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Abstract

This paper investigates key drivers and barriers behind homeowners' decisions to switch from a fossil fuel (i.e. oil or gas boiler) to a renewable residential heating system (RHS). For this purpose, we draw on data from a 2010 questionnaire survey among owners of existing 1-family or 2-family homes in Germany that had received a financial grant for installing an (at least partly) renewable RHS (i.e. heat pump or wood pellet boiler). We analyze the data by means of logistic regression techniques. First, our results show that the motivation to deal with external threats (i.e. environmental protection and reduction of dependence on fossil fuels) and a higher degree of RHS-related knowledge are key drivers for switching to a renewable RHS. Second, we identify the different barriers that prevent homeowners from adopting a specific RHS. In particular, for the adoption of fossil fuel RHS, the perceived strong reliance on pricey oil or natural gas is found to be a major hurdle. For the heat pump, we find that the perceived difficulty of getting used to the system and a misunderstanding of its principal functioning are important obstacles. Finally, for the wood pellet boiler, our results imply that non-adopters perceive the low usability, the labor-intensive operation, and the systems' high fault liability to be important barriers. We conclude that homeowners often fear major changes to their current status quo (e.g. replacement of the existing heating system infrastructure) and, thus, tend to opt for minor and thus quick adjustments to their RHS (e.g. replacing only the boiler). Likewise, a higher replacement rate of fossil fuel by renewable RHS requires the homeowners' willingness to relinquish old habits and perceptions of how an RHS works and operates.

Key words: Residential heating systems, Private households, Technology replacement, Adoption barriers, Consumer choice

JEL Classification Nos.: C25, D12, O33, Q41

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1 Introduction

In the coming decades, Germany will have to face the challenge of ambitious climate protection goals, including an 80% to 95% reduction of greenhouse gas emissions by the year 2050 compared to 1990 levels. This objective concerns to a large extent energy-related CO_2 emissions. Consequently, the energy concept (*Energiekonzept*) of the German government from September 2010 and the bundle of laws from summer 2011 targeting the transition of the energy system aim at realizing a more sustainable energy system. This involves the transformation from a fossil fuels-based to an almost completely renewable-based energy system (*Energiewende*), and a significant improvement of the energy end-use efficiency in all sectors of the economy. Against this background, fuel production, electricity generation, and the provision of heat are seen as important pillars for realizing the transition towards a more sustainable energy system.

The provision of heat for industrial processes, hot water generation, or residential space heating purposes accounts for a large portion of the final energy demand in Germany. Since fossil fuels such as oil or natural gas are commonly used for heat generation, a major share of the energy-related CO_2 emissions stems from this activity. According to DLR et al. (2012), heat generation consumed 58% of the final energy demand and was based to 72% on fossil fuels in 2008. Consequently, about 40% of the energy-related CO_2 emissions originated from this activity. Space heating in residential, office, or industrial buildings seems to be the most significant field of application. In 2008, about 50% of the final energy demand for heat generation was used for space heating. Thereof, residential buildings consumed about two thirds. This shows the high importance of the residential heating sector for realizing the climate protection targets. Hence, in 2010, the German government announced the goal to reduce the primary energy requirements of the residential buildings stock by at least 80% by 2050. Renewable energy sources are supposed to cover the remaining energy requirements.

Accordingly, besides reducing the energy requirements of residential buildings by improvements to the building shell or the installation of innovative residential heating systems (RHS) in newly built homes, the replacement of outdated and inefficient fossil fuel RHS by more efficient appliances primarily based on renewable energy sources in existing homes plays a crucial role in the transition of the energy system. For the coming decades, this requires that most owners of existing homes will have to convert their old fossil fuel, and thus CO_2-intensive RHS, into a less CO_2-intensive and renewable RHS. However, as RHS have the characteristics of highly durable goods and therefore a long lifetime, only few opportunities will arise in a homeowner's life for replacing the RHS.

The current RHS stock in Germany is characterized by a relatively high number of outdated and inefficient fossil fuel RHS. Data from the German Federation of Chimney Sweeps (Bundesverband des Schornsteinfegerhandwerks – Zentralinnungsverband, ZIV) for the year 2012 show that about 63% of the oil- and gas-fired RHS installed in 1-family or 2-family homes (i.e. installed capacity < 50 kW) were older than 15 years (ZIV, 2013). In particular, 47% of the RHS were 15 to 21 years old and 16% were even 22 years and older. Since the lifetime of an RHS is typically about 20 years (Shell and BDH, 2013), this shows that almost two thirds of the current stock of RHS will have to be replaced by new installations soon. Moreover, an RHS replacement decision determines the potential CO_2 emissions of a home for the same period of time, assuming that there are no changes in behavior and intensity of use. Hence, there is indeed a window of opportunity for realizing high energy and CO_2 savings in the residential heating sector within the coming years by introducing renewable RHS on a large scale. However, achieving this goal requires that homeowners switch from fossil fuels to renewable energy sources to heat their homes. In contrast, for the year 2012, data on the annual market shares of newly installed RHS in Germany show that more than 80% of the new installations are still based on fossil fuels such as oil or gas (see figure 1). Moreover, in 2011 the large majority of RHS installations (84.9%) took place in existing buildings, whereas only a small number (15.1%) were installed in newly built homes (Destatis, 2012).

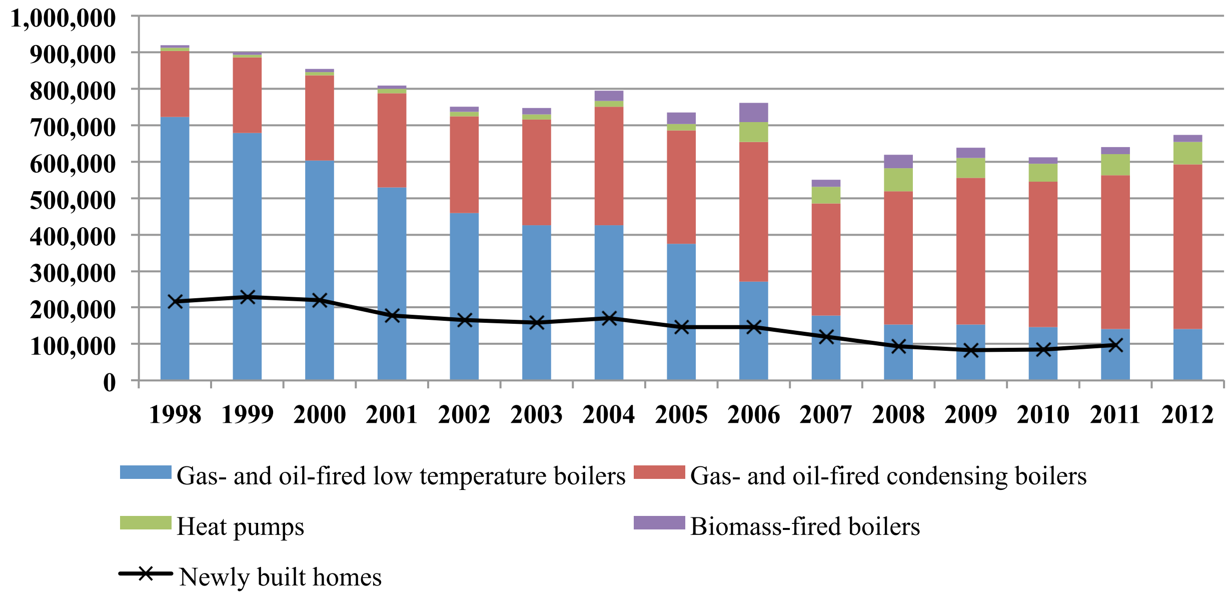

Figure 1: Annual number of newly installed RHS and newly built homes in Germany.
Source: Own illustration, based on data from BDH (2012) and Destatis (2012).

