E.ON Energy Research Center
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FCN Working Paper No. 2/2010

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Integrated Theoretical Framework for a Homeowner's Decision in Favor of an Innovative Residential Heating System

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Abstract

Insight into the homeowner's adoption decisions in favor of a specific innovative residential heating system (RHS) helps us to understand and assess the dynamics of the adoption and diffusion of such technological systems as a "social" phenomenon. This phenomenon emerges from the individual decisions of a set of heterogeneous actors on the market. In our research, we develop an integrated theoretical framework for assessing a homeowner's adoption decision in favor of a specific innovative RHS. Taking the *theory of planned behavior (TPB)* (Ajzen, 1991) and the *perceived characteristics of innovations (PCI)* (Moore and Benbasat, 1991) as a starting point, we propose a framework that explicitly accounts for external factors (esp. economic aspects) and personal-sphere determinants. This allows us to gain a deeper understanding of the role of a homeowner's personal-sphere as well as of the influence of perceived economic and other external factors on the RHS adoption process. We motivate our research with background on the case of Germany. Our theoretical framework can serve as a basis for empirically researching homeowners' adoption decisions in favor of a specific RHS and for developing a conceptual multi-agent simulation model for investigating the diffusion of RHS.

Key words: Technological adoption, consumer behavior, economic psychology, residential heating systems

JEL Classification Nos.: D83, O33, R22;

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1 Introduction

Residential heating demand accounts for a large fraction of the overall energy demand of private households. For example, private households in Germany consumed about 1884 PJ for residential heating in 2006. This equals 73.3% of the total final energy demand for residential purposes (Mayer and Flachmann, 2009). In Germany, residential heat supply is mainly based on the fossil fuels, oil and gas. According to the Bundesverband der Energie- und Wasserwirtschaft (BDEW, 2009), about 48.5% of the housing units were using gas, while about 30% had an oil-based RHS in 2008. About 60% of newly built homes are equipped with a gas-based system (BDEW, 2009). Therefore, overall, residential heating is strongly connected to considerations related to global warming, the security of the energy supply, and increasing energy prices.

In order to deal with such issues, the German government has set the goal of raising the share of renewable energies in the residential heat supply from 6% to 14% by 2020 (EEWärmeG, 2008). A number of policy measures targeting residential heating demand have been implemented for achieving this goal. These measures target the insulation of the building shell as well as the conversion efficiency of residential heating systems in newly built and existing residential buildings. Regulatory frameworks, such as the "Act on the Promotion of Renewable Energies in the Heat Sector (EEWärmeG)" or the "Energy Saving Ordinance (ENEV)", oblige owners of newly built single- or two-family homes to choose a residential heating system (RHS) which is at least partly based on renewable energy sources.[2] For owners of existing homes undergoing a major renovation the situation looks somewhat different. In most federal states there are no obligations to use renewable energies for residential heating, except for the federal state of Baden-Württemberg (10% share of renewable energies). However, for most owners of homes undergoing a major renovation it is reasonable to install an innovative RHS.

As a result, homeowners basically have the choice today between a gas-fired condensing boiler in combination with a solar thermal collector, an electric heat pump and a wood pellet-fired boiler.[3] All of these innovative RHS provide the same output in the form of thermal

[2] Homeowners who insulate their buildings to the point at which the building's thermal performance is 15% better than required under the Energy Savings Ordinance (ENEV) consume significantly less energy and are, therefore, not required to also use renewable energies.

[3] Besides these three options, it is for example also possible to supplement an electric heat pump or wood pellet-fired boiler-based system with solar thermal collectors. Moreover, a mechanical ventilation heat recovery system

comfort; however, there are significant differences in their characteristics. Today, it is not clear which of the competing solutions for renewable-based RHS will diffuse most successfully under given framework conditions. Therefore, studying the underlying determinants of a homeowner's adoption decision with respect to a specific innovative RHS can contribute to a better understanding of the RHS market. Since the decision context is more or less homogeneous for most homeowners, the personal-sphere or behavioral elements, which include attitudes or norms, seem to play a role in the process of adopting a specific RHS.

Economic research on the adoption and diffusion of sustainable energy technologies has often disregarded the impact of behavioral elements beyond that of a rational actor with or without full information and with or without full foresight. The traditional economic point of view sees cost-benefit considerations and utility maximization as the main determinants of an individual's energy technology adoption decision (see, for example, Faiers et al., 2007). However, the adoption of sustainable energy systems can be seen as personal- or private-sphere behavior and therefore includes, besides economic considerations, behavioral elements as well (see, for example, Stern, 2005, for a discussion).

In this paper, we argue that the group of homeowners is heterogeneous in terms of their attitudes and preferences. This argument implies that behavioral elements play a certain role in an individual's process of adopting a specific RHS. Against this background, research on the dynamics of behavioral determinants and external economic factors in technology adoption can contribute to a better understanding of that process. The following questions can guide such research: What determines the individual adoption decision of a homeowner? What factors explain differences in the homeowners' adoption decisions? What is the influence of perceived economic factors on a homeowner's adoption decision? To what degree is behavior driven by perceived economic factors including, for example, perceptions about energy prices or investment costs?

In particular, studying the influence of perceived economic factors on personal-sphere determinants can contribute to a better understanding of the interrelations between these two aspects. Moreover, a broader understanding of these dynamics can help to design better policies aimed at the taking up of environmentally friendly technologies.

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is an alternative which is increasingly considered as an option by owners of a passive house. However, in most cases such a system supplements an air-source heat pump. In only a few cases, the mechanical ventilation heat recovery system is installed as a stand-alone RHS.

The goal of this paper is to introduce an integrated theoretical framework for investigating a homeowner’s adoption decision in favor of a specific RHS. The model will contribute to the understanding and the explaining of the adoption behavior of a homeowner and to identifying important determinants of the adoption decision. In particular, we propose a model which accounts for perceived economic factors and personal-sphere determinants. We motivate our research with background on the characteristics of RHS, on the development of annual adoption rates over time, and on the policy framework for RHS in Germany (section 2). In section 3, we briefly present and discuss different models of decision-making from various disciplines, with a focus on the adoption decision of an individual homeowner. Moreover, we link the implications of the different approaches to the case of adopting a specific RHS. On this basis, we develop an integrated theoretical framework in section 4, which draws on the findings from the review of decision-making models and the case of Germany as a background. In particular, we apply the *theory of planned behavior (TPB)* by Ajzen (1991) and operationalize it with an extended version of Moore and Benbasat’s (1991) *perceived characteristics of innovations (PCI).* Since both the *TPB* and *PCI* do not fully account for external influences and economic aspects, we extend them by explicitly considering perceived economic factors and the influence of these on personal-sphere determinants. Finally, in section 5, we discuss the implications of our theoretical framework in the context of a homeowner’s decision in favor of a specific RHS, and draw some conclusions for further empirical research.

2 Background to the case of innovative RHS in Germany

Over the past few years, innovative RHS based on renewable energy sources, such as the heat pump, wood-pellet boiler or condensing boilers supplemented with a solar thermal collector, have gained the increasing attention of policy-makers and homeowners in Europe and in particular in Germany. In order to motivate our research, this section gives a brief overview of the technical characteristics and the dynamics of annual adoption rates of selected RHS over time as well as an overview of the related policy framework in Germany. This information serves as a foundation for the development and application of the theoretical framework for the case of RHS, which follows in section 4 below.

2.1 Technical characteristics of selected RHS

All RHS provide the same output in the form of thermal comfort; however, they differ substantially in their characteristics, including space and maintenance needs, the required energy carrier, investment, energy and maintenance costs, or environmental impact. In the following, we briefly outline the main characteristics of the three selected RHS in the German context.

2.1.1 Condensing boiler

Gas- and oil-fired condensing boilers utilize waste heat in their exhaust fumes. For this purpose, the heat is extracted by condensing the water vapor in the exhaust fumes (for details see Day et al., 2003). Usually, solar thermal collectors supplement this type of RHS. While the gas-fired condensing boiler is widely used in regions with access to the gas grid, the oil-fired one is an alternative condensing boiler technology for areas with no grid access. The space requirements for gas-fired condensing boilers are the smallest among the three alternative RHS considered in our analysis, while the oil-fired condensing boiler has similar high space needs to those of the wood-pellet boiler. However, gas-fired condensing boilers require a gas port in the home, and oil-fired condensing boilers sufficient space for an oil tank. Furthermore, these systems need suitable roof space for solar thermal collectors. According to a study by the Leipziger Institut für Energie (IE, 2009), the current installation costs for a gas-fired condensing boiler are the lowest compared to the alternative RHS in our analysis, while the oil-fired condensing boiler has slightly higher costs due to the necessity of installing i.e. an oil tank.[4] Moreover, there is a high exposure to the volatility of the world market prices for oil and gas. Based on 2009 energy prices, the fuel costs are moderate compared to the other RHS. Gas- and oil-fired condensing boilers have a relatively high adverse environmental impact compared to the other two options, since the former two rely on fossil fuels, although the integration of solar thermal collectors can reduce this impact.

