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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.

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