While there has been an increasing tendency towards renewable RHS in newly built homes in recent years (also driven by legal obligations to cover a certain share of heat from renewable sources), fossil fuel RHS still dominate the replacement decision in existing homes (Shell and BDH, 2013). Therefore, increasing the share of renewable RHS in existing homes is of high relevance for achieving the climate protection targets of the German government in the residential heating sector. A number of policy instruments targeting RHS have been implemented in Germany (e.g. Michelsen and Madlener, 2012). While the installation of renewable RHS in newly built homes is targeted by regulations and some financial support programs, such as the "Energieeffizient Bauen" of the government-owned development bank KfW, the installation of renewable RHS in existing homes is mostly promoted by financial incentives such as capital grants or low-interest loans. In particular, for newly built homes, the "Act on the Promotion of Renewable Energies in the Heat Sector" requires a minimum share of heat from renewable sources (i.e. solar, biomass, or geothermal) for covering the homes' energy requirements for space heating and hot water preparation. Financial support programs, such as the Market Incentive Program (MAP), implemented by the German Federal Office of Economics and Export Control (BAFA – *Bundesamt für Wirtschaft und Ausfuhrkontrolle*), or the Energy-Efficient Refurbishment Program of KfW offer low interest loans or capital grants connected to the renewal or initial installation of an innovative RHS. On the level of the federal states or the communities, there are also a number of similar financial incentive programs and information campaigns targeting RHS. Finally, some utilities offer financial incentives to support the installation of certain RHS. However, for achieving the goals of the *Energiewende*, a number of additional policy instruments targeting the residential heating sector will have to be implemented in the coming years in Germany. Thus, a better understanding of what motivates homeowners to stick with a fossil fuel RHS or to switch to a renewable RHS is of high relevance for realizing the goals of the energy transformation process in Germany.

Against this background, our research empirically investigates drivers and barriers of actual RHS replacement decisions of owners of existing 1-family or 2-family homes in Germany. In particular, the focus is on the determinants of switching from a fossil fuel to a renewable RHS. In this paper, we argue that the drivers and barriers of the replacement decision can be grouped into different categories, including elements of rational decision-making, emotional characteristics as well as attributes that relate to socio-economic characteristics of the homeowner and properties of the home. Thus, our two research questions are: 1. What are the drivers behind homeowners' decisions to switch from a fossil to a renewable RHS? 2. What are the barriers that prevent homeowners from converting their fossil fuel into a renewable RHS?

For the purpose of our research, we carried out a representative, self-administered mail survey among randomly selected owners of already existing or newly built 1-family or 2-family homes in Germany. The participants were sourced from a list of homeowners that had received a financial grant from BAFA between January 2009 and August 2010 for installing a new RHS that was (at least partly) based on renewable energy sources. Our research is restricted to the four most frequently adopted types of RHS in Germany: oil-fired and gas-fired condensing boiler with solar thermal support, heat pump, and wood pellet-fired boiler. Hereby, we gathered a unique set of micro-data on the homeowners' actual RHS replacement decisions as well as reasons for their not adopting an alternative RHS.

Our empirical approach is based on regression models for categorical outcomes and is divided into two steps. In a first step, we analyze the positive RHS replacement decision, i.e. the drivers behind the homeowners' decisions to switch from a fossil fuel to a renewable RHS. For this purpose, we apply a binary logit regression model (adoption of a renewable RHS as dependent variable). As independent variables, we use socio-economic and home characteristics, the geographical location, knowledge level, and motivational factors behind the RHS replacement decision. In a next step, we investigate the negative RHS adoption decision. In particular, we study the barriers that prevented adopters of a certain type of RHS from choosing an alternative RHS (i.e. what drives the active decisions of homeowners who stick with fossil fuel RHS to not take up renewable RHS at all, and vice versa). For the econometric estimation, we use a multinomial logit (MNL) model with the non-adopted RHS as dependent variable. Perceived economic and non-economic barriers and perceptions about specific attributes of the non-adopted RHS serve as independent variables.

While empirical economic research on *energy appliance and fuel choice* is relatively extensive and covers different sectors, studies on *energy appliance and fuel switching behavior* focus to a large extent on stoves and fuels for cooking in developing countries by applying the so-called "energy ladder model" (see Van der Kroon et al., 2013, for a recent meta-analysis). For explaining switching behavior, most of the studies use as explanatory variables socio-economic characteristics (in particular, income), attributes of the home and the location, or energy prices, while the role of motivational aspects or energy-related knowledge has been analyzed much less. Thus, our research adds to the literature on the households' energy appliance and fuel switching behavior in the context of an industrialized country. For the case of the non-adoption decision, the literature mainly focuses on the *energy efficiency gap* (see Jaffe and Stavins, 1994, or Sorrell et al., 2004, for a general overview of this theoretical concept) and the *consumers' resistance to innovations* (Kleijnen et al., 2009) by investigating the influence of different barriers that prevent consumers from choosing a certain (energy) technology. While the number of empirical studies on the determinants of positive RHS adoption decisions (see above) has been increasing over the past years, there is only relatively little empirical research that explicitly studies the reasons for not adopting a certain RHS (i.e. negative adoption decision). Therefore, our research also contributes to a better understanding of barriers to adopting renewable instead of fossil fuel RHS.

The remainder of this paper has the following outline: section 2 frames our research and gives an overview of the theoretical and empirical literature on the consumers' product replacement decisions and the literature on barriers to adopting a certain technology with a focus on RHS. Section 3 describes the research design including the survey procedure, data used, and empirical methodology applied. In section 4, we present the results of the empirical analysis. Finally, in section 5, we discuss the implications of our research and provide some conclusions and recommendations for policy-making, business, and further research.

2 Literature review

2.1 Technology replacement and switching behavior

The determinants of energy technology adoption have been extensively studied, both from a theoretical and empirical perspective, by scholars from various disciplines (for a literature review, see Cowan and Daim, 2011). In particular, empirical research on *energy appliance and fuel choice* covers different sectors, such as transport (e.g. He et al., 2012), energy utilities (e.g. Tauchmann, 2006), private households (e.g. Liao and Chang, 2002; Mansur et al., 2008), or energy technologies (e.g. Braun, 2010; Lillemo et al., 2013; Mahapatra and Gustavsson, 2007, 2008, 2009; Michelsen and Madlener, 2012, 2013; Sopha and Klöckner, 2011).

However, *replacement purchases of energy technologies* have so far been less investigated. The literature on product replacement decisions (for a general overview, see Guiltinan, 2010, or Goldenberg and Oreg, 2007) mainly deals with information and communication technologies, such as personal computers (Kretschmer, 2004), video players (Van Rijmsoever and Oppewal, 2012), or mobile phones (Jun and Kim, 2011), and household appliances (Kivi et al., 2012; Prinzie and Poel, 2007). Research on energy technologies and fuels so far has focused to a large extent on the replacement behavior for stoves and fuels for cooking in developing countries by applying the *energy ladder model* (Van der Kroon et al., 2013). In this concept, private households are modeled in a neoclassical framework as utility-maximizing consumers that move from primitive fuels (e.g. animal or agricultural wastes, firewood), over transition fuels (e.g. charcoal, kerosene, coal) to advanced energy carriers (e.g. biofuels, electricity, or liquefied petroleum gas) as they gain socio-economic status. For explaining switching behavior, most of the empirical studies applying the energy ladder model use as explanatory variables selected socio-economic and socio-demographic characteristics (e.g. income, education, age, household size, or gender of the household head). Further variables describing attributes of the home (e.g. indoor water, number of rooms, or access to fuels), the location of the home (e.g. region) or fuel prices are used less frequently. In most studies, the roles of motivational aspects, attitudes, or energy-related knowledge are not analyzed. The energy ladder model mainly focuses on an increasing socio-economic status of a private household for explaining fuel- switching behavior and, thus seems to be less adequate at first sight for investigating the case of replacement purchases of RHS in industrialized countries.