2.1.2 Electric heat pump

A heat pump uses electricity to move the renewable energy source "environmental heat" from a cool into a warm space. Because it transports rather than generates heat, a heat pump can provide up to four times the amount of energy that it consumes (see Langley, 2002, for details). The heat sources can be divided into air and ground (geothermal) sources. A geothermal heat pump has usually a higher efficiency, and represents the most common heat pump used for residential heating. An air-source heat pump can also be combined with a mechanical ventilation heat recovery system. A heat pump is a compact box that can be placed anywhere in the home, and has relatively low space requirements. Furthermore, a

[4] IE (2009) serves as a basis for our comparison of full costs. A newly built single-family home is the reference case for the full costs calculations.

chimney is not required. However, the ground-source heat exchanger requires sufficient vertical or horizontal space outside the building. According to IE (2009), the ground-source heat pump currently has the highest installation costs among the three alternatives. However, the heat pump has the lowest energy and maintenance costs. Moreover, a heat pump reduces the dependency on price fluctuations of fossil fuels such as oil or gas. The environmental impact in terms of CO_2 emissions depends on the efficiency of the heat pump and on the electricity mix. In the context of newly built or retrofitted homes with a high insulation standard, the CO_2 emissions are usually lower than those of condensing boilers.

2.1.3 Wood pellet-fired boiler

A wood pellet-fired boiler has a similar mode of operation to that of a conventional boiler, but uses biomass as fuel. The space requirements are the highest of the three selected RHS, since a storage tank for the wood pellets is necessary (see Loo and Koppejan, 2008, for details). The ashes from the combustion process also have to be removed on a regular basis. Moreover, the purchase and delivery of wood pellets has to be organized. According to IE (2009), the wood pellet-fired boiler currently has moderate installation costs, but high fuel and operating costs. A wood pellet-fired boiler is to a large extent independent from fluctuating oil and gas prices and, thus, can help to lower the dependency on energy imports. The environmental impact is the lowest of the three alternatives, since wood pellets are a renewable energy source.

2.1.4 Summary

Based on the descriptions of the RHS above, Table 1 summarizes and compares the three selected RHS considered in our analysis. As can be seen, condensing boilers currently have the lowest, while heat pumps have the highest investment costs. The comparison of the investment costs in Table 1 does not consider the current level of subsidies. According to IE (2009), the consideration of subsidies contributes to a leveling of the full costs for the wood pellet-fired boiler, the condensing boiler in combination with solar thermal collectors, and the heat pump. However, these cost comparisons depend very much on the assumed fuel costs and current level of subsidies. In this analysis, we use cost and subsidy levels of the year 2009 as a basis.

Table 1: Comparison of the characteristics of selected RHS in Germany

	Condensing boiler + solar thermal collector	Heat pump	Wood pellet-fired boiler
Energy carrier	Gas or oil combined with solar thermal heat	Electricity and air-source or geothermal heat	Biomass
Space and infrastructure requirements	Availability of a gas port or space for oil tank and suitable roof space	Availablity of a suitable heat source and sufficient space for the ground source heat exchanger	Space for a wood pellet storage tank
Degree of automation	**High (gas-fired)** Moderate-High (oil-fired)	**High**	Moderate-High
Installation costs	Moderate (oil-fired) **Low** (gas-fired)	High (geothermal) Moderate (air-source)	Moderate
Operating costs	Moderate	**Low**	High
Fuel costs	Moderate	**Low**	High
Environmental impact	High	Moderate	**Low**

Source: Own illustration; comparisons of energy carriers, space and infrastructure requirements and degree of automation are based on Day et al. (2003), Langley (2002), Loo and Koppejan (2008), while the comparison of costs and environmental impact are based on IE (2009).

2.2 Historical data on annual market shares for innovative RHS

In Germany, the gas-fired condensing boiler gained considerable market shares in the period between the years 1998 and 2008. More recently, other innovative RHS, such as the electric heat pump and biomass-fired boilers, started to penetrate the market in larger numbers and successfully compete for shares. Figure 1 shows the annual market shares of the different innovative RHS in Germany. We can observe a decline in the annual adoption rates of gas- and oil-fired low temperature boilers over time. The diffusion of the heat pump and the biomass-fired boiler (mainly based on wood pellets) took off recently, while the diffusion process of the condensing boiler is in a more mature state. Variations in the market shares of the biomass-fired boiler can be explained by changes in governmental support or variations in the price of wood pellets.

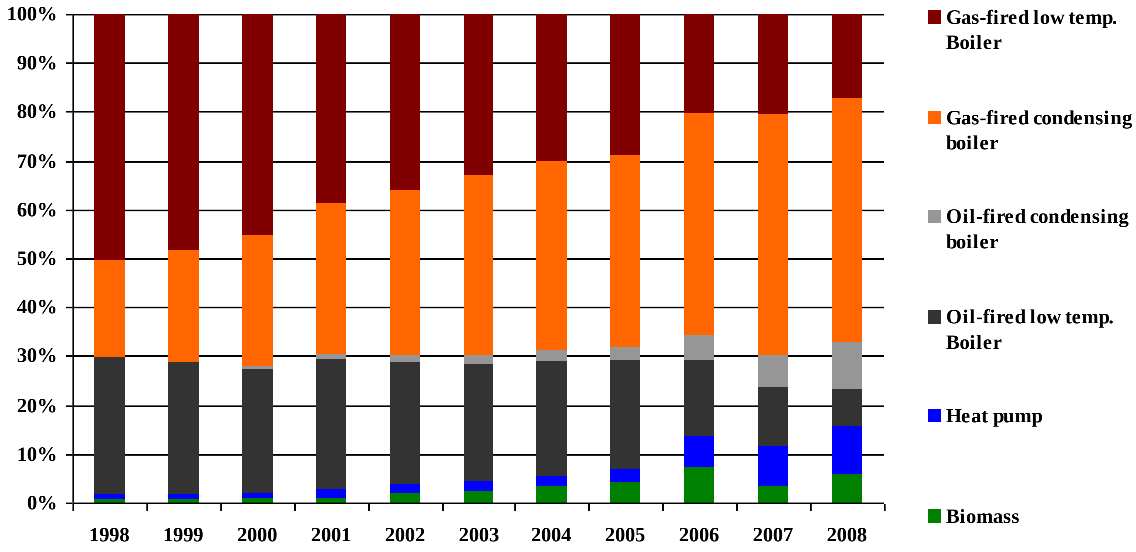

Figure 1: Annual market shares of newly installed RHS in Germany between 1998 and 2008

Source: Own illustration, based on data from BDH (2009)

Figure 2 shows the cumulated number of installed solar thermal systems for supporting residential heating systems (including water heating) in Germany in the period 1999-2008.

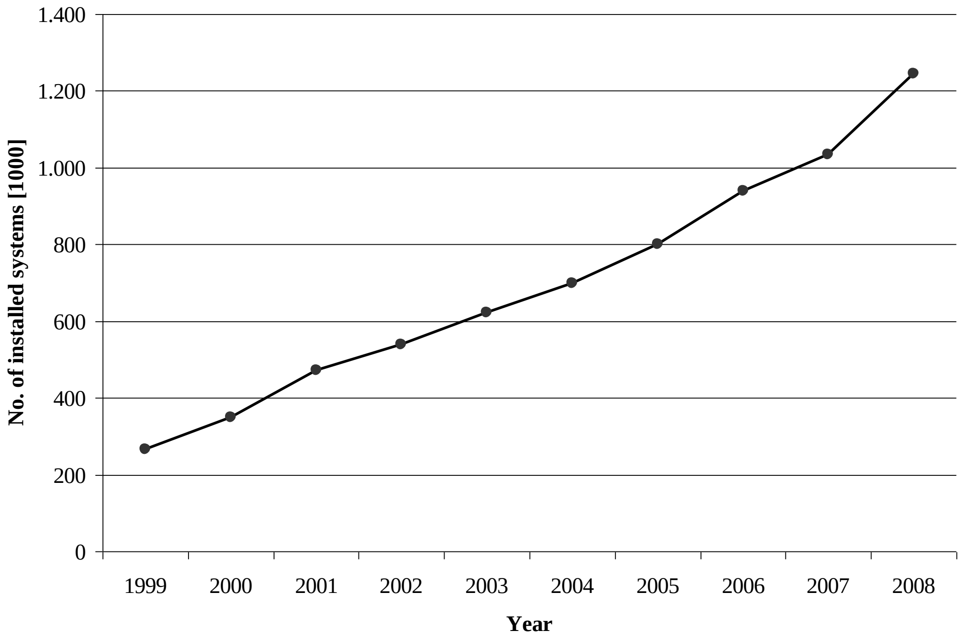

Figure 2: Number of installed solar thermal systems in Germany between the years 1999-2008

Source: Own illustration, based on data from BSW (2009)

Especially in the past few years, we can observe an accelerated increase in the number of installed solar thermal systems. Since stand-alone systems are rare, this implies that more and more homeowners in Germany are combining RHS with solar thermal systems.

