 2013)	• Social network theory	• Survey data and internet sources
(Faber et al., 2010)	• No theory as basis defined	• No empirical data used, publicly available data
(Friege, 2016)	• Social impact theory	• Survey data, publicly available data
(Hicks & Theis, 2014)	• Multiplicative utility function • Probabilistic choice mechanism	• Survey data
(Hicks et al., 2015)	• Multiplicative utility function	• Survey data
(Maya Sopha et al., 2011)	• Theory of planned behavior • Social network theory • Meta-theory of consumer behavior	• Survey data
(McCoy & Lyons, 2014)	• Utility function	• Survey data

(Sopha et al., 2013)	• Theory of planned behavior • Meta theory of consumer behavior	• Survey data, National statistics data
(Noori & Tatari, 2016)	• Utility function	• Data from previous studies
(Palmer et al., 2015)	• Multi-attribute utility function	• Statistical data
(Rai & Robinson, 2015)	• Theory of planned behavior • Relative agreement algorithm	• Survey data
(Silvia & Krause, 2016)	• Diffusion of innovations	• Empirical data and probabilities
(Snape et al., 2015)	• No theory as basis defined	• Predictions from other studies
(Wolf et al., 2015)	• Theory of innovation adoption • Homophily in social networks	• Survey data
(Zhang et al., 2014)	• No theory as basis defined	• Dataset from the California Solar Initiative
(Azar & Menassa, 2011)	• No theory as basis defined	• No empirical data used
(Chen et al., 2012)	• Network theory	• Data from empirical experiment
(Kowalska-Pyzalska et al., 2014)	• Theory of planned behavior • Value-belief-norm model	• No empirical data used (theoretical model)
(Byrka et al., 2016)	• Theory of planned behavior • Network theory	• No empirical data used (theoretical model)
(Jensen et al., 2016)	• Theory of planned behavior	• Empirical data used
(Jensen et al., 2015)	• Theory of planned behavior	• Commercial data used

A last theory that is used in the reviewed agent based modeling studies is social network theory. This theory does not aid in describing the decision making logic of agents but does make use of agent based modeling's strengths. By creating a social network of agents the diffusion of knowledge about technologies can accurately be modelled. Studies that make use of social network theory are Chappin and Afman (2013), Friege (2016) and Maya Sopha et al. (2011).

The reviewed ABM studies seem to be divided into a number of groups that base their decision making logic on different theories or models. There are the studies that base their logic largely on behavioral and psychological research: the theory of planned behavior. Next there are studies that use utility functions to describe agents and are thus largely based on economic theory. And lastly there are ABM studies that do not use any theory to describe the decision making logic of agents. These studies ground their decision making logic in empirical data.

3.4. Type of data used in ABM studies

Lastly, the type of data that is used to support the agent based modeling studies is discussed. Table 2 shows that a good majority (13 out of 23) of studies uses data from surveys or empirical studies to support the agent based model. Usually this data is used to set parameters in the model or to calibrate parameters. Some modeling studies, like Cao et al. (2017), Faber (2010), Palmer et al. (2015), Snape et al. (2015) and Azar and Menassa (2011) do not make use of empirical research to support their parameterization. Instead these studies use data from other sources like: government institutions, outcomes and predictions from other research reports or internet sources to parameterize model inputs. Naturally, the data collection method or data source (survey, or research results), depends on the data demand of the agent based model. For agent based models that are based on behavioral theories the use of empirical data that supports the theory and parameterization is needed. Agent based models based on economic theory (utility functions) may benefit more from other types of data like statistical data.

Overall, it can be observed that all agent based modeling studies are using data that suits the decision making approach chosen, to substantiate their model results and validity. Agent based modelers thus fit their model to the data available to them or expand their study with a suited empirical research.

4) Conclusions

Agent based modeling is increasingly being used to model the adoption of energy efficient technologies by households. Agent based modeling is considered as a suitable modeling method because it can effectively address the complex attitudes, preferences of households and the complex interactions between and among households. In this paper 23 agent based modeling studies on the adoption of energy efficient technologies have been reviewed. A number of conclusions regarding these agent based modeling studies can be drawn.

Firstly, many of the reviewed agent based modeling studies focus on the adoption of relatively novel energy technologies. These technologies fulfill the same function as their established counterparts, for example the electric vehicle versus regular petrol car. Many of the studies also focus on the adoption of one type of technology. Comparisons between different technologies are only done in some of the studies. One avenue for further research is therefore to model the adoption of more established residential energy technologies and comparing the adoption of different efficiency models of this technology. Technologies one could think of are for instance the fridge, freezer, air conditioner, washing machine, dish washer, etc. These type of energy technologies are deeply embedded in households and replacing them for more efficient alternatives is therefore a very complex issue, which is interesting to explore using agent based modeling.

Secondly, the efficiency policies that are included in the reviewed agent based models are rather limited to financial incentives and regulation. This may be due to the focus of most of the reviewed agent based modeling studies on the adoption of a certain technology. For this reason, an interesting future ABM research could shift this focus from energy efficient technologies to the efficiency policies that affect adoption. Mundaca et al. (2010) list many different policy instruments, such as: tax exemptions, subsidies, tradable white certificates, soft loans, performance standards, labeling and certification programs, awareness raising campaigns, energy efficiency tenders and energy efficiency obligations (Mundaca et al., 2010). Future ABM studies could explore the effectiveness of these different energy efficiency policies. Moreover the effect of third parties that influence the adoption process (intermediary parties) on the adoption of energy efficiency by households is left unexplored.

From the analysis on decision making theories and data sources a few conclusions can be drawn as well. Different groups can be distinguished according to the type of decision making logic is used. One group of studies bases their decision making logic on behavioral theories like the theory of planned behavior. Another group uses utility functions to describe the motivations and decisions agents make in the model. Lastly, some models do not base their decision making logic on any sort of theory. Another conclusion that can be drawn is that most of the agent based modeling studies are well supported by empirical data. Almost all studies use some sort of externally acquired data for the parameterization of their agent based model.

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