Only little empirical research so far deals with the determinants of fuel switching and energy appliance replacement behavior of private households in industrialized countries. For example, there are some studies that investigate the replacement behavior of car owners (e.g. de Haan et al., 2006, Koo et al., 2012, and Nayum et al., 2012) or the choice between gasoline or diesel and alternative fuels such as sugarcane ethanol (e.g. Anderson, 2012, Pacini and Silveira, 2011, and Salvo and Huse, 2013). For the case of RHS, some of the rare empirical studies include Fernandez (2001) on the replacement of home appliances in the US and Sopha et al. (2010) on the factors that influence the homeowners' preferred type of anticipated future RHS. Fernandez (2001) studies the replacement of electric space heaters and air conditioners by estimating a duration model. She finds that household demographics and product features explain replacement decisions. Sopha et al. (2010) analyze the factors that determine the intention to replace the current RHS by a sustainable heating system, such as heat pump or wood pellet-fired boiler. Their results show that socio-demographic factors (in particular, the age of the homeowner), communication among households, perceptions about the importance of RHS attributes (in particular fuel supply security and operational cost), and the applied decision strategy will influence the choice of a sustainable RHS in the future. Thus, our research contributes to the empirical literature on the households' energy appliance and fuel-switching behavior in the context of an industrialized country.

2.2 Barriers to technology adoption

There are several strands in the literature that investigate barriers to adopting innovative technologies in general and energy technologies in particular (i.e. negative technology adoption decisions). In order to frame our research, we review the *energy efficiency gap* and the *con-*

sumer resistance to innovations literature. Moreover, we give an overview of the empirical literature on barriers to adopting RHS.

The term *energy efficiency gap* (first introduced by Hirst and Brown, 1990; for a further discussion, see e.g. Jaffe and Stavins, 1994; Sorrell et al., 2004; Allcott and Greenstone, 2012) is used by economists to describe the phenomenon that investments in energy-efficient technologies are seemingly suboptimal, i.e. an individual does not carry out an investment that appears cost-effective on an estimated life-cycle basis. Empirical evidence shows that the energy efficiency gap or energy paradox can be observed in a number of cases (for a review of empirical studies see e.g. Brown et al., 1998 or Allcott and Greenstone, 2012). According to Wilson and Dowlatabadi (2007), traditional economics explains the energy efficiency gap with market and non-market barriers, such as a lack of information on available technologies, limited access to capital, misaligned incentives, imperfect markets for energy efficiency technologies, and organizational obstacles (see also Brown, 2001, or Levine et al., 1995). These barriers prevent individuals from making decisions that are rational from a resource use and economic perspective, i.e. decisions are neither energy-efficient nor economically efficient. In the literature, the classification of these barriers varies, but includes mostly categories such as risk, high upfront costs for technologies, split incentives (such as the landlord-tenant dilemma), imperfect information, hidden costs, and bounded rationality (for a detailed classification, see e.g. Jaffe and Stavins, 1994). In this context, barriers to switching from a fossil-fired to a renewable RHS may, for example, be high installation costs in the beginning, financial risk connected to uncertainty stemming from the stochastic future of energy prices, negative perceptions about RHS-specific attributes (e.g. ease of use), or regulatory barriers (e.g. restrictions on ground-source heat pumps in certain areas).

The *consumer resistance to innovation* literature (see Kleijnen et al., 2009, for a general overview) investigates the influence of different barriers that prevent consumers from choosing a certain (energy) technology. Kleijnen et al. (2009) propose a conceptual framework for studying consumer resistance, which includes the following three major components of resistance: (i) rejection, (ii) postponement, and (iii) opposition. As main groups of antecedents to consumer resistance they identify the degree of change required and conflicts with the consumer's prior belief structure. For the purpose of our research, we focus the review *of the consumers resistance to innovations* framework on the first component, i.e. "… the active decision to not at all take up an innovation" (Kleijnen et al., 2009, p. 352) and relate the findings to the case of RHS. We follow Claudy (2011) who proposes a classification of resistant consumer categories and applies this to the case of microgeneration technologies. As main determinants of this type of high-resistance to innovations, *functional* and *psychological barriers* are identified based on Claudy (2011). Functional barriers describe problems that consumers associate with adopting an innovation. These barriers can be perceptions related to the usage, value, and risk of the innovation. Usage barriers can be characterized by perceived incompatibility with personal values, past experiences, and/or existing practices (e.g. maintenance requirements of the RHS, fuel acquisition). Moreover, this can also be an unsuitable existing infrastructure (e.g. if a home lacks the storage space for wood pellets or a gas port). The second functional barrier, a low perceived value of the innovation, can be described by the perceived relative advantage (i.e. the degree to which consumers believe that an innovation is superior to another one) and costs of the innovation (i.e. certain cost types are too high). For instance, homeowners may decide not to adopt a certain RHS if the comfort or environmental performance of an alternative RHS is perceived to be relatively higher. Moreover, homeowners may be threatened by high investment costs of an RHS. High perceived uncertainty or risk represents the third functional barrier explaining resistance to innovations. This can be the perceived risks related to the performance of an innovation (e.g. homeowners are suspicious about the functional reliability of an RHS) and/or the perceived complexity (e.g. homeowners perceive an RHS to be difficult to use or understand). The second type of barrier, psychological obstacles, relates to mental conflicts that can result in resistance. Claudy (2011) distinguishes between compatibility with values (e.g. how does a homeowner feel about a technology?) and subjective norms (e.g. what is the perceived social acceptance of a technology?). In particular, innovations that require consumers to deviate from their existing principles and customs are likely to result in higher resistance. Moreover, if the social acceptance of an innovation is perceived to be low, consumers may be more likely to have higher resistance.

Empirical research that explicitly studies the reasons for not adopting a certain RHS is relatively scarce. For the case of Norway, Sopha et al. (2011) investigate differences between adopters and non-adopters of wood pellet-fired RHS. They show that there are significant differences between these two groups with respect to socio-demographic characteristics, decision-related factors, heating systems adopted, and reasons for shifting heating systems. As being the main barriers to adopting a wood pellet-fired RHS they identify high installation costs, difficulties of refitting the home for this RHS, and an insufficiently high capital grant. Claudy (2011) studies the resistance of Irish homeowners to microgeneration technologies, including wood pellet-fired boilers, solar panels, and micro wind turbines. The results show that homeowners are heterogeneous with respect to their resistance levels. In particular, functional (i.e. incompatibility with their existing infrastructure and daily habits and routines, relatively less value), and psychological (i.e. perceived image) barriers and socio-demographic factors (older homeowners are likely to be more resistant) influence the resistance to a new technology. Further studies on barriers to adopting RHS include Grieve et al. (2012) on energy-efficient hot water systems in New Zealand, Balcombe et al. (2013) on microgeneration technologies in the UK, and Stieß and Dunkelberg (2013) on energy retrofits (including renewable heating systems and high-efficiency condensing boilers as possible options) by private homeowners in Germany.

