Key Drivers and Barriers for Energy Efficient and Sustainable Household Investments

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Jan Paul Baginski
geboren in Dortmund

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Zweitgutachter:	Prof. Dr. Hartmut Holzmüller

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1 Introduction

1.1 Background and motivation

Since the start of industrialisation, modern societies are depending on fossil energy sources to fulfil their need for energy. The consumption of fossil fuels is responsible for carbon dioxide (CO_2) and other greenhouse gas emissions that are the drivers of climate change. Over the last decades, climate change has become a primordial political and societal concern and ranks among the biggest challenges of our times. Global warming, concomitant with climate change, represents an urgent and potentially irreversible threat to human societies and the planet (UNFCCC 2015). Hence, it requires the widest possible cooperation by all countries and their participation in an effective approach to achieve a rapid and sustained reduction of global greenhouse gas emissions. Notably, global warming needs to be limited to maintain a viable environment for future generations. Knowing about the connection between energy use, i.e. the burning of fossil fuels, CO_2 emissions and climate change, policy makers have issued several legal requirements to lower energy demand and the use of fossil fuels.

Most noticeably, the member states of the United Nations Framework Convention on Climate Change met in Paris 2015 and agreed on legally binding climate protection targets (UNFCCC 2015): Hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels. The Paris Agreement superseded the Kyoto Protocol of 1997 (UNFCCC 1997), where first greenhouse gas emission reductions were legally stipulated. The climate protection targets agreed upon in Paris are based on national goals and climate protection measures, so-called national contributions, which each individual country aims to accomplish. In particular, the German government adopted the *Klimaschutzplan 2050* in 2016 to conform to the Paris Agreement. It reinforces the targets decided on already in the *Energiekonzept* of 2010: Reduce CO_2 emissions by 40% until 2020 and by 80-95% until 2050, compared to 1990 levels (BMUB 2016). The *Klimaschutzplan 2050* embraces the guidelines of the *Energiekonzept* to lead Germany into an age of energy efficiency and renewable energy sources, which is to be achieved under consideration of the energy policy triangle: sustainability, security of supply and economic efficiency. The radical change of the German energy system towards a low carbon society can be subsumed under the term *Energiewende*, which made its first appearance in 1980 (Krause et al. 1980) but especially refers to the reorientation of the energy supply after the Fukushima nuclear disaster in 2011.

With 40% of final energy consumption and 30% of greenhouse gas emissions, the building sector is a policy focus for the implementation of the *Energiewende* and regarded crucial for the attainment of emission reduction targets (BMWi 2014). A prominent target is to reach an almost climate neutral building stock by 2050 (German Federal Government 2010). This implies that buildings have an extremely low energy demand and that the remaining demand is primarily covered by renewable energy sources. Notably, residential buildings need to be decarbonised entailing that domestic household energy consumption requires substantial changes. Policy interventions are attempting to foster the implementation of energy efficiency measures (insulation of the building envelop i.e. façade, roof etc.; replacement of windows with insulation glazing) and the installation of sustainable generation technologies (e.g. solar thermal heating, heat pumps, photovoltaic systems).[1] However, private households do not seem to sufficiently respond to current policy instruments, which contributes its share to the foreseeable failing of the German 2020 CO_2 emission reduction target. In addition, the long-term target of a climate neutral building stock is rather optimistic once compared to the development of residential energy use in recent years.

Understanding energy-related household decisions is of great relevance for climate mitigation policies, but at the same time these decisions are considered an under-analysed field of research (Kastner and Stern 2015; Wilson et al. 2015). Additionally, and in contrast to other actors in the energy sector, household decision-making is multi-faceted and goes beyond straightforward economic profitability considerations (Zundel and Stieß 2011; Vom Hofe 2018). Hence, it is expected that research on energy-related household decisions can contribute substantially to reach the ambitious 2030 and 2050 climate protection targets.

[1] Household decisions on these cost-intensive measures are referred to as energy-related household decisions in the following. Certainly, there are other types of household decisions influencing energy consumption and environmental effects (cf. Weber 1999).

The overarching objective of this thesis is therefore to improve the understanding of household decision-making regarding energy efficient and sustainable investments. A model to describe and analyse the decision-making process is conceptualised and key drivers and barriers are identified. This conceptualization is complemented by a specification of (spatial) econometric models to analyse the spatial and temporal diffusion of sustainable generation technologies (domestic photovoltaic systems and solar thermal installations) in Germany. Against this background, the (insufficient) effects of policy instruments are evaluated and implications derived.

The remainder of this introduction is organized as follows. Sections 1.2 to 1.4 present more specifically the context of this thesis regarding energy use, energy policies and decision-making in households. Section 1.5 formulates the research questions of this thesis. A manuscript overview is given in section 1.6.

1.2 Energy supply and consumption in German households

The energy system encompasses several conversion steps: Primary energy is the energy available from natural sources or energy carriers, for example hard coal, lignite, crude oil and natural gas. Water, wind, solar radiation and nuclear fuels are also primary energy sources. Secondary energy is obtained through conversion of primary energy carriers or other forms of secondary energy. Examples are fuel oil, gasoline, electricity or district heat. The end user, for example a household, purchases final energy and uses so-called useful energy to acquire his requested energy services. Final energy is measured by installed meters and determines energy costs. In households, (final) energy is amongst others used for lighting, heating or cooling purposes in order to satisfy individual needs, like a heated room or a cold drink. Figure 1 shows the energy flow chart for Germany and the share of economic sectors in the consumption of final energy. It also shows the conversion losses between primary and final energy.

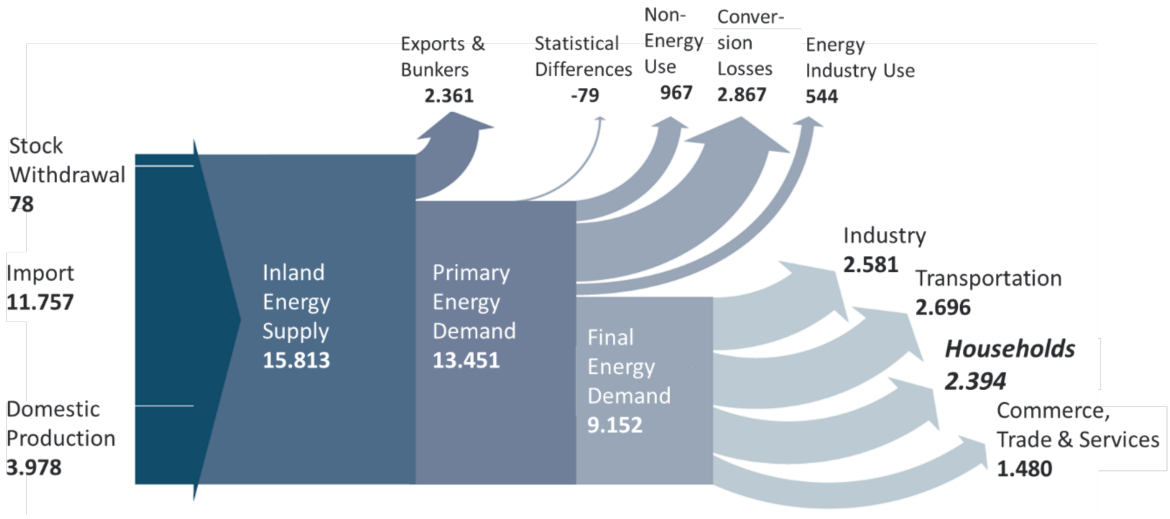

Figure 1 Energy flow chart of Germany 2016 in PJ; own illustration based on BMWI 2018

Roughly 41 million German households consume 26% of final energy demand.[2] They are accountable for 11% of energy-related CO_2 emissions (BMWI 2018). The most energy intensive service in the household sector is heating. In 2016, space and tap water heating was responsible for 84% of energy consumption (Figure 2). Another 6% of final energy is used as process heat, i.e. cooking and washing. The remaining 10% are associated with electricity consumed for lighting, cooling, and using information and communication technologies.

Whereas the share of renewable energy in the electricity sector increased from 12% in 2006 to 32% in 2016, the share of renewable energy in the heating sector only increased from 8% to 13% in the same period (BMWI 2017). Residential heating is still dominated by fossil fuels, where at present oil, gas and district heating cover 80% (Figure 2). These sources produce negative environmental impacts by the generation of CO_2 emissions. As of today, only a very limited share of households uses sustainable heat and electricity generation technologies.

[2] Without fuel consumption. It is captured in the transportation sector.

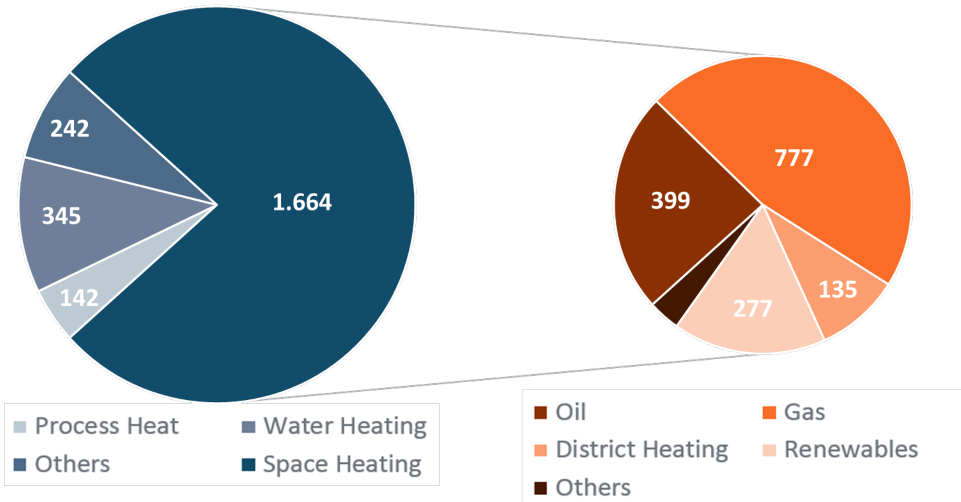

Figure 2 Energy use in German Households 2016 and energy sources for space heating in PJ; own illustration based on BMWI 2018

Household energy consumption takes place in the home and is thus predetermined by the energy efficiency level of the building and the included technologies. As demand is driven by heating, cold winters or cold temperatures highly influence annual household energy consumption and lead to annual fluctuations. Although higher energy efficiency resulted in a decreasing per capita energy consumption over the last two decades, absolute household energy demand stayed unchanged between 1990 and 2016 (BMWI 2018). First, this is attributable to the increased number of households: The German population slightly increased and average household size decreased (Destatis 2018a). Smaller households exhibit a higher per capita energy consumption, leading to a higher absolute consumption. Second, living space increased inducing higher space heating needs. Although efficiency gains cause a lower final energy demand per square meter, energy savings are to some extent offset by larger residences. Also, rebound effects, for example increased room temperatures after improving the insulation of the building envelope, eat up enhanced energy efficiency (Sunikka-Blank and Galvin 2012). Two thirds of the 19 million German residential buildings were built before the first guideline on energetic standards was established in 1977 and their efficiency level is rather low (BMWI 2014). Today’s high efficiency standards only apply for new buildings and in cases of extensive refurbishments (EnEV 2015). At the same time, demolition and construction rates are small (Destatis 2018b). Thus, energy efficiency measures in existing buildings are likely to be one of the main levers for emission reductions in the household sector. Efficiency levels of the future building stock have to increase considerably to over-compensate rebound-effects and repercussions of larger dwelling space and smaller households.

1.3 Household energy use and German policy interventions

As presented in the previous section, a significant amount of current emissions is the result of energy consumption in households. This section has two objectives: First, to give an overview of potential market failures affecting energy efficient and sustainable household investments. Second, focussing on Germany, summarize relevant policies addressing the household sector.

Economic theory implies under some idealizing assumptions, that market forces would lead to an efficient allocation of resources and secure efficient structures of supply and demand of energy (Jochem and Gruber 1990; Johansson 1991). Yet, multiple of the theoretical prerequisites are violated in the actual decision-making of households regarding energy efficient and sustainable products. The latter is not (and cannot be) based on full information and fully rational utility maximization (cf. section 1.4). At the same time, market failures exacerbate the underinvestment in energy efficient and sustainable technologies. As a consequence, policy interventions are necessary and potentially beneficial (Brown 2001; Levine 1995).

Violations of perfect market assumptions relevant for individual household decisions are commonly conceptualized around the energy efficiency gap (Jaffe and Stavins 1994). The energy efficiency gap captures the persisting difference between the technological and economic potential and actual market behaviour (Wilson and Dowlatabadi 2007). In view of the topic of the present thesis, the consideration of market failures is not limited to energy efficiency measures but extended to sustainable generation technologies, available for purchase to households. Selected, commonly cited market failures are outlined in the following.

First, the conversion and consumption of energy is associated with environmental externalities and other external costs. Negative external effects (e.g. air pollution) are not fully reflected by market prices, which induces an overuse of energy relative to the social optimum (Groba and Traber 2010). Additionally, actual consumer prices may not reflect marginal social costs as utilities commonly charge constant time-invariant prices, which leads to non-optimal energy consumption (Gillingham et al. 2009).

Second, financial constraints constitute impediments for energy saving measures and renewable generation technologies (Kastner and Stern 2015; Achtnicht and Madlener 2014). Households are deterred from buying specific products due to a lack of credit. Their unwillingness to take loans is aggravating this issue (Zundel and Stieß 2011).

Lastly, the market suffers from asymmetric information, with full information not available to end users. Consumers lack of information about the availability and the savings potential from energy efficient and sustainable investments, which is thus ignored in the decision-making (Jochem and Gruber 1990). Principal-agent problems, arising notably between landlords and tenants, are also related to asymmetric information on energy efficiency investments (Jaffe and Stavins 1994). It is apparent, that households face enormous informational transaction costs, which violates assumptions of a perfect market.

Since several conditions are not fulfilled, a pure competitive market will generally not lead to pareto-efficient outcomes (Bauermann 2015) and prevents energy efficient and sustainable technologies to gain market shares (Gillingham et al. 2009). It is widely agreed that specific energy policy interventions are needed to tackle these market failures. The German government has introduced various policy measures concerning the energy consumption of households, embracing regulation, financial funding and information strategies. They can be separated into instruments regarding the electricity and the heating market.

Heating market policy in Germany started after the 1973/74 oil crisis with the *Energieeinsparungsgesetz* of 1976 (EnEG 1976). The EnEG formed the basis for two ordinances aiming at higher energy efficiency in new buildings (WärmeschutzV 1977) and minimum efficiency standards for residential heating systems (HeizAnlV 1978). The major objective was thereby initially to reduce oil (and gas) import dependency and household heating expenses. In 2002, the *Energieeinsparverordnung* (EnEV) was enacted and merged the two previous ordinances. It defines standards for the primary energy demand of buildings, taking into account the insulation standard and the efficiency of heat generation, distribution, storage and transmission. It was revised several times, amongst others to fulfil the requirements of the European Directive on the energy performance of buildings (EPBD 2002). A further major legislative step took place in 2009, when the *Erneuerbare-Energien-Wärmegesetz* (EEWärmeG 2009) complemented the EnEV. The EEWärmeG defines mandatory shares of renewable energy in final heating energy demand for new constructions. The latest amendment to the EnEV has been enacted in 2014 to integrate the EPBD recast of 2010 and includes a further tightening of the energy performance requirements from 2016 onwards.

Regulations and standards for insulation and heat production hence contribute significantly to achieve energy policy objectives. In addition, offering financial assistance helps to activate households and supports the realisation of energetic refurbishments and the adoption of renewable generation technologies (Wilson et al. 2015; Achtnicht and Madlener 2014). In Germany, grants and low interest credits are made available mainly by two institutions: the *Kreditanstalt für Wiederaufbau* (KfW) and the *Bundesamt für Wirtschaft und Ausfuhrkontrolle* (BAFA). The KfW supports either full-scale renovations to new building standards or specific energy efficient retrofit measures such as thermal insulation and modernization of windows. Also, low interest loans for the construction of new houses with primary energy consumption below prescribed EnEV standards are provided. The BAFA promotes the installation of innovative and sustainable heating systems under the *Marktanreizprogramm* (MAP) with direct grants.

Electricity market policy relevant to households traditionally targets electricity consumption. Regulations require end-use appliances to be more efficient and can be decisive to reduce consumption and concomitant greenhouse gas emissions. For example the *Energieverbrauchsrelevante-Produkte-Gesetz* (EVPG 2015) transposes European into national law and outlines informational duties of producers. It specifies mandatory information on the product, such as its energy consumption and determines guidelines for energy labels. By providing households with information on the efficiency of appliances, incentives for the consideration of energy consumption in the purchase decision are set.

Besides targeting electricity consumption with regulations, residential low-carbon electricity generation is financially supported. The promotion of renewable energy sources in the electricity sector is organized under the *Erneuerbare-Energien-Gesetz* (EEG 2000). It replaced the *Stromeinspeisungsgesetz* of 1991. Several amendments led to the current EEG (EEG 2017). It introduced the exercise of tenders to determine the feed-in tariff for larger wind, photovoltaic and biomass power plants. Predominantly relevant to household decisions is the guaranteed feed-in compensation for small photovoltaic (PV) systems. Electricity generation of small rooftop PV installations is remunerated with a predetermined feed-in tariff, which is granted for the year of commissioning and the following 20 years, providing considerable security for investors.

In addition to regulation and funding, Germany is running several informational campaigns and services on the national, federal and municipality level to acquaint households with energy efficient and sustainable products. They include energy advice, energy performance certificates, community renovation schemes as well as public information campaigns. To name one program in detail, the *Bundesministerium für Wirtschaft und Energie* (BMWi) supports energy counselling in residential buildings by paying a part of consultancy costs. The mostly in-house advice identifies potentials for energy investments, specifies efficiency gains and informs about financial support.

The above-mentioned interventions all have the potential to improve energy-related household decisions distorted by incomplete and asymmetric information, liquidity constraints and externalities. In economic textbook theory, the use of emission taxes or tradable emission permits are advocated over other types of policy interventions as the first-best instruments for emission abatement and climate protection (Pigou 1920; Weitzman 1974). External effects are internalised to ameliorate the (energy) price signal that does not include all related costs. While the European Emission trading system (ETS) has addressed the electricity market in a comprehensive way, the German heating market lacks effective regulation to overcome the problem of external effects (Bauermann 2015). Yet, the Federal Government refers to the ETS as the major CO_2 pricing instrument. No additional pricing scheme in the heating market is currently scheduled (Bundesregierung 2018) although several German institutions call for CO_2 pricing in all sectors (IW 2018; bdew 2018).

1.4 Theories on energy-related decision-making

Understanding how individuals make decisions is important for researchers and policy makers concerned with the impact of purchase decisions on energy demand and the environment (Brewer and Stern 2005). Literature examining decisions on energy efficient and sustainable products at the residential or household level uses heterogeneous approaches and comes up with diverse results.

As a starting point, neoclassical conceptions suggest that energy efficiency measures will be implemented if the net present value resulting from the measure is positive. This is based on the idea that households discern these measures as investments and therefore, in the first place, evaluate profitability. In a market perspective, the household is perceived as a rational decision maker or *homo oeconomicus*, who maximizes his utility by choosing the optimal bundle of goods considering his budget constraints and market prices (Kirchgässner 2008). Households have perfect and costless information about products and prices, and are capable to determine optimal alternatives.

Because of the observed gap between potentially profitable and actually implemented measures, reasons for deviations from standard economic assumptions are proposed. Psychological and sociological studies find that the assumption of perfect consumer rationality does not hold in reality. These insights are also incorporated in models of behavioural economics. The most relevant contributions are thereby given by prospect theory, bounded rationality and heuristic decision-making (Groba and Traber 2010). Contributions evoke risk aversion, uncertainty and irreversibility, sunk costs, the use of short term discount rates, heterogeneity of preferences, transaction costs, behavioural inertia, limited sensitivity to changes of energy service attributes and the relative unimportance of energy costs as explanations for the observed gap (Wilson and Dowlatabadi 2007; Zundel and Stieß 2011).

The prospect theory (Kahneman and Tversky 1979) of decision-making under uncertainty postulates that individual welfare changes loom greater from expected losses than from gains of the same magnitude. This aggravates consumer's risk aversion, who avoid risky investments with uncertain results. Upfront costs at the beginning of an investment in energy-saving measures are perceived as larger than the gains by energy cost savings during the utilisation phase. Bounded rationality implies that individuals face cognitive constraints in processing information (Wilson and Dowlatabadi 2007) and do not fully know the available options. Relating to this issue, individuals simplify the decision problem and default to heuristic decision-making. In order to reduce the cognitive load, households tend to follow sequential decision strategies that deviate substantially from conventional utility maximization assumptions (Gillingham et al. 2009).

These explanations yet presuppose that household decisions on energy efficient and sustainable products are driven by financial and economic motivations. However, refurbishing and insulating the façade, or installing a new heating system are measures that also improve the residential environment. They deliver not only economic profit but also other useful features which generate co-benefits, including improved comfort of living or reduced environmental impact (Gram-Hanssen et al. 2007; Jakob 2006).

Hence, it is not very likely that the decision about these measures is based on economic considerations alone. Consequently, recent approaches are broader and incorporate behavioural and psychological factors such as attitudes, motivations, expectations and trust (Aravena et al. 2016; Brewer and Stern 2005; Claudy and O'Driscoll 2008), environmental concern (Allan and McIntyre 2017; Decker and Menrad 2015) and peer effects (Richter 2013; Rode and Weber 2016). This leads to a wide range of non-economic drivers for adopting energy efficient and sustainable technologies: increasing thermal comfort, embellishing the building appearance, reducing the environmental impact and lowering the dependence on classic suppliers (Wilson et al. 2015; Kastner and Stern 2015; Hecher et al. 2017; Jakob 2006; Zundel and Stieß 2011). Also, numerous barriers have been identified including inconvenience, concern about the quality of options and the work of craftsmen as well as such investments being considered superfluous or that the right time has not come (Curtis et al. 2018; Aravena et al. 2016; Achtnicht and Madlener 2014). In addition, the vividness of information matters. Face-to-face interactions and personal information have a greater impact on decisions than anonymous brochures (Zundel and Stieß 2011). This means that energy advisers as well as peers in the social environment can promote but also impede the adoption of energy efficient and sustainable technologies.

Lately, the influence of locational characteristics and regionally varying factors on energy-related household decisions have been increasingly studied using the rather new method of spatial econometrics (Dharshing 2017; Schaffer and Brun 2015; Allan and McIntyre 2017; Graziano and Gillingham 2015). This approach builds on concepts from regional science and takes Tobler's first law of geography as a starting point: "everything is related to everything else, but near things are more related than distant things" (Tobler 1970, p. 236). The studies agree that even after controlling for a range of regional characteristics (such as economic capability, settlement structure and climatic suitability) spatial dependence is an important driver for technology diffusion. They also converge in demonstrating significant spatial spillover between adjacent regions (e.g. postcode or administrative districts). In particular, the likelihood of adopting a solar technology in a region increases with the penetration of these systems in neighbouring regions (Dharshing 2017). One of the discussed explanations for spatial spillover are neighbourhood or peer effects i.e. potential adopters follow decisions by households nearby (Rode and Weber 2016). The installation of a solar PV panel is conspicuous and creates a persistent signal that peers (neighbours and passers-by) observe. Observational learning from adoption decisions of others may provide free information gathered by an adopter to other households and facilitate the decision (Richter 2013). Besides such peer effects, other forces potentially cause spatial spillover and contribute to geographical clusters of adoption rates. The installation of innovative products requires specific knowledge of craft producers and certified experts which may be highly localised (Schaffer and Brun 2015). Neighbouring areas will likely benefit from technical installation expertise, implying regional knowledge spillover. In this vein, spatial dependence seems to be a relevant non-economic determinant for household investment in efficient and sustainable technologies.

1.5 Research questions

In the aforementioned context, the major objective of the thesis evolves: Contribute to an improved understanding of the energy-related decision-making in households and establish a framework to describe and analyse these decisions. This leads to the research question:

A) How can the complexity of individual decision-making and its interactions with policy interventions be conceptualized adequately?

Furthermore, the thesis aims to identify relevant incentives and barriers for investments in energy efficiency and sustainable energy solutions. Hence, the following research question is to be addressed:

B) What motivates or prevents households to invest in energy efficient and sustainable technologies? Which influences foster or impede the adoption decision?

Besides an analysis of individual, household specific motives and attributes, the investigation of the impact of regional characteristics and spatial effects has turned out as an interesting approach in recent years. This leads to the questions:

C) What empirical evidence exists on regional drivers and spatial adoption patterns of energy efficient and sustainable investments?

D) Does spatial spillover between adjacent regions affect adoption and how can spatial dependence be modelled adequately?

Empirical evidence so far suggests that the impact of current policy interventions is limited in view of a decarbonisation of the building energy use. Hence, the implications of the developed concepts and analyses for energy policy formulation are of interest:

E) What can be inferred from more sophisticated models of households' energy-related decision-making for energy policy formulation? Can more adequate and efficient policy measures be identified that enable a better target achievement?

1.6 Thesis structure and overview

The main part of this thesis is organised in three chapters that comprise papers addressing the research questions raised above. The context of these chapters, their content and focus as well as their methodological approach are described briefly in below. The final chapter concludes and provides answers to the formulated research questions.