2.3 Policy framework in the context of innovative RHS

The policy framework targeting RHS affects the adoption of such systems. The German government has set the goal of increasing the share of renewable heat supply from the 2007 level of about 6% to 14% in the year 2020 (see BMU, 2007, for a detailed description of the relevant policy framework). A number of instruments have been implemented to achieve this goal: From January 1, 2009, onwards, the "Act on the Promotion of Renewable Energies in the Heat Sector (EEWärmeG)" obliges homebuilders to use a minimum share of heat from renewable sources, such as solar, biomass or geothermal heat (BMU, 2008). In addition, the Market Incentive Program (*Marktanreizprogramm*) offers financial support for selected innovative RHS (BMU, 2008). Furthermore, programs of the promotional bank KfW, such as the "CO_2 modernization of buildings program", offer low interest loans and grants connected to the renewal or installation of an innovative RHS (KfW, 2009).

2.4 Summary

The current regulatory framework in Germany mainly favors three innovative RHS (heat pump, biomass-fired boiler, and condensing boiler in combination with solar collectors). Against this background, we can expect a shift towards these three types of RHS in the coming years. The historical data on the dynamics of annual market shares lend support to the hypothesis that the group of homeowners in Germany is heterogeneous with respect to their motivation to take up a certain RHS. In other words, there may be for example, homeowners in the same neighborhood, who are building comparable homes but making decisions in favor of other types of RHS. Since the full costs for most types of RHS are in the same range, and the context for the adoption (e.g. available technologies and their characteristics, information availability, or regulations) should be similar for all homeowners, differences in the adoption might be explained by variations that can be attributed to behavioral and personal factors as well as to individual perceptions about economic factors and of the context. Therefore, we argue that the adoption of competing types of RHS has strong behavioral determinants, such as personal capabilities, social norms, and individual attitudes.

3 Theoretical background

This section briefly reviews individual decision-making models from different research approaches, such as economics, technology adoption research, psychology, and sociology. Furthermore, we link the implications of the reviewed theoretical approaches to the case of a homeowner's adoption decision in favor of a specific RHS. There are a number of literature reviews and overview articles on individual decision-making models. Examples include Claudy (2008) or Wilson and Dowlatabadi (2007). Our review of the literature on individual decision making models follows the structure proposed by these two articles. Moreover, we include more recent literature and give an overview of empirical studies drawing on the theoretical frameworks presented.

According to Wilson and Dowlatabadi (2007), theoretical approaches towards decision-making in an applied field, such as a homeowner's adoption decision in favor of an innovative RHS, have two purposes. The first purpose is to help explain behavior and to identify important behavioral drivers behind a decision. The second purpose is to provide a framework for empirical research in the field of decision-making.

The objectives of this section are twofold: In particular, we review different disciplinary approaches on individual decision-making and its determinants. Furthermore, we extract general lessons from the reviewed models and theories, and apply them to the case of a homeowner's adoption decision in favor of a specific innovative RHS. This review serves as a foundation for the subsequent section where we develop an integrated theoretical framework for assessing the adoption decision in favor of a specific innovative RHS in Germany. Since our focus is on the individual adoption decision for an innovative RHS, where both personal factors and perceptions of economic aspects play an important role, we concentrate our review on the economic and technology adoption perspective.

3.1 The case of the energy efficiency gap

The case of investing in energy-efficient technologies can serve as a starting point for a closer examination of behavioral determinants in the process of adopting a specific RHS. In this context, we can often observe the fact that investments in energy-efficient technologies are suboptimal, i.e. an individual does not carry out an investment that appears cost-effective on an estimated life-cycle basis. Economists describe this phenomenon as the *energy efficiency gap* (Jaffe and Stavins, 1994; Sorrell et al., 2004). Empirical evidence shows that the energy efficiency gap can be observed in a number of cases (see Brown et al., 1998, for a review). According to Wilson (2007), traditional economics explains the energy efficiency gap with 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 an 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 (see, for example, Jaffe and Stavins, 1994, for a detailed classification). In this context, barriers to making a choice for a specific cost-effective RHS may, for example, be high installation costs in the beginning, financial risk connected to uncertainty stemming from the stochastic future of energy prices, or regulatory barriers, such as restrictions on ground-source heat pumps in certain areas.

According to Stern (1992), many of these market and non-market failures relate to individual decision-making, and thus include behavioral elements. This means that external forces do not only drive investment decisions but also behavioral determinants, which are internal to the decision-maker. Therefore, many behavioral economists focus their research on bounded rationality, i.e. that individuals are biased in their decision-making. In the following, we give a brief overview of different decision-making models from the social sciences, which considers economic as well as behavioral aspects.

3.2 Utility-based decision models and behavioral economics

Traditionally, buying or investment decisions have been investigated from an economic point of view. This approach models decisions as a rational choice process from a microeconomic perspective (*rational choice theory*). Generally, this approach assumes a "rational actor" with fixed preferences aiming at utility maximization under given budget constraints. Decision-makers behave like rational actors, having preferences that are ordered, known, invariant, and consistent. In this context, an actor prefers outcomes with a higher utility to alternatives with lower utilities. The construct "utility" measures the preferences expressed for different outcomes but can also be used as a proxy for well-being or the "betterness" of an outcome. Utility may stem from monetary or non-monetary sources. Applied to RHS, these assumptions imply, for example, that homeowners have complete information regarding the future development of energy prices and that there should be no differences in the decisions of individual homeowners when the context is a similar one. A homeowner will always choose the alternative with the highest utility (i.e. the alternative with the highest net present value).

In contrast, the *behavioral economics* approach aims at a better understanding of the psychological rather than the contextual factors underlying an individual's decision. In particular, this direction of research takes possible biases and errors in human cognition and judgment into account that may deviate from the assumption of the rational actor ("bounded rationality"). It tries to integrate more robust psychological concepts into rational choice theory. For instance, Sorrell (2004:48) states, “behavioural economics argues that the biases in human decision-making need to be taken seriously if a fully explanatory account of economic organization and behaviour is to be improved”. Research in behavioral economics has shown that choices are influenced by other factors than rational cost-benefit considerations. For instance, findings show that consumers may use different kinds of discount rates for different types of goods and situations (Sanstad, 2006). In the case of RHS, this could, for example, imply that mature and proven systems have lower discount rates than new and less proven systems. Other findings show that consumers are influenced by the way a decision context is represented (“framing effects”, e.g. the presentation of different RHS focuses on the dependency on fossil fuels, which favors wood-pellet boilers in this context) and that consumers rely too much on only one piece of information (“anchoring”, e.g. the focus is only on the required up-front costs for a new RHS, and no consideration of the possible future development of energy prices) (Kahneman and Tversky, 1974). Furthermore, individuals often use heuristics or rules of thumb, despite the availability of technically accurate information on the costs and benefits of a measure in order for to reduce the complexity of decisions. These could be “recognition heuristics” (e.g. selection of the RHS that was chosen last time or the one that is most familiar) or “elimination heuristics” (e.g. no consideration of a certain RHS categorically) (Wilson and Dowlatabadi, 2007).

These findings show that decision-makers do not act in line with the standard economic model of rational choice in many cases. Against this background, economists have started to research behavioral elements in the decision process. However, most economic research in this field has failed to address the role of non-economic and personal-sphere factors in the decision process. Such factors could, for instance, include an individual’s attitudes, or social norms. Research on (non-economic) personal-sphere factors can mostly be found in disciplines such as psychology or marketing. Therefore, the following sections take a closer look at those research approaches which account for personal-sphere factors.

3.3 Attitude-based decision models

3.3.1 Introduction

In contrast to the economic approach, the *technology adoption perspective* as well as the *social and environmental psychological perspective* argue that mainly communication processes, information, values, attitudes, or social networks determine an individual’s decision in favor of a certain technology (Wilson and Dowlatabadi, 2007). In particular, the content of information in the decision context and the feedbacks or characteristics of the actors play an important role. This implies that the attractiveness of monetary incentives may vary between different groups of actors. Such variations may be explained by social and psychological factors, which affect the individual perception of external conditions, such as monetary incentives. Applied to the case of RHS, this means that individual actors have a different understanding of economic factors, such as installation costs, energy prices or the length of the payback period. Such variations in the understanding may be explained by differences in individual values, attitudes and norms, such as environmental conciseness, or attitudes towards certain energy carriers.