3 Methodology and data

3.1 Survey development and implementation

The data analyzed in this paper stem from survey responses of owners of existing 1-family or 2-family homes in Germany who replaced their old oil- or gas-fired RHS between January 2009 and August 2010 either by a new gas- or oil-fired condensing boiler with solar thermal support, a heat pump, or a wood pellet-fired boiler. It represents a subsample of a representative mail survey conducted in 2010 among owners of newly built and existing 1-family or 2-family homes that received a capital grant by BAFA for the installation of a new RHS (for details of the survey, see Michelsen and Madlener, 2012).

The questionnaire consisted of four parts. The first one contained questions about the installed RHS and the determinants of the adoption decision. The second part dealt with the decision not to adopt an alternative RHS. For this purpose, the participants were asked to indicate whether they had also considered an alternative RHS in their decision process. If an alternative RHS had been considered, we asked more detailed questions about economic and non-economic barriers to adoption and the participants' perceptions about certain attributes of the non-adopted RHS.[1] In parts three and four, the survey participants were asked about selected attributes of their homes and socio-demographic characteristics. A discussion of possible limitations related to the survey can be found in Michelsen and Madlener (2012, 2013).

[1] For example, if a homeowner adopted a gas- or oil-fired condensing boiler with solar thermal support, we asked whether any of two possible alternative RHS (heat pump and wood pellet-fired) had also been considered. If the homeowner indicated that the heat pump had been considered in the decision-making process but had eventually not been selected, we asked further questions regarding economic and non-economic barriers to adoption and the participants' perceptions about certain attributes of the heat pump. We carried out the same procedure for the second alternative RHS (wood pellet-fired boiler in our example). If the homeowner indicated that an alternative RHS had not been considered, no further questions regarding this RHS were asked.

The questionnaire was mailed to 5000 randomly selected homeowners who had received a BAFA grant. 2985 questionnaires were returned, which corresponds to an overall response rate of 59.7%. We excluded all observations where large sections of the questionnaire had not been filled out or the questionnaire had not been filled out at all, where the owner did not live in the home (i.e. no self-usage), where there was a multi-family home, or where the installed main RHS was not a gas- or oil-fired condensing boiler, a heat pump, or a wood pellet-fired boiler. This reduced the gross sample to N=2682 observations.

Since the first objective of our research is to study the drivers and barriers of actual RHS replacement decisions of owners of existing homes, we excluded all observations for newly built homes and where the old RHS was neither oil- nor gas-fired. Thus, the gross subsample consisted of N=1419 observations. In a next step, drawing from the gross subsample, we excluded all observations where at least one of the independent variables was missing (casewise deletion). Therefore, the net subsample for investigating the decision to switch to a renewable RHS consisted of N=1125 observations.

The dependent variable is binary and describes the RHS replacement decision taken (i.e. switch from a fossil fuel to a renewable RHS, or not). Moreover, there are 17 independent variables that can be grouped into three categories. The first two categories capture control variables, including socio-demographic aspects and attributes of the home. The third category consists of variables capturing motivational aspects of the adoption decision (cost considerations, perceived usability and compatibility with existing habits and norms, capital grant from the government, reactions to external threats, such as environmental protection and independence from fossil fuels, comfort considerations, and influence of peers, such as family, friends or neighbors) and the degree of RHS-related knowledge of the homeowner (i.e. perceived familiarity with the oil- or gas-fired condensing boiler, heat pump, or wood pellet-fired boiler). The six variables describing motivational factors are based on Michelsen and Madlener (2013) and consist of three to six items each. Table 1 displays the summary statistics for the data on the RHS replacement decision.

Table 1: Summary of sample statistics for the RHS replacement decision (*N*=1125)

Variable label	Variable description	Scale	*N*	%
Dependent variable				
Switch	Switch from a fossil fuel to renewable RHS	binary (yes; no)	584	51.9%
Independent variables *Socio-demographic characteristics:*				
Income	Net income of the household	1 < €2000	175	15.6
		2 = €2000 to €2999	384	34.1
		3 = €3000 to €3999	277	24.6
		4 = €4000 to €4999	155	13.8
		5 = €5000 to €5999	65	5.8
		6 > €6000	69	6.1
Age	Age of the homeowner	metric	53.6 (Mean)	11.2 (S.D.)
University	Homeowner has a university degree	binary (yes; no)	334	29.7
Female	Homeowner is female	binary (yes; no)	154	13.7
Attributes of the home:				
Size	Size of the home	1 < 100 m^2	36	3.2
		2 = 100 to 149 m^2	454	40.4
		3 = 150 to 199 m^2	330	29.3
		4 = 200 to 249 m^2	204	18.1
		5 > 250 m^2	101	9.0
Home_age	Age of the home	metric	45.8 (Mean)	32.1 (S.D.)
Retro	Parallel major retrofit of the home	binary (yes; no)	304	27.0%
Rural	Rural region	binary (yes; no)	431	38.3%
East	Eastern Germany	binary (yes; no)	100	8.9%
South	Southern Germany	binary (yes; no)	486	43.2%
Motivational factors and knowledge:			**Mean**	**S.D.**
Costs[*]	Cost considerations	5-point Likert scale	2.84	0.92
Attitude[*]	Perceived usability and compatibility with existing habits and norms	5-point Likert scale	4.03	0.65
Grant[*]	Relevance of capital grant from BAFA	5-point Likert scale	2.62	0.97
Threats[*]	Reactions to external threats (environmental protection and independence from fossil fuels)	5-point Likert scale	3.93	0.87
Comfort[*]	Comfort considerations	5-point Likert scale	3.07	0.96
Peers[*]	Influence of peers	5-point Likert scale	2.25	0.80
Knowledge[**]	Degree of RHS-related knowledge	5-point Likert scale	3.11	1.06

[*] These components are measured on a 5-point Likert scale: 1 = "completely disagree / unimportant" – 5 = "completely agree / very important". For further details on the six motivational factors, please refer to Michelsen and Madlener (2013).
[**] This component consists of three items ("When making your RHS adoption decision, how familiar were you with the following types of RHS? (i) Gas- or oil-fired condensing boiler with solar thermal support, (ii) Heat pump, and (iii) Wood pellet-fired boiler". The items were measured on a 5-point Likert scale: 1 = "not familiar at all" – 5 = "absolutely familiar") and together have a Cronbach's alpha (α) of 0.82.

For the second research question on the barriers that prevented homeowners from switching from a fossil fuel to a renewable RHS (i.e. non-adoption decision), we drew from the gross subsample of *N*=1419 participants. We excluded all observations where the participants indicated that no other RHS had been further considered in the decision process. This reduced the sample to 747 participants. Moreover, we excluded all observations where at least one of the independent variables was missing (casewise deletion). As a result, the net subsample consisted of responses from 665 participants. Since it was possible to indicate up to two alternative RHS that had been considered in the decision process, but eventually not adopted, the final number of observations for our analysis was at *N*=921.

The non-adopted RHS, which can either be a gas-fired or oil-fired condensing boiler with solar thermal support (FOSSIL), heat pump (HEAT-P) or wood pellet-fired boiler (WOOD), represents the dependent variable. For explaining the decision not to adopt a certain RHS, we use 21 independent variables that belong to the categories perceived as economic and non-economic barriers to adoption, and the assessment of RHS-related attributes. Table 2 displays the summary statistics for the non-adoption decision.