Chapter 2

A consumer decision-making process? Unfolding energy efficiency decisions of German owner-occupiers

By Jan Paul Baginski and Christoph Weber

Chapter 2 elaborates on the decision-making of German households regarding energy efficiency measures. The refurbishment rate in Germany stagnates at 1% per year, indicating limited success of introduced policy instruments. The presupposition that homeowners are motivated to renovate to save money, but are prevented from doing so by capital constraints and uncertainties regarding profitability is questioned. In order to design more effective policies that promote widespread refurbishment activities, this paper investigates the, to this point under-researched, decision-making of homeowners. A qualitative-explorative research approach is chosen, to cope with the diversity and inconsistency of consumer behaviours and the individual household situations. In-depth interviews with independent energy advisers have been conducted. The household decision towards energy efficient refurbishment measures qualifies as an extensive consumer decision rather than a pure investment decision. A process model of consumer decision-making serves as a suitable framework to structure the decision, including problem recognition, information search, evaluation of alternatives, choice and implementation, usage and assessment. It allows to identify drivers and barriers at each process step and to derive implications on how to activate households and to promote energy efficiency in each step. The identified drivers and barriers are taken into consideration when constructing the input variables for the performed econometric analyses of chapters 3 and 4.

Chapter 3

Coherent estimations for residential photovoltaic up-take in Germany including spatial spillover effects

By Jan Paul Baginski and Christoph Weber

Chapter 3 focusses on the spatial diffusion of roof mounted PV systems and the underlying drivers in Germany. The share of solar energy in electricity generation has increased strongly over recent years. This is largely due to guaranteed feed-in tariffs together with decreasing solar panel prices. Residential PV systems offer households the possibility to contribute to the *Energiewende* and benefit from the use of renewable energy. The regional adoption of domestic PV systems varies distinctly across Germany implying different requirements in distribution grids as well as uneven utilization of national policy measures. Chapter 3 augments traditional regression analysis and uses spatial econometric models to consider cross-regional spillover of PV systems. Further, it extends previous literature findings by including unprecedented explanatory variables. Estimation results show that high values for solar radiation, the share of detached houses, electricity demand and inverse population density of a region favour regional PV uptake. In addition, spatial spillover is found to be a relevant determinant for regional patterns of PV adoption. Both, spatial lag and spatial error dependence contribute to an accelerated PV diffusion in a region and its surroundings. However, it is supposed that spatial spillover is not mainly driven by social imitation but by other regional characteristics not included in our model.

Chapter 4

Spatio-temporal diffusion of residential solar thermal systems in Germany: A spatial panel data analysis

By Jan Paul Baginski

Chapter 4 focuses on residential solar thermal (ST) heating systems, which received a grant under the so-called *Marktanreizprogram* (MAP) between 2001 and 2015. The German government started to promote the use of renewable energy in the heating sector in 1994 to reduce CO_2 emissions and decrease fossil fuel dependence. The MAP still is the most important political instrument for the promotion of renewable heating systems. Its grants brought forth over 1 million ST systems. Yet, the diffusion of residential ST systems shows great variations over the years and between regions. Chapter 4 builds on the methodological approach of chapter 3 by addressing the spatial dimension of adoption decisions, but also considers the time dimension through the use of panel data. Thereby traditional panel models are taken as a starting point and extended by spatial interactions. The analysis is based on NUTS3-year combinations as the observational units. The use of ST systems entails heating energy cost savings making the purchase potentially profitable. Hence, an economic model is built incorporating system costs, grants, solar radiation and energy prices to understand the relationship between ST uptake and profitability. Results indicate that higher profitability, induced by differences in solar radiation and recent and expected fossil fuel prices, increases the propensity to adopt ST systems. Besides economic viability, household size favours ST uptake while the effect of household income and environmental attitude (measured by Green party voters) stays inconclusive. Further, spatial spillover is found to be a significant driver of ST diffusion.

Chapter 5

Conclusion and Outlook

The final chapter of the dissertation consist of a summary and a discussion. Main results of the three articles are summarized and evaluated with reference to the above-formulated research questions. On this basis, practical implications are derived on how to decarbonise the household sector. The dissertation terminates with a discussion of limitations and suggestions for future research.

2 A consumer decision-making process? Unfolding energy efficiency decisions of German owner-occupiers

Jan Paul Baginski and Christoph Weber

Abstract

The German housing stock needs substantial energetic retrofit to meet carbon reduction targets. Various instruments are available to motivate building owners to improve the energy efficiency of their dwellings. These instruments mainly focus on the economic issue of funding and financing energy efficient refurbishments as the decision is interpreted as a rational choice of an investment. Their success is rather low as the refurbishment rate stagnates around 1% per year for more than a decade. The objective of this study is to gain deeper insights into the decision-making of owner-occupiers regarding energy efficient refurbishments and to offer an adjusted framework to analyse the decision. A qualitative-explorative research approach is chosen, whereby in-depth interviews with independent energy advisers have been conducted.

Results point out that the decision of owner-occupiers towards energy efficient refurbishment measures qualifies as an extensive consumer decision rather than a pure investment decision. The refurbishment measure implies high cognitive as well as emotional involvement. Owner-occupiers use several criteria to evaluate refurbishments, which superpose monetary determinants. The standard process model of consumer decision-making, reaching from need recognition to post-purchase evaluation, qualifies for structuring the decision. It allows analysing drivers and barriers stepwise and deriving implications for activating homeowners and for promoting energy efficiency in each step. Current policies partly choose unrewarding argumentations to stimulate energy efficient refurbishments since they do not take all relevant factors of this consumer decision into account.

Keywords: Energy efficient refurbishments; decision-making process; consumer purchase decision

1 Introduction

Housing is a sector with high priority in environmental policy. In the energy concept of 2010, the German government sets the target to reduce primary energy demand in buildings by 80% in 2050 to accomplish a “climate neutral” building stock (BMWI 2010). Two thirds of German residential buildings were erected before the first guideline on energetic standards was established in 1977 (BMWI 2014). The majority of these buildings is inefficient and has an energy demand way above current standards. At the same time, construction and demolition rates are quite low, leading to the presumption that today`s building stock is likely to cover a large share of the residential buildings in 2050. Thus, the refurbishment of existing buildings is an important lever for Germany’s energy efficiency objectives. It relies on two pillars: First, reduce heat demand through building envelope refurbishments like thermal insulation of façades, roofs and ground floors as well as replacing windows; second, supply remaining heat demand with efficient and/or renewable technologies. The long lifetime of building components implies that immediate action needs to be taken in order to avoid lock-in into inefficient buildings and building technologies (Hecher et al. 2017). Still, residential heating is dominated by fossil fuels, as oil, gas and district heating cover 80% of heating demand (BMWI 2018). Renewable heating systems like wood pellet heating or heat pumps are only slowly gaining market shares. In addition, the annual refurbishment rate stagnates at 1%. Estimations claim that the rate has to double to meet the envisaged climate neutral building stock in 2050 (UBA 2013). Various policy instruments are available to motivate building owners to reduce the environmental impact of their dwellings. These include: energy advice, energy performance certificates, financial incentives (grants, subsidies, tax credits, low interest loans, third party financing), community or neighbourhood renovation schemes (collective procurement), and marketing and information campaigns (Wilson et al. 2015). However, existing instruments do not succeed in facilitating a comprehensive uptake of energy efficient refurbishments.

Most introduced instruments and policies are influenced by the presupposition that homeowners are motivated to conduct energy efficiency measures (EEM) by the prospect to save energy costs, but are prevented from doing so by capital constraints and uncertainties regarding profitability (Wilson et al. 2015). They mainly focus on the economic rationale, arguing that homeowners perceive EEM as investments (Kastner and

Stern 2015). The impact of non-economic factors on the decision is underestimated and uncared for in politics. Policy makers have generally neglected behavioural determinants of individuals' decision-making such as motivations, attitudes and social norms (Claudy and O'Driscoll 2008). In order to design more effective policies that promote widespread energetic refurbishment activities, it is fundamental to reproduce the decision-making of homeowners (Aravena et al. 2016). Previous research on owner-occupiers' decision to conduct EEM mainly follows four perspectives: conventional and behavioural economics, technology adoption theory and attribute based decision-making, social and environmental psychology, and sociology (Wilson and Dowlatabadi 2007). Notwithstanding these approaches, the understanding of the decision-making appears to be unsatisfying (Wilson et al. 2015) and research still needs to be done (Kastner and Stern 2015). To our understanding, a consumer oriented perspective on EEM decision has not been taken so far. Also, most existing studies addressing refurbishment decisions wrongfully focus on one decision stage, not the entire process (Aravena et al. 2016). Hence, this study contributes to literature by associating the EEM decision with extensive problem solving prevalent in high-involvement purchases. The decision is framed in a consumer decision process model, which encompasses the stages: Need recognition, information search, evaluation of alternatives, choice and implementation, usage and assessment. With regard to these decision stages, we improve the understanding of homeowners' decision-making and derive drivers and barriers as well as leverage points for policy interventions. The study is based on empirical findings gathered through interviews with energy advisers. The majority of EEM discussed with energy advisers in Germany are capital intensive, having a cost range of approximately 5.000 to 50.000 EUR. Energy advice focuses on owner-occupied single-family, detached or semi-detached houses. Around 46% of the 40 million dwellings in Germany are owner-occupied, with single-family houses representing the largest share (Zensus 2011). Their contribution to energy efficiency is crucial. Owner-occupiers are independent decision makers and are directly affected by their decisions' consequences. Both aspects are to some extent a precondition for the suggested decision framework. Since energy advisers are the information source of the present study, results especially apply to the targeted homeowners.

The remainder of this study is structured as follows. We review relevant literature and propose the conceptualization of energy efficient refurbishments in the frame of a consumer decision process model (Chapter 2). In Chapter 3, the material and method of the own field study are described. Results are presented in Chapter 4 and implications derived in Chapter 5. Finally, a conclusion is given.

2 Background

Numerous conceptual and empirical studies have analysed decisions on energy efficient refurbishments. They agree that owner-occupiers' decision-making not only includes monetary factors, such as upfront costs or annual energy cost savings, but also non-monetary factors, such as social norms, status, environmental benignity and indoor comfort. Table 1 gives a concise overview of literature findings on homeowners' motives and barriers.

Table 1 Motives and barriers when evaluating energy efficient refurbishments (Friege and Chappin 2014; Kastner and Stern 2015; Wilson et al. 2015)

	Motives and Drivers	**Barriers and Constraints**
	An energy efficient refurbishment	Residents may
Economic	• is profitable • increases home's value • reduces energy bills • provides security against volatile prices, future supply problems and dependency on classic suppliers • utilizes funding	• drop option due to high upfront costs • lack necessary financial resources • be reluctant to raise a (further) loan • be uncertain about pay-back period and energy cost savings
Non-economic	• increases thermal comfort, convenience, and status • embellishes the building appearance • reduces energy demand, environmental impact, and greenhouse gas emissions • increases resilience against climate change • falls together with necessary maintenance	• think no refurbishment is needed and are satisfied with the home's current state • find the retrofit process too complicated and have no interest to deal with it • be concerned about the quality of options and the work of craftsmen • fear increased risk of mould and dampness • argue the right time has not come and fear that refurbishment causes dirt and stress

Although non-economic decision determinants have been established in recent research, approaches to explain EEM decisions still focus on monetary determinants (Zundel and Stieß 2011). Wilson et al. (2014) emphasize that non-monetary determinants are systematically understudied in the area of energetic refurbishments. Klockner and Nayum (2016) conclude that this might bias research findings toward overemphasizing economic determinants. Notably, Zundel and Stieß (2011) propose that most homeowners do not regard energy efficient refurbishment measures solely as an investment but rather as a consumer good. They refer to Gram-Hanssen et al. (2007) who argue that energy efficient refurbishment measures are strongly linked to feelings of convenience and comfort and deliver not only economic profit but also other useful features. Unlike investments, the building is not only perceived as a financial asset and not primarily sought for to earn interest. Owner-occupiers see their building as a home, the focal point of private life and a place to feel comfortable and safe (Gram-Hanssen et al. 2007; Wilson et al. 2015).[1] The installation of thermal insulation or renewable heating systems shapes not only the asset "building" but also creates domesticity (Offenberger 2016). The daily utilization (living in the building) and experience of EEM consequences distinguishes them from investment decisions. Following these arguments, we propose that it may be rewarding to analyse EEM decisions as consumer purchase decisions. In consumer research, an effort continuum is used to cluster purchase decisions, ranging from habitual decision-making to extended problem solving. The level of effort consumers put into decisions depends on the level of involvement (Kroeber-Riel et al. 2011). Involvement is induced by a person's high perceived relevance of an object, based on inherent needs, values and interests (Zaichkowsky 1985). High perceived risk usually means higher involvement and is present if a purchase has potentially significant negative financial (losses), physical (discomfort) and/or social (embarrassment) consequences (Solomon et al. 2014). High-involvement purchases force the decision maker to deal with the purchase both cognitively and emotionally. The decision requires careful information searching and processing as well as evaluating options before making a final choice. EEM, similar to cars or kitchens, rate as high-involvement purchases, as they meet several criteria that increase involvement (Kastner and Stern 2015). They constitute complicated, unknown, expensive and often innovative products for homeowners. Hence, the decision-making is

[1] The construction of home as a sanctuary is expressed in phrases like "my home is my castle". Saunders and Williams (1988) discuss the perspective on home in contrast to house.

elaborate and implies extensive problem solving. In addition, EEM decisions have a high ecological relevance, which, due to the long lifetime of building components, shape a household's ecological impact of the following decades. The choice of the insulation level sets boundaries for heating energy demand and the heating system choice determines the primary energy source and resulting CO_2 emissions. Environmental impacts of these decisions can a posteriori merely be reduced by energy saving behaviour in the utilization phase. Bodenstein et al. (1997) claims that environment-related consumer decisions of this type involve an unusually high use of cognitive resources and characterizes strategic consumer decisions by three aspects: long planning horizon, high specific investment and high emotional involvement. Subsequently, we subsume EEM decisions under the definition of environment-related strategic consumer decisions associated with extensive problem solving.

For analysing the purchase of high-involvement products, consumer research most frequently applies structural models (Kroeber-Riel et al. 2011), which may be traced back to Howard and Sheth (1969). These models align a decision process according to several decision stages. The application of decision stages has been carried out by some environment-related decision studies. Lane and Potter (2007) examine the total process of consideration, adoption, use, consolidation and/or rejection for low carbon vehicles. Following Rogers' innovation diffusion model Rogers (2003), Nair et al. (2010b) use a three step model of decision-making to evaluate Swedish homeowners' adoption of building envelope components. The decision process starts with homeowners' need for a new building envelope component, leading to information collection and finally the selection of a component. A similar approach is used by Hecher et al. (2017) to analyse the triggers for homeowners' heating system choice in Austria. Klockner and Nayum (2016) structure EEM decisions into four stages, which are referred to as "not being in decision mode" (mind-set in the pre-decision phase), "deciding what to do" (people consider alternatives and explore options), "deciding how to do it" (planning gets more concrete and an alternative is prioritized) and "deciding how to implement" (implementation arrangements are made). In these studies, the decision process ends with the implementation, adoption or non-adoption of a refurbishment measure. We see the termination at this decision stage as a weakness since the utilization phase is neglected. A different approach, which in our view (partially) overcomes this weakness is made by

Aravena et al. (2016). They study motives of Irish households at three different stages of the EEM decision-making process: (ex ante) motivations for the application of grants; motivations during the adoption of measures; and (ex-post) motivations governing further refurbishment decisions.

In order to cope with a broad range of stages in the decision process, we base our analysis of EEM decisions on a general consumer decision process (CDP) model. The CDP model by Blackwell et al. (2006) represents a widely used structural model and captures the activities that occur when consumers make decisions in a schematic format (cf. Figure 1).[2] It depicts how different internal and external forces interact and how they affect consumers' reasoning, evaluating and acting (Blackwell et al. 2006). It helps marketers to analyse how individuals make purchase decisions and to guide communication and sales strategies. When consumers engage in extended problem solving, they usually complete the entire decision-making process: Need recognition, search for information, pre-purchase evaluation, purchase, consumption, post-consumption evaluation, and divestment.[3] The objective of our research is then to develop a version of this CDP model that is specifically adapted to describe homeowners' decision making for EEM decisions and thus captures the key findings of our empirical analysis.

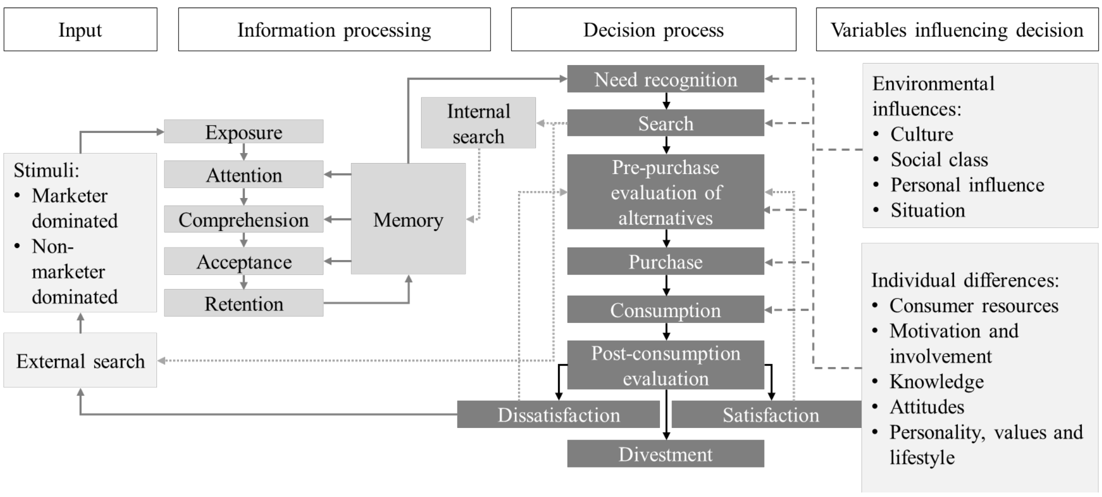

Figure 1 Consumer decision process model; own illustration based on Blackwell et al. (2006)

[2] The first edition was already published in 1968 (Blackwell et al. 1968). We present the CDP model version illustrated in the 2005 edition.
[3] Stages are sometimes consolidated leading to five or six decision stages. The steps relevant to our study are briefly described in Table 2 in the appendix.

3 Methodological approach

Research on eco-conscious strategic consumer decisions has to build on qualitative surveys in order to comply with the diversity and inconsistency of actions and subjective setting of consumer priorities (Bodenstein et al. 1997). For gaining a thorough understanding of homeowners' decision-making process when conducting EEM, we choose a qualitative research approach. Its objective is to understand the experiences of the participants and to identify underlying reasons (Maxwell 2005). Our approach is based on interviews and complements prior studies, which mainly rely on quantitative approaches.

There are yet two challenges when it comes to interviewing households themselves on their EEM decisions: the first one is recruitment. Since owner-occupiers will on average engage only every twenty to hundred years into extensive EEM , random sampling of households will lead by construction to very low relevant interviewees.[4] Even if recruitment is managed in a more efficient and still non-biasing way, the response rate may turn out to be low due to lack of time etc. The second issue with direct interviews is potential bias: As owner-occupiers are highly involved in the decision, usually lack relevant technical and economical knowledge and are subject to social desirability effects, answers would possibly be biased (Rennings et al. 2013). In pro-environmental behaviour studies, this is commonly described as the attitude action gap (Kollmuss and Agyman 2002). Therefore, energy advisers are selected as the information source for this study. Energy advisers have accumulated knowledge through multiple consultations. This is advantageous for this explorative research, since we can get valuable and detailed insights with a limited number of interviews. Also, as we only interview supplier-independent advisers, we get a rather unbiased view of owner-occupiers' decision-making.[5] Advisers reason with homeowners in person and gain direct insight into the considerations, motivations and barriers before, during and after the uptake of energy saving measures. Advice services differ in their duration, depth of analysis and setting (stationary or on-site). Throughout, key elements are the evaluation of the current building status, identification of potential EEM and quantifications of energy savings. In addition,

[4] The lower bound is derived from the average lifetime of heating systems as the most short-lived equipment in that field. The upper bound corresponds to the inverse of the observed refurbishment rate.
[5] Supplier independent energy advice is subsidized in Germany, e.g. by the BAFA.

profitability calculations and implementation concepts are assessed. Individual energy consulting is likely to provide the most reliable information in refurbishment decisions (Kastner and Stern 2015). Eventual deficits in knowledge about the outcome of EEM are reduced and make the decision for homeowners more manageable. Consultations generally lead to an investment in more ambitious and qualitatively better EEM (Stieß and Dunkelberg 2013).

During the empirical study, twelve interviews with energy advisers in North-Rhine Westphalia (Germany) were conducted between September and December 2016. Advisers were selected based on their long-time experience, academic background and gender, following purposeful sampling (Patton 2015) (cf. Table 3 Appendix). To get heterogeneous information, we sampled advisers who offer (currently or in the past) initial energy advice, detailed energy advice and door-to-door advice. A semi structured interview guide was prepared, to have a framework of selected themes to be explored, while allowing for new aspects to be brought up during the interviews (cf. Table 4, Appendix). Besides initial questions regarding the adviser, his background and his common advice practice and concluding remarks, where advisers could address unresolved issues, we grouped the interview questions into five subthemes: occasions for energy advice and EEM in general, home-owners decision process and the role of energy advice, motives and barriers for EEM, the role of profitability, the relation of energy advice and implementation of EEM. Within these topics, we altered questions depending on the individual course of conversation. The interviews took 50 minutes on average, were recorded and transcribed. Thereby the interviewed advisers were made anonymous. Subsequently, we used the software MAXQDA for qualitative content analysis and abductive coding of the interview transcripts (Kuckartz 2009). We designed a code system to structure the high complexity and specificity of individual statements. The codes basically comply with the above mentioned subthemes, but entail several subcategories. Remarks were allocated to one or more subcategories. Then, similar remarks within subcategories were aggregated to meaningful propositions and general conclusions from the interviews were drawn and formulated.

As the study is based on a limited number of interviews, the results are not expected to be representative of all EEM decisions throughout Germany. Certain analytical generalizations can nevertheless be generated from qualitative studies (Maxwell 2005).

Notably, results have to be regarded in the specific context of energy advice in Germany, where only a small share of homeowners frequents energy advice when conducting EEM (Gossen and Nischan 2014). Arguments for not deploying an adviser are seemingly sufficient knowledge about energy saving potentials and measures, as well as lacking trust in the objectivity of energy advice. Thus, a selection bias might be present, as advisers experience is only based on homeowners who consulted them. Also, advisers' statements might be influenced by self-serving bias, which represents a limitation to the chosen approach.

4 Key results

The analysis of the interview transcripts indicates that homeowners consider EEM as consumer durables as opposed to investments. EEM rather compete with amenity renovations like a new driveway, new furniture or a new bathroom than with investments. For example, homeowners do not consider spending their money on stocks instead of insulating the roof.

Our findings are summarized in a modified version of the CDP model given in Figure 2. This developed CDP model for the context of EEM decisions differs from the original CDP (cf. Figure 1) as e.g. stimuli (triggers & occasions) and individual differences are specified. In addition, the decision stages are concentrated and supplement by the stage "backtrack", implying that homeowners can withdraw from the decision-making and postpone or dismiss the implementation. In the next sub-sections, findings are presented in detail and structured according to the decision stages (cf. Figure 2). Further, we put our findings into context by referring for each decision stage to results established by others that are relevant here and either validated, extended or disproved by our own findings.

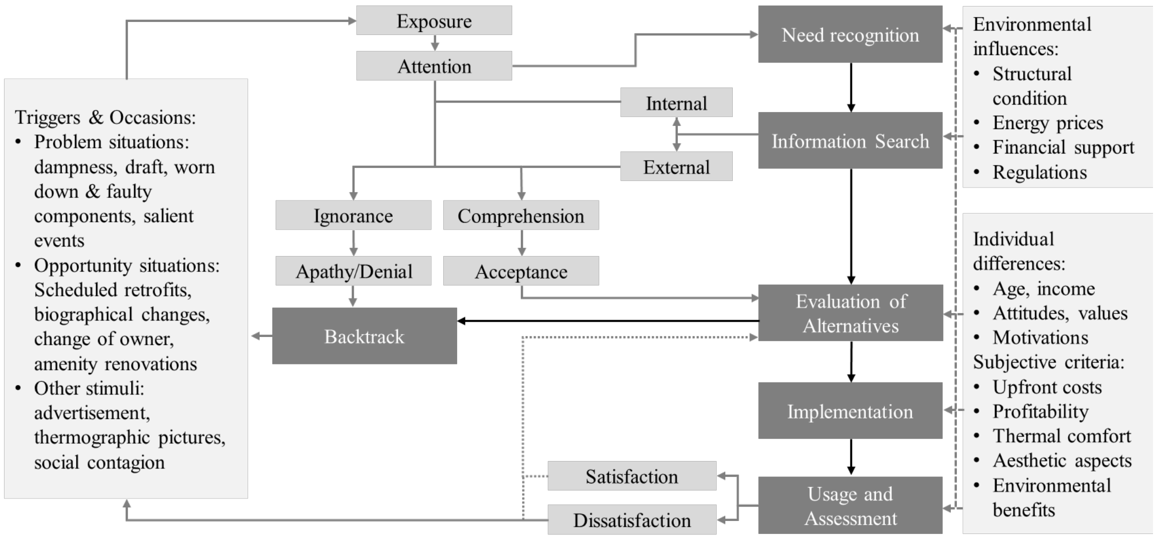

Figure 2 Consumer decision process model for energy efficiency measures (EEM)

4.1 Stimuli and problem recognition

The starting point of each EEM decision is the homeowner's recognition of a need or problem. It occurs when "… an individual senses a difference between what he or she perceives to be ideal versus the actual state of affairs." (Blackwell et al. 2006) In general, need recognition is hardly achieved and constitutes the first barrier for EEM. Many owner-occupiers regard their homes as ideal and do not perceive a demand for alterations (Zundel and Stieß 2011). Misperception or ignorance of the current energy demand and a low salience of energy costs is common (Wilson et al. 2015; Hille 2016). Energy is usually taken for granted and merely reaches consumers upon receiving the energy bill (Hille 2016). A segment of homeowners is not aware of the condition of their home's insulation or that thermal properties of existing insulation have deteriorated (Nair et al. 2010b). Moreover, procrastination tendencies are obvious, as owner-occupiers tend to argue that the right time to refurbish has not come (Klockner and Nayum 2016).