The dominant model in the field of adoption and diffusion theories is the *diffusion of innovations (DoI)* model of Rogers (2003). This model describes the adoption and diffusion of innovations as a social communication process that influences the technology adoption decision. A number of key assumptions underlie the *DoI* model. They include that of a decision being a process, which moves from a change in knowledge over awareness and intention to a change in behavior, and that is determined by prior conditions, such as values and norms. Moreover, adopter characteristics and the technology's attributes influence the formation of knowledge to attitudes (see section 3.3.2 below). Finally, this approach assumes that there are feedbacks between the different stages of the decision process, which could be both internal or psychological or external and communicative. Applied to the case of RHS, this means that person-to-person communication (e.g. advice from architects respectively energy consultants), or communication via media channels (e.g. information campaigns for innovative RHS), can be expected to have a certain influence on the adoption decision.

The *value-belief-norm theory (VBN)* by Stern (1999) and the *theory of planned behavior (TPB)* by Ajzen (1991) represent examples of psychological approaches. According to Kaiser et al. (2005, p.2151) the *TPB* "is grounded in self-interest-based and rational-choice-based deliberation" i.e. this theory represents a cognitive approach. Stern's *VBN* can be categorized as a normative theory since it draws on values and norms.

The *VBN* is a theoretical framework for attitude-related research from a psychological view. It focuses on the role of values and moral norms in a decision process (Stern, 1999). Contrary to the *TPB,* this approach does not account for external conditions, such as economic factors or regulatory constraints. However, the explanatory power of values or attitudes may decline in situations where decision-makers are faced with significant external conditions. According to Gatersleben et al. (2002), the explanatory power of decision models that do not explicitly account for external constraints decreases when a behavior requires high-effort, high-cost, and high-involvement decisions. RHS adoption decisions are connected to high upfront and information acquisition costs and require in most cases a high involvement. Furthermore, decision-makers may perceive that they lack the relevant capabilities, including skills, time or money for the adoption of a specific RHS. This implies that besides psychological factors external conditions play an important role in the adoption decision of a homeowner in favor of certain RHS. For instance, such external constraints can comprise legislations and regulations imposed by the government or other institutions, availability of policy instruments and measures to support a certain behavior, capabilities and constraints provided by the built environment and technology (availability of technology or the design of a building) as well as features from a broader context in the field of social, political, and economic aspects (e.g. the price of certain energy carriers, interest rates, or sensitivity of the government to public pressure and interest groups). Understanding the influence of these factors on an individual's behavior is crucial. For instance, if contextual factors leave no leeway for personal determinants to influence the behavior, a policy instrument, such as an information campaign targeting a certain action, might be useless. On the other hand, personal factors may provide the only levers to encourage changes in an individual's behavior when policies cannot change the context. According to Stern (2000), individuals with differences in their attitudes and beliefs could have a different understanding of certain contextual factors. Moreover, lifestyles and demographic factors can have a moderating influence on the importance of the constructs "attitude" and "subjective norm". For example, a high price of an RHS can be an economic barrier to invest, while for others it can be a sign of social status.

We argue that the *TPB* offers a good starting point for developing an integrated theoretical framework for identifying and investigating the influence of personal-sphere and external economic factors in the adoption decision in favor of a specific RHS. In the following, we give a brief overview of the *TPB.*

3.3.2 The theory of planned behavior

The *TPB* was developed by Ajzen (1991), and has its roots in the research around attitude formation and social psychology.[5] Fishbein and Ajzen's (1975) *theory of reasoned action (TRA)* represents the predecessor of the TPB.

The *TRA* belongs to the class of expectancy-value models (see, e.g., Fishbein 1963 and Rosenberg 1956). According to Pollard et al. (1999, p.443) these models "formalized the view

[5] Today, the TPB finds its applications in various disciplines for investigating attitudes towards carrying out certain behavior. A large number of empirical studies and research builds on this theoretical framework.

that consumers' anticipated satisfaction with a product (and hence the purchase of that product) is determined by their beliefs that the product fulfills certain functions and that it satisfies some of their needs". According to Bang et al. (2000), individuals assess the possible outcomes of alternative behaviors before engaging in them, and choose to carry out actions they associate with desirable results. The *TRA* can be modeled as follows:

Behavioral intentions determine actual behavior and can serve as a proximal measure of behavior. Moreover, *behavioral intention* depends on an individual's *attitude* (A_{act}) towards performing the behavior, and the *subjective norm* (*SN*) i.e. the influence of "important others" on the behavior. *Behavioral intentions* represent the subjective utility assigned to a certain behavior.

Attitudes towards behaviors represent an assessment of the outcomes (e_i) of a behavior and an estimate of the probability (b_i) of the results of a behavior. Attitude can be represented as follows:

$$A_{act} = \sum_{i=1}^{n} b_i e_i \tag{1}$$

For example, this implies that someone who believes that reducing dependency on fossil fuels is something desirable that can be realized by installing a biomass-based instead of a fossil fuels-based RHS, is likely to perform a positive attitude towards biomass-fired boilers.

***Subjective norm* (*SN*)** represents another driver to carry out a certain action by considering the influence of significant others. For example, significant others include individuals such as family members, friends or neighbors or institutions such as religious organizations, political parties or non-governmental organizations. Each significant other holds "normative beliefs" (*NB*) about a certain behavior and the individual considering carrying out a behavior has a certain motivation to comply with these values and norms. Thus, *subjective norm* can be modeled with the probability that a significant other holds a normative belief (NB_j) and the motivation to comply (MC_j) with the values. Thus, *subjective norm* can be expressed as:

$$SN = \sum_{j=1}^{n} NB_j MC_j \, . \tag{2}$$

For example, professional or non-professional peers claiming that biomass-fired boilers are too expensive or difficult to use can negatively influence the decision to purchase this RHS.

However, behavior is not always under an individual's full volitional control. Sanhi (1994, p.442) puts this in other words by stating that "the performance of many behaviors depends not only on motivations but also on non-motivational factors like a person's ability to actually perform the behavior". This means that motivational factors (including the *TRA* attributes attitudes and social norms) do not provide a sufficient explanation of behavior whenever control over behavior is limited by external factors or personal capabilities.

The *TPB* tries to overcome these problems. For this purpose, the *TRA* is extended by the component ***perceived behavioral control*** **(*PBC*)** to capture external (non-motivational) factors, such as resources availability, skills or external constraints to predict behavior more accurately. Ajzen (1991) defines *PBC* as an individual's belief as to how difficult or easy carrying out a behavior will be. Control beliefs underlie an individual's *PBC,* as they represent the influence of a factor (P_i) to support the action and the perceived availability of the factor (C_i). Thus, *PBC* can be expressed as:

$$PBC = \sum_{i=1}^{n} P_i C_i \ . \qquad (3)$$

In contrast to *attitudes* and *subjective norms*, *PBC* has both a direct and indirect effect on behavior through intentions. The execution of a behavioral intention into action is to some degree determined by external as well as individual factors. This means that no matter how positive an individual's *attitude* towards the behavior and irrespective the size of the social pressure *(subjective norm)*, individuals who believe they are missing the necessary resources and skills are unlikely to implement the behavior. In turn, this implies that the formation of behavioral intentions via attitude or subjective norms is also affected. This has an indirect effect on behavior. Thus, if we consider a behavior with reduced control, the inclusion of *PBC* gets useful as it adds an explanatory factor to the model.

Applied to the case of RHS, this means that, for example, the obligation to connect to district heating, individual financial constraints regarding the investment costs or infrastructure issues (e.g. a lack of space for a wood-pellet tank or insufficient exposure of the home's roof to the sun) constrain individual behavior. Figure 3 summarizes the concept of the *TPB.*

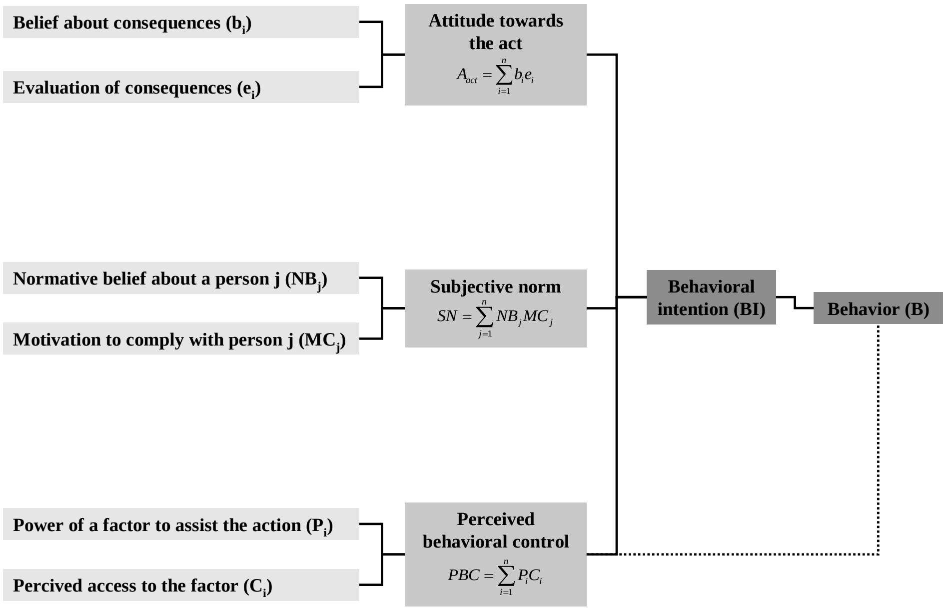

Figure 3: Concept of the TPB

Source: Own illustration, based on Ajzen (1991)

In general, the *TPB* states that the stronger each of the three factors is, the stronger the individual's *intention* to perform the behavior. However, *attitude*, *social norm* and *perceived behavioral control* are not always weighted equally when predicting an individual's volitional (voluntary) behavior. Therefore, the model includes weighting factors (w_i). As a result, the *TPB* can be modeled as follows:

$$B \approx I = (A_{act})w_1 + (SN)w_2 + (PBC)w_3 \tag{4}$$

According to Miller (2005), these three factors can have very different effects on behavioral intention since they are driven by the individual and the context. The following example serves as an illustration of this case. An individual can have a generally positive attitude towards an action (i.e. adopting a wood-pellet boiler) but may feel that he or she lacks the necessary financial resources to perform the behavior. In such a case, *PBC* would be expected to provide the greatest explanatory power for behavioral intention.