Table 2: Summary of sample statistics for the non-adoption decision (*N*=921)

Variable label	Variable description	Scale	*N*	%
Dependent variable				
Not_adopted	RHS considered in the decision process but eventually not adopted	1 = FOSSIL	234	25.4
		2 = HEAT-P	417	45.3
		3 = WOOD	270	29.3
Independent variables				
Perceived economic and non-economic barriers:			**Mean**	**S.D.**
Regulation	Regulatory constraints	5-point Likert scale[1]	1.71	1.01
Loc_home	Constraints related to the property	5-point Likert scale[1]	2.44	1.46
Infra_home	Infrastructural constraints	5-point Likert scale[1]	2.90	1.64
Rec_peers	Advice from peers	5-point Likert scale[1]	2.21	1.18
Rec_experts	Advice from experts	5-point Likert scale[1]	2.76	1.36
Budget	Financial scope for RHS	5-point Likert scale[1]	2.66	1.45
Price	Investment costs for RHS	5-point Likert scale[1]	2.80	1.46
Price_BAFA	*Price* minus BAFA capital grant	5-point Likert scale[1]	2.54	1.36
Main_costs	Maintenance costs	5-point Likert scale[1]	2.34	1.16
Current_fuel_price	Current fuel price	5-point Likert scale[1]	3.01	1.34
Future_fuel_price	Expected future fuel price	5-point Likert scale[1]	3.40	1.39
Total_costs	Total costs of the RHS	5-point Likert scale[1]	2.93	1.24
Payback_period	Payback period	5-point Likert scale[1]	2.75	1.27
Evaluation of RHS-related attributes:				
Ease	RHS easy to use	5-point Likert scale[2]	2.56	1.07
Demo	Easy to explain the RHS to others	5-point Likert scale[2]	3.12	1.16
Habits	Easy to get used to the RHS	5-point Likert scale[2]	2.96	1.17
Effort	Low effort (maintenance, fuel acquisition)	5-point Likert scale[2]	3.06	1.11
Enviro	Eco-friendly RHS	5-point Likert scale[2]	2.50	1.11
Energy	Low energy consumption	5-point Likert scale[2]	2.88	0.95
Fault	Low fault liability	5-point Likert scale[2]	3.09	0.95
Indep	More independent from oil and natural gas	5-point Likert scale[2]	2.40	1.39

[1] Barriers to adoption measured on a 5-point Likert scale: 1 = "prevented me not at all" – 5 = "prevented me completely".
[2] Perceptions about RHS-specific attributes measured on a 5-point Likert scale (re-coded): 1 = "applies completely" – 5 = "does not apply at all".

3.2 Model specification

For the purpose of our research, we use discrete choice analysis and apply logistic regression techniques on the data. For investigating the RHS replacement decision, we use a binary logit model, whereas we explore the non-adoption decision by means of an MNL model. We use the Stata commands *logit* and *mlogit* to estimate parameters. The following brief introduction to these two logistic regression methodologies is based on Train (2003) and related), but applied to our specific approach.

3.2.1 Binary logit model

For homeowners, the decision of whether or not to replace their fossil fuel RHS with a renewable RHS is a "yes or no" binary choice. Therefore, the investigation of the RHS replacementing decision is a discrete choice analysis for which we construct a model covering the homeowners' decisions to switch to a renewable RHS. Our discrete choice model is grounded on a stochastic utility model of homeowners (i.e. decision-makers) and assumes that decision-makers seek to maximize utility when they decide to replace their RHS. This implies that when homeowners are willing to switch, it must be that the utility (*U*) of switching is higher than the utility of not switching, i.e. $U_{switch} > U_{no\_switch}$. We assume that the homeowner's utility of switching can be explained by several explanatory variables, including the different dimensions of the RHS adoption motivation and RHS-related knowledge as well as control variables in the categories socio-demographic characteristics and attributes of the home (see table 1 for an overview of the variables). Therefore, the utility of a homeowner *i* (i = 1, …, *I*) provided with alternative *j* (*j* = 1, …, *J)* can be formalized as follows:

$$U_{i,j} = \beta' X_{i,j} + \varepsilon_{i,j}. \quad (1)$$

where $X_{i,j}$ is the vector of explanatory variables $x_{i,j}$ with *n* elements (*n* = 1, …, *N*), β' the related vector of estimated parameters (i.e. unknown coefficients), and $\varepsilon_{i,j}$ the error term.

Note that in the binary case there are two alternatives in our choice set (*J* = 2), including the decision to switch (*j* = 1) or not to switch (*j* = 2). Thus, the switching probability for homeowner *i* is as follows:

$$P_{i,switch} = Prob\left(U_{i,switch} \geq U_{i,no\_switch}\right) = Prob\left(\beta' X_{i,switch} + \varepsilon_{i,switch} \geq \beta' X_{i,no\_switch} + \varepsilon_{i,no\_switch}\right). \quad (2)$$

Equation (2) describes the fact that homeowners base their evaluations on certain motivational factors and RHS-related knowledge, attributes of their homes, and socio-demographic aspects. If a homeowner perceives the utility of switching to a renewable RHS to be higher than sticking with a fossil fuel system, the homeowner will choose to switch. Further, it is assumed that $\varepsilon_{i,j}$ are independently and identically Gumbel-distributed. In other words, this means that $\varepsilon_{i,NU} - \varepsilon_{i,U}$ is assumed to be logistically distributed. Hence, the probability for switching to a renewable RHS is a binary logit given by

$$Prob\left(U_{i,switch} \geq U_{i,no\_switch}\right) = P_{i,switch} = \frac{exp\left(\beta' X_{i,switch}\right)}{exp\left(\beta' X_{i,switch}\right) + exp\left(\beta' X_{i,no\_switch}\right)}. \quad (3)$$

Equation (3) shows that the attribute difference between switching and no switching influences the switching probability, i.e. the probability is driven by the attributes' relative rather than absolute values. Moreover, this also shows that the quintessence of choice-theoretical models is choosing an alternative that is relatively better, rather than the absolute best. The estimated parameters show how the different independent variables impact the switching probability. For interpreting the results, we calculate average marginal effects (M.E.) of a change in variable $x_{i,n}$. This is useful, since a coefficient's magnitude and sign in non-linear models cannot be interpreted directly as the marginal effect of explanatory variable $x_{i,n}$ on the dependent variable $P_{i,switch}$. Marginal effects show the change in probability that a homeowner will switch to a renewable RHS if a selected explanatory variable $x_{i,n}$ is changed by one unit (keeping all other variables constant). The M.E. of a change in variable $x_{i,n}$ is:

$$\frac{\partial P_{i,switch}}{\partial x_{i,n}} = P_{i,switch}\left[\beta_{n,switch} - P_{i,no\_switch}\,\beta_{n,no\_switch}\right]. \quad (4)$$

Equation (4) shows that the marginal effect does not depend on the coefficient's estimate $\beta_{n,upgrade}$ alone, but also on the remaining coefficient estimates and variables.