Our research agrees that in case no extraordinary event occurs, the actual state of affairs does neither require nor provoke changes. If the current heating system has worked for the last decade and has warmed the house, owner-occupiers trust in the old system. Homeowners are deeply rooted in their houses and for some, it is emotionally difficult to alter their homes. There is no need to think about EEM and apathy regarding heat consumption is observable. Even though energy prices have increased over time and maintaining a warm house has become more expensive, it is often not putting enough pressure on homeowners to consider reducing energy consumption. Advisers state that in recent years, the issue of high energy costs as a reason for EEM ceased to persist. However, the annual billing is still raising somewhat the attention level. Notably, cold winters with potentially subsequent payments induce problem recognition and are a reason to consult energy advisers.

Studies agree, that EEM decisions are likely to be launched in the course of replacing broken or worn components and after a change of owner (Stieß and Dunkelberg 2013). Nair et al. (2010b) allege three possible triggers: a components' ageing (the physical condition, the thermal performance or aesthetic aspects[6]), the awareness of high energy costs and environmental concern. Hecher et al. (2017) distinguish between problem situations (e.g., technical defects) and opportunity situations (e.g., the replacement of a heating system in the course of refurbishment measures on the building envelope). Referring to problem situations, Wilson et al. (2015) use the term 'salient events', which serve as triggers for EEM.

Our findings underpin that the sheer need to replace a building component, which no longer performs adequately, is the dominant reason to conduct EEM. The decision process literally starts with problem recognition, where deficiencies range from a sordid façade over mould, damp walls and draughts to faulty heating systems. In terms of actually implementing EEM, this kind of need recognition is the most promising, as residents no longer want to bear the situation and thus, a decision and implementation is forced. In contrast, opportunity situations implicate free will and a voluntary decision. A scheduled retrofit is the best opportunity for EEM. All advisers claim that tiling a roof without insulating it is a waste of this opportunity. If owner-occupiers do not integrate thermal insulation, a cost effective occasion vanishes. Another opportunity situation is a planned addition or alteration to the building. These situations are rare, but provide points of leverage for cost-effective refurbishments and thus have to be harnessed consequently. We find that changing living situations are another reason to reflect on EEM. Wilson et al. (2015) also identify transition periods in a household lifecycle as possible triggers. Our results point to two major transition periods. The first encompasses people who recently bought or inherited a house. Usually young couples or families who move into

[6] Aesthetic aspects are limited to visible components such as windows, roofs and facades, in contrast to, basement ceilings or heating boilers.

their first own property are thinking about what can or has to be done to guarantee a comfortable home and what budget is available. In principle, a turnover offers the occasion to assess the quality of a building. Here lies a huge potential as new owners are usually planning on living in the building for the next decades. If it is achieved that a complex planning of EEM is done and a refurbishment roadmap is developed, EEMs are likely to be implemented. New owners often want to modify the entire building but due to time or budget constraints rather plan to do it in consecutive steps. This stepwise refurbishment plan is financially and socially more compatible. They start with the most important and postpone further measures. Concerning energy savings, this group is promising, as the outreach (of energy advice) is the greatest since the entire building is considered and a final energy reduction target is set. Yet, if a building is inherited, obvious construction defects are often neglected or accepted. The heir knows that the building served for the last decades and is positive that it can be lived in in the future. Thus, heritage can become an impediment to problem recognition. The second group that considers EEM are settled homeowners (roughly between 55 and 70 years). They have lived in their home for a long time, are financially well off and are eager to prepare the house for retirement. In comparison to younger homeowners, they are often only planning single measures. With reduced living expectations, the willingness to accept long amortisation times reduces. Thus, the energy saving potential in this group is usually smaller. Discussions ,e.g., by Thøgersen and Crompton (2009), have questioned whether spillover of pro-environmental consumer behaviour is observable. Our findings suggest, that there are rare occasions where homeowners follow the EEM uptake of neighbours. Family members and other social influences can put the idea of EEM into motion. However, refurbishments do not go viral through a neighbourhood.

4.2 Information search and evaluation of alternatives

Once problem recognition occurs, consumers begin searching for information, internally and/or externally. External sources are mass media or interpersonal channels such as neighbours, friends or energy advisers. The search can either be passive, by simply becoming more receptive to information or active, by engaging in search behaviours. In extensive consumer decisions, the information search and processing phase is most important, as consumers devote considerable time and effort to analyse alternatives (Kroeber-Riel et al. 2011). Homeowners make the decisions to refurbish rarely in their biography and generally cannot rely on internal information. Further, technical and financial details of EEM tend to overwhelm them, leaving them uncertain about what to do. As a consequence, EEM decisions usually involve an external search with interpersonal sources being most important (Nair et al. 2010a). Our findings indicate that it is of utmost importance for owner-occupiers to understand that what they are planning is reasonable and useful. They cannot filter contradicting information and are suspicious about non-personal information sources. Driven by critical media messages, homeowners are bewildered, have doubts and objections. Also, they demand reassurance whether statements of, e.g., the heating installer, are correct, and thus consult independent energy advisers. In the category of passive information, our results suggest that the exposure to thermography pictures helps to raise attention, even if the consecutive stages of the decision process do not follow immediately. The graphical, colourful results are appealing, easy to interpret and can be used as an eye-catcher before an active information search starts.

Independently from the information source, owner-occupiers are looking for information regarding their subjective evaluation criteria, “the standards and specifications used to compare different products” (Blackwell et al. 2006). Depending on the kind of trigger, Hecher et al. (2017) find that economic factors are important in opportunity situations. However, operational convenience, thermal comfort and aesthetic aspects are important as well (cf. (Friege and Chappin 2014; Zundel and Stieß 2011). In line with Nair et al. (2010a), Aravena et al. (2016) find that individuals prioritise reducing energy bills over environmental benefits. In the same vein, Organ et al. (2013) conclude that environmental benefits may be a by-product rather than the fundamental motivation for EEM. Hence, environmental consequences are only relevant for individuals with pro-environmental value orientation (Kastner and Matthies 2016) and environmentally concerned homeowners have a higher propensity to implement EEM (Martinsson et al. 2011). Notably, EEM decisions are not driven by one motive, but by an alliance of motives (Stieß and Dunkelberg 2013).

Our empirical results agree that in most refurbishment decisions monetary aspects are essential determinants. However, the main concern is not profitability but financial feasibility.[7] Homeowners' objective is not to choose the alternative with the highest rate of return (or net present value), as it would be with an investment. Considerations focus on which alternative is affordable. Thus, upfront costs outweigh profitability reflections. Especially concerning extensive measures, financial feasibility is the main barrier to EEM. This is aggravated by the fact that homeowners are often not willing to take a loan, even not subsidised low-interest credits. In view of budget restrictions, owner-occupiers rarely conduct comprehensive refurbishments but rather implement single measures. Hence, a promising strategy are stepwise refurbishments: Start with the most important measure and postpone the rest, while keeping the final efficiency standard in mind.

Even if profitability calculations are considered, owner-occupiers tend to be demoralized and overwhelmed by "long" payback periods above 15 years. Given that some building components have a lifetime of 40 years, amortisation times of over 20 years should be acceptable. However, this does not fit into manageable timeframes for homeowners, who like to hear about 3 or 4 years amortisation time. In addition, especially older homeowners fear that they are not much longer able to get on in the house. This uncertainty (of having to sell the house and not being able to profit from a refurbishment) often keeps them from undertaking EEM. Hence, the conservation of value is subordinate, with the exception of a planned inheritance. Yet, a refurbishment is cumbersome, implies dirt and often means too much stress for elderly homeowners.[8]

The majority of homeowners perceives the prospect that less gas or oil is burned after conducting an EEM as saving money. We agree with previous studies (cf. (Aravena et al. 2016), that homeowners rarely reflect on reduced CO_2 emissions or environmental benefits and at most, perceive it as a nice co-benefit. Nonetheless, some owner-occupiers are ecologically motivated (often reflected in their entire lifestyle). Ideas to do something pro-environmental are however often shrinking to affordable measures ("backtrack" in Figure 2). Here, homeowners are willing and ready to use wood pellet or solar systems, but financial restrictions prevent them from actually adopting and they stick to conventional technologies. For homeowners, who are not motivated by prospective

[7] This dichotomy has been analysed deeper as we asked what kind of profitability calculations homeowners or advisers conduct and what individual owner-occupiers understand by profitability. Advisers state that owner-occupiers rarely request profitability calculations but trust their gut instinct that at some point a measure will pay off.

[8] Wilson et al. (2015) argues the anticipated 'hassle factor' of having home life disrupted, while the renovation takes place, is a barrier.

energy cost savings or environmental benignity, other aspects have the potential to increase the willingness to spend money on EEM (given their financial capability). First, comfort losses like air draught, problems with cold indoor temperatures or enhanced demand for thermal comfort favour the implementation of EEM. Second, visibility of refurbishment activities (e.g., new windows or solar systems), which embellish the building's appearance or symbolise wealth, support the adoption of EEM. Third, interest in and fascination with new technology is a factor that can upstage monetary aspects in the adoption decision. In this context, one energy adviser claims: "We have to retreat from the cost-benefit discussion of thermal insulation. The focus should not only be on the cost side and on how do I benefit financially. Because thermal insulation has many other benefits which could be stressed instead and pushed forward." (Interview 11) Owner-occupiers regard these non-monetary criteria, which have the potential to upstage financial aspects and foster the diffusion of EEM.

4.3 Choice and implementation

After opting for a specific EEM, homeowners still need to choose how to implement. With other products, the purchase is influenced by sales persons and point-of-purchase advertising (Blackwell et al. 2006). Consumers sometimes buy something quite different from what they intended or decide not to buy at all, because of what happens during the purchase stage. In the case of refurbishments, mainly artisans and to some extent energy advisers influence the final choice and implementation. Our empirical investigations suggest that homeowners have already made a decision or more specifically, have chosen a certain EEM before approaching energy advisers. They usually seek validation and wish to rationalize prefabricated decisions. Notably, energy advisers struggle to persuade owner-occupiers of alternative, more adequate measures, as they are often not responsive to rational arguments: "It principally is an emotional decision and the energy adviser is frequented in order to check, whether the decision is actually reasonable. But after the possible rational input, the decision is again made emotionally." (Interview 2) Concealed beneath rational criteria, the decision is influenced by emotions, individual dispositions, and rather taken with gut instinct. Sunikka-Blank and Galvin (2016) conclude that there is logic behind homeowners' decision-making, but it is not necessarily economically rational. Our findings reveal that only after the EEM decision is made, homeowners ask whether receiving a grant is an option, implying free-rider behaviour. Here, funding does not trigger the EEM decision, but is willingly embraced later on. However, application procedures for some funds are complicated and time-consuming, which prevents homeowners from using them. The implementation of EMM can still be hampered by lacking access to competent or trustworthy contractors (Weiss et al. 2012). Our findings support that EEM decisions can still be retracted, if no qualified or willing artisan is available. In addition, mistrust regarding artisans or the perception to overpay for mediocre quality can impede the implementation.

4.4 Usage and assessment

After the purchase, consumers utilize a product and assess the outcome: “Satisfaction occurs when consumers’ expectations are matched by perceived performance. When experiences and performance fall short of expectations, dissatisfaction occurs.” (Blackwell et al. 2006, p. 83) It is important to ensure homeowners’ satisfaction with the overall process of implementing EEM, including information search, advice services, artisans and post purchase experiences. Unlike investments, thermally insulated building envelope components or efficient heating systems are consumer goods, which deliver a range of useful services (Gram-Hanssen et al. 2007; Zundel and Stieß 2011; Wilson et al. 2015). Owner-occupiers experience the manifold effects and evaluate convenience, comfort and lower energy costs during utilization. For adopters of EEM compared to non-adopters, Aravena et al. (2016) find the increase in comfort is significantly more important in the ex post evaluation. In addition, the authors find that households who experienced energy savings as a consequence of implementing EEM, are more likely to undertake further measures. Homeowners store the outcome of EEM in memory and a positive outcome is necessary to ensure further adoptions. If the assessment turns out positive, the message is likely to be propagated, which might trigger refurbishment activities of others. Yet, if unsuitable measures are taken or measures are implemented badly, dissatisfaction occurs, evokes reservations towards EEM and obstructs activities of others. Therefore it is crucial to reach owner-occupiers early enough in the decision-making process to ensure that gainful measures are conducted. Our findings add, that small, low-cost measures that achieve energy savings or comfort gains might be a promising starting point for more extensive EEM. However, retrofitters often miss to quantify achieved energy and cost savings. E.g., no heat meter is installed with a solar thermal system and it is not possible to evaluate performance. Here lies a large potential to enhance satisfaction, for instance through visualisation of achieved savings or follow up advice including before/after comparisons. With big-ticket items like EEM, consumers often have second guesses regarding the product, which can be subsumed under post purchase regret or cognitive dissonance. In response, a successful strategy to ensure customer satisfaction is the provision of additional information, e.g., toll-free numbers to answer questions, brochures or follow up phone calls.

5 Implications for efficiency policy

In the marketing of consumer goods, retailers and manufacturers only succeed when strategic efforts are addressing all stages of the consumer decision process (Blackwell et al. 2006). Hence strategies aiming to facilitate EEM should also consider the decision stages. The specific design of marketing measures or policy interventions is beyond the objective of this study, but is an important area for future research. Nonetheless, from our empirical findings, we derive some tentative recommendations for policy makers to guide promotion and communication strategies for EEM.

Most public policies are trying to influence consumers at the purchase stage through monetary incentives. At this stage, costs and budget constraints are often the limiting factor for undertaking EEM. Hence, we agree on the importance of reducing investment costs, which can be done through subsidies or reduced-interest loans, as it is already common in Germany. However, prior to that, a broader need recognition is required to enable and accelerate the diffusion of EEM. We limit our recommendations to the decision stage of need recognition, as it is identified as a main barrier to EEM uptake. In marketing, there are two strategies to tackle this problem. First, innovations and product improvements can raise consumers' awareness of unperceived needs. Improving energy efficient products reduces barriers to implement them, as advantages prevail and costs decrease. Also, the level of awareness itself influences adoption of innovative products (Rogers 2003). Several EEM are market-ready but might still not have reached owner-occupiers' awareness. More attention to the availability and positive consequences of innovative heating systems or efficient building components should be attracted. The communication and advertising could include success stories of individual homeowners to illustrate the benefits. Unfortunately, current German energy policy (information campaigns, funding brochures) focusses on profitability and has largely ignored other benefits of EEM such as increased thermal comfort. Advisers already advertise EEM via comfort aspects and retreat from focussing only on financial aspects. Aravena et al. (2016) confirm that policies stressing comfort gains may be more efficient than those highlighting financial aspects. Hence, to encourage consumers to conduct EEM, it might be rewarding for policies to pay greater attention to increased thermal comfort or reduced environmental impact.

Second, consumers' recognition of their undesirable current state may induce problem recognition. Notably, awareness of (relatively) high energy bills or a household's high environmental impact could be enhanced. Concerning low heating energy prices, a first best instrument to internalize external effects of heating energy use, are CO_2 prices (e.g. through a tax or certificates). Higher energy prices would raise consumers' awareness and induce need recognition. Regarding environmental damage, it is possible to change a consumer's environmental judgement of his current state through social influence (comparison, persuasion). Earlier findings by Hansen and Schrader (1997) or Bodenstein et al. (1997) claim that an awareness that a business as usual attitude aggravates climate change has to be created and greater information efforts are necessary to engender pressure. Campaigns about the possible harmful effects of current behaviours could translate into more eco-friendly decisions (Hille 2016). If owner-occupiers perceive using more energy than necessary as socially wrong, this feeling might internally drive need recognition (Klockner and Nayum 2016). Information strategies should increase homeowners' awareness of their "invisible" energy use and concomitant environmental impact. Special campaigns, such as door-to-door energy advice or neighbourhood approaches including thermographic pictures succeed in raising problem recognition.[9] Hence, to activate potential renovators, the supply of out-reach consulting through energy advisors should be enforced and local craftsmen, chimney sweeps or plumbers could be harnessed for the communication of possible EEM. Wilson et al. (2015) suggest that

[9] This idea was raised by the interviewed advisers, but e.g. also promoted in the project InnovationCity Ruhr (http://www.icruhr.de), where it was found to be effective for activating EEM (Tappeser and Fromm 2018). In neighbourhood activities, a neighbourhood (300 – 500 households) with a low refurbishment rate and high potential is chosen. In addition, areas with changing owners are picked as low hanging fruits. The residents get a letter from the mayor or another highly renowned person of the city, telling them about the campaign including pictures of the advisers to raise trust. This appeal is supported by public address though media, e.g. newspaper articles. Residents can then approach the organizer to schedule an energy advice service. In addition to the public advertisement, the energy advice is further promoted by a price reduction (by 50%) compared to regular advice costs.

policies should promote the bundling of EEM into other types of home renovations (amenity renovations). Our results add that a chance to get a 'foot in the door' with elderly people is the implementation of barrier-free options in combination with energy efficiency (e.g. new doors). This opens up opportunities for policy approaches advertising bundled renovations. In the long term, a stronger pro-environmental value orientation may be created early on with broad educational measures in school. Another approach is to generate a broad agreement that EEM connote improved status (similar to other consumer goods like new kitchens). This may motivate owner-occupiers to spend money on energy efficiency and facilitate a broader uptake.

6 Conclusions

Widespread energy efficient refurbishment activities are necessary to reduce building energy demand and achieve German carbon reduction targets. Immediate action is needed to avoid lock-in into inefficient buildings and technologies. German politics have tried to motivate individual homeowners to improve energy efficiency of their dwellings, but existing instruments fail to accomplish a widespread adoption of efficiency measures. Hence, a better understanding of the complex decision-making is required. A qualitative research approach was chosen to comply with the diversity and inconsistency of homeowners' decision-making. Guided interviews with energy advisers were conducted, transcribed and analysed. Against the background of recent studies and our own empirical findings, we find that EEM decisions are not sufficiently explained when treated as ordinary investments. An improved understanding can be reached with the definition of environment-related strategic consumer decisions (Bodenstein et al. 1997), associated with extensive problem solving (Kroeber-Riel et al. 2011).

Kollmuss and Agyman (2002) argue that the question of what shapes pro-environmental behaviour is so complex that it can hardly be visualized through one single model. Yet, we find that the here proposed consumer decision process model (cf. Figure 2) provides an appropriate framework to explain and analyse homeowners' decision-making. It considers the entire decision-making process including problem recognition, information search and evaluation of alternatives, choice and implementation, usage and assessment. Also, the CDP model encompasses the internal information processing, occasions and triggers, environmental influences and individual differences.

Since need recognition is a precursor to action, it is essential to understand what triggers off or prevents owner-occupiers to undertake EEM. For two major reasons, need recognition is a serious impediment for energy efficiency. First, salience of energy expenditures is rather low, because of low energy prices and the only yearly recurring energy bill. Second, owner-occupiers regard their homes as ideal and resilient. As a consequence, they are at ease with domestic energy consumption and do not demand any changes. Notably, unless they face ‘salient events’, the decision-making processes is hardly ever initiated. These events emerge in technical failures, structural deterioration or biographical changes. Subsequently homeowners search for adequate EEM and evaluate alternatives. Within monetary decision determinants, upfront costs are crucial and profitability is secondary. Yet, non-monetary criteria have the potential to upstage monetary aspects and increase the willingness to spend money on EEM. These are, amongst others, enhanced comfort, reduced environmental impact or the use of innovative technologies. Strategies aiming to facilitate energy efficient refurbishments should henceforth consider the entire decision-making process and be targeted accordingly. With regards to evaluative criteria, policies paying greater attention to increased thermal comfort instead of profitability might be more rewarding in incentivizing EEM.

More research is needed to improve and redevelop policy interventions to promote EEM and thus, alleviate climate change. Our results provide first important implications. However, it is essential to acknowledge the limitations of the current study. Primarily, it cannot be concluded from the rather small sample (12 interviews) that every owner-occupier completes the decision-making process when adopting or not adopting EEM. Further, results have to be regarded in the specific context of energy advice in Germany, where only a small share of homeowners frequents energy advisers. The handling of EEM decisions as a consumer purchase decision in future studies, questioning directly owner-occupiers is advisable to test the robustness of our findings.

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Appendix

Table 2 Consumer decision-making process (Blackwell et al. 2006, Solomon et al. 2014)

Stage of the decision process	Description
Problem recognition	Problem or need recognition occurs when an individual perceives an important difference between the actual and a desired state of affairs.
Information search and processing	Information search may be internal (retrieving knowledge from memory) or external (collecting information from peers, family, reference groups and the marketplace).
Pre-purchase evaluation	Consumers employ different evaluative criteria (standards and specifications used to compare alternative options), that are important to them and decide which options are feasible. They narrow down the field of alternatives before they finally resolve to buy one of them.
Purchase and consumption	The act of purchasing involves what and where to buy. After the purchase, consumers can use the product immediately or delayed. The correct use of the product influences the satisfaction and how likely consumers are to buy a similar product in the future.
Post-purchase evaluation	The buying and consumption experience generates satisfaction or dissatisfaction. The outcome is significant as consumers store their evaluations in memory and refer to them in future decisions.

Table 3 List of interviewed energy advisers

Interview	Qualification	Gender	Main Occupation	Time of occupation	Location
01	Architect	F	Employed (consumer organisation)	About 20 years	Düsseldorf
02	Civil engineer	M	Employed (consumer organisation)	About 15 years	Oberhausen
03	Architect	M	Employed (consumer organisation)	About 20 years	Alsdorf
04	Architect	F	Employed (consumer organisation)	About 10 years	Aachen
05	Architect	M	Employed (business)	About 10 years	Hamm
06	Architect	F	Employed (business)	About5 years	Hamm
07	Architect	F	Self-employed	About 10 years	Münster
08	Architect	F	Self-employed	About10 years	Münster
09	Architect	M	Self-employed	About 10 years	Gelsenkirchen
10	Carpenter	M	Self-employed	About 10 years	Düsseldorf
11	Chemist	M	Employed (consumer organisation)	About 15 years	Bonn
12	Physicist	M	Self-employed	About 5 years	Duisburg

Table 4 Interview guide (translated; original guideline and interviews were conducted in German)

Introductory words		
Initial questions		
Topic/subtopic	***Main questions***	***Follow-up questions/information***
Introduction of interviewee Information on adviser Information on advice portfolio and advice process	• **Please introduce yourself and tell me how you became an energy consultant?** • **Please describe how a consultation process usually works - from the first contact to the end of the process.**	• Personal information • Qualification • How long have you worked as an energy adviser? • How many consultations have you performed? • Which type of advice do you mainly conduct? • How many inquiries do you get per week? • **How does the making contact proceed?**
Information on advice-seeker	• Which persons make use of your consultations?	• Building types • Homeowners, owner-occupiers, landlords • Education, income, age
Interest in energy advice	• How do you rate the interest in or the demand for energy advice and its development in recent years?	• What do you estimate: What percentage of building owners in your "advice area" know about the possibility of energy consulting? • What percentage of all retrofitters engage an energy consultant?
Cost of different advice types	• Do you think that the cost of counselling is a problem?	• What role does the promotion of counselling play?
Occasions for energy advice		
Occasions for energy advice	• **When or on what occasion do people come to your consultation?**	• Are these events identical to those for refurbishments?
Social influences	• Do any recommendations from neighbours or neighbours' refurbishments play a role in getting in touch?	• Do you receive follow-up orders based on recommendations?
Decision-making process of retrofitters		
General decision-making	• **Describe the general decision-making process of refurbishing households from your experience.**	• When in this process do people seek advice?
Advice in the decision-making	• **In your estimation, do consultations directly initiate energetic renovations or are consultations more likely to redevelop the outcome of a decision already made?**	• So do the deliberations rather extend already planned activities, change the ranking or set new priorities?