The meta-analysis of Armitage and Conner (2001) provides support for the efficacy of the *TPB* as a predictor of *intentions* and *behavior*. It includes a review of 185 empirical studies with the *TPB* as a theoretical framework. The overall findings show that the *TPB* accounts for 27% of the variance in behavior and 39% of the variance in intention. The *subjective norm* is generally found to be a vague predictor of intentions.[6] The *perceived behavioral control* construct independently predicts intentions and behavior in a wide number of domains.

Results of empirical studies on information and communication technologies show an inconsistent picture. In some studies *subjective norm* has the major influence (Karahanna et al., 1999, on IT; Fitzgerald and Kiel, 2001, on online purchasing), whereas in other studies, *attitude* has the highest effect on the adoption (Moore and Benbasat, 1996, on IT; Karahanna et al., 1999; Hardgrave et al., 2003, on software developers; Hebert and Benbasat, 1994, on IT in hospitals; Chau and Hu, 2001, on IT). In the study of Teo and Pak (2003) on WAP-enabled mobile phones, *subjective norm* and *attitude* have almost the same influence.

3.3.3 The concept of characteristics of innovations

The concept of *characteristics of innovations* is often applied in technology adoption research for describing properties of innovations in more detail or for analyzing drivers and barriers in the adoption process of an innovation. Rogers (2003) was one of the first researchers to present a concept for systemically characterizing innovations. Based on Rogers' *attributes of innovations*, there have been attempts to develop this approach further. On the one hand, the *technology acceptance model (TAM)* aims to simplify and reduce the number of characteristics, while on the other hand, the *perceived characteristics of innovations (PCI)* scale aims at developing a comprehensive and unified measure. In the following, we briefly introduce and discuss the three concepts.

- **Attributes of innovations**

Rogers' *attributes of innovations* have been applied in a number of studies. Already in the early 1980s, first researchers applied Rogers' characteristics of innovation. Rogers (2003) introduces five different attributes in order to describe innovations in more detail.

Relative advantage measures the perceived advantage over the incumbent technology. It can be used to characterize the construct *attitude* of the TPB. Compared to other attributes, the definition of *relative advantage* is broad. For the case of RHS, this attribute can, for example, include perceived economic factors (e.g. savings in the field of investment, maintenance or fuel costs), environmental issues (e.g. reduced CO_2 emissions), security of energy supply, energy-saving potential, personal comfort, or considerations related to technical issues (e.g. space requirements of the installation).

[6] This goes back to the fact that norms are typically measured by a single item. Multiple-item measures of subjective norms have significantly stronger correlations with intention.

Compatibility measures the consistency with existing values, needs, problems or experiences of the potential adopters on the one hand, and with the available infrastructure on the other hand. The constructs *attitude* and *perceived behavioral control* of the *TPB* can be characterized with this attribute. This means for example that the attitude towards a certain RHS can be explained with the *compatibility* of the adopter's values regarding environmental issues or habits connected to the purchase of fuel. Furthermore, the compatibility with the existing infrastructure (e.g. the possibility to connect to the gas grid, or sufficient roof space which is exposed to the sun) is important when it comes to operationalizing the construct *perceived behavioral control*.

Complexity measures the ease of use of an innovation, i.e. the degree to which an innovation is perceived to be user-friendly. It operationalizes the *TPB* construct *attitude*. In the case of RHS, this includes perceptions about the effort to adopt a technology, the required skills and capacity, the system automation, technicality, maintenance intervals or the required cleaning effort (e.g. handling of ashes in the case of a wood-pellet boiler).

Trialability measures the possibility to test an innovation prior to the adoption. It can be used for characterizing the construct *attitude*. Regarding RHS, this would be the possibility to experiment with an RHS before the final installation. However, it is rather difficult since the installation of an RHS is irreversible. On a limited basis, *trialibility* in the context of RHS may include the possibility to test different RHS out on residential building fairs or in show houses as well as including prior experiences with similar RHS (e.g. experiences involved in the handling of an oil-based RHS, which can be transferred to the case of a wood-pellet boiler). Therefore, peer experience and social feedback can contribute to reducing uncertainty in the adoption process of RHS.

Observability measures the visibility of innovations to potential adopters. Again, this attribute characterizes the *TPB* construct *attitude*. For RHS, the visibility of the results to others is low. For instance, only the case of solar thermal collectors is observable to others, while the utilization of a heat pump or a wood pellet boiler is hardly visible.

- **Technology acceptance model (TAM)**

The *TAM* aims at predicting the acceptance and utilization of IT innovations at work (Davis et al., 1989). The approach draws on the *TPB* and consists of only two explanatory variables:

Perceived usefulness measures the degree to which a person believes that the usage of a system will improve the workflow. Rogers' attributes *relative advantage* and *compatibility* are summarized in this attribute. This variable influences the *attitude* towards an innovation and the *intention* to use an innovation.

Perceived ease of use measures the degree to which a person believes that the usage of a system will not be connected to any additional effort. Rogers' attribute *complexity* is represented in this variable. This variable has an impact on the *perceived usefulness* as well as the *intention* to use an innovation.

- **The perceived characteristics of innovations (PCI) scale**

Moore and Benbasat (1991) developed the *PCI* scale for investigating the adoption of IT innovations by individuals within organizations. In their research, they added two new characteristics to Rogers' *attributes of innovation*:

Image (perceived improvement of the social status by adopting the innovation, operationalizes the TPB construct *subjective norm*). This implies that using a certain RHS may improve the adopter's status as an environmentalist or innovator.

Voluntariness (degree to which an innovation is adopted voluntarily, operationalizes the TPB construct *perceived behavioral control*). External conditions such as regulations, availability of space for the installation or local infrastructure conditions reduce the free will regarding the choice of a certain RHS.

Furthermore, they split Rogers' attribute *demonstrability:*

Result demonstrability includes the observability of the results to others and can be used for characterizing the TPB construct *attitude*. For RHS, the direct observability of the results of using a certain RHS to others is only possible when, for example, visiting a home. Observability can also be indirect, i.e. users tell potential adopters about the results of using a certain RHS.

Visibility describes the observability of the usage of a RHS to others. The TPB construct *subjective norm* can be operationalized with this attribute. The observability of the usage of a certain RHS is only possible for solar collectors. For other RHS, it is more difficult to observe their usage, since RHS are usually hidden away in the basement. However, observability of the usage could also be indirect via communication between users and non-users.

We use the assignment of *PCI* attributes to TPB constructs as depicted in Figure 4.

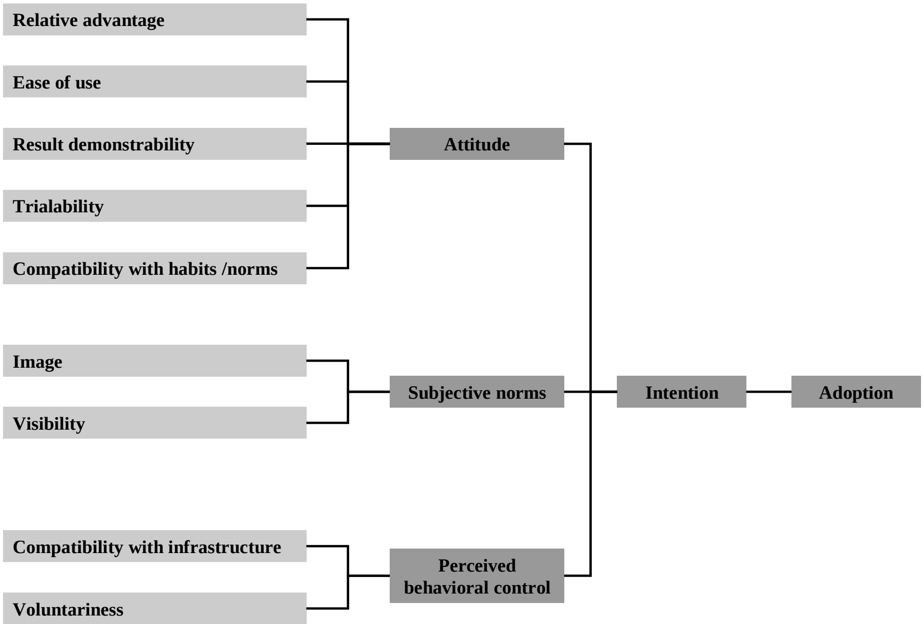

Figure 4: Operationalization of the TPB with the PCI scale

Source: Own illustration

Table 2 illustrates and compares these three instruments for characterizing innovations.