3.2.2 MNL model

For analyzing the non-adoption decision, we use an MNL model for investigating the probability that a homeowner decides against a specific RHS out of a choice set of three unordered alternative RHS (FOSSIL, HEAT-P, and WOOD). This allows predicting the probability of not adopting a specific RHS. We use the not adopted RHS as the dependent variable and selected perceived economic and non-economic barriers to adoption as well as the assessment of RHS-related attributes as independent variables (see table 2). For this purpose, our choice set is extended to three alternatives and eqs. (2) to (4) are adjusted accordingly (for a more detailed technical description, see e.g. Train, 2003). The independence from irrelevant alternatives (IIA) is an important assumption of the MNL approach, i.e. the relation of the probabilities for choosing any two alternatives is independent of the presence of any other alternative. In order to examine the validity of this assumption, a standard Hausman test can be applied (Hausman and McFadden, 1984).

4 Results and discussion

First, we show the results for the RHS replacement decision. This allows insights into the drivers and barriers behind the homeowners' decisions to switch from an old fossil fuel to renewable RHS. Second, we present the findings on the barriers to adopting a certain RHS.

This allows a better understanding of how homeowners evaluate selected attributes of non-adopted RHS and gives insights into perceived economic and non-economic barriers.

4.1 RHS replacement decision

In this section, we explore the determinants of the homeowners' RHS replacement decisions by means of a binary logit model. When replacing an outdated fossil fuel RHS, owners of existing homes can basically choose to stick with a fossil fuel RHS (i.e. oil- or gas-fired condensing boiler with solar thermal support) or to switch to a renewable RHS (i.e. heat pump or wood pellet-fired boiler). Table 3 presents the results of the analysis.

Table 3: Results for the replacement decision based on a binary logit model (*N*=1125)

	M.E.		S.E.
Costs	0.012		0.015
Attitude	**-0.059**	***	**0.019**
Grant	0.018		0.014
Threats	**0.285**	***	**0.010**
Comfort	**-0.067**	***	**0.013**
Peers	0.011		0.015
Knowledge	**0.061**	***	**0.012**
Size	**0.028**	**	**0.012**
Home_age	**-0.001**	**	**0.000**
Retro	0.042		0.027
Rural	**0.042**	*	**0.025**
East	**0.140**	***	**0.040**
South	**0.050**	**	**0.025**
Income	-0.007		0.010
Age	**-0.005**	***	**0.001**
Female	-0.049		0.035
University	**-0.059**	**	**0.028**
Log-likelihood	-501.45		
Pseudo-R^2	0.3563		
N	1125		

Notes: Average marginal effects (M.E.), standard error (S.E.), superscripts ***, ** and * indicate statistical significance at the 1%, 5%, and 10% level, respectively.

We find the motivation to deal with external threats and the level of RHS-related knowledge to be significant drivers for switching to a renewable RHS. In particular, our results show a statistically significant and strong effect for the variable *Threats* that includes concerns related to the dependency on fossil fuels and the desire to contribute to environmental protection

(0.285^{***}). Consequently, homeowners with a preference for environmental protection and independence from fluctuating fuel prices and geopolitical crises that impact the oil and gas supply have a relatively high probability of converting to a renewable RHS. Moreover, we find a statistically significant and positive influence of RHS-related knowledge (*Knowledge*), i.e. more informed homeowners are found to have a higher probability of switching to a renewable RHS (0.061^{***}). This highlights the importance of information on and knowledge of aspects related to different RHS in the adoption process. On the other hand, we find homeowners who are motivated by comfort considerations (i.e. low effort with fuel acquisition, modest maintenance requirements, and improved utility of the home) and the compatibility with daily habits and routines to be less likely to switch a renewable RHS. In particular, a higher preference for comfort (*Comfort*) makes a homeowner more likely to stick with a fossil RHS (-0.067^{***}). A possible reason may be that homeowners still perceive renewable RHS to require relatively more attention during their operation. Moreover, if the homeowner is motivated by compatibility of the new system with existing habits and routines (*Attitude*), we also observe a lower probability to switch to a renewable RHS (-0.059^{***}). This can be explained by the fact that homeowners may fear required changes to their RHS-related habits and routines that are expected to arise from a switch to a renewable RHS. Thus, homeowners are more likely to stick with a system they are familiar with. For the motivational factors capital grant (*Grant*), or peers such as family, friends, and neighbors (*Peers*), we find no statistically significant results.

The findings for the control variables (socio-demographic characteristics and attributes of the home) have the expected signs and reflect the findings reported in Michelsen and Madlener (2012). In particular, we find for building characteristics that the size of the home (*Size*) has a significant positive effect on the switching probability (0.028^{**}). This implies that owners of larger homes have a higher probability of moving to a renewable RHS. A possible explanation is that large homes have more space for storing wood pellets or are more suitable for floor heating, which is usually combined with a heat pump. For age of the home (*Home_age*), we find a significant negative but relatively small effect (-0.001^{**}). A possible reason may be that switching to a renewable RHS often requires changes to the heating infrastructure (e.g. water tank for storing heat or suitable radiators), which are more difficult and costly to implement in older homes. In contrast, sticking with a fossil fuel RHS is connected to less upfront costs and requires in many situations only the replacement of the boiler and some minor adjustments to the energy system infrastructure of the home (e.g. chimney). Moreover, the geographic location of the home also has an effect on the switching probability. Homeowners in *Rural* areas

(0.042*), in the *East* (0.140***) or the *South* (0.050**) of Germany are more likely to switch. As discussed in Michelsen and Madlener (2012), this may reflect regional differences in the infrastructure (e.g. degree of development of the gas grid or price and distribution system for wood pellets), properties of the home (e.g. homes in certain regions are more suitable for renewable RHS), or heating traditions (e.g. history of heating with certain systems or more common to use biomass in rural areas). Moreover, there is not such a long tradition of heating with oil or gas in the East of Germany. Due to this, owners of existing homes in the former German Democratic Republic may be less susceptible to oil- or gas-based RHS and be more open to renewable-based systems.

Finally, for socio-economic characteristics of the homeowner, our analysis shows that these control variables are relatively less important determinants for switching to a renewable RHS. For the age of the homeowner (*Age*), we find a statistically significant influence that is relatively small and negative (-0.005***). This implies that younger homeowners are more open towards RHS that are based on renewable energy sources, whereas older homeowners are relatively more likely to stick with well-established, fossil fuel RHS. A reason for that may be that older homeowners fear the higher investment costs of renewable RHS and the required changes to the heating infrastructure of the home. For the variable *University*, we find a statistically significant negative effect (-0.059**). Thus, homeowners who have a university degree are apparently more likely to stick to a fossil fuel RHS. The household production theory by Becker (1965) offers a possible explanation for this observation. Usually, a university degree leads to a higher income, and, thus, increased opportunity costs of "home production". Therefore, homeowners with a university education are more likely to decide in favor of an RHS that is perceived to be a proven system and does not require much attention during operation in terms of maintenance needs and personal effort (e.g. fuel acquisition).

4.2 Reasons for non-adoption

In this section, we investigate the influence of perceived barriers on the probability of adopting either a fossil fuel RHS (FOSSIL) or a renewable RHS, including HEAT-P and WOOD, by means of an MNL model. In particular, we investigate the role of financial and non-financial barriers as well as the homeowners' assessments of selected attributes of the RHS. Table 4 presents the results of our analysis.