Motives and barriers		
Reasons for seeking advice Important topics Motives Barriers	• **Which topics play the biggest role for advice-seekers during the counselling process or which questions are most frequently asked?** • In your experience, is there a ranking of motives and if so, what are the top five motives?	• Which motives are (in your opinion) behind the decision to refurbish? • What are the barriers to refurbishments and what are people's fears and concerns?
Rational or emotional	• How would you describe the decision-making behaviour? Do rational factors or emotional factors prevail?	• What formulations bear fruit?
The role of profitability		
Advice-seekers awareness	• **What do the advice-seekers understand by cost-effectiveness of refurbishment measures?**	• Which figures are important to advice-seekers?
Presentation of profitability in advice	• **How do you present profitability of measures in the consultation and why?**	
Assessment of profitability	• What is your general assessment of the cost-effectiveness of energy-saving measures and which factors have a particularly strong impact on profitability?	• In your experience, what measures are profitable (in which building types and ages)?
Relation between advice and implementation		
Realisation after advice	• **To what extent do you accompany the implementation after the consultation and are you aware of whether and which measures are implemented?**	• Are recommended measures implemented or is the advice only used for information? • In how many cases does advice lead to refurbishment?
Rejection of certain measures	• In your judgement, what is preventing advice-seekers from implementing certain measures, or which proposals for measures are being rejected?	• To what extent is the decision dependent on whether or which measures advice-seekers have considered in advance of the consultation?
Criticism of advice	• Do advice-seekers see your work sceptical or do they face you with trust?	
Final remarks		
Are there any things we have not talked about yet that you still consider important?		

3 Coherent estimations for residential photovoltaic uptake in Germany including spatial spillover effects

Jan Paul Baginski and Christoph Weber

Abstract

The share of solar energy in German electricity generation has increased strongly over recent years. This is largely due to guaranteed feed-in tariffs together with decreasing prices for solar panels. Residential PV systems play a decisive part providing households with a possibility to contribute to the *Energiewende* and benefit from the use of renewable energy. Their regional distribution varies distinctly across Germany implying different requirements in distribution grids as well as uneven utilization of national policy measures. Our paper focusses on the spatial diffusion of roof-mounted PV systems and the underlying drivers in Germany. We extend previous findings not only by including additional explanatory variables but also by considering cross-regional spillover using spatial econometric models.

Estimation results show that high values for solar radiation, the share of detached houses, electricity demand and inverse population density of a region favour the PV uptake. In addition to these effects, spatial dependence is found to be a relevant determinant for regional patterns of PV adoption. Recurrent visual perception or peer-effects might explain spatial autocorrelation as potential adopters follow decisions by actors in the proximity. Another reason for spatial dependence might be a concentration of craft skills or solar initiatives, which leads to an accelerated diffusion in a region and its surroundings. Whereas the first explanation corresponds to the specification of a spatial lag model, the latter is in line with a spatial error specification. However, our results indicate that although spatial lag is present, spatial dependence in the residuals has higher explanatory power. Hence, we conclude that spatial spillover is not mainly driven by social imitation but by unobserved regional characteristics.

Keywords: residential photovoltaic; spatial econometrics; spatial spillover

1 Introduction

The limited availability of fossil resources and more importantly their contribution to climate change have driven the deployment of sustainable electricity generation technologies. Numerous countries have rolled out policies to encourage the use of renewable energies (REN21 2017). Germany was among the first countries to introduce a feed-in tariff (FIT) for photovoltaic panels (PV) by the Renewable Energy Sources Act (EEG). As a result, Germany became a pioneer for PV and still has the highest installed PV capacity per capita worldwide (REN21 2017), despite solar radiation being rather low compared to other countries. The share of German electricity demand covered by solar energy systems has risen from below 1% in the year 2008 to around 6% in the year 2016. A distinctive feature of PV panels is their scalability, making them attractive at the utility, commercial and residential scale. Residential customers, who are in the focus of this study, can easily install roof-mounted PV panels and become small-scale producers (Groote et al. 2016). From a households' perspective, PV systems bundle both investment opportunities (delivering a net present value derived from the generated electricity) and an apparent support of renewable energies (the general perception that a house becomes "greener") (Dastrup et al. 2012). From a political perspective, these characteristics may considerably contribute to the social acceptance of renewable energy and induce a commitment of private households (Schaffer and Brun 2015). In Germany, small-scale PV installations (below 10 kWp) account for about 5.4 GW as of December 2015, representing 14% of total capacity.

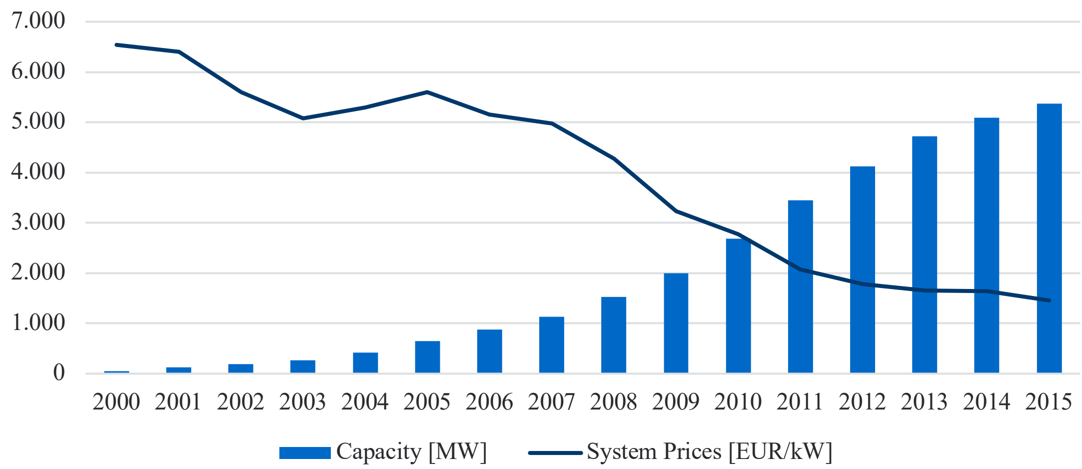

Figure 1 PV capacity and system prices for small-scale systems (below 10 kWp) in Germany from 2000 to 2015; own illustration and calculation based on data from German TSOs (2016) and IEA (2016)

Besides guaranteed FIT, decreasing PV system prices enhance their popularity among households, leading to a growing capacity over the years (cf. Figure 1). However, only about 2.4% of Germany's 38 million households have installed PV panels. Mainzer et al. (2014) estimate the total technical residential building roof potential in Germany to be above 200 GW. Considering this huge potential for small-scale roof-mounted PV installations, the maturing PV sector and the ambitious renewable energy targets, two related questions arise: How do residential PV systems spread over space and what drives the regional uptake?

A variety of studies has discussed barriers and drivers for the adoption or non-adoption of residential PV. They use qualitative methods, such as interviews (Schelly 2014) and case studies (Braito et al. 2017), or quantitative methods, including (log-)linear regression analysis (Groote et al. 2016) based on data from large surveys (Rai et al. 2016) or publicly available data. From an economic perspective, a household will invest in a PV system if it is profitable, meaning it has e.g. a positive net present value (Klein and Deissenroth 2017). Ceteris paribus, higher solar irradiation increases yields making it more likely to invest in PV panels in locations with high irradiation (Schaffer and Brun 2015). However, findings indicate that beyond solar irradiation and economic motives, the built environment (Graziano and Gillingham 2015), knowledge of grants and costs (Vasseur and Kemp 2015), administrative burdens (Palm 2018), regional policies (Zhang et al. 2011), ecological attitudes (Braito et al. 2017), , and the influence of installers (Rai et al. 2016) determine the decisions to install roof-mounted PV panels.

In addition, "peer effects" also known as, "social contagion", "social effects", "social interaction", "imitation", or "neighbourhood effects" are an established phenomenon in research on the diffusion of innovation (cf. (Burt 1987; van den Bulte and Lilien 2001; Rogers 2003; Welsch and Kühling 2009). Peer effects occur when a certain behaviour of an individual is affected by the prevalence of this behaviour in the social environment (Manski 1993). The behaviour spreads from one person to another and is influenced by the strength of interpersonal ties but also by geographical proximity (Curtius et al. 2018). Peer effects can be active (involving direct communication with a peer) or passive (when someone becomes aware of the activities of a peer, e.g. seeing a newly installed PV system in their neighbourhood) (Rai and Robinson 2013). In particular, the existence of peer-effects has recently been demonstrated as a significant influence for the installation of PV systems in the US (Graziano and Gillingham 2015), the UK (Richter 2013), Sweden (Palm 2017) and Germany (Rode and Weber 2016). Notably, the likelihood of PV adoption increases with the existence of previous installations in the neighbourhood (e.g. a street or postcode district). The installation of a solar PV panel is conspicuous and creates a persistent signal that peers (neighbours and passers-by) observe. PV systems in the surroundings reduce uncertainty through observational learning from spatially close households and might thus lead to a correlation of adoption decisions within neighbourhoods (Richter 2013). Others actors in the same region know PV adopters and this community level re-enforcement may further spread the uptake of PV panels (Dastrup et al. 2012). Although most authors agree that peer-effects are localized and diminish with distance (cf. (Rode and Weber 2016), effects are likely to exceed regional borders and spread out to spatially adjacent areas (Dharshing 2017). Hence, recent studies not only examine PV uptake within a region, but include PV adoption rates in neighbouring regions i.e. counties or administrative districts (Schaffer and Brun 2015; Balta-Ozkan et al. 2015; Allan and McIntyre 2017). Scholars in regional science have posited that spatial dependence is an important driver of regional development (e.g. (Anselin and Bera 1998; Florax et al. 2003). They invoke Tobler's first law of geography: "everything is related to everything else, but near things are more related than distant things" (Tobler 1970, p. 236). Following this line of reasoning, PV adoption in a region might indeed be affected by the neighbouring regions' penetration with PV installations. By investigating accumulated PV uptake at a regional level, the emergence of solar clusters, which spread across delimited spatial units is demonstrated (Balta-Ozkan et al. 2015; Schaffer and Brun 2015). This is certainly due to geographical similarities between adjacent regions (e.g. solar radiation, income). However, after controlling for solar radiation, studies converge in identifying spatial spillover as a significant driver for PV uptake. The first driver for spatial spillover may the above-mentioned peer or neighbourhood effect. Besides such social effects, other forces potentially cause spatial spillover. In particular, the installation of PV systems requires technical expertise and specified knowledge: concentration of skilled artisans may be localized and contribute to spatial dependence (Schaffer and Brun 2015). Neighbouring areas will likely benefit from technical installation expertise, implying regional knowledge spillover. Also, an increasing adoption in one area reduces new installation opportunities, leading installation companies to seek fresh installation opportunities in adjacent regions (Allan and McIntyre 2017). In addition to artisans, effects from local solar initiatives are likely to span regional borders and are another potential source of spillover (Schaffer and Brun 2015). These effects are possible routes of spatial spillover in the adoption of PV systems, which go beyond imitative behaviour or peer effects.

For the prospects of future PV build-up, it is relevant whether social imitation effects, spatial knowledge spillover effects or rather economic or ecological considerations essentially drive PV expansion. In the first two cases, regional disparities are likely to be self-reinforcing, at least in the mid-term. This has obvious implications for regional policy initiatives, business strategies as well as grid planning. Here, the identification of the underlying drivers for PV uptake are important to identify opportunities to foster the development, but also to foresee potential problem situations. The accumulation of decentral PV systems in specific regions can cause bidirectional flows in the distribution grid, which can for instance cause voltage problems (Balta-Ozkan et al. 2015). This issue was often not accounted for when designing the (rather old) grid infrastructure and has to be met with either reinforcements or some flexibility options. A recent strategy in German energy policy is to favour self-consumption by funding battery storage systems (Wittenberg and Matthies 2016). With increasing electricity generation coming from decentral PV, preserving grid stability however becomes more challenging in certain regions. The lack of local differentiation in the feed-in-tariff for small-scale PV systems (cf. EEG) could potentially further reinforce the tendency towards spatial clustering.

Before proposing remedies to potential problems, it is yet key to identify the causes of these developments. Thereby it is important to acknowledge that standard estimation procedures like Ordinary Least Squares Regression (OLS) lead to biased estimates if regional characteristics and the presence of spatial spillover influence PV uptake (Anselin and Bera 1998). In this context, a key contribution of this paper therefore is the explicit use of spatial econometric models and the comparison of different competing specifications to explain PV diffusion over space. We thus examine the underlying spatial drivers for PV uptake while controlling for regional differences in adopter characteristics and settlement structure. We extend previous findings on the regional diffusion of roof-mounted PV systems in Germany not only by including additional explanatory variables but also by considering different forms of cross-regional spillover. The analysed PV sample comprises all installations with a capacity up to 10 kWp erected by the end of

2015. By normalizing the entire dataset to households, a coherent specification and interpretation of model results is achieved. Another advance of our study is the consideration and comparison of various spatial model specifications to select the model which performs best to fit the data and to capture the underlying spatial process. Further, we differentiate between direct and indirect effects (LeSage and Pace 2009), which has no precedent in the literature regarding PV adoption analysis with spatial econometric models. We thus contribute to the literature by deepening the interpretation of spatial model estimations in the context of residential PV diffusion research, by providing new results including unprecedented variables as well as aligning our results with previous findings..

The remainder of this paper is structured as follows: Section 2 outlines the relevant literature. Section 3 describes the methodological approach for the spatial regression analysis including the identification of direct and indirect effects. Section 4 provides data and descriptive statistics. Estimation and test results of the spatial econometric analysis are described in section 5. The final chapter concludes.

2 Related literature

The here mentioned articles share the use of spatial econometric models (cf. section 3) to identify determinants for residential PV adoption (cf. Table 1). They agree that spatial spillover is a major determinant for explaining residential PV uptake. Another common driver is solar irradiation. Higher irradiation entails higher electricity generation and consequently greater PV expansion.[1] Further, the built environment and settlement structure has a strong influence on residential PV adoption. Building density (residential buildings per sqm) is identified as a positive influence by Schaffer and Brun (2015). They argue that roof space is a prerequisite for rooftop installations and hence greater building density induces higher PV adoption.[2] Graziano and Gillingham (2015) and Balta-Ozkan et al. (2015) find that adoptions decrease with higher population density, which comes along with multi-storey buildings with limited roof space. Density measures do not capture building features, which usually supplement the analysis. Balta-Ozkan et al.

[1] Electricity is usually fed into the grid and remunerated under a FIT (the EEG in Germany). FIT for small-scale PV systems were in place in the considered countries and timeframes, except in Graziano and Gillingham 2015, who analyse a data sample with different support policies in place.
[2] However, building density does not capture building type e.g. specifying dwellings per building.

(2015) embraces the share of detached houses as a predictor for PV adoption and finds a positive influence. Compared to terraced houses, detached houses offer better access to possibly larger rooftops, which simplifies construction work. Dharshing (2017) presumes that owners of single-family houses are often the target for PV marketing and more likely to install PV systems.[3] However, the author does not discover a significant effect. Similarly, researchers anticipate PV adoption to increase with the share of owner-occupied buildings. Owner-occupiers might be financially well off and have savings to invest in PV systems. In addition, the planning and installation process is easier to manage as owner-occupiers can decide freely whether to install PV. They might show a higher willingness to invest in building technologies as they directly profit from anticipated yields. In contrast renters may not have permission to install PV panels (Graziano and Gillingham 2015) and the presence of the user/investor-dilemma hampers PV uptake.[4] Schaffer and Brun (2015) ascertain a positive impact of owner-occupied buildings and similarly Graziano and Gillingham (2015) find a negative impact of rented dwellings. Yet, Balta-Ozkan et al. (2015) surmise an opposing effect.

Despite continuously decreasing solar panel prices, initial costs still impede the diffusion of residential PV systems. Hence, households' disposable income might increase the propensity to invest in a PV system. Balta-Ozkan et al. (2015) and Zhang et al. (2011) do however not find any significant effect of per-capita income. In contrast, Dharshing (2017) and Schaffer and Brun (2015) reveal a positive influence of (per-capita) income. Yet, Schaffer and Brun (2015) use the Gross Regional Product to control for income, which may not be a suitable indicator to reflect household income. It remains hence unclear whether high-income households are more likely to adopt PV panels.

The merit of PV systems to generate electricity environment friendly, without CO_2 emissions during operation, may incite environmental aware households to adopt the PV technology. Again empirical evidence so far is mixed: Zhang et al. (2011) find a positive effect of environmental consciousness on PV installations. Schaffer and Brun (2015)

[3] Dharshing 2017 controls for new constructions as a predictor variable and deduces a negative influence on PV uptake, indicating that owners of older buildings might install PV systems during renovation activities.

[4] In multi-family houses, with the owner occupying one dwelling, the decision is rather straightforward as well. In condominiums with several owner-occupied flats, a common decision about installing PV cells on the roof is necessary which raises the barrier to action. However, condominiums are a building segment of limited relevance in Germany.

results show no significant impact of ecological attitudes and Dharshing (2017)'s results are ambiguous. Balta-Ozkan et al. (2015) find that households' PV adoption increases with a higher electricity demand. This might build on incentives to reduce electricity costs, to reduce the environmental impact of a high electricity demand or the desire to become more self-sufficient.

Table 1 Corresponding literature

Authors	Dataset & spatial resolution	Methodological approach & explained variable	Key findings
Allan and McIntyre (2017)	269,449 domestic PV systems with an average capacity of 3.45 kWp in the UK (only England) in 326 local authorities	Cross-sectional spatial model; number of PV systems per household	• Local socio-economic factors, including wealth, housing type and population density explain uptake of FIT • "Green" attitudes are not important • Significant spatial coefficients
Balta-Ozkan et al. (2015)	384,043 PV systems in the UK, under 10 kWp installed until June 2013 in 134 NUTS3 regions	Cross-sectional spatial model; (log of) absolute number of PV installations	• Electricity demand, population density, pollution levels, education and detached housing affect PV adoption • Rather than income, accumulated capital and financial savings are key drivers for PV uptake in the UK • Significant spatial spillover effects
Dharshing (2017)	589,202 PV Systems in Germany (2000-2013), with a capacity between 1 and 10 kWp in 402 NUTS3 regions	Spatial panel model; number of PV installation per owner-occupied building	• Differences in economics influence spatial and temporal patterns of PV adoption • Socioeconomic status has an impact on PV adoption, but effect of environmental attitude and settlement structure is ambiguous • Significant spatial spillover effects between neighbouring counties
Graziano and Gillingham (2015)	3833 PV systems in Connecticut, USA installed between 2005 and September 2013, with a capacity below 5 kWp on block group level	Fixed effects panel model including spatial parameters; number of PV systems	• Spatial clustering beyond distribution of income or population • Positive relationship between previous PV installations nearby as well as built environment and PV adoption • Spatial effect decreases with distance and time
Rode and Weber (2016)	576,056 German PV systems installed from 1992 until the end of 2009 smaller or equal to 30 kWp with exact location	Epidemic diffusion model; PV systems per building (proxy for potential number of adopters)	• Imitation behaviour is important factor for diffusion of PV • Decreasing influence of distance on localized imitation
Schaffer and Brun (2015)	Over 820,000 PV systems in Germany installed between 1991 and 2011, with a capacity under 16 kWp in 402 NUTS3 regions	Cross-sectional spatial model; PV capacity per square kilometre	• House density, homeownership, solar radiation and per-capita income explain PV uptake • Ecological attitude has no impact on investment decision • Significant cross-regional spatial spillover

3 Methodology: Spatial econometric models

Either a specific-to-general or vice versa a general-to-specific approach can be chosen to arrive at a suitable model to capture spatial interaction effects (Florax et al. 2003; Mur and Angulo 2009; Elhorst 2010). The latter approach starts the analysis with a non-spatial linear regression[5], the standard approach in empirical work. It presumes that the manifestation of the dependent variable in a region is independent from the manifestation of the dependent variable in regions nearby. The approach proceeds by testing whether or not the model specification needs to be extended with spatial interactions effects (Elhorst 2010). Omitting possible spatial dependence may lead to biased and inconsistent parameter estimates (Anselin, Bera 1998). The former approach means to start with a general spatial model that contains a series of simpler models representing all the alternative economic hypotheses worth considering. According to Manski (1993) three types of interaction effects may explain why an observation associated with a specific location may depend on observations at other locations:(i) endogenous interaction effects, where the decision of a spatial unit (or its decision makers) depends on the decisions taken in other spatial units; (ii) exogenous interaction effects, where the decision of a spatial unit to act in some way depends on independent explanatory variables of the decisions taken in other spatial units; and (iii) correlated effects, where similar unobserved characteristics result in similar decisions. The Manski model, also known as the general nesting spatial model, includes all three proposed spatial interactions and nests several reduced models. Figure 2 provides formulas of relevant spatial specifications and their connectedness.

[5] As the linear regression is usually estimated by ordinary least squares (OLS), we label this regression and its results as OLS.

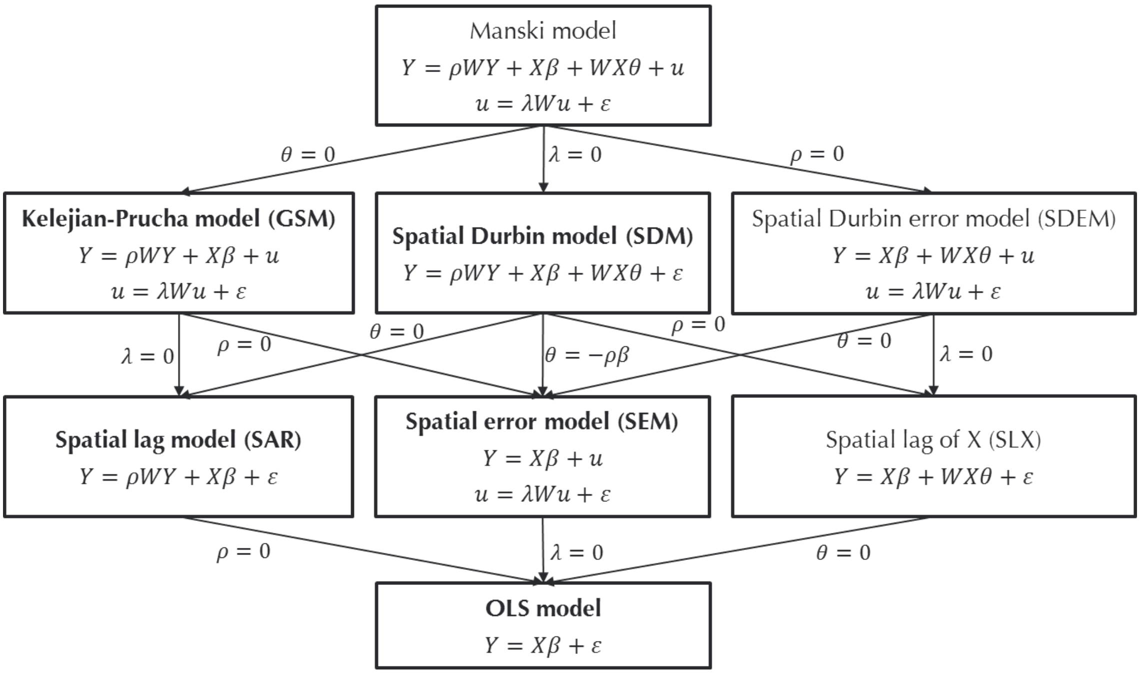

Figure 2 Different spatial model specifications and their connectedness (tested models in bold print); own illustration based on (Elhorst 2010)

W is a $N \times N$ matrix (spatial weights matrix) reflecting the spatial structure of the units in the sample. There are thereby different options to define the spatial weights matrix W based on concepts of contiguity and distance or a combination of both (Anselin and Bera 1998). In the “queen contiguity”, the matrix elements are set to one, if spatial units are neighbours[6] and zero otherwise (Eq. 1a). In distance-based approaches, the matrix elements are commonly defined as the inverse distances of the spatial units (Eq. 1b). By convention, the diagonal elements of the weights matrix ($w_{i,i}$) are set to zero as no spatial unit is viewed as its own neighbour and row elements are standardized such that they sum to one. Additionally, a cut-off point d^* can be introduced to limit spatial units as neighbours to a given distance (Eq. 1c)

$$w_{i,j} = \begin{cases} 1, if\ neighbour\ to\ j \\ 0, otherwise \end{cases} \tag{1a}$$

$$w_{i,j} = \frac{1}{d_{i,j}} \tag{1b}$$

$$w_{i,j} = 0, if\ d > d^* \tag{1c}$$

[6] Neighbour means an entity that shares a common side or vertex with the region of interest (Le Sage 1999, p. 12).

In this study, a queen contiguity matrix is used and its spatial structure for German NUTS3 region is presented in Figure 3. Since the selection of the spatial weights matrix W is to some extent arbitrary, it has become a common practice to examine whether the results are robust to the specification (Elhorst 2010). Thus, we have also specified the inverse distance weights matrix and have estimated the same spatial models. We use the NUTS3 centres to calculate the distances. As we expect the effect of spatial units on the entity of interest to decrease with distance and eventually vanish, we introduce a cut-off distance at 65 km. Thereby we ensure that each region has at least one neighbour. As results have shown no significant differences, we just provide graphical illustration of the used weights matrices (cf. Figure 3).[7] When only direct neighbours are considered, the number of neighbours is rather small. If instead neighbours are defined based on distance, urban areas have multiple neighbours, which gets obvious in the meshed structure.