Table 2: Characteristics of innovations by Rogers (2003), Davis (1989), Moore and Benbasat (1991)

Source	Category							
Rogers 2003 (Attributes of innovations)	**Relative advantage**	**Compatibility**	**Complexity**	**Observability**		**Trialability**		
Description	"the degree to which an innovation is perceived as being better than the idea it supersedes"	"the degree to which an innovation is perceived as consistent with the existing values, past experiences, and needs of potential adopters"	"the degree to which an innovation is perceived as relatively difficult to understand and use"	"the degree to which the results of an innovation are visible to others"		"the degree to which an innovation may be experimented with on a limited basis"		
Davis 1989 (TAM)	**Perceived usefulness**		**Perceived ease of use**					
Description	"the degree to which a person believes that using a particular system would enhance his or her job performance"		"the degree to which a person believes that using a particular system would be free of effort"					
Moore and Benbasat 1991 (PCI)	**Relative advantage**	**Compatibility**	**Ease of use**	**Result demonstrability**	**Visibility**	**Trialability**	**Voluntariness**	**Image**
Description	see Rogers	see Rogers	see Davis	"the degree to which the results are observable to others"	"degree to which the usage of the innovation is visible to others"	"the degree to which an innovation may be experimented with before adopting it"	"the degree to which use of an innovation is perceived as being voluntary or of free will"	"the degree to which use of an innovation is perceived to enhance one's image or status in one's social system (social approval)"

Source: Own illustration

Rogers' *attributes of innovations*, the *technology acceptance model* and the *perceived characteristics of innovations* have been applied in a number of studies (see, e.g. Schwarz 2007, for a useful overview). In particular, the *PCI* is widely used in a range of disciplines. For instance, a number of studies use this instrument for predicting the more general constructs of the *TPB*. In their meta-analysis Jeyaraj et al. (2006) review studies on the acceptance of IT-Innovations. In the reviewed studies, the most frequently used predictors include *perceived usefulness*, *ease of use*, *attitude*, *relative advantage*, *complexity* and *subjective norm*. The most important attributes with regard to the individual intention include *perceived usefulness*, *relative advantage* and *subjective norm*. For the adoption decision, the most important attributes include *management assistance*, *computer experience*, *perceived usefulness*, *intention* and *support*.

The meta analysis of Teo, Chan and Parker (2004) reviews studies dealing with e-commerce adoption by SMEs. They identify eight main factors affecting e-commerce adoption. These attributes include *perceived relative advantage*, *perceived compatibility*, *perceived complexity*, *pressure from trading partners*, *pressure from competitors*, *external change agents*, *knowledge and expertise* about e-commerce as well as *management attitudes* towards e-commerce. Teo et al. group these factors into three categories: technological, environmental and organizational. According to their findings, *relative advantage* is one of the most important predictors for the adoption decision. Here, the aspects of efficiencies and cost savings play a significant role. With regard to *compatibility*, it can be seen that there has to be a level of compatibility between the financial resources of the firm and the e-commerce technology being adopted. *Complexity* is important for the adoption decision. For this attribute, the factors *ease of use* and *understanding the application* are relevant. In the case of e-commerce adoption, pressure from trading partners has the highest influence. The level of pressure depends on the SME's dependency on the trading partner. *External change agents* and *pressure from competitors* are further important factors. Regarding the *pressure from competitors*, for example, a majority of SMEs decide to implement e-commerce if the level of adoption in their industry is above a certain threshold. Moreover, the attributes *knowledge and expertise* about e-commerce within the firm and the *management's attitudes* are strongly related to the degree of adoption. This means, for example, that firms need a certain level of e-commerce expertise prior to the adoption.

Research by Lowry (2002) shows for the case of building management systems that *compatibility*, *relative advantage* and *ease of use* are the main determinants for the acceptance of an innovation. These findings can also be transferred to the case of RHS.

Studies on the adoption of energy technology innovations show a consistent picture. Various studies use Rogers' *attributes of innovations* in order to assess an adopter's intention. *Relative advantage*, *compatibility*, *complexity*, *trialability* and *observability* are the most commonly used attributes in these studies (Faiers et al. 2006, solar power systems; Labay and Kinnear 1981, solar power systems; Völlnik et al. 2002, energy conservation interventions). Labay and Kinnear added the attribute *perceived risk* to Rogers' attributes. Madlener and Artho (2005) investigate barriers to the adoption of wood chip-fired boilers among residential building cooperatives in Switzerland. The authors use Rogers' attributes of innovation and the technology diffusion model as a theoretical framework for their empirical investigation. Besides non-economic factors, the attribute *relative advantage* includes a number of different economic factors, such as planning costs, investment costs, operational costs or payback time. The studies of Mahapatra and Gustavsson (2007, 2008, 2009) on the adoption of residential heating systems in Sweden use more detailed attributes such as *annual costs of heating*, *investment costs*, *functional reliability*, *indoor air quality*, *security in fuel supply*, *system automation*, *system is environmentally benign*, *increased market value of the home*, *low GHG emissions*, and *time required to gather information*.

In many studies, *relative advantage* is the most important attribute with regard to the adopter's intention. *Compatibility* has also an important effect in many cases. The significance of other attributes like *complexity*, *trialability* and *observability* differs in the studies. *Complexity* shows an effect in the studies of Völlnik et al., *trialability* in the studies of Faiers et al. and Labay and Kinnear; and *observability* in the study by Labay and Kinnear. In the studies by Mahapatra and Gustavsson, *Costs* have the most important effect on the individual intention. *Reliability* is also a significant factor. Further, *security of fuel supply* and *environmental aspects* can be mentioned. Interestingly, the study by Madlener and Artho finds that costs only play a minor role in the attitude formation process.

- **The basis of competition framework**

Another approach towards describing the characteristics of innovations is the *basis of competition framework* by Christensen (1997). This approach stems from the business management literature, and can be used for describing and analyzing market creation. Furthermore, companies can use the framework by Christensen to deal with customer demand (Tapaninen et al., 2009). It includes the buying criteria *functionality*, *reliability*, *convenience* and *price*. Tapaninen et al. (2009) combine the approach by Christensen with Rogers's *attributes of innovations* for studying perceived factors in adopting wood-pellet heating technology. Enterprises compete with each other for the customers' adoption decision. The attributes determining the buyer's decision differ in each phase of the adoption decision. According to Christensen, the adoption and buying decision is a gradual and evolutionary process which has four phases. In the first phase, *functionality* determines the choice by the customer, i.e. the ability of the RHS to heat the home in question. In a next step, customers tend to base their decision on *reliability*, i.e. the ability of the RHS to cover the heat demand of a home and a trouble-free operation. When the market demand for *reliability* is fulfilled, the buyers' choice criterion is *convenience*, i.e. the number of maintenance and cleaning intervals of an RHS. Finally, the competition shifts to *price*, i.e. the costs connected to the installation and operation of an RHS. This approach has also certain similarities to Rogers's phases of the diffusion process (see Rogers 2003 for details).

The study by Tapaninen et al. (2009) about barriers towards adopting wood-pellet boilers applies the *basis of competition framework* in combination with Rogers' *attributes of innovation*. For this purpose, the authors first perform a survey among homebuilders in Finland on perceived barriers. They categorize the qualitative answers according to Rogers' *attributes of innovation* and Christensen's *basis of competition framework*. *Relative advantage* plays a key role for the adoption of wood-pellet heating systems. Moreover, *compatibility* and *complexity* also influence the adopter's intention. Tapaninen et al. show that *price* is the most important factor for the evaluation of the *relative advantage*. The main driver of *compatibility* is *functionality*, while *convenience* has the highest influence on *complexity*.

3.4 Social construction of decision making

The sociological view questions individual decision-making models and considers the broader social and technological context in which decisions for, e.g. a certain RHS are embedded (Wilson and Dowlatabadi, 2007). According to Wilson and Dowlatabadi (2007), the *sociotechnical regime*, i.e. the interrelation between social norms, human behavior, and technological systems, shapes the adoption decision of homeowners in favor of a certain RHS. Therefore, the adoption decision on an RHS has a social dimension, which can be characterized by embeddedness (residential heating is embedded into daily routine), constraints on choice (constraints imposed by supply-chain factors, knowledge and ability or the skills of tradesmen and contractors), counter-marketing (dominant message regarding RHS, to which households are exposed) and impetus (systematic driving force towards a certain RHS). Improved insulation standards for homes, regulations regarding RHS, or drivers related to environmental considerations are examples of factors which have a social dimension and constrain the choice set for RHS.