Table 4: Results for the non-adoption decision based on a multinomial logit model (*N*=921)

	FOSSIL			HEAT-P			WOOD		
	M.E.		S.E.	M.E.		S.E.	M.E.		S.E.
Regulation	0.0056		0.0103	**-0.0654**	***	**0.0135**	**0.0598**	***	**0.0107**
Loc_home	-0.0037		0.0066	**0.0821**	***	**0.0085**	**-0.0784**	***	**0.0081**
Infra_home	**-0.0344**	***	**0.0060**	0.0043		0.0084	**0.0302**	***	**0.0072**
Rec_peers	-0.0077		0.0096	-0.0196		0.0133	**0.0273**	**	**0.0118**
Rec_experts	0.0013		0.0083	**0.0347**	***	**0.0113**	**-0.0359**	***	**0.0101**
Budget	**-0.0406**	***	**0.0097**	0.0160		0.0134	**0.0246**	**	**0.0120**
Price	-0.0160		0.0170	**0.0483**	**	**0.0200**	**-0.0323**	**	**0.0159**
Price_BAFA	0.0222		0.0174	-0.0205		0.0192	-0.0016		0.0147
Main_costs	**-0.0337**	***	**0.0112**	**-0.0393**	**	**0.0155**	**0.0731**	***	**0.0132**
Current_fuel_price	**0.0632**	***	**0.0121**	**0.0531**	***	**0.0186**	**-0.1163**	***	**0.0161**
Future_fuel_price	0.0008		0.0129	**-0.0593**	***	**0.0181**	**0.0585**	***	**0.0153**
Total_costs	**0.0210**	*	**0.0124**	-0.0273		0.0187	0.0063		0.0169
Payback_period	-0.0099		0.0110	0.0253		0.0161	-0.0154		0.0142
Ease	0.0051		0.0113	**-0.0473**	***	**0.0162**	**0.0422**	***	**0.0143**
Demo	0.0080		0.0102	0.0177		0.0148	**-0.0258**	*	**0.0134**
Habits	**-0.0470**	***	**0.0120**	**0.0752**	***	**0.0172**	**-0.0283**	*	**0.0154**
Effort	0.0053		0.0115	**-0.0835**	***	**0.0166**	**0.0782**	***	**0.0144**
Enviro	0.0028		0.0109	**-0.0281**	*	**0.0156**	**0.0253**	*	**0.0139**
Energy	**-0.0745**	***	**0.0117**	**0.1239**	***	**0.0159**	**-0.0494**	**	**0.0144**
Fault	0.0173		0.0117	**-0.0739**	***	**0.0176**	**0.0566**	***	**0.0158**
Indep	**0.0745**	***	**0.0070**	-0.0192		0.0123	**-0.0554**	***	**0.0115**
Log-likelihood	-480.94								
Pseudo-R^2	0.51								
N	921								

Notes: Average marginal effects (M.E.), standard error (S.E.), superscripts ***, ** and * indicate statistical significance at the 1%, 5%, and 10% level, respectively. Reference category: FOSSIL.

For all samples, we performed Hausman and Likelihood Ratio (LR) tests to examine the robustness and quality of our empirical approach. The results of the Hausman tests show that the IIA assumption holds for each sample. Thus, the MNL regression approach is a suitable empirical approach for the purpose of this analysis. Moreover, LR tests for the dependent variables show that the merging of categories does not improve the quality of the results.

In the following, we discuss the statistically significant results for the assessment of specific attributes of the non-adopted RHS as well as the economic and non-economic barriers to adoption in more detail. All signs of the statistically significant coefficients have the expected direction.

4.2.1 FOSSIL

The main reason for homeowners to decide against an oil- or gas-fired RHS with solar thermal support is found in the anticipated high dependency on oil and natural gas (*Indep*, 0.075^{***}) that results in a strong exposure to recent price increases for these resources in Germany. In particular, barriers can be found in the current fuel price (*Current_fuel_price*, 0.063^{***}) and the expected life-cycle costs (*Total_costs*) that include all expenses over the system's lifespan (0.021^{*}). This may reflect that non-adopters are seriously concerned about the recent developments in fossil fuels prices (i.e. oil and natural gas are no longer perceived as low-cost fuels) and that FOSSIL is no longer seen as an RHS with low life-cycle costs. Note that this European situation is in stark contrast to the situation in Northern America, where oil and gas production by means of hydraulic fracturing ('fracking') has led to marked decreases in fossil fuel prices.

In contrast, aspects not related to fossil fuels seem to play only a minor role in the decision against this RHS. This indicates that homeowners are generally satisfied with FOSSIL. Especially, we find that homeowners have the perception that they could easily accustom themselves to this system (*Habits,* -0.047^{***}), and that a fossil fuel boiler would have low energy consumption (*Energy*, -0.075^{***}). Likewise, shortcomings in the infrastructure of the home (*Infra_home*), i.e. the home does not correspond to a standard home, are found to be less of a barrier to adoption (-0.034^{***}). This may reflect that homeowners perceive FOSSIL to be an RHS that can easily be installed, regardless of the available infrastructure of the home. We also find non-adopters to see economic aspects, such as the financial scope foreseen for purchase and the installation of the new RHS (*Budget*, -0.041^{***}) and the maintenance costs (*Main_costs*, -0.034^{***}) as relatively less important barriers to adoption. Thus, non-adopters apparently perceive the replacement of a fossil fuel boiler as comparatively easy to implement at predictable costs and to be linked to low maintenance expenditures.

4.2.2 HEAT-P

The homeowners' decisions against a heat pump are mainly driven by the perceived difficulty of getting used to the system (*Habits*, 0.075^{***}) and a misunderstanding of the functioning of this technology, i.e. homeowners assume this system to have relatively high energy needs (*Energy*, 0.124^{***}). Possible reasons may be that homeowners do not fully know how an electric heat pump works or confuse this technology with energy-intensive electric resistance heaters. This is also reflected by the fact that the current price for electricity (*Current_fuel_price*) is seen as a barrier (0.053^{***}). Moreover, the location of the home

(*Loc_home*), characterizing attributes of the property, also represents an obstacle (0.082^{***}). Note that this may also include situations where the prevailing soil conditions prevent the installation of a ground source heat pump or the home is located in a water protection zone. We also find experts, such as installers, energy consultants, or architects (*Rec_experts*), to be more likely to advise against this system (0.035^{***}). Reasons for the dissuasion by experts can be that the installation of HEAT-P often requires a major energy retrofit of the building or adjustments to the heating infrastructure for creating an optimal operating environment (i.e. low flow temperature of the heating system). Such a constraint may contribute to making HEAT-P less attractive for existing homes with a low energy standard or unsuitable radiators. Lastly, we find the purchasing price of the RHS (*Price*) to be a significant barrier to the adoption of HEAT-P (0.048^{***}). This reveals the relatively high costs connected to the installation of a heat pump (e.g. drilling of wells or digging of trenches in which to place the pipes that carry the heat exchange fluid).

In contrast, non-adopters perceive HEAT-P as an environmentally sound (*Enviro,* -0.028^{*}), reliable (*Fault*, -0.074^{***}) and easy to handle (*Ease*, -0.047^{***}) technology with relatively modest maintenance and cleaning requirements linked to the operation (*Effort*, -0.084^{***}). This is also reflected by the relatively low importance of the maintenance costs (*Main_costs*, -0.039^{**}) as a further barrier. Our findings for the perceived level of the future fuel prices (*Future_fuel_price*) show that homeowners are relatively less concerned about the future development of the electricity price for heat pumps (-0.059^{***}). For non-financial barriers, we find that the perceived influence of regulatory constraints (*Regulation*) is less relevant (-0.065^{***}).