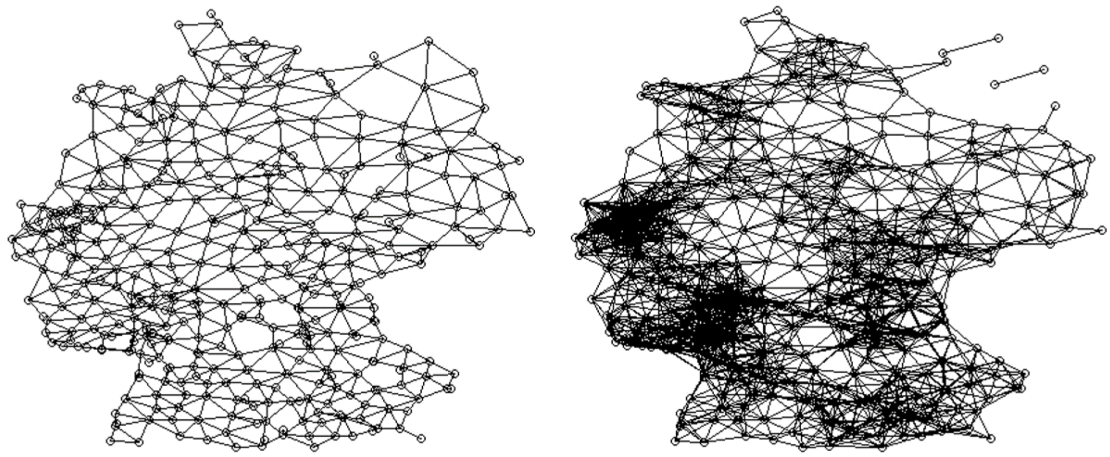

Figure 3 Neighbourhood structure of queen contiguity spatial weights matrix (left) and inverse distance spatial weights matrix with cut-off distance at 65 km (right) of German NUTS3 regions

Following the suggestion of Florax et al. (2003) and Elhorst (2010), we start our analysis with an OLS regression and then expand the model with a spatially lagged dependent variable, leading to the spatial lag or spatial autoregressive model (SAR):

$$Y = \rho WY + \beta X + \varepsilon \tag{2}$$

[7] Results for inverse distance matrix are provided upon request. Elhorst (2010) suggests that if a model is estimated for different spatial weight matrices, the matrix exhibiting the highest log-likelihood function value should be selected.

Thereby Y denotes a $N \times 1$ vector of observations on the dependent variable and X is a $N \times K$ matrix of observations on the explanatory variables with an associated $K \times 1$ vector of regression coefficients β. The variable WY denotes endogenous interactions among the dependent variable, associated with ρ, the spatial autoregressive parameter. It measures the effect of spatial lag in the dependent variable. ε represents an independently and identically distributed error term with zero mean and constant variance σ^2. Then we specify the spatial error model (SEM), incorporating a spatial autoregressive process in the error term:

$$Y = \beta X + u;\ u = \lambda W u + \varepsilon \tag{3}$$

Wu denotes spatial interactions among the residuals of spatial units, associated with λ, the spatial autocorrelation parameter. It measures the effect of spatial error dependence. Under most circumstances, LeSage and Pace (2009) propose using a spatial Durbin model (SDM), since spatial dependence among the dependent and independent variables is considered:

$$Y = \rho WY + \beta X + WX\theta + \varepsilon \tag{4}$$

WX captures exogenous interactions among independent variables, with the $K \times 1$ vector θ representing spatial lag in the predictor variables. The advantage of this model over others is the capacity to generate unbiased parameter estimates, regardless of the underlying spatial process (Elhorst 2010; LeSage and Pace 2009; Botzen 2016). Further, estimating a SDM model is still appropriate if spatially correlated variables are omitted (Bowen and Lacombe 2017). As the underlying spatial process is usually unclear, another approach is to employ an even more general model combining all three spatial effects (Manski-Model) (cf. Figure 2). However, Elhorst (2010) proves that one of the components has to be excluded in order to distinguish between spatial coefficients and to interpret the results. Hence, we exclude the lag of predictor variables and estimate the Kelejian-Prucha (Keleijan and Prucha 1989) or general spatial model (GSM), controlling for both a spatially lagged dependent variable and a spatial autoregressive process in the error term:

$$Y = \rho WY + \beta X + u;\ u = \lambda W u + \varepsilon \tag{5}$$

To support the interpretation of the β coefficients in spatial econometric models, associated measures are necessary (Bivand and Piras 2015). LeSage and Pace (2009) show that point estimates may lead to erroneous conclusions and partial derivative interpretations of the impacts represent a more valid basis.[8] The change in a single region associated with any explanatory variable that affects the region itself is called direct impact whereas the potential effect on all other regions is called indirect effect (LeSage and Pace 2009). The sum of both effects leads to the total effect. Impact measures can be determined for any model including a spatially lagged variable (either the dependent variable WY or the explanatory variables WX). In an OLS and SEM, the β coefficients are similar to direct effects, and indirect effects are zero (Elhorst 2010).

4 Data, descriptive statistics and model specification

4.1 Solar PV installation data

Following the approach of previous studies, our analysis relies on NUTS3 data.[9] In the classification scheme of the European Union a NUTS3 region corresponds to a German county. The PV data are retrieved from a transparency platform, which contains renewable energy plant data of the four German transmission grid operators (Amprion, Tennet, Transnet and Hertz 50 (2016)).[10] Renewable plants other than PV systems are removed from the dataset. As this paper focusses on household PV investments, the considered capacity should mirror the boundaries for rooftop installations on residential buildings. The academic literature uses either a 10 kWp boundary (Dharshing 2017; Balta-Ozkan et al. 2015), a 16 kWp boundary (Schaffer and Brun 2015) or a 30 kWp boundary (Mainzer et al. 2014; Rode and Weber 2016) to delineate small-scale roof top installations. These power boundaries are deduced from assumptions on the average available roof top space of residential buildings and differ consequently. According to the EEG, a higher feed-in tariff is granted for systems smaller or equal to 10 kWp.[11] Taking this as a basis, we use a 10 kWp threshold as the condition for small-scale rooftop PV installations and consider all PV systems installed before 2016. After cleaning the data,

[8] For mathematical prove see LeSage and Pace 2009 and for examples see Elhorst 2010.
[9] This is mainly due to data availability. Data on smaller units e.g. postcode regions is not available for all variables. The German term for county is „Landkreis“.
[10] www.netztransparenz.de/EEG/Anlagenstammdaten
[11] Cf. EEG 2017, § 48, Abs. 2, Nr.1: Erneuerbare-Energien-Gesetz vom 21. Juli (BGBl. I Sp. 1066), das zuletzt durch Artikel 1 des Gesetzes vom 17. Juli 2017 (BGBl. I Sp. 2532) geändert worden ist.

892.452 PV installations across Germany with an average capacity of 6 kWp are considered. Since NUTS3 regions differ in size and population, the absolute domestic PV capacity is hardly comparable. Hence, installed power should be normalized to increase comparability between regions and reduce heteroscedasticity of residuals in the regression analysis. The decision to purchase a PV system is usually made at the household level. As we want to explain the diffusion of PV systems among households, we normalize the PV capacity to the number of households. It is noteworthy that not every decision-maker (household) is in the position to install PV panels. This mainly is true for households in multifamily houses, or in general, households living in rented apartments. Nonetheless, this approach is advantageous, since it allows not only normalizing the PV capacity to the number of households but also the predictor variables. This enables a consistent specification and interpretation of the model. In this vein, the impact of households living in rented dwellings is captured through the (complementary) share of owner-occupied apartments in total dwellings. Household data are obtained from the German 2011 census. Such comprehensive population and building surveys are only conducted every ten years, yet only limited changes in the number of households per county are expected between 2011 and 2015 given slow population dynamics.[12] Figure 4 shows the dependent variable of this study, the cumulated capacity of small-scale PV installations per household.

[12] At least before the 2015 migration wave.

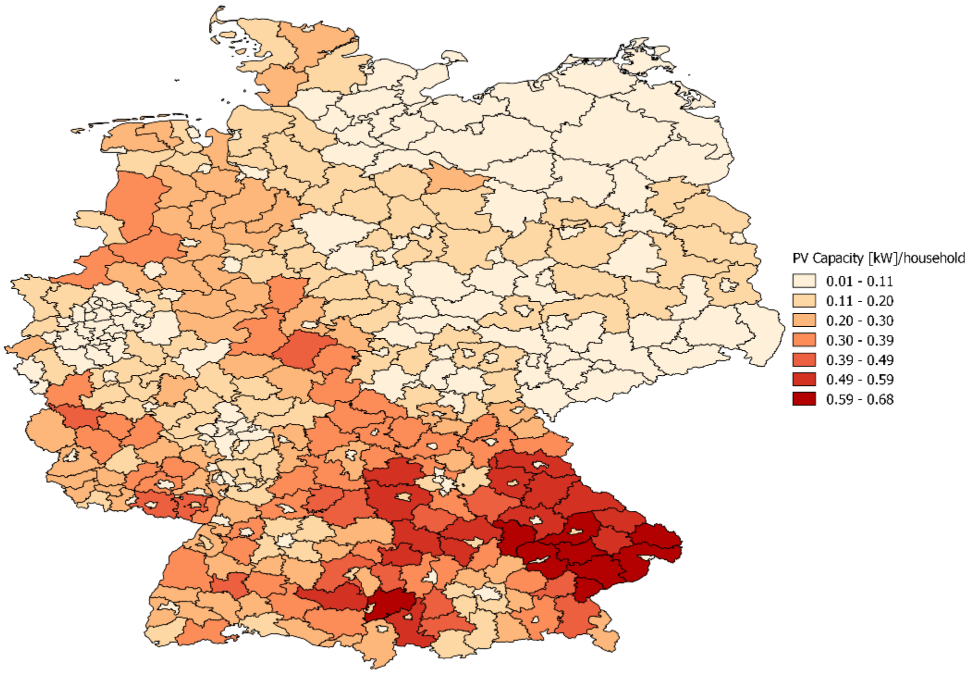

Figure 4 Accumulated installed capacity of small-scale installations (kWp/household) in German counties by the end of 2015; own calculations and illustration based on data from German TSOs (2016).

The average household PV capacity in NUTS3 regions shows significant differences ranging from 0.01 kW to 0.68 kW. The spatial pattern of households' PV uptake shows a downward gradient from south to north. A divide between East and West Germany is also visible, with lower capacity levels in the East. Cities show rather low adoption levels as well, presumably related to high shares of multi-storey buildings and a large denominator, i.e. the number of households. High capacity levels occur especially in South Germany revealing spatial clusters, e.g. in Bavaria. As the feed-in tariff defined by the EEG is applicable in every NUTS3 region, the differences in regional distribution have to be attributed to other determinants (cf. Section 4.2).

4.2 Explanatory variables - determinants for PV adoption

First, a region's cumulated installed capacity is expected to increase with solar irradiation. We capture solar radiation using the sum of global solar irradiation at NUTS3 region centres. The data are retrieved from the German Weather Service (DWD 2015). To characterise adopters of PV systems, we include share of Green voters, share of welfare recipients, household electricity demand and disposable household income. Following previous approaches, we use the share of voters for the Green party (labelled "Green voters" subsequently) in the 2013 federal election to capture environmental. As no official electricity consumption data are available for NUTS3 regions, electricity demand has not been analysed as a predictor variable for PV uptake in Germany before. We use information from a comparison portal that evaluated 200.000 electricity contracts in 2014 and provides the annual per capita electricity consumption for 120 German counties, the majority being cities (cf. preisvergleich.de (2015)). Hence, 120 of 402 data points are available. Here, total electricity consumption of households is determined as the result of the per-capita consumption multiplied by the average household size in the NUTS3 region. In case of missing data, the following approximation is made: For each federal state, the average per capita electricity consumption is calculated based on the available data points within that state. The missing NUTS3 values are then based on these state averages but are adjusted to capture the impact of household size on per-capita consumption. Particularly, per-capita electricity consumption decreases with household size (cf. bdew 2014, bdew 2017). In the available data basis, small households are overrepresented, as household size is generally lower in cities (where most data points are situated)[13]. Hence, per-capita electricity consumption in larger households (that are situated in countryside regions) may be underrepresented and therefore a selection bias present. By adjusting per-capita consumption using deviations in household size, we derive smaller per-capita consumption levels in regions with larger households. More information on the construction of this variable is given in Appendix A. It could be argued that households who already adopted PV have a lower electricity demand, as more electricity is produced locally and not purchased. This would lead to an endogeneity problem. However, electricity generation from PV rooftop installations is measured by a second meter (under the EEG) and thus does not interfere with household electricity demand. Hence no endogeneity problem is expected in these data. Disposable household income in NUTS3 regions of the year 2014 is retrieved from regional account data provided by the German Federal Statistical Office. As not only income, but also wealth, i.e. accumulated historical income, may determine the capability to purchase PV systems, we try to capture the effect of asset ownership. In general, it is difficult to find proxies for wealth, since data are hardly available. As one indicator, we use the share of owner-occupied dwellings, as home-ownership generally indicates a higher financial status. Data

[13] E.g. in Bavaria, average household size for NUTS3 regions with electricity consumption data available, is 1.93 in contrast to 2.27 for the entire state.

are derived from the 2011 census. As income from capital shows a clear divide between East and West Germany (Federal and State Statistical Offices 2014), we add an east-west dummy. Data on the income from capital might be a better indicator for financial assets than owner-occupied dwellings. Unfortunately, this data could not be obtained. In addition, the east-west dummy controls for differences in East and West Germany beyond income, e.g. possible different mind-sets. Achtnicht and Madlener (2014) find differences of East and West German households regarding energy efficient retrofits, indicating more price sensitive households in East Germany. As a (negative) control variable for prosperity in a region, the share of welfare recipients is included, containing beneficiaries of unemployment benefits as well as other social benefits. The sensitive financial situation might not offer the possibility to purchase the PV technology. Data are retrieved from the German Federal Statistical Office for the year 2014. To control for settlement structure, we include the share of detached houses, share of single-family houses and the share of owner-occupied dwellings. The data are based on the 2011 census. As correlation between these variables may be high, the analysis includes corresponding tests. Since we normalize to the number of households, we do not consider population or household density nor household size. However, we include the county area, which normalized to the number of households yields the inverse of the household density. A high inverse household density occurs in rural areas with a higher fraction of non-settlement area, less multi-storey buildings and larger residences. Descriptive statistics for all variables are presented in Table 2. Other influences, such as age or education variables are omitted in this study, since previous studies have found mixed evidence on their impact (cf. Dharshing 2017, Graziano and Gillingham 2015, Balta-Ozkan et al. 2015). Also we do not want to overload the analysis and presume that the main drivers for PV adoption are covered.

Table 2 Descriptive statistics of model variables

Variable	Description	Mean	Std. Dev.	Min.	Max.
PV Capacity	kWp/household	0.187	0.148	0.011	0.683
Solar radiation	Global radiation [kWh/m^{2}a]	1,115	60	987	1,262
Green voters	Share of Green party voters	0.090	0.035	0.027	0.239
Electricity demand	Electricity demand/household	3.620	434	2,469	4,976
Available income	EUR/household	46,306	7,642	29,509	92,251
Welfare recipients	Share of welfare recipients	0.171	0.075	0.038	0.423
Owner-Occupier	Share of owner-occupiers	0.519	0.144	0.128	0.769
Single family houses	Share of single family houses	0.388	0.152	0.085	0.753
Detached houses	Share of detached dwellings	0.627	0.208	0.122	0.974
County area	County area [m^2]/household	13,108	10,763	424	57,929

4.3 Model specification

To investigate the determinants of PV adoption across the 402 German NUTS3 regions (i), the following model is applied:

$$PV_i = \beta_0 + \beta_1 solar_i + \beta_2 green_i + \beta_3 elec_i + \beta_4 income_i + \beta_5 welfare_i + \beta_6 owner_i + \beta_7 detach_i + \beta_8 area_i + \beta_9 east_i + u_i. \tag{6}$$

The dependent variable in Equation (1) is the PV capacity of installations under 10 kW normalized to the number of households. The explanatory variables encompass solar irradiation ($solar$), share of green voters ($green$), household electricity demand ($elec$), household income ($income$), share of welfare beneficiaries ($welfare$), share of owner-occupied dwellings ($owner$), share of detached buildings ($detached$) and area per household ($area$). Except solar radiation, all variables are normalised to the number of households in NUTS3 regions. The specification of the error term is varied in order to test various spatial regression models (cf. section 3 and Figure 2).

5 Estimation results and discussion

5.1 OLS results and tests for spatial dependence

As single-family houses are often detached and occupied by the owner, the use of all variables leads to collinearity problems.[14] Collinearity causes instability in parameter estimation and must be avoided. We hence exclude the share of single-family houses as a regressor.[15] Standardized coefficient estimates of the OLS model are presented in the first column of Table 4. Results reveal that solar radiation, electricity demand, detached houses and area per household have a positive impact on the regional uptake of PV installations. Available income, welfare recipients, green voters and the east dummy variable turn out to affect negatively the adoption of PV. Ownership seems to be negligible. The negative impacts of available income and green voters are rather surprising and rise questions on the validity of the specification although the obtained R^2 of 0.74 indicates a rather good model fit. To test for spatial correlation, we calculate Moran's I (Moran, 1950) and carry out Lagrange multiplier (LM) tests. Moran's I test statistic is a global indicator of spatial association.[16] The positive values (cf. Table 3) indicate spatial dependence of PV capacity as well as OLS residuals. Also, Moran's scatter plots in Figure 5 and Figure 6 provide a visual representation of spatial associations, i.e. how similar the observed values are to their neighbouring observations. On the horizontal axis (x-axis), the value of an observation (PV capacity in Fig. 5 and OLS residuals in Fig. 6) is shown. The vertical axis (y-axis) displays the weighted average or spatial lag of the corresponding values on the horizontal axis. Data points in the upper right and lower left quadrants indicate positive spatial correlation between neighbouring regions.

As discussed in section 3, we use a row standardized queen contiguity weights matrix for the tests and the subsequent spatial models. LM_{error} and LM_{lag} tests, in addition to their robust versions, test the null hypothesis of no spatial dependence against alternatives of

[14] We use the variance of inflation factor (VIF) to detect collinearity. The VIF is based on the square of the multiple correlation coefficients resulting from regressing a predictor variable against all other predictor variables. A VIF greater than 10 signals a collinearity problem in the model. We have also tested other specifications excluding detached houses or owner-occupied houses. Yet those have led to lower explanatory power (as measured by R^2) which justifies the omission of the single-family houses.

[15] Results including single-family houses are provided upon request.

[16] Moran's I: $I = \frac{N \cdot \sum_{i=1}^{N} \sum_{j=1}^{N} [w_{ij} \cdot (y_i - \bar{y}) \cdot (y_j - \bar{y})]}{\sum_{i=1}^{N} \sum_{j=1}^{N} [w_{ij} \cdot \sum_{i=1}^{N} (y_j - \bar{y})^2]}$

spatial error and spatial lag dependence respectively (Anselin, 1988; Florax et al., 2003). LM tests (cf. Table 3) indicate that the null hypothesis of no spatial dependence should be dismissed. OLS regression seems inappropriate and may result in biased estimates, as spatial forces driving PV adoption are not confined by NUTS3 borders but are likely to spill over to proximate regions. Given the positive and significant values of LMerror and LMlag tests and their robust versions, the OLS model is rejected in favour of both the SAR and the SEM. Hence, also the SDM should be estimated (Elhorst 2010). In addition, we employ a GSM, incorporating both spatial lag and error correlation, but neglecting spatial dependence in explanatory variables. Table 4 provides estimation results. In addition, Table 6 shows impact measures of the SDM and GSM.

Table 3 Test for spatial dependence in the OLS regression

Test	
Moran's I for PV capacity	0.596
Moran's I for residuals	0.310
LM_{error}	82.68^{***}
Robust LM_{error}	20.36^{***}
LM_{lag}	71.26^{***}
Robust LM_{lag}	8.94^{**}

*** Significance level at 0.1%
** Significance level at 1%.

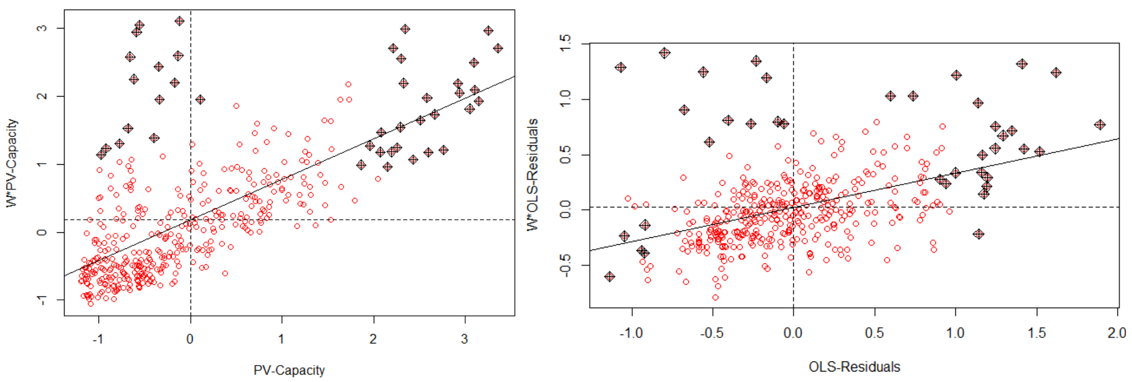

Figure 5 and Figure 6 Moran's I scatter plots (PV capacity (left) and OLS residuals (right))

Table 4 OLS and spatial model estimation results

Variable	OLS	SAR	SEM	SDM		GSM
	Estimate	Estimate	Estimate	Estimate	θ Estimate	Estimate
Intercept	0.000	-0.057	-0.029	-0.027		-0.032
	(0.026)	(0.024)	(0.047)	(0.026)		(0.046)
Solar radiation	0.268***	0.163***	0.219***	0.138	-0.020	0.214***
	(0.034)	(0.033)	(0.049)	(0.122)	(0.134)	(0.050)
Green voters	-0.148***	-0.067*	-0.043	0.018	-0.152*	-0.044
	(0.034)	(0.032)	(0.037)	(0.042)	(0.067)	(0.038)
Electricity demand	0.315***	0.248***	0.255***	0.240***	-0.027	0.254***
	(0.055)	(0.050)	(0.056)	(0.058)	(0.098)	(0.056)
Income	-0.143**	-0.067	-0.102*	-0.075	0.001	-0.101*
	(0.047)	(0.044)	(0.046)	(0.049)	(0.096)	(0.047)
Welfare recipients	-0.260***	-0.133**	-0.162**	-0.102.	-0.038	-0.161**
	(0.051)	(0.048)	(0.053)	(0.058)	(0.094)	(0.054)
East dummy	-0.181***	-0.035	-0.111.	-0.065	0.029	-0.104.
	(0.051)	(0.049)	(0.058)	(0.097)	(0.121)	(0.062)
Ownership	0.077	0.176**	0.093	0.097	0.040	0.101
	(0.064)	(0.059)	(0.070)	(0.077)	(0.111)	(0.071)
Detached houses	0.194**	0.151**	0.227***	0.265***	-0.196.	0.223***
	(0.06)	(0.055)	(0.065)	(0.071)	(0.102)	(0.065)
County area	0.200***	0.166***	0.228***	0.235***	-0.165*	0.225***
	(0.041)	(0.037)	(0.044)	(0.047)	(0.065)	(0.044)
ρ		0.316***		0.453***		0.034
		(0.043)		(0.057)		(0.0.77)
λ			0.519***			0.487***
			(0.054)			(0.080)
R^2 /adj. R^2	0.743/0.737					
Log Likelihood	-297.08	-268.54	-259.96	-252.29		-259.89
AIC	616.17	561.08	543.92	546.57		545.80
BIC	660.13	609.04	591.87	630.50		597.75
Breusch Pagan Test	68.49	73.48	49.13	88.03		50.46

Note: The values in parentheses are standard errors.
*** Significance level at 0.1%
** Significance level at 1%.
* Significance level at 5%
. Significance level at 10%

5.2 Spatial model results and comparison

Considering the results of the OLS regression model as a benchmark, the findings are partly revised when spatial models are estimated. All models including spatial terms offer a better model fit (in terms of Log Likelihood, Akaike information criterion (AIC) and Bayesian information criterion (BIC)) than OLS estimation. Results point to strong spatial correlation between PV adoption levels in adjacent counties, confirming residential PV forms local clusters in certain regions. The positive and statistically significant estimate of the spatial autoregressive parameter ρ in the SAR and SDM indicates spatial lag of PV adoption. Hence, endogenous interaction effects, i.e. the type (i) of spatial interaction identified by Manski (1993) (cf. Section 3) drive levels of solar panel uptake to spill over NUTS3 borders and facilitate PV adoption in neighbouring regions. Recurrent visual perception of PV installations and peer-effects as drivers of social imitation (cf. Section 1) might explain this spatial autocorrelation as potential adopters follow decisions by actors in the proximity.