This view can be used for explaining the emergence of the existing choice set for RHS. However, we argue that behavioral factors play a certain role when it comes to choosing a particular RHS from the available possibilities.

3.5 Summary and implications

Our review shows that a number of factors explain the adoption decision in favor of a specific RHS. These factors range from personal-sphere determinants, including behavioral aspects (e.g. attitudes or norms) perceptions about economic factors on the individual level (e.g. available income or discount rates) as well as perceived contextual determinants (e.g. regulations, infrastructure or economic framework conditions including energy prices or investment costs), which are external to the individual decision-maker. The *TPB* offers a good starting point for developing an integrated theoretical framework for investigating both the influence of personal-sphere as well as perceived contextual factors on the adoption decision in favor of a specific RHS. Figure 5 illustrates the extended *TPB.*

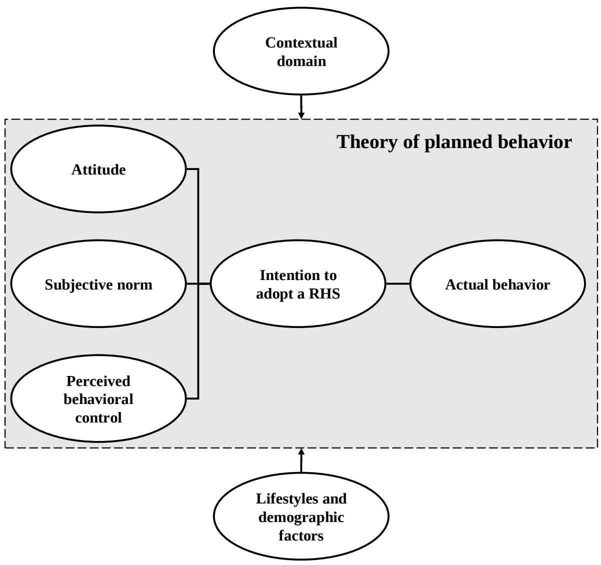

Figure 5: Extended version of the theory of planned behavior

Source: Own illustration

We argue that perceptions about specific contextual factors, including policies, regulations, or economic framework conditions, influencing an individual's decision, need to be assessed at the same time when considering individual adoption behavior. Moreover, we argue that perceived contextual factors influence personal-sphere determinants. Applied to the case of

RHS, this means that perceived economic factors, such as perceptions of energy prices or investment costs, have an impact on the formation of attitudes, subjective norms and perceived behavioral control. This is in line with Christensen's (1997) *basis of competition framework* that sees *price* as the most important adoption criteria. For example, Mahapatra and Gustavsson (2007) show in their empirical research that costs are an important factor in the adoption decision on an RHS. Our approach is in accordance with Stern (2000), who calls for an integrated examination of contextual and personal-sphere aspects of environmentally significant behaviors. Moreover, lifestyles and demographic factors can have a moderating effect on personal-sphere factors.

4 An integrated theoretical framework

In the following, we introduce and discuss an integrated theoretical framework for assessing the homeowner's decision on a specific RHS. Our framework serves as a basis for deriving hypotheses and implications for further research.

4.1 Model description

In our theoretical framework, we use the *TPB* to explain the dynamics of personal-sphere determinants in a homeowner's adoption decision in favor of a specific RHS. We describe the adoption decision with personal-sphere determinants explaining the intention to adopt a certain RHS (which can be categorized according to the predictors of the *TPB* including *attitude*, *subjective norm* and *perceived behavioral control*) on the one hand, and perceived external factors (individual perceptions of economic and non-economic factors) on the other hand. In particular, we assume that perceptions of economic factors have an influence on the personal-sphere determinants. The different predictors of the *TPB* are operationalized with the *PCI* scale, tailored to the context of RHS. Perceptions of economic and non-economic external factors shape the contextual domain of an adoption decision. Knowledge about the impact of perceptions of external economic and non-economic factors helps to improve our understanding of the role of the different personal-sphere determinants in the technology diffusion process. Figure 6 outlines the structure of our model.

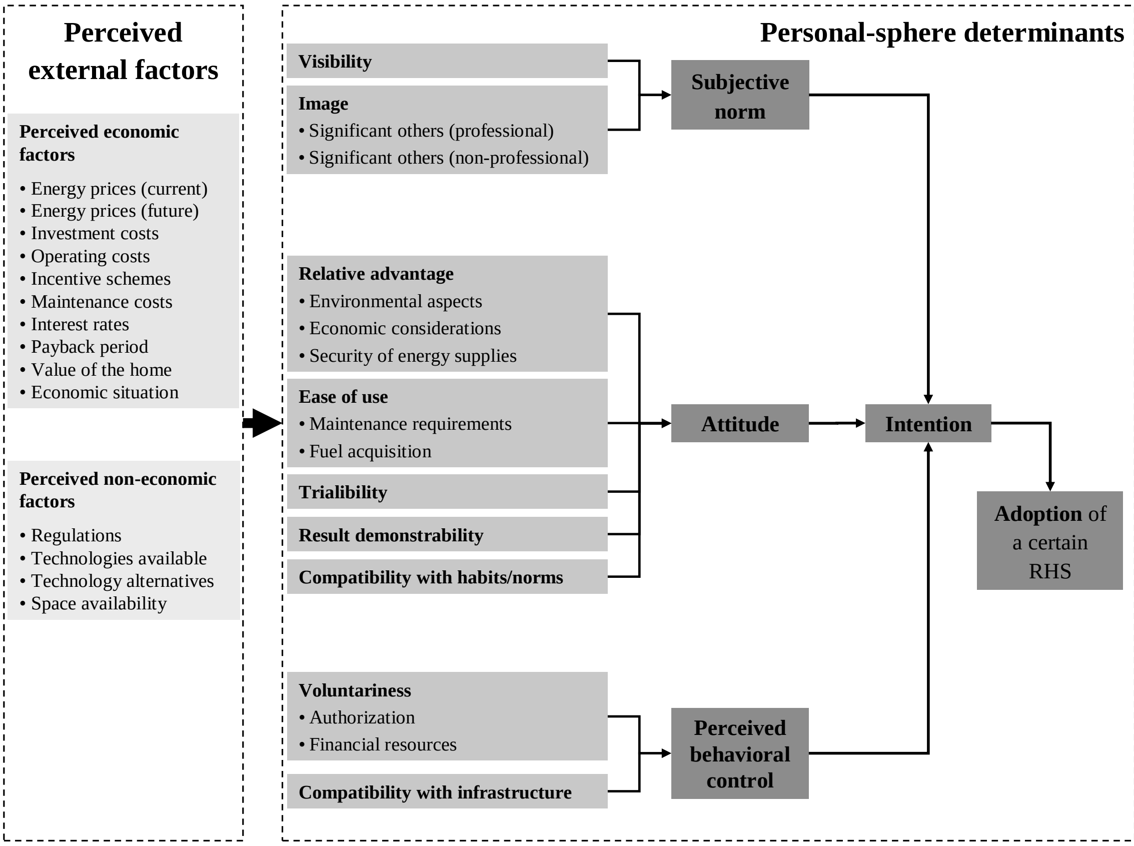

Figure 6: An integrated theoretical framework for assessing a homeowner's adoption of a certain RHS
Source: Own illustration

Attitude describes a homeowner's beliefs and attitudes towards an RHS. A homeowner expects certain individual benefits from adopting a specific RHS. This implies that the higher the compliance of the perceived characteristics with personal values, beliefs or needs, the higher the perceived benefits of a particular RHS. Consequently, this means that a homeowner needs a certain level of understanding of the functioning of an RHS for the attitude formation process. In our framework, we operationalize *attitude* with a number of different *PCI* constructs. In order to account for perceived economic factors, we extend the PCI constructs by economic aspects. We describe *attitude* with more general constructs, such as *relative advantage* of a specific RHS compared to other systems, *ease of use* of a RHS, *result demonstrability* (effort to learn about the results of using a certain RHS), *trialibility* (possibility to learn about and experiment with a system before adopting it), and *compatibility* with individual habits and norms. In order to account for the specifics of RHS, we further operationalize the construct *relative advantage* with *environmental aspects* (e.g. low CO_2 emissions or the possibility to use renewable energy sources), *security of energy supplies* (e.g. the degree of the dependency on fossil fuels), and *economic considerations* (e.g. perception of economic factors). Moreover, we specify the construct *ease of use* with *maintenance* *requirements* (e.g. perceived efforts connected to cleaning out of ashes, the sweeping of the chimney, or the length of maintenance intervals) and *fuel acquisition* (e.g. the perceived effort of fuel acquisition).