4.2.3 WOOD

For the wood pellet-fired boiler, our findings show that non-adopters are mainly concerned about a perceived lack of necessary skills that makes using the system more demanding (*Ease*, 0.042^{***}) and the amount of work (*Effort,* 0.078^{***}) required for operating the system (e.g. disposal of ash) as well as the high fault liability (*Fault*, 0.057^{***}). Consequently, maintenance costs (*Main_costs*) for, e.g., the chimney sweep or cleaning, maintenance, and repair of the boiler are seen as the main financial barrier to adoption (0.073^{***}). Further economic barriers include doubts about the assumption that the wood pellets price will continue to be low in the future (*Future_fuel_price*, 0.059^{***}) and the perception that the switch to WOOD would require going beyond the financial scope foreseen for the new RHS (*Budget*, 0.025^{**}). This is in line with the study of Sopha et al. (2011), who identify high installation costs as a barrier. As non-financial barriers, we find the perceived influence of regulatory constraints (*Regulation*) to be an important obstacle (0.060^{***}). This may reveal that homeowners perceive the different regulations targeting wood pellet-fired boilers (e.g. the firing ordinance targeting the installation of wood pellet-fired boilers or the federal emission control ordinance setting limits for pollutant emissions) as relevant barriers to adoption. Likewise, the perception that the home does not correspond to a standard home (*Infra_home*) is a significant barrier to adopting WOOD (0.030^{***}). This may include shortcomings such as a lack of storage space for wood pellets. This finding is also reflected by Sopha et al. (2011) who find that difficulties in refitting the home for this RHS to be a barrier and Claudy (2011), who shows that the incompatibility with the existing infrastructure may represent an obstacle. Furthermore, non-adopters perceive WOOD to be less environmentally friendly (*Enviro*, 0.025^{*}), which may reveal concerns related to particulate matter or the sustainability in biomass production. Finally, the decision against WOOD is also exacerbated by the dissuasion of peers, such as family, neighbors, or friends (*Rec_peers*, 0.027^{**}). A possible reason may be that this RHS still has a relatively low reputation among non-experts compared to more proven and better known heating systems, such as FOSSIL and HEAT-P.

In contrast, homeowners appreciate the independence from fossil fuels (*Indep*, -0.055^{***}) and the perceived low energy consumption of WOOD (*Energy*, -0.049^{**}). Moreover, non-adopters assume that they could easily accustom themselves to WOOD (*Habits*, -0.028^{*}) and that they could communicate possible benefits connected to WOOD to others without difficulty (*Demo*, -0.026^{*}). For economic barriers, we find the purchasing price of the RHS itself (*Price*, -0.032^{**}) to be less relevant. This may reflect that homeowners are more concerned about the costs that go beyond the purchasing price of the heating system (i.e. required changes to the home's infrastructure, or operating costs). Moreover, homeowners perceive wood pellets to be a relatively cheap fuel at today's prices (*Current_fuel_price*, -0.116^{***}). The location of the home (*Loc_home*), including characteristics of the property (e.g. soil conditions or exposure to the sun), is found to be less a barrier to adoption (-0.078^{***}). Lastly, we find experts to be less relevant for the decision against WOOD (*Rec_experts*, -0.036^{***}). This may reveal the relatively high acceptance of WOOD as an alternative RHS among experts.

5 Conclusions

The reduction of CO_2 emissions from residential space heating plays a crucial role in the transition towards a more sustainable energy system. In particular, this requires targeting the existing residential building stock. Besides lowering the energy needs of existing homes by improving their energy efficiency (e.g. better insulation standard), a switch from fossil fuels (mostly oil or natural gas) to renewable energy sources as fuels for heating is another option. For the coming decades, this involves most owners of existing homes having to replace their old fossil fuel, and thus CO_2-intensive RHS, by a less CO_2-intensive and renewable RHS. So far, research has mainly focused on energy appliance and fuel choice, while replacement purchases and fuel switch decisions have been less investigated. Therefore, the aim of this paper was to investigate key drivers and barriers behind the homeowners' decisions to replace a fossil fuel-fired by a renewable RHS. For this purpose, we analyzed data from a 2010 survey of owners of existing 1-family or 2-family homes that had received a financial grant for installing a (partly) renewable RHS. In the following, we revisit the research questions and discuss their implications.

Firstly, our research shows that there are different drivers behind the homeowners' decisions to switch from a fossil fuel to a renewable RHS. We show that motivations, attitudes, and preferences regarding RHS-specific attributes are specifically important, while socio-demographic characteristics, attributes of the home, and locational variables seem to have a lesser impact. Above all, we find the motivation to deal with external threats (i.e. environmental protection and independence from fossil fuels) to be a key driver to switching to a renewable RHS. This shows that homeowners need to be aware of and, consequently, be concerned about possible negative consequences (both on a global and individual level) stemming from the usage of fossil fuels. Hence, a possible implication may be to increase the homeowners' awareness about such undesirable outcomes. Moreover, a higher degree of RHS-related knowledge seems to be an important driver for switching to a renewable RHS. Thus, providing information about possible benefits related to different alternative RHS (e.g. information campaigns targeting renewable RHS, or on-site energy consulting) may facilitate the homeowners' switching decision. Our results also show that homeowners still need to be convinced about the convenience, comfort, and suitability with daily habits and routines of renewable RHS. Thus, homeowners who are well informed about the different alternative RHS seem to be a key towards an increased replacement of fossil fuel by renewable RHS. This includes a basic understanding of the technical principles and functioning as well as an awareness of possible consequences linked to the usage of the alternative RHS.

Secondly, our study shows that there are RHS-specific barriers to adopting a solar-assisted fossil fuel RHS, heat pump, or wood pellet-fired boiler. For the oil- or gas-fired condensing boiler with solar thermal support, the reliance on high-priced fossil fuels is found to be the main barrier. Thus, decreasing prices for fossil fuels may lead to a higher uptake of this RHS again. In order to prevent such a development that runs counter to the *Energiewende*, a carbon tax on oil and natural gas or the integration of the residential buildings sector into an emissions trading system may help to render the adoption of fossil fuel RHS less attractive. For the heat pump, we show that the main barrier to adoption is the perceived difficulty of getting used to the system and a misunderstanding of its principal functioning. Moreover, the purchasing price is found to be an additional barrier. For the wood pellet-fired boiler, our findings point in a similar direction. Non-adopters perceive the usability to be demanding, the operation to be labor-intensive, and the systems' fault liability to be high. Moreover, non-adopters are concerned that the decision in favor of such a system would eventually exceed the financial scope foreseen for this investment. Indeed, our findings on the barriers to adopting a heat pump or wood pellet-fired boiler show the need for a better communication of the basic technical principles and the usability of this technology. This may remove prejudices and increase the acceptance of these RHS among homeowners. Moreover, financial support (i.e. capital grants or low interest loans) may also enhance the diffusion of the heat pump and the wood pellet-fired boiler.

Based on the answers to our research questions, we can conclude on a more general level that homeowners often fear major changes to their status quo (e.g. replacement of the entire existing heating infrastructure, earth moving operations in the garden, major energy retrofit of the home) and, thus, tend to allow only minor and quick adjustments to their current RHS (e.g. replacement of the boiler). Thus, a higher replacement rate of fossil by renewable RHS requires the homeowners' willingness to relinquish old habits and perceptions of how an RHS works and operates. Moreover, for financial support measures, such as capital grants from the government, we can conclude that such policy instruments may better be combined with information and awareness campaigns on renewable RHS in order to increase their effectiveness. For RHS manufacturers, we conclude that marketing strategies should also aim at explaining basic technical principles and how to operate this system to potential adopters. Finally, our findings contribute to a better understanding of the likely future transition dynamics of the energy system in the residential heating sector, which is a highly policy-relevant issue.

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