The positive and statistically significant parameter estimate of the spatial autocorrelation parameter λ in the SEM indicates spatial dependence in the residuals. Spatially close regions are likely to have similar (unobserved) characteristics or face similar political, institutional, or environmental conditions, resulting in correlated effects (the type (iii) of spatial interaction identified by Manski (1993), cf. Section 3). Also spatial knowledge spillover effects (cf. Section 1) will induce similar correlation patterns. Hence, similar unobserved characteristics lead to similar decisions in neighbouring NUTS3 regions. Here, a local concentration of craft skills, solar initiatives (Schaffer and Brun 2015), local PV supplier activities or information and advertising campaigns are examples of potentially relevant spatial knowledge spillover, which might lead to an accelerated PV diffusion in a region and its surroundings. Admittedly, this interpretation of the spatial association is tentative and may certainly relate to other than the discussed factors.

Combining both results, an influence of PV installations in one county on PV installations in neighbouring counties as well as a remaining unexplained spatial dependence indicated by the residuals is present. Consequently, the GSM should best fit to capture the spatial processes. The GSM results show positive estimates of both ρ and

λ indicating a combined spatial dependence similar to an ARMA time series specification. However, in contrast to the SAR and SDM the spatial autoregressive parameter ρ becomes insignificant. Since the models are estimated by maximum likelihood, we can perform a likelihood ratio (LR) test to examine whether the SDM or GSM can be reduced to the SAR or SEM (cf. Figure 2). LRs indicate that neither the SDM nor GSM should be reduced to a SAR (cf. Table 5). In contrast, the SDM model could be reduced to a SEM as the LR test is insignificant. Further, a model reduction of the GSM to a SEM seems plausible as the LR is small and insignificant, notably visible in the only infinitesimal different log likelihood. Hence, the effect of spatial lag does not offer additional explanatory power when considering spatial dependence in the residuals.[17] According to our results, hence the influence of correlated effects seems to outweigh endogenous effects. Or put differently: social imitation is according to our analyses less relevant than spatial knowledge spillover and similar, not directly observable effects. This is also supported by log-likelihoods and AIC which show that SEM and SDM perform best and improve upon to the OLS and SAR specifications (cf. Table 4). In terms of BIC the SEM shows the best results, lending credence to its choice. The Breusch–Pagan test indicates the presence of heteroscedasticity in residuals of all models, although it is somewhat reduced in the spatial estimations. SEM and GSM, taking spatial dependence of residuals into account, show the best results.

Table 5 Likelihood ratios for nested spatial models

SDM vs. reduced model		GSM vs. reduced model	
SAR ($\theta = 0$)	32.01^{***}	SAR ($\lambda = 0$)	17.29^{***}
SEM ($\theta = -\rho\beta$)	15.34	SEM ($\rho = 0$)	0.12

Regarding the β estimates, a difference between the OLS and spatial models are the generally smaller coefficients in the spatial models. This implies that their direct influence is less pronounced than estimated earlier, and partly attributable to spatial association. In this vein, the east dummy is insignificant in spatial models. As expected, solar radiation maintains a positive influence on PV uptake in the spatial models.[18] Yet solar radiation is

[17] Although this is indicated by the robust LM_{lag} test (cf. Table 2).
[18] The effect of solar radiation is statistically insignificant in the SDM, which has no plausible interpretation.

not the predominant factor in our analysis, as other variables show higher coefficients. Contrary to expectations, Green votership has a negative influence on PV uptake (OLS and SAR) or is insignificant (SEM und GSM). In the SDM, the estimate is positive whereas the lag estimate is negative. This finding is supported by the impact analysis (cf. Table 6). It suggests that a high share of Green voters in a region negatively influences PV adoption in adjacent regions, which has no plausible interpretation at first glance. When visualising the share of Green voters in NUTS3 regions, it however becomes obvious that the share of Green voters is especially high in cities. Here, the PV capacity per household is rather low, which might entail a negative relation. In less densely populated suburbs, meaning regions adjacent to cities, the PV uptake under consideration is rather high, which again might explain the negative spatial lag impact. Admittedly, the use of other indicators for environmental awareness than Green party voters might involve different results, in particular that environmental motivation favours PV uptake.[19] E.g. Wittenberg and Matthies (2016) find that the use of green electricity tariffs and energy efficient appliances is higher for PV adopters, indicating higher environmental awareness than average households.

A major predictor for PV uptake is household electricity demand. It has the highest positive coefficient estimates. Similarly, Wittenberg and Matthies (2016) find that electricity consumption of PV adopters is medium to high compared to the German average. A household's comparatively higher demand may entail higher environmental concerns and lead to a the desire to compensate the higher demand by green electricity production (Balta-Ozkan et al. 2015). The decision could also be motivated by the financial consideration to reduce the household's comparatively higher electricity costs or the wish to become self-sufficient.

A negative impact of household income on cumulated PV capacity is suggested by spatial estimation results and supported by the impact analysis (cf. Table 6). This implies that high income is no precondition for meeting the upfront costs of PV systems. For high-income households, the potentially profitable purchase of a PV system may not be a concern, as saving money (or energy costs) is not an issue. Also, higher incomes are potentially earned in densely populated areas, where limited roof potentials hinder the

[19] Yet, the authors could not obtain a sound data basis available on the level of NUTS3 regions. Hence, this is left as a promising avenue to future research.

growth of installed capacity per household. Obviously, there is an indirect effect of income on PV uptake through the increased probability for living in a detached and owner-occupied house. However, the positive impact of homeownership is only significant in the SAR specification and insignificant in the remaining models. We assume the reason to be the high correlation of detached and owner-occupied dwellings. If detached houses are excluded as a regressor, the impact of owner-occupied dwellings is positive in all models. Similarly, a positive impact is found when including single-family houses instead of detached or owner-occupied dwellings. Hence, detached houses in our data (building on the German 2011 census) are to some extent congruent with owner-occupied dwellings as well as single-family houses. However, the explanatory power of detached houses is the highest. They are a main driver for PV adoption indicated by high β estimates in all models. In addition, county area per household substantially favours PV uptake.[20] This again hints at a positive impact of rural areas with larger properties and higher shares of detached single- or double-family houses. Detached houses improve PV panels' exploitation of sunlight, since they usually encounter no shadowing and have larger roofs (Dharshing 2017). Further, construction work is easier compared to terraced houses (Balta-Ozkan et al. 2015). The share of welfare recipients mitigates regional PV uptake, hence indicating a positive relationship between higher socio-economic status and PV uptake, which could not be obtained from the income variable. In this vein, initial investment costs seem to deter socially deprived households (who are also more likely to rent) from adopting PV systems. Although FITs offer or increase profitability of PV systems, they do not reduce the high upfront investment costs. Balta-Ozkan et al. (2015) use the findings of Graziano, Gillingham (2015) on the importance of accumulated capital for PV uptake and suggest that the early adopters of PV panels seem to be post-family householders capable to cover the high investment. Notably, in older post family households (two-person, retired), electricity demand is rather high as more time is spent at home (Wittenberg and Matthies 2016). In affluent regions, these households are likely to live in detached houses and entail enough capital savings to invest in PV panels.[21]

[20] Population density negatively affects household PV adoption, as county area per household has a positive impact in all models.
[21] In the appendix (cf. Table 6), we detail our results and compare them to literature findings.

Table 6 Impact measures for SDM and GSM

	SDM			GSM		
Variable	Direct	Indirect	Total	Direct	Indirect	Total
Solar radiation	0.143	0.073	0.216**	0.214***	0.007	0.221***
Green voters	0.003	-0.247*	-0.244*	-0.044	-0.002	-0.045
Electricity demand	0.249***	0.140	0.389*	0.254***	0.009	0.263***
Income	-0.079	-0.057	-0.136	-0.101*	-0.003	-0.104*
Welfare recipients	-0.111*	-0.145	-0.256.	-0.161**	-0.006	-0.166**
East dummy	-0.065	-0.001	-0.066	-0.104.	-0.004	-0.108.
Ownership	0.106	0.144	0.250	0.101	0.003	0.104
Detached houses	0.256***	-0.131	0.125	0.223**	0.008	0.230**
County area	0.229***	-0.101	0.128	0.225***	0.008	0.233***

Note: The values in parentheses are standard errors.
*** Significance level at 0.1%
** Significance level at 1%.
* Significance level at 5%
. Significance level at 10%

The θ coefficients of the SDM, representing spatial lags of the independent variables, are only statistically significant for county area, detached houses and Green voters. Similarly, indirect impact measures in the SDM are only significant for Green voters and insignificant in the GSM (cf. Table 6).[22] This implies that spatial lags of independent variables and indirect impacts do not offer meaningful explanations of PV adoption. Hence, most effects are local, as mostly direct impacts are significant and surpass indirect impacts. In this vein, the analysed exogenous variables do not seem to explain spatial association, i.e. the type (ii) of spatial interaction identified by Manski (1993), is not relevant here (cf. Section 3). Consequently, PV uptake in a region depends on its own adopter-characteristics and settlement structure, and less so on those of its neighbours. In addition, positive direct (or total) impact measures of the SDM and GSM confirm that solar irradiation, detached houses, electricity demand and county area favour PV uptake. Negative influences of income and welfare recipients are also substantiated.

[22] The effects estimates for the SAR give a similar picture (cf. Table 10).

5.3 Key findings

To sum up, it is clear from the results that the data exhibit significant spatial dependence independently of the chosen specification. By testing different model specifications, we can derive implications based on all model results. However, from coefficient estimates and test results, the SEM performs best to interpret the impact of PV uptake within a region. This indicates that although spatial lag is present, spatial dependence in the residuals has higher explanatory power. Hence, we suppose that spatial spillover is not mainly driven by social imitation but by other regional characteristics not included in our model – with non-formal arguments suggesting that knowledge spillover may play an important role there.

Detached houses in spacious regions offer favourable conditions for PV adoptions. Also, households living in (their own) detached buildings might have financial savings to invest in PV systems. The share of welfare recipients seem to be a suitable negative proxy for wealth, having an impeding influence on a regions PV uptake. We hence suggest that it is not income but rather wealth i.e. accumulated capital, which contributes to regional differences in PV uptake. Further, households with higher electricity demand are inclined to adopt PV panels. Neither disposable income nor our proxy for ecological attitude (Green voters) qualify to explain higher levels of PV adoption and rather show a negative impact. No support can furthermore be given to a supposed specific East German mind-set which would impede PV adoption.

Besides the availability and choice of data, the configuration of the spatial weights matrix (Mur and Angulo 2009) is crucial for the regression results and their interpretation. We have additionally tested an inverse distance matrix and results are robust across this alternative specification.

6 Conclusion

Considering the finite nature of fossil resources and their effect on climate change as well as the huge potential for small-scale roof-mounted PV installations and the support mechanisms in place, more small-scale PV installations are likely to emerge. This article studies the drivers and barriers influencing the diffusion of small-scale solar PV systems across space. We use cross-sectional data on PV installations in Germany, along with adopter characteristics, settlement structure and radiation data to find key determinants for accumulated capacity of small-scale PV systems in NUTS3 regions.

Spatial dependence is a significant explanatory factor for residential PV diffusion, implying positive spillover to adjacent regions and the manifestation of PV clusters in certain regions. Besides the expected impact of explanatory variables like solar radiation, shares of detached houses, electricity demand and inverse population density, non-observed regional characteristics also strongly contribute to explain PV uptake. The distinction between endogenous effects and correlated effects as sources of spatial interactions is important: while endogenous effects (e.g. peer-effects) lead to a social multiplier, correlated effects do not. (Richter 2013). The test of different spatial specifications clearly indicates that correlated effects have higher explanatory power than endogenous effects. Hence, social imitation, induced e.g. by recurrent visual perception, social interactions or peer-effects, is less likely to explain spatial patterns observed in PV diffusion on the aggregation level of NUTS3 regions. According to our results, political activities aiming to induce social imitation are therefore likely to have only limited impact. The same may be true for campaigns aiming at the promotion of general green attitudes, as this variable (represented by Green voters) does not have significant positive impacts on PV uptake. This is in line with findings by Allan and McIntyre (2017) and Schaffer and Brun (2015), who ascertain no positive impact of green attitudes on PV adoption.[23] On the other hand, simple economic causalities focusing on income as an explanatory variable for PV uptake are also refuted by the data – rather a certain non-urban, settled lifestyle manifesting in lower population density and detached housing seems to favour PV installations. A similar result is obtained by Balta-Ozkan et al. (2015), who state that PV adopters seem to be elderly, post-family homeowners who spend most of their time at home with higher electricity demand and some savings to pay for the high initial capital costs.

And then there are those aforementioned non-observed regional characteristics, which lead to correlated spatial effects. These may include differences in supplier characteristics: While in certain regions, installers are strongly oriented towards PV systems (or started earlier to do so) and provide free assistance and information, other

[23] Besides Green votes, Allan and McIntyre 2017measure green attitudes by Green party candidates and household recycle rate.

regions may suffer from lacking (qualified) PV supply agents. Possibly this is a consequence of artisans being unwilling or unforced (because of well-filled order books) to alter routine product portfolios. Besides differences on the PV supply side, other (in our model) non-observed regional characteristics are likely to exist e.g. local solar-initiatives or other networks encompassing municipal utilities, consumer organisations or energy advisers. These require further in-depth analysis in order to provide policy makers with a better understanding of the “soft factors” that facilitate the energy transformation at the scale of private households. Our results at least indicate there is not something as simplistic as a specific “East German” mind set which would explain the active participation in green energy production.

As 62% of German residential buildings are detached, there is further rooftop PV potential to be exploited. Potential new business models such as solar leasing or tenant (sub-) metering might grow and make rooftop PV accessible to a broader market. As pointed out by Dharshing (2017), the spatial dependencies imply that regional differences lead to variations in the local benefits of policy measures.

Our findings deepen the understanding on the regional diffusion of small-scale PV but research is still needed, as spatial dependence in residuals hints at unobserved drivers for regional uptake. E.g. editing data on local solar initiatives in NUTS3 regions and taking it as a predictor variable might account for some of the spatial error correlation. Shortcomings of our research which could be addressed include the following: Notably, we do not account for innovation diffusion effects over time, as proposed by Rogers (2003). Hence, a temporal dimension could be integrated in the analysis leading to a spatial-temporal model. Klein and Deissenroth (2017) analyse when household’s invest in PV systems and find that not only profitability, but also the change in profitability compared to the status quo determines the uptake. Yet a precondition for including time effects is the availability of the data. As we do not want to capture effects over time (e.g. cost decreases) but rather (nearly) time invariant features of different regions we focus on readily available cross-sectional data instead of panel data. Time invariant variables are incorporated in the fixed effects (FE) of standard FE panel models, which complicates evaluation of these variables. Our results regarding imitation should also be rechecked using spatial data with higher granularity. Notably Rode and Weber (2016) find that imitation in household PV adoption is highly localised, but influence decreases over distance. Richter (2013) also notices stronger social effects of domestic solar PV for smaller spatial units. In light of these findings, our spatial units seem to be rather big to investigate social interaction between households. Considering smaller spatial units such as zip codes in the analysis might hence improve our findings on spillover effects. However, data availability at a zip code level for the predictor variables used in this study has limited the spatial disaggregation

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Appendix A: Construction of the household electricity demand variable

For the NUTS3 regions with missing data on per capita consumption the following approach is used:

The mean per-capita electricity consumption in a state $\bar{d}_{state}^{obs}$ is calculated according to Equation 7 from observed NUTS3 values d_i^{obs} in this state.

$$\bar{d}_{state}^{obs} = \frac{1}{|I_{State}|} \sum_{i \in I_{state}} d_i^{obs} \tag{7}$$

Equation 8 then describes the computation of the per-capita consumption in a NUTS3 region, covering the either observed or approximated value. As data is mainly available for cities, per-capita electricity consumption in countryside regions may be underrepresented and therefore a selection bias present. We try to capture one major difference in city and countryside per-capita electricity consumption, namely average household size. The average state per-capita consumption $\bar{d}_{state}^{obs}$ is adjusted with the absolute difference between the household size in a respective NUTS3 region Hhs_i and the average household size for available data points within a state $\overline{Hhs}_{state}^{obs}$, multiplied with the difference in per-capita electricity consumption between an average two-person and an average three-person household Δd available from (bdew 2014). This difference is taken as household size in NUTS3 regions lies between 1.77 and 2.74 with an average of 2.20. Δd amounts to -212.5 kWh according to bdew (2014), meaning that per-capita consumption in a three-person household is by about 10% lower than in a two-person household. Hence, if households in a NUTS3 region are larger than the state average, per-capita consumption is reduced.

$$d_i = \begin{cases} d_i^{obs} & if\ d_i^{obs}\ available \\ \bar{d}_{state}^{obs} + \left(Hhs_i - \overline{Hhs}_{state}^{obs}\right) \cdot \Delta d & else \end{cases} \tag{8}$$

We then calculate the total household electricity consumption in a NUTS3 region by multiplying the per-capita consumption d_i with the population pop_i. By normalizing to the number of households Hh_i, the average household size in a region is then included in the household electricity demand variable D_i^{Hh}.

$$D_i = d_i \cdot pop_i \tag{9}$$

$$D_i^{Hh} = \frac{D_i}{Hh_i} \tag{10}$$

Appendix B: Additional results

Table 7 Summary of effects on PV uptake

Variable	Literature findings	Our findings
Solar Radiation	Schaffer and Brun (2015) and Balta-Ozkan et al. (2015) propose a positive effect: Higher irradiation means higher electricity generation that is generally fed into the grid and remunerated under a FIT. Insignificant impact in Allan and McIntyre (2017).	High positive impact in most specifications: Households consider financial yields when deciding whether to adopt PV.
Green voters	Proposed to be insignificant by Schaffer and Brun (2015) and Allan and McIntyre (2017); inconsistent finding by Dharshing (2017).	Inconclusive; negative effect in the OLS and SAR estimation and insignificant in other spatial models. Not only ecological conscious households adopt PV.
Electricity Demand	Balta-Ozkan et al. (2015) find a positive effect: Households with higher demand may be more interested in becoming self-sufficient.	High positive impact: Higher interest to reduce comparatively high electricity costs or desire to compensate higher demand by green electricity production.
Available Income	Schaffer and Brun (2015) and Dharshing (2017) find a positive influence of income: higher income households may be more capable to manage high upfront costs of PV systems.	Small negative effect: Income is no precondition to adopt PV. Finding in line with Balta-Ozkan et al. (2015), Zhang et al. (2011) and Graziano and Gillingham (2015). Supposedly, accumulated capital more important than income.

Welfare recipients	Dharshing (2017) finds negative effect of unemployment rate, indicating poor local economy hampers PV adoption.	Negative impact: Sensitive financial situation of households does not offer the chance to purchase PV; Effect of accumulated capital bigger may be bigger than effect of income.
Home ownership	Balta-Ozkan et al. (2015) find a negative effect in the UK and claim cumulated capital is more important.	Positive effect (but due to correlation with detached houses insignificant except in the SAR): Homeowners are more likely to invest in building technologies and planning is easier as they can freely decide what to put on their roof; in line with Schaffer and Brun (2015).
Detached Houses	Balta-Ozkan et al. (2015) find a positive effect: Compared to terraced homes or block development, construction work could be easier.	High positive impact: Detached houses may offer more suitable roof space for rooftop PV installations and do not suffer from shadowing. Higher explanatory power than single-family houses and owner-occupied dwellings in our analysis.
Single-Family Houses	Dharshing (2017) finds positive impact in panel SEM, but insignificant effect in FE and panel SAR. Impact remains unclear.	Due to correlation between detached, owner-occupied and single-family houses excluded form regression.
County Area per Household (Inverse Population Density)	Schaffer and Brun (2015) find positive influence of house density: Scalable roof-top PV may be suitable for densely populated regions and rural areas with little inhabitation offer less roof potential.	High positive impact: More county area per household indicates larger properties with presumably larger roof spaces, characterised by a higher share of single and double family homes. Finding in line with Balta-Ozkan et al. (2015).

Table 8 Correlation matrix

Variable	Sol.	Green	Elec.	Inc.	Wel.	East	Own.	Sing.	Det.	Area
Solar Radiation	1.00									
Green Voters	0.07	1.00								
Electricity Demand	0.03	0.29	1.00							
Income	0.27	0.38	0.72	1.00						
Welfare recipients	-0.49	-0.23	-0.52	-0.69	1.00					
East Dummy	0.02	-0.55	-0.75	-0.59	0.32	1.00				
Ownership	0.01	-0.05	0.64	0.57	-0.62	-0.30	1.00			
Single	-0.15	-0.14	0.54	0.38	-0.42	-0.14	0.89	1.00		
Detached	0.02	-0.01	0.55	0.50	-0.65	-0.24	0.88	0.77	1.00	
County Area	-0.01	-0.35	0.09	0.03	-0.26	0.29	0.57	0.65	0.60	1.00

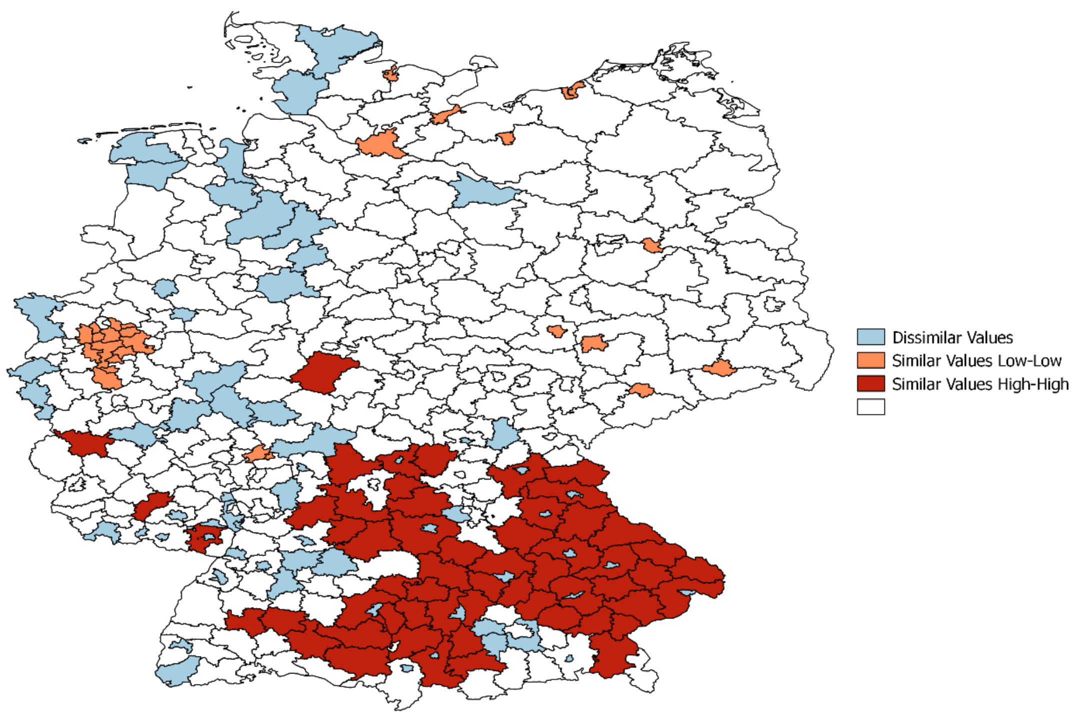

Figure 7 Local Moran’s I showing similar and dissimilar values in neighbouring counties

Table 9 OLS estimation results with whole data set

Variable	Coefficient	Std. error	t-value	p-value	VIF
Intercept	0.000	0.026	-0.001	0.999	
Solar radiation	0.270***	0.035	7.654	0.000	1.894
Green voters	-0.149***	0.035	-4.291	0.000	1.837
Electricity demand	0.309***	0.058	5.290	0.000	5.182
Income	-0.142**	0.047	-2.996	0.003	3.404
Welfare recipients	-0.262***	0.051	-5.103	0.000	4.014
East dummy	-0.186***	0.054	-3.470	0.001	4.393
Ownership	0.057	0.089	0.643	0.521	12.018
Single family houses	0.023	0.071	0.323	0.747	7.654
Detached houses	0.197**	0.061	3.237	0.001	5.616
County area	0.196***	0.042	4.627	0.000	2.730

*** Significance level at 0.1%
** Significance level at 1%.
* Significance level at 5%
. Significance level at 10%

Table 10 Direct and indirect effects of SAR

Variable	Direct	Indirect	Total
Solar radiation	0.167***	0.072***	0.239***
Green voters	-0.069*	-0.03.	-0.098*
Electricity demand	0.254***	0.109***	0.363***
Income	-0.069	-0.03	-0.098
Welfare recipients	-0.136**	-0.058**	-0.194**
East Dummy	-0.036	-0.015	-0.051
Ownership	0.18**	0.078*	0.258**
Detached houses	0.155**	0.067*	0.221**
County area	0.169***	0.073***	0.242***

*** Significance level at 0.1%
** Significance level at 1%.
* Significance level at 5%
. Significance level at 10%

Table 11 Sensitivity OLS and spatial model estimation results for PV system up to 16 kWp

Variable	OLS	SAR	SEM	SDM		GSM
	Estimate	Estimate	Estimate	Estimate	θ Estimate	Estimate
Intercept	0.000 (0.027)	-0.057 (0.025)	-0.029 (0.052)	-0.026 (0.027)		-0.022 (0.063)
Solar radiation	0.258*** (0.037)	0.149*** (0.035)	0.212*** (0.053)	0.154 (0.128)	-0.057 (0.141)	0.219*** (0.061)
Green voters	-0.189*** (0.037)	-0.083** (0.034)	-0.043 (0.040)	0.027 (0.045)	-0.210** (0.071)	-0.037 (0.041)
Electricity demand	0.289*** (0.059)	0.204*** (0.053)	0.233*** (0.059)	0.225*** (0.061)	-0.077 (0.102)	0.236*** (0.060)
Income	-0.167** (0.050)	-0.070 (0.046)	-0.096. (0.049)	-0.063 (0.051)	-0.012 (0.102)	-0.095. (0.050)
Welfare recipients	-0.290*** (0.055)	-0.126* (0.051)	-0.129* (0.056)	-0.063 (0.061)	-0.116 (0.099)	-0.123* (0.057)
East dummy	-0.280*** (0.055)	-0.111* (0.051)	-0.179** (0.063)	-0.163 (0.102)	0.040 (0.128)	-0.188** (0.069)
Ownership	-0.040 (0.069)	0.091 (0.063)	-0.007 (0.074)	0.005 (0.081)	0.055 (0.116)	-0.021 (0.077)
Detached houses	0.169** (0.065)	0.130* (0.058)	0.204** (0.070)	0.228** (0.075)	-0.165 (0.107)	0.211** (0.070)
County area	0.314*** (0.044)	0.255*** (0.040)	0.340*** (0.047)	0.350*** (0.049)	-0.212** (0.069)	0.346*** (0.048)
ρ		0.352*** (0.044)		0.427*** (0.057)		-0.091 (0.089)
λ			0.540*** (0.023)			0.616*** (0.070)
R^2 /adj. R^2	0.705/0.698					
Log Likelihood	-325.35	-291.25	-283.34	-273.23		-283.14
AIC	672.70	606.50	590.68	588.46		592.27
BIC	716.67	654.46	638.63	672.38		644.23
Breusch Pagan Test	72.92	81.61	51.00	104.00		46.37

*** Significance level at 0.1%
** Significance level at 1%.
* Significance level at 5%
. Significance level at 10%

4 Spatio-temporal diffusion of residential solar thermal systems in Germany: A spatial panel data analysis

Jan Paul Baginski

Abstract

Solar thermal roof-top installations offer the potential to meet an important share of residential water and space heating demand in Germany. These systems are subsidised with grants under the so-called market incentive program. The political goal is to encourage the adoption of renewable energy and to reduce CO_2 emissions in the heating market in view of a low-carbon building stock. Solar thermal adoption levels are currently rather low after a high period in 2008 and 2009. Also, solar thermal adoption rates distinctly vary between regions. This paper tries to disentangle influences governing regional and temporal differences in residential solar thermal uptake. Spatial panel regression models are estimated to capture spatial interactions, while controlling for potential adoption determinants, including economic considerations, household characteristics and climatic suitability. The panel data contain observations for over 1 million solar thermal installations across 402 German regions covering the period from 2001 to 2015.