Subjective norm represents the homeowner's motivation to comply with significant others. We operationalize the predictor *subjective norm* with the more general PCI constructs *image* and *visibility*. The perceived improvement of one's social status by adopting a certain RHS and the perceived visibility of the usage to others explain the construct *social norm*. Moreover, in order to account for RHS specific aspects, we further operationalize *image* with *influence of significant others* and the desire to comply with their advice or norms. *Significant others* can be *professional* (e.g. architects, installers of heating systems, energy consultants, or media, such as professional journals) and *non-professional* (e.g. family, neighbors, or friends).

Perceived behavioral control includes the homeowner's control over the adoption decision in favor of a certain RHS. We characterize this variable with the PCI constructs *voluntariness* (i.e. the degree to which a homeowner perceives the adoption as a decision out of free will) and *compatibility with existing infrastructure* (e.g. the availability of a gas port, suitable roof space, sufficient storage capacities for wood pellets, or suitable space outside the home for geothermal collectors). We account for RHS-specific aspects by further operationalizing *voluntariness* by *authorization* (i.e. authorization for geothermal drilling) and *financial resources* (e.g. available capital for the investment, financial incentive schemes, or income).

Perceptions about the ***contextual domain*** or external factors influence the personal-sphere variables *attitude*, *subjective norm* and *perceived behavioral control*. Perceived external factors can either facilitate or constrain the personal-sphere. Some of the variables are specific to the individual (e.g. available capital or income), while other variables can be attributed to many individuals (e.g. energy prices or investment costs). We categorize external factors into perceived economic and non-economic factors. *Perceived economic factors* can, for example, be perceptions about investment costs, current and future expectations about future energy prices, operating and maintenance costs, financial incentive schemes, interest rates, payback periods, impact on the value of the home when installing a certain RHS, or the individual and general economic situations. *Perceived non-economic factors* include the availability of suitable space and infrastructure, regulations favoring certain RHS, or the set of available technologies and their alternatives.

4.2 Hypotheses for further research

In this section, we derive three hypotheses on the adoption decision of a homeowner in favor of a specific RHS. In particular, we focus on the influence of external economic factors on the personal-sphere determinants of a homeowner's decision on an RHS. We assume that perceptions about external economic factors have a high influence on personal-sphere predictors and thus on the adoption decision in favor of a specific RHS while the influence of perceptions of non-economic factors plays a lesser role. Therefore, we explicitly account for external economic factors in the three hypotheses, while we do not consider other external non-economic factors, different lifestyles or demographic issues. For the case of RHS, we expect that perceptions about external economic factors influence the intention to adopt a certain RHS via all three constructs of the TPB. The three hypotheses derived from our theoretical framework try to capture most of the possible impact of perceptions about economic factors on the intention to adopt a certain RHS. In the following, we briefly outline the three hypotheses.

We expect that perceived economic factors influence attitude formation through the general characteristic *relative advantage*. In particular, they influence *attitude* via the specification *economic considerations* (e.g. perceived cost-benefit ratio, investment costs or energy prices connected to a certain RHS in comparison with alternative RHS). Therefore, we formulate our first hypothesis as follows:

Hypothesis 1: Perceived external economic factors have an impact on the attitude formation towards a certain RHS. In particular, they influence attitude formation via the PCI characteristic "relative advantage" and, in particular, via the specification "economic considerations".

Based on our theoretical framework, we expect that perceptions of external economic factors influence the *perceived behavioral control* through the characteristic "*voluntariness"* and, in particular, via the specification "*financial resources"* (e.g. perceptions of income or available capital resources for the investment). This leads to our second hypothesis:

Hypothesis 2: Perceptions of external economic factors have an impact on the perceived behavioral control of an adoption decision in favor of a certain RHS. In particular, they influence perceived behavioral control via the specification "financial resources" of the PCI characteristic "voluntariness".

In our third hypothesis, we expect that the perceptions of significant others with regard to external economic factors, such as investment costs or energy prices will influence the *subjective norm*.

Hypothesis 3: External economic factors have an impact on the subjective norm influencing the adoption decision in favor of a certain RHS. In particular, they influence the subjective norm via the specifications "professional and non-Professional significant others" of the PCI characteristic "image".

Figure 7 illustrates the three hypotheses in the context of our theoretical framework.

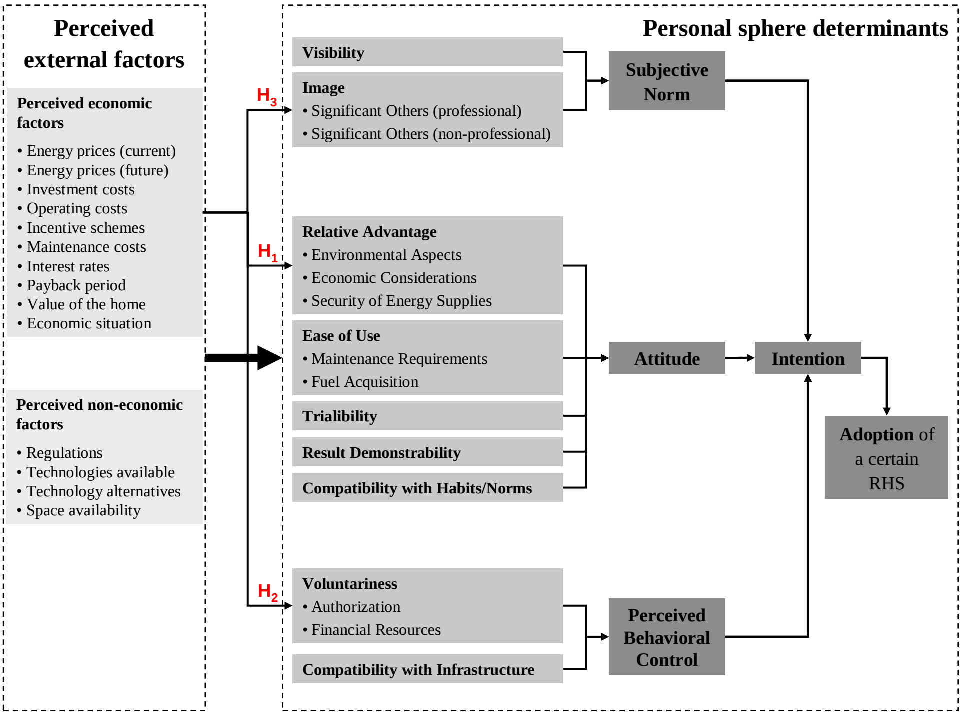

Figure 7: Hypotheses on the impact of perceived external economic factors on the personal-sphere

Source: Own illustration

5 Conclusions and scope for future research

In the following, we outline implications of our model and give an outlook on some opportunities for further research.

Our integrated theoretical framework suggests that personal-sphere determinants of a homeowner determine the adoption decision in favor of a particular RHS. Perceptions of contextual factors, which can be economic or non-economic, have an indirect influence on the homeowner's adoption decision in favor of a particular RHS through personal-sphere determinants. This implies that perceived economic framework conditions explain the adoption decision only to a certain extent. Behavioral factors, which can be attributed to the personal-sphere and to external non-economic factors, represent further factors determining a homeowner's adoption decision in favor of a specific RHS. However, we expect economic factors to have a significant influence on the adoption decision, since RHS are connected to e.g. high investment costs, current and future energy prices, or the assumed payback period.

Against this background, it would be interesting to study the role of perceived economic factors in the adoption of a particular RHS and through which channels they have an impact on a homeowner's personal-sphere. This would lead to a better and deeper understanding of economic and non-economic as well as behavioral factors in the technology adoption process. Moreover, such research also has implications for the design of policy instruments targeting residential heating demand or for the marketing strategy of manufacturers of RHS.

Our integrated model may serve as a starting point for empirical research on a homeowner's adoption decision in favor of a specific innovative RHS. Such research will help to identify relevant variables and to analyze through which channels these act on a homeowner's adoption decision. In particular, it would be interesting to empirically test the hypotheses derived from our theoretical framework, and to investigate the influence of the contextual and personal-sphere determinants on the adoption decision. Furthermore, it would be interesting to test the explanatory power of the different constructs of the TPB and the PCI scale for the adoption decision in favor of a certain RHS. Multivariate analysis, including factor analysis and structural equation modeling, may be a suitable tool for such an analysis of relations between multiple (latent) variables. Moreover, the theoretical framework could serve as a basis for developing a multi-agent simulation model for investigating the diffusion of competing RHS as a social phenomenon, which emerges from the individual adoption decisions of a set of heterogeneous homeowners on the market. In particular, our framework could contribute to describing the individual characteristics of different types of homeowners. Furthermore, it could contribute to deriving decision rules for the set of homeowners considered in the multi-agent simulation model. In order to develop a more realistic model for the case of competing RHS in Germany, such a multi-agent simulation model could then be substantiated with the insights gained from the empirical analysis.

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