Results indicate that differences in profitability influence the spatial and temporal patterns of solar thermal uptake. Regional diffusion is mainly driven by solar radiation. The development of fossil fuel prices is accountable for different adoption rates over time. New constructions do not seem to foster solar thermal use, indicating that solar heating is easily applied to existing houses. Larger households are more inclined to use solar heating, given that they use more efficiently solar generated heat. Results also show that spatial dependence drives the diffusion of solar thermal systems. These findings imply that there is potential for new policies and business models to increase the geographic and social diversification of solar thermal adoption.

Keywords: domestic solar thermal heating; spatial econometrics; panel data

1 Introduction

In view of a sustainable energy supply and climate protection, the German government introduced a "directive to promote the use of renewable energies" in 1994. The use of renewable energy should reduce CO_2 emissions, decrease fossil fuel dependence and provide sustainable heat and electricity generation. The directive targeted solar thermal (ST) and geothermal heating as well as water and wind power plants. Heat pumps, combined heat and power plants as well as photovoltaic (PV) systems enlarged the promotion portfolio in 1995. In the year 2000, the directive has been revised and the caption *Marktanreizprogramm* (MAP) (market incentive program) adopted. It has been directed towards the promotion of renewable heating systems, whereas subsidies in the electricity sector have been organised under the *Erneuerbare-Energien-Gesetz* (renewable energy act).

The MAP has become the most important funding instrument for the use of renewable energy in the heating sector. It provides direct grants and low-interest loans for innovative and sustainable heating technologies. Potential buyers can apply for direct grants to the *Bundesamt für Wirtschaft und Ausfuhrkontrolle* (BAFA) (federal office for economics and export control) or for loans to the *Kreditanstalt für Wiederaufbau* (reconstruction loan corporation). The MAP aims to provide investment incentives for private users, to boost sales and to reduce costs of renewable heating technologies. Subsidised technologies include ST systems, biomass boilers, heat pumps and geothermal heating plants. In 2016, ST systems accounted for 35% of investment subsidies, followed by biomass boilers (35%) and heat pumps (27%) (BMWI 2017a). Besides financial incentives, a specific regulation stimulates the diffusion of renewable energy in the German heating market since 2009: The *Erneuerbare-Energien-Wärmegesetz* (EEWärmeG) (renewable energies heating act) introduced a renewable use obligation in new constructions.[1] The required share of renewable energy to cover space and water heating demand varies between energy sources. In the case of harnessing solar radiation, a minimum of 15% is legally binding.

[1] Erneuerbare-Energien-Wärmegesetz (EEWärmeG)) of 7thAugust 2008 (BGBl. I p. 1658), and revised by paragraph 2, section 68 of this law on 22nd December 2011 in order to fulfil European law (BGBl. I p. 3044).

The German government has set the goal of increasing the share of renewable energy in heating and cooling supply to 14% in the year 2020. This target seems to be achievable as in 2016, the share of renewable energy amounts to 13% (BMWI 2017a). However, this share has been 12% in 2011 already and only increased marginally ever since. Compared to the electricity sector, where the share of renewable energy in electricity consumption keeps rising and exceeded 30% in 2016, the heating sector lags behind (BMWI 2017a). Residential heating is still dominated by fossil fuels (BMWI 2017b) and only a few households use renewable heating technologies. The long-term target of an almost climate neutral building stock in the year 2050 seems thus rather ambitious when compared to the past development of renewables in the heating market.

Hence, this paper seeks to identify drivers for the uptake of renewable heating systems in German households. Determining enabling and constraining factors is crucial in learning how to best promote renewable energy in the heating market and consequently to decarbonise the building stock. Notably, the analysis focusses on ST systems. First, because solar thermal heat generation is an established technology, which has a huge untapped potential. Currently solar generated heat amounts to 28 Petajoule per year (PJ/a) (BMWI 2017b). Estimations quantify only the domestic roof-mounted ST potential in Germany to be between 127 PJ/a and 174 PJ/a (Corradini 2013). Second, because a sound data basis for ST installations is attainable. This study uses data on over 1 million ST household installations funded with a direct grant under the MAP. Installations are allocated to 402 German NUTS3 regions over the period from 2001 to 2015.

The acceptance of MAP-grants and the adoption of ST systems respectively show great differences over the years (cf. section 2, Figure 2) and between regions (cf. section 4.1, Figure 3). A first explanation addressed in this study builds on economic considerations. As the use of ST energy entails heating cost savings, the purchase is potentially profitable and cost savings can recoup investment expensed. Hence, a profitability index is developed to capture the relationship between ST uptake and economic viability. It incorporates system costs, MAP-grants, solar radiation, interest rates, energy prices and price expectations. Yet, households' adoption decisions cannot be reduced to a pure economic calculus (Zundel and Stieß 2011; Welsch and Kühling 2009) and a broader approach to examine ST uptake should be applied. Hence, non-financial determinants, like peer-effects, climatic and household characteristics are included in the analysis. In addition, it is tested whether spatial effects influence the purchase of ST systems and hence drive regional diffusion. This presumption builds on the insight that spatial spillover is present in PV adoption (e.g. Allan and McIntyre (2017); Dharshing (2017); see Baginski & Weber (2018) for a literature review). Also, the geographic distribution of residential ST installations in Germany indicates spatial clustering. This study therefore employs traditional panel estimations, which are extended to spatial panel models. Thereby, potential adoption determinants are captured, while controlling for spatial interactions. The analysis is based on NUTS3-year combinations as the smallest unit of observation.[2] The paper contributes to literature in performing the first econometric analysis of regional ST uptake in Germany using a granular panel dataset on real adoption decisions. In addition, it adds to the rather topical research stream of spatial econometrics in energy-related decisions.

The remainder of the paper is structured as follows: Section 2 gives an overview of the policy framework, especially the MAP and section 2.2 reviews related literature. Section 3 describes the empirical strategy. Section 4 provides data, descriptive statistics and profitability calculations. Results, including sensitivity and robustness checks are presented in section 5. The final chapter concludes.

2 Solar thermal: policy framework and customer choices

There are two solar technologies types available for residential use offering the potential to tap an almost limitless source of energy. PV cells use sunlight to generate electricity, whereas ST collectors convert direct and indirect solar radiation into useful heat. Over 95% of ST applications in Germany are collectors on single- or double-family houses (Solar Heating & Cooling Program 2018). The market is dominated by flat plate collectors with a share of about 90% (Stuible et al. 2016). Since solar radiation substantially fluctuates daily (and yearly), collectors are usually combined with a hot water storage to balance daily demand. Smaller ST systems with average collector sizes of 4-7 m² are only used to heat tap water. Larger ST installations with average collector areas of 10-14 m² are used to heat tap water and to provide space heating support (combi-systems). Residential ST applications in Germany are usually not the main heating system

[2] This is mainly due to data availability. Data on smaller units e.g. postcode regions is not available or free of charge for all variables. A NUTS3 region within the European Union is equivalent to a German county (“Landkreis”).

but are operated in combination with another residential heating system (RHS) (e.g. a gas boiler). Since both systems feed heat into the same hot water storage, heating energy provided by the ST system replaces conventional heat generation to some extent. Depending on the design of collectors and storage, ST systems can cover around 20% to 40% of annual heat demand (Corradini 2013).

2.1 Policy framework

Under the MAP, the installation or expansion of ST systems equipped with a heat meter is subsidised with a direct grant.[3] The grants in 2001 amounted to 128 €/m^2 for flat-plate collectors, 166 €/m^2 for evacuated tube collectors and 51 €/m^2 for system-expansions.[4] However, the MAP was revised and grant levels changed almost annually between 2001 and 2015 (cf. Figure 1). In the revision of 2004, grants were no longer differentiated between collector types. In 2005, the use of solar energy for space heating was incentivised with higher grants, while grants for water heating were reduced. The MAP 2005 was well received and funds were exhausted by October. This lead to an upscaling of funds and a degression of funding rates in 2006. Yet, the high number of grant applications continued in 2006; funds were again exhausted and rates reduced in June 2006. These cutbacks held in 2007. However, as the number of applications declined drastically, grants were restored (cf. Figure 1). Further, a bonus of 750 € was added, if the existing RHS was replaced by a condensing boiler in the course of the ST installation.

[3] As a technical requirement, systems need a "Keymark-Certificate" showing a yearly solar yield of at least 525 kWh/m^2.

[4] Directive to promote the use of renewable energy in the heating market, 23rd March 2001. An exchange rate of 1 Euro = 1,95583 DM was used.

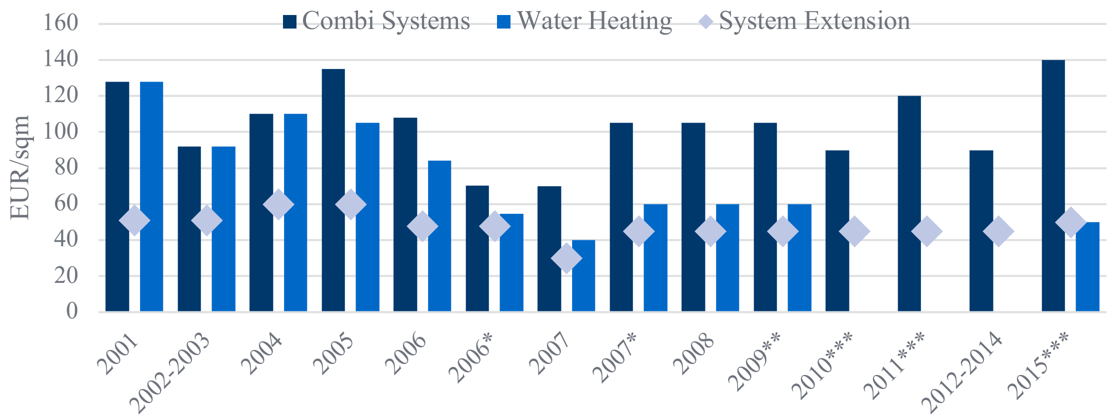

Figure 1 MAP-grants for solar thermal systems (*Grants changed within year, **Grants for new buildings reduced by 25%, ***Grants only applicable for building stock); Own illustration based on MAP directives

Because of the use obligation under the EEWärmeG, the MAP as a political funding instrument had to be enshrined in the law, entailing two major implications: First, renewable heating systems that merely comply with the obligation are no longer subsidised.[5] Second, grants are differentiated between existing and new buildings, as new buildings are subject to the EEWärmeG. Subsidies were reduced by 25% for renewable heating systems in new buildings.

A temporary suspension of the MAP took place in 2010 (May 3, 2010 to July 11, 2010), so the program came into force only in August. Notably, this MAP version entailed a disruption for solar energy: Water heating systems were dropped from the MAP and funding was only granted for combi-systems (cf. Figure 1). In addition, still with respect to the EEWärmeG, subsidies for new buildings were abandoned completely. In the current version of the MAP 2015, ST system for only water heating purposes are readmitted.[6] Combi-system grants are 140 €/m^2 with a minimum of 2000 € for new systems. The bonus for additional replacement of the existing RHS is still in place but decreased to 500 €.

The funding under the MAP hence has shown several structural breaks, which lead to unstable market conditions. The installed collector area of ST systems subsidised under the MAP shows great variations between 2001 and 2015 (cf. Figure 2). While many ST systems were erected in 2008 and 2009, a huge drop is reported in 2010 (cf. Figure 2). An essential reason is the suspended funding between May and June 2010. Additionally,

[5] For technically sophisticated systems and for over-accomplishing obligations, funding is still granted.
[6] Directive to promote the use of renewable energy in the heating market, 11th March 2015.

the dropped support for pure water heating systems, as well as the dropped support in new buildings took a toll on supported installations (Langniß et al. 2011). Besides MAP installations, total annual solar installations in Germany are falling since 2011. According to the BDH, reasons for a declining ST market are too little (or no) cost decreases, high installer margins and high workload of artisans (Stuible et al. 2016).

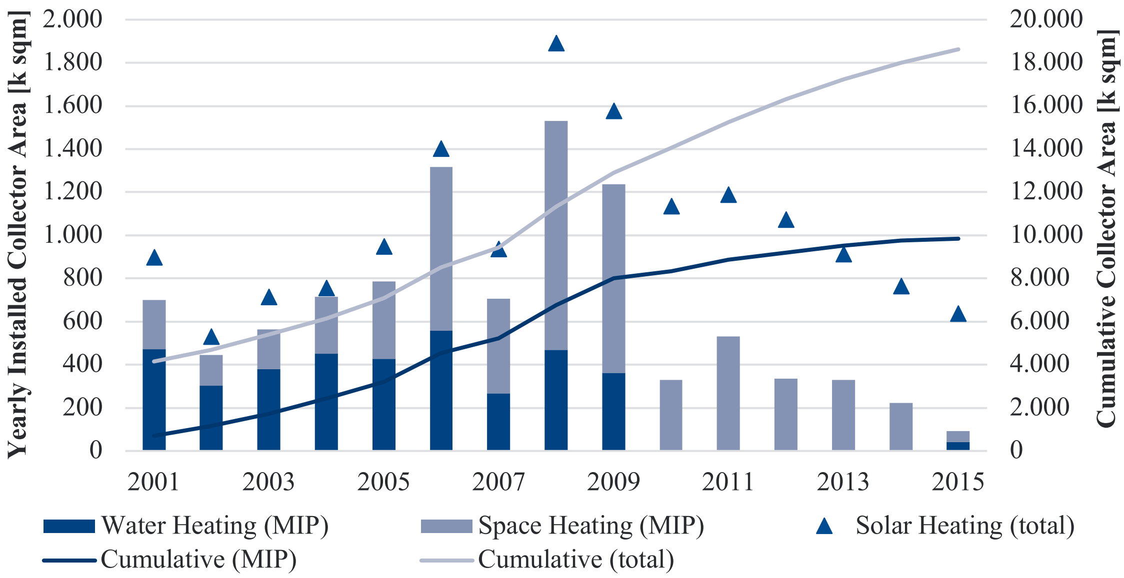

Figure 2 Solar thermal installations in Germany from 2001 to 2016, own illustration with data from (BSW 2017) for MAP installations and (BMWI 2017b) for all solar thermal installations[7]

2.2 Residential heating system choice studies

Existing studies investigate decisions on RHS in Germany (Braun 2010; Michelsen and Madlener 2012; Decker and Menrad 2015; Michelsen and Madlener 2017), Austria (Hecher et al. 2017), Norway (Lillemo et al. 2013), Ireland (Curtis et al. 2018) and other European countries. As the decision is a discrete appliance choice, they usually specify a (multinomial) logit or probit model to identify drivers and barriers. Mostly, large surveys are used and revealed or stated RHS preferences together with building and household characteristics are analysed. Building characteristics (e.g. type: detached or terraced, single- or multi-family) and settlement structure (e.g. populations density) are key determinants for RHS choice (cf. (Braun 2010)). The decision to install a RHS differs

[7] With regards to the entire ST collector area in Germany installed between 2001 and 2015 (BMWI 2017b), almost 60% is attributable to domestic ST applications, subsidised by the MAP. While this share was higher between 2001 and 2009 (83%), it fell to 27% after 2009. This again is due to he changed support scheme, dropping subsidies for new buildings and water heating systems.

between new and existing buildings, as technical features are easier to account for during construction. Michelsen and Madlener (2012) find that in existing homes, the decision is driven by socio-demographic, home and spatial characteristics while in new buildings, preferences about RHS specific attributes are more relevant. Depending on the type of RHS households choose, different determinants seem to be important. Adopters of gas- and oil-fired condensing boilers with ST support have a strong preference for energy savings, while adopters of heat pumps or wood pellet-fired boilers prefer being more independent from fossil fuels (Michelsen and Madlener 2012). In the same vein, Decker and Menrad (2015) find that economic aspects are important to users of oil heating but less relevant for users of wood pellets. The latter seem to accept higher investment costs and regard ecological advantages as more important.[8] Belonging to an ecology cluster is one of the most significant variables separating the users of different RHS (Decker and Menrad 2015). In contrast Curtis et al. (2018) find that past environmental behaviours, socioeconomic and dwelling characteristics have only little explanatory power in determining RHS choice, whereas the proximity to a fuel network, specifically natural gas, is the key determinant. Ambiguous results are provided regarding the influence of household income. Curtis et al. (2018) find no substantial difference in the likelihood of choosing a particular RHS between income groups. In contrast, Michelsen and Madlener (2012) find that income affects RHS choice.

Obviously, ST systems are hardly comparable to other RHS as they usually support a main heating system. Solar collectors are moreover preferably installed on unshaded roofs directly exposed to sunlight. Such conditions may be more prevalent in rural areas with higher shares of detached houses. Determinants for the addition of ST heating may thus deviate from drivers and barriers for other (main) heating systems. Three studies specifically study the adoption of ST heating and are briefly examined in the following. Mills and Schleich (2009) build a probit model based on a 2002 survey regarding energy usage of 20,325 German households to identify characteristics that favour the adoption of ST systems. 114 respondents reported having a solar combi-system and 423 having a solar water heating system. Results indicate that ST adoption decreases with heating

[8] Within Decker and Menrad's 2015 survey, respondents had to evaluate 11 statements addressing topics such as climate change, sustainability, environmental pollution, and environmental protection and are grouped to five ecology clusters afterwards: Environmentally indifferent consumers; environmentally nihilistic consumers; ecologically minded, active altruists; ecologically-minded, active egoists and miserly pseudo environmentalists.

degree-days (HDD) and city size (local population density). HDD are a measure of local climate based on daily temperatures and are broadly proportional to the heating energy demand in a residence. Households in rented residences show a lower propensity to adopt ST systems (Mills and Schleich 2009). In general, the apportion of costs and savings between tenants and landlords hampers the adoption of energy efficient investments in rented dwellings (Jaffe and Stavins 1994). Mills and Schleich (2009) find that higher levels of solar radiation, household size and a recent construction year (in occurrence the years 2001-2002) positively affect ST adoption. Household income on the contrary is found to have no impact on ST adoption.

Schelly (2009) uses logistic regressions to test residential ST adoption at the county level throughout the United States. The author employs three indices to capture socioeconomic circumstances, environmental concern, and ecological conditions.[9] The socioeconomic index is the most robust predictor for ST use. It indicates that counties with higher education levels, less unemployment, and higher levels of disposable or investment income (measured through income and home value) are more likely to entail households who adopt ST systems. As the author uses the absolute number of ST systems, a positive impact of the number of households within a county is found, which is purely a consequence of having more dwellings. Yet, populous counties are also more likely to have businesses to provide the necessary technology and services available to inform and assist in renewable energy investments (Schelly 2009).

Woersdorfer and Kaus (2011) analyse the adoption of solar thermal systems with a probit model building on a survey of nearly 500 consumers, undertaken between July and September 2007 in the region of Hannover (north-western Germany). The study distinguishes pioneers and potential imitators among the respondents and classifies outcomes into the categories “interest to purchase” and “plan to purchase” a ST system. The authors summarize that product knowledge, environmental attitude, and income seem to be important but not sufficient determinants of prospective purchases of ST systems.

[9] The socioeconomic index encompasses employment rates, median household income, median home value, and education rates in a county. The environmental concern index includes the use of “soft transportation” (public transports, biking, or walking), support for environmental causes, the percentage of county residents who claim to recycle, county participation in the International Council for Local Environmental Initiatives, the number of environmental non-profits within the county, and the percentage of the county that voted for a Democratic candidate. The environmental index encapsulates the natural-environmental factors that may influence ST technology adoption, notably solar radiation and temperature averages.

Only peer group behaviour proves essential to trigger the concrete adoption plan. Once potential adopters show an interest for ST systems, the activities in the social environment decide if the installation is actually envisaged or not.

Several authors suggest that peer-effects determine the ST adoption decision, indicated by a higher likeliness of adoption when peers (e.g. neighbours, friends) have already adopted the technology. Mills and Schleich (2009) find that households' propensity to adopt solar water heating increases with installed ST capacity per-capita within that Federal State. Also, Michelsen and Madlener (2013) and Woersdorfer and Kaus (2011) state that peers influence renewable heating system choices. In the same vein authors claim that regional characteristics i.e. conditions that cannot be assigned to an individual home or homeowner, influence the RHS adoption decision. Braun (2010) states that spatial aspects are important as clear differences prevail between East and West Germany. Schelly (2009) plots ST adoption at the county level across America. Although her plots indicate that ST use shows regional clusters (it is concentrated in the Southwest of the U.S., in the Northeast and in the state of Florida), the author does not suggest regional spatial spillover as a predictor. Hence, more research is needed to disentangle the sources of regional ST system diffusion, especially focusing on peer effects and other sources of spatial spillover.

3 Methodological approach

There has been a growing interest in the specification and estimation of econometric relationships based on panel data (Elhorst 2003). Panel data offer extended modelling possibilities compared to cross-sectional or time-series data, since they are more informative, contain more variation and less collinearity among the variables (Baltagi 2005). They consist of observations on the same $i \in \{1, \dots, n\}$ entities (cross-section dimension) at more than one period $t \in \{1, \dots, T\}$ (time dimension). In the present data, n corresponds to 402 geographically delimited NUTS3 regions and t to the years 2001 to 2015, which leads to $N = n \times T = 6030$ observations.[10] A linear estimation approach

[10] Estimation of the models and all the spatial data analyses were done using "plm", "splm" (Croissant and Millo, 2015; Millo and Piras, 2015) and "spdep" packages (Bivand, 2016) implemented in R statistical software. The packages are available on the CRAN package repository (www.cran.r-project.org) while codes used to obtain reported results and all additional information useful to make research reproducible will be made available by the authors on request.

pools all the data across i and t and performs an ordinary least squares (OLS) regression. The main objection to this model is that it does not account for individual or temporal heterogeneity (Elhorst 2014). In panel data, individual units are likely to differ in their background variables, which are usually space-specific and time-invariant variables that affect the dependent variable (Elhorst 2003). Further, time specific events (e.g. structural breaks in support policies or nationwide policy announcements) apply to all regions and influence the dependent variable, but are difficult to measure or hard to obtain. Failing to account for these variables increases the risk of obtaining biased estimation results. One remedy is to assume that the error term has separate components. Depending on the properties of the error component, individual and temporal heterogeneity can be introduced as fixed or random effects. In a random effects model, it is assumed that effects are rather unobserved random variables which follow a probability distribution with finite parameters. Observed panel units should be representative of a larger population, and the number of units should potentially be able to go to infinity in a regular fashion (Elhorst 2003). When panels are specified for a given set of spatial units, such as regions in a country, the population is sampled exhaustively (Nerlove and Balestra 1996), and the individual units have characteristics that actually set them apart from a larger population (Anselin 1988). Hence, in the present study, the random effects model is not appropriate and the primary focus will be on fixed effects estimations.

A fixed effects model incorporating variable intercepts to model regional and time-period heterogeneity (two-way FE), takes the form:

$$\begin{gathered} y_{it} = \beta^T x_{it} + \mu_i + \eta_t + \varepsilon_{it} \\ \varepsilon_{it} \sim N(0, \sigma^2 I_n) \end{gathered} \tag{1}$$

y_{it} contains observations on the dependent variable and x_{it} observations on the K independent variables. β is a $K \times 1$ vector with regression coefficients, μ_i are (time-invariant) individual fixed effects for each region (regional FE) and η_t are time-period fixed effects (space-invariant) for each year (time FE). The coefficients in a regional FE model declare how Y given X within a region changes over time, while controlling for individual departure points. Coefficients of any variable x, which does not change over time are eliminated as they are implicitly included in the regional FE μ_i (Elhorst 2014). Impacts of time-invariant variables, which may be important to the analysis, cannot be estimated and evaluated. Similarly, in a time FE model, the coefficients of variables that do not change across space cannot be estimated when controlling for time FE η_t (Elhorst 2014). Hence, the focus lies on the development of Y given X between regions over time. Given this study wants to particularly derive explanations for ST uptake over space, including time-invariant, the focus will be on time FE estimation. In addition, regional FE and two-way FE models are deployed.

In order to capture the possibility that the dependent variable y_{it} depends on previous outcomes, i.e. $y_{i,t-1}$, a lagged dependent variable may be introduced, leading to a dynamic panel model (cf. Eq. 2). Not including a lagged dependent variable may lead to omitted variable bias and makes results less reliable.

$$\begin{gathered} y_{i,t} = \tau y_{i,t-1} + \beta^T x_{i,t} + \mu_i + \eta_t + \varepsilon_{it} \\ \varepsilon_{it} \sim N(0, \sigma^2 I_n) \end{gathered} \tag{2}$$

The effect of the time lag in the dependent variable is captured in τ. Still, a problem may arise when panel data incorporate a locational component because spatial dependence may exist between the regions (Elhorst 2003). A $N \times N$ spatial weights matrix W_N is required to reproduce the neighbourhood structure of the panel regions, to test for spatial dependence, and to specify spatial models. In this study, a queen contiguity matrix is used, meaning two regions are defined as neighbours when they share a border. The spatial weights matrix takes the form:

$$w_{i,j} = \begin{cases} 1, if\ neighbour\ to\ j \\ 0, otherwise \end{cases} \tag{3}$$

Since the selection of the spatial weights matrix W is to some extent arbitrary, it is a common practice to examine whether results are robust to other specifications (Elhorst 2010a). Therefore, the applied models are also tested with an inverse distance weights matrix.[11]

The time FE estimation are tested for spatial error and spatial lag dependence with Lagrange Multiplier tests (LM error and LM lag) together with their robust

[11] Plots of neighbourhood structures and the definition of the inverse distance matrix are presented in the Appendix A.

versions (Anselin et al. 1996).[12] Subsequently, the model is extended to incorporate these two types of spatial dependence. The first specification is the spatial lag model, where the dependent variable in a region i is affected by dependent variables in neighbouring regions j (spatial autoregressive model, SAR). The equation of the SAR including time FE takes the form (a SAR regional FE effects includes μ instead):

$$
\begin{gathered}
Y = \lambda(I_T \otimes W_N)Y + X\beta + \eta + \varepsilon \\
\varepsilon \sim N(0, \sigma^2 I_n)
\end{gathered}
\tag{4}
$$

Subscripts i and t are dropped in view of readability. Since a spatial panel is present, W_N is extended with an identity matrix I_T of dimension T. $\otimes$ denotes the Kronecker product. λ is the spatial autoregressive parameter, which measures the effect of spatial lag in the dependent variable.

The second type of spatial dependence implies that error terms across spatial units are correlated (spatial error model, SEM). This indicates unobserved or omitted variables that result in similar decisions in adjacent regions. The SEM time FE panel model can be represented as follows:

$$
\begin{gathered}
Y = X\beta + \eta + u \\
u = \rho(I_T \otimes W_N)u + \varepsilon \\
\varepsilon \sim N(0, \sigma^2 I_n)
\end{gathered}
\tag{5}
$$

u denotes a vector of spatially autocorrelated error terms, with the spatial autocorrelation parameter ρ. It measures the effect of spatial error dependence.

[12] Tests for a missing spatially lagged dependent variable (LM lag) test that $\lambda = 0$; tests for spatial autocorrelation of the error (LM error) test whether $\rho = 0$. RLM error tests for error dependence in the possible presence of a missing lagged dependent variable. RLM lag tests for a missing spatial lagged dependent variable in the possible presence of spatial error dependence.

4 Data description and variable specification

4.1 Solar thermal data

ST data is collected from an online platform called "Solaratlas" (BSW 2017). It provides information on ST installations, which received a MAP-grant. The platform offers data starting from the year 2001 and contains NUTS3 level sums of installations as well as collector area. Installations are distinguished according to collector type (flat-plate-collector, tube-collector, and air-collector), sectors (i.e. private households, trade and commerce, industry etc.) and application (space heating, water heating, process heat). Further, total investment costs and granted subsidies are available. Investment costs include components, assembly as well as installation expenses. Regrettably, it is not possible to distinguish between ST installations of property owners or tenants. Also, data does not separate installations in existing or new buildings. Hence, no separate estimations can be made, yet the impact of both factors is captured by including them as independent variables.

Annual installed combi-systems of all collector types in private households are specified as the dependent variable in this study. After cleaning the data, a total number of 487,110 systems with a collector area of 6.1 million m^2 remains.[13] Yearly installations are normalized to the number of households, so the dependent variable represents the diffusion rate of ST systems within a region. The installation rate is preferred to a simple counting variable as the number of households varies considerably across NUTS3 regions. Dividing by the number of households controls for this variation.[14] Further, the explanatory variables are normalized to households to achieve a coherent data basis for the econometric analysis. The number of households in a region is only available for the

[13] Some installations are not clearly allocated to a NUTS3 region (below 1% of total installations) and not considered.

[14] For the normalisation, the number of households is preferred over other regional characteristics. Some studies restrict their sample to homeowners, reflecting the concept that only owners are actually able to choose the RHS. Others also include renters. It can be argued that unobserved factors influencing the tenure chosen also influence the selection of RHS and accordingly both household types need to be included (Braun 2010). When a household seeks to rent, the available heating type can be supposed to influence the decision. It is plausible that the renter has only limited influence on the RHS decision of the landlord in the short term. In a longer term perspective, one can argue that the sum of the households' or renters' preferences will probably also influence decisions of building owners (Bauermann 2015). In that sense, a household not only actively decides to rent a particular home, but also consciously decides on the RHS attached to that unit (Braun 2010).

cross-section of 2011, the year of the last German census. It is assumed to be constant over time for the normalization of the variables.

The spatial pattern of households' ST uptake shows a North-South gradient and a divide between East and West Germany, with lower levels in the east (Figure 3). Cities also show a rather low adoption, presumably related to the higher number of households living in multi-storey dwellings. Clustering in southern Germany, (e.g. in Bavaria) is visible and increasing over time. ST systems have a relatively low penetration rate, with a maximum of 7% of households using ST combi systems in a region by the end of 2015.

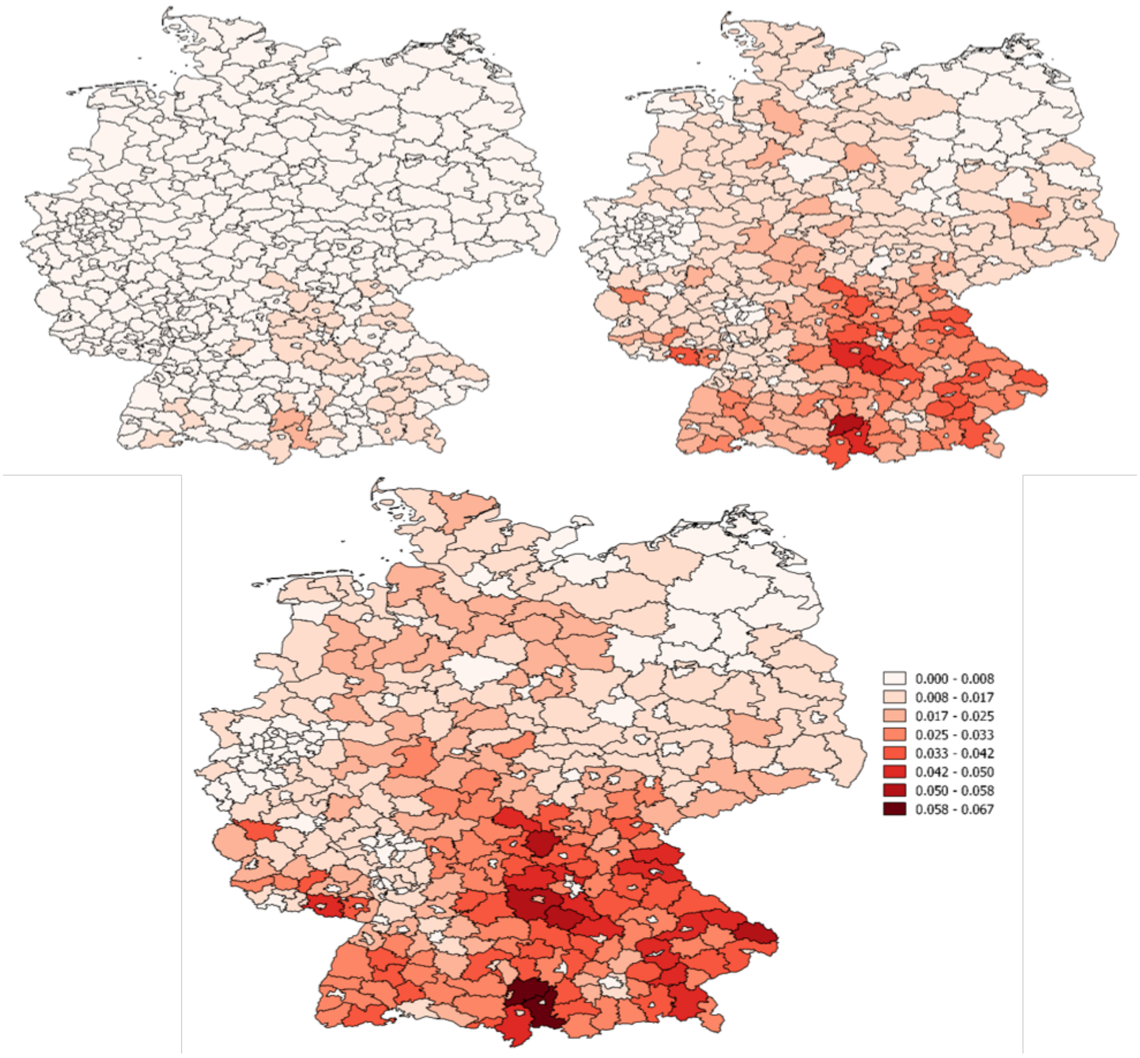

Figure 3 Regional distribution of household solar thermal Combi-systems in the years 2005, 2010 and 2015; Own illustration with data from BSW (2017)

4.2 Investment profitability index

A major barrier for a wider adoption of the ST technology are higher upfront costs in comparison with other RHS (Solar Heating & Cooling Program 2018). Overall, heating energy cost savings may recoup investment expensed, making ST systems a profitable investment – yet this depends on a number of factors. First, financial viability depends on upfront costs, the main heating energy source, energy prices and interest rates. Second, it depends on the usable energy output of the ST system, which in turn is subject to several factors inter alia heating demand, outdoor temperatures, collector area and storage size. A detailed profitability analysis of individual ST installations is not the focus of this study. Yet, the impact of changing energy prices and system costs over time and cross-sectional variation of solar radiation on ST adoption is to be captured in a consistent way.

The profitability of ST systems is modelled based on the following approach: In technical ST literature, a factor q_{sol} is defined as the usable solar net-energy amount in kWh per m^2 collector area in a year (Schabbach and Leibbrandt 2014). Heating losses of the collector circulation and pipe system are thereby already deducted. q_{sol} depends on individual characteristics including climatic factors (e.g. outdoor temperature, solar radiation), building characteristics (e.g. roof inclination, orientation, shadowing), and household behaviour (e.g. consumption profile, heating temperature). ST system features are furthermore important: inclination and orientation of collectors, collector size, storage size and system control (e.g. starting and stopping temperatures). Besides q_{sol}, a factor f_{sav} is used to capture the ratio between fossil energy consumption before and after the installation of a ST system.[15] q_{sol} and f_{sav} can be determined by simulations or laboratory and field measurements (Corradini et al. 2014). Schabbach and Leibbrandt (2014) use simulations to determine q_{sol} for combi-systems in Germany. The authors obtain annual averages between 250 kWh/m^{2}a and 400 kWh/m^{2}a. For f_{sav} they report values between 19% and 46.4%, depending on the collector size. Based also on simulations, Drück and Müller-Steinhagen (2004) obtain similar values. Thür et al. (2011) measure 10 combi-

[15] The definition postulates, that both installations use the same conventional energy source, provide the same heating energy and thermal comfort. Definition of EN 12977-2: $f_{sav} = \frac{(Q_{conv} - Q_{aux})}{Q_{conv}}$ with $Q_{aux} = \frac{Q_{aux,net}}{\eta_{aux}}$ and $Q_{conv} = (Q_d + Q_{l,conv})/\eta_{conv}$; Q_{conv}: Energy demand of a fossil heating system without solar support; Q_{aux}: Energy demand of a fossil heating system with solar thermal support. Q_d: Heat demand; $Q_{l,conv}$: Storage losses of conventional heating system.

systems in Austria and get q_{sol} values between 274 kWh/m^{2}a and 428 kWh/m^{2}a with an average of 322 kWh/m^{2}a. This leads to fossil energy savings between 21% and 30%. Jordan and Vajen (2001) arrive at similar results. Tjaden et al. (2013) present savings between 5% and 28% based on simulations for German single-family houses, with the numbers depending on the collector area and thermal storage volume. f_{sav} increases from 15% up to 50% with better insulation levels. Corradini et al. (2014) simulate different single-family houses in Germany and get results for f_{sav} between 15% and 35% for combi-systems.

Holding all other things constant (ceteris paribus), higher global radiation entails more usable solar energy, a higher q_{sol}(Tjaden et al. 2013) . In the present study, this effect is captured and differences in solar radiation between NUTS3 regions are modelled. The usable thermal energy of a solar system in region i is defined as $q_{sol,i}$ $[kWh/m^2a]$ and represents the solar generated heat, which directly replaces thermal energy generation by the conventional heating system. It is calculated by multiplying the annual global solar radiation in a region rad_i with a reference usable energy $q_{sol,ref}$, divided by the reference radiation rad_{ref}:

$$q_{sol,i} = \frac{rad_i}{rad_{ref}} \cdot q_{sol,ref} \tag{6}$$

In the present study, the reference usable solar heat $q_{sol,ref}$ is set to 300 kWh/m^{2}a and rad_{ref} is set to 1091 kWh/m^{2}a, the mean annual global radiation in our dataset.[16] The derived $q_{sol,i}$ is in the range of 266 to 336 kWh/m^{2}a, which is in line with the previously mentioned results of others and indicates realistic assumptions.

In line with a German standard for the calculation of economic efficiency of building installations (VDI 2067), profitability of ST systems is assessed with the annuity $A_{i,t}$ (Eq. 7). It represent the potential profitability in EUR/m^2 of a solar system in year t and region i. The term “profitability index” is used in this study. To calculate substituted fuel consumption (gas or oil) and finally avoided energy expenses (revenues), $q_{sol,i}$ is divided by the efficiency of the conventional heating system η_{conv} and multiplied

[16] $q_{sol,ref}$ values are varied in a sensitivity analysis leading to similar regression results. rad_{ref} of 1091 kWh/m^{2}a corresponds to the global radiation of Würzburg. Climate factors of Würzburg are commonly used as reference values for heating system sizing in Germany (cf. Schabbach and Leibbrandt 2014,Corradini 2013.).

with the energy price p_t in year t. η_{conv} is set to 75% (EN 12977-2). Revenues are multiplied with the price dynamic cash value factor b_t and the annuity factor a_t to account for annual changes in expected energy prices and interest rate effects.[17] Investment expenditures (EUR/m^2) result from average investment costs IC_t minus subsidies Sub_t and are annualized. Operation-related costs are calculated by multiplying investment costs with effort factors for servicing and inspection f_{W+Insp} and repair f_{Inst} (VDI 2067). Finally, annual capital and operation expenditures are subtracted from energy cost savings:

$$A_{i,t} = \left(\frac{q_{sol,i}}{\eta_{conv}} \cdot p_{i,t}\right) \cdot a_t \cdot b_t - (IC_t - Sub_t) \cdot a_t - IC_t \cdot \left(f_{Inst} + f_{W+Insp}\right) \tag{7}$$

Figure 4 shows average values of the profitability index. It is obvious that investment costs (including MAP-grants) do not decrease over time. Further, price volatility of gas and oil including different price expectations leads to varying cost savings. The approximation of profitability in this study indicates that investments can only be recouped in the years 2008, 2012, 2013 and 2014. This is in line with other studies stating that investments in ST systems are hardly viable (Corradini et al. 2014).

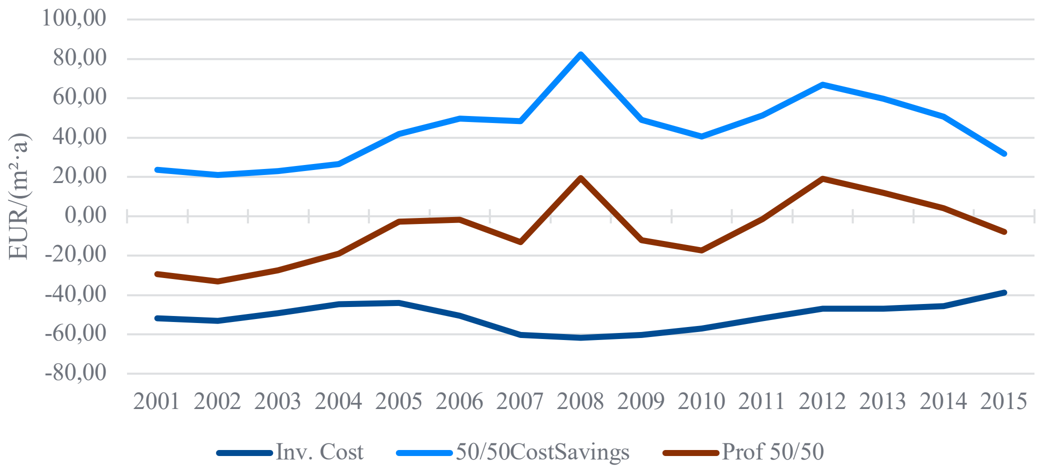

Figure 4 Average solar thermal system costs, generated energy cost savings and profitability index between 2001 and 2015

[17] Price dynamic cash value factor $b_t = \frac{1-\left(\frac{1+j_t}{1+i_t}\right)^T}{i_t - j_t}$ and annuity factor $a_t = \frac{(1+i_t)-1}{1-(1+i_t)^{-T}}$ both from VDI 2067. T: Lifetime, set to 20 years as supposed by VDI 2067 for flat plate collectors. j_t: expected energy price changes [%], i_t: interest rate [%]. Assumptions for annual interest, energy prices and expected price increases can be found in Appendix A.

For the illustrated profitability index (used in the base estimations), the average of consumer gas and oil prices is used.[18] As gas is the dominant heating technology in Germany (BMWI 2017b), gas prices are appropriate to calculate avoided energy expenses. However, especially single- and double family houses are equipped with oil-heating, making oil prices a similarly relevant indicator. Regional gas prices are obtained from a database which gathers prices of main gas providers on a zip code level (Michael Houben 2016).[19] Oil prices are obtained from a provider for petroleum products but are only available on state level (mobene 2018).[20] Not only present but also expected future energy prices are a driver for RHS replacements (Achtnicht and Madlener 2014). Hence, annual expected price increases j_t are included in the profitability calculation. j_t are based on the historical consumer price development of the last ten years. As heating systems are a long term investment with an expected lifetime of 20 years, a price development of a rather long time period seems appropriate. However, more recent price developments (e.g. last three years) may be more present to consumers and have a greater impact on the decision. Thus, other time-frames of historical price developments are used to describe future price expectations and tested in the sensitivity analysis.

4.3 Explanatory variables

Besides economic incentives, different influences determining ST adoption are controlled for. Depending on the data source, a unique five-digit combination for municipalities (German term: Amtlicher Gemeindeschlüssel) or the postal code is used to match data to NUTS3 regions. As administrative district boundaries in Germany were redesigned between 2001 and 2015, the correct allocation of data is quite challenging. The NUTS3 version of 2013 is used and data are harmonized. However, while installation data are available in panel form, some of the characteristics are only available at NUTS3 level as cross-sectional data for the year 2011, the year of the last census in Germany (cf. Table 1). These include household size, owner-occupied houses, single-family houses and detached houses (Zensus 2011). These NUTS3 characteristics are included in the analysis as

[18] Results using only gas, only oil prices or constant price increases and interest rates are also calculated (cf. section 5.3).
[19] Regional prices include data from 2004 to 2015 for around 80% of NUTS3 regions. Missing NUTS3 data is approximated by state means. For the years 2001-2003, regional distribution factors of the years 2005-2008 are used and weighted with BMWI 2017b prices.
[20] A regional index for states is calculated based on oil prices between 2015 and 2017 and fitted to meet annual BMWI 2017b consumer energy prices for 2001 to 2015.

indicators for settlement structure. In addition, county area normalized to the number of households (the inverse of household density) is used to control for the effect of population density. To capture financial capability of a region, the share of welfare recipients is included, yet, due to data availability, only as a cross section of the year 2015 (Destatis 2018b). The share of social beneficiaries entails households who receive unemployment as well as other social benefits. As climatic characteristics, data on solar radiation and temperatures are retrieved from the German Weather Service (DWD 2015). They are almost time-invariant and average values of historical climate data are used when planning a ST system. Hence, long term averages are used in this study. Solar radiation represents the sum of global solar irradiation at the centre of a NUTS3 region. Heating Degree Days (HDD) are used to control for colder climates and extended heating needs. In this study they are defined as the sum of differences between 20° Celsius and the daily average outside temperature, when the daily average outside temperature is below 15° Celsius. Using these time-invariant NUTS3 characteristics entails the assumption that the factors are considered constant over the examined timeframe (2001-2015). It also implies that they are included in the regional FE and cannot be estimated in regional FE estimations. However, in time FE models, estimations allow insights into these (time-invariant) NUTS3 specific characteristics.

As household characteristics available in panel data form, average disposable household income (Destatis 2017) and share of green voters for the 2002, 2005, 2009 and 2013 federal election is included (Bundeswahlleiter 2016). Following the approach of previous studies (Schaffer and Brun 2015; Dharshing 2017), the share of Green voters (second votes for the Green party) is a proxy for environmental attitude. As a panel data variable for settlement structure, yearly residential constructions are considered (Destatis 2018a).

At last, to control for the effect of the EEWärmeG, which stopped subsidies for ST systems in new buildings by 2010, a EEWärmeG-dummy is introduced (as a time FE). As a sensitivity, only the period from 2001 to 2009 is examined to test whether the observed predictor variables have different impacts. As described in Sec. 3, potential spatial dependence might explain ST adoption. As a measure for spatial spillover of ST systems, the annual ST installations in adjacent regions are used. Table 1 provides descriptive statistics of the used variables.

Table 1 Descriptive statistics

Variable	Dimension (N x T)	Description	Mean	Std. Dev.	Min.	Max.	VIF[21]
ST systems	15 x 402	Annual Adoption rate [-]	0.0011	0.0013	0.0000	0.0106	
Profitability Index	15 x 402	Annuity [EUR/m^2]	-7.37	16.37	-36.48	34.27	1.50
System costs	15 x 1	Installation costs [EUR/m^2]	871.92	93.65	714.20	992.25	
Subsidies	15 x 1	Grants [EUR/m^2]	130.62	27.27	89.80	199.38	
Energy price	15 x 402	Consumer price [EURCent/kWh]	6.16	1.34	3.68	9.17	
Price expectation	15 x 1	10 year price development [%]	5.67	2.12	1.92	10.30	
Interest rate	15 x 1	10-year German bonds [%]	3.25	1.34	0.53	4.98	
Solar radiation	1 x 402	Global radiation [kWh/m^{2}a]	1,091	57	970	1,222	
New buildings	15 x 402	Annual built res. buildings/household	0.0037	0.0024	0.0000	0.0225	2.34
Income	15 x 402	Disposable house-hold income [EUR]	41,529	7,436	23,529	86,212	2.71
Green voters	4 x 402	Green party second votes [%]	0.081	0.035	0.026	0.287	1.63
Household size	1 x 402	Household members [-]	2.20	0.19	1.77	2.74	9.29
Owner-occupied	1 x 402	Owner-occupied dwellings/household	0.519	0.144	0.128	0.769	14.44
Single family houses	1 x 402	Single family houses/household	0.388	0.152	0.085	0.753	8.29
Detached houses	1 x 402	Detached family houses/household	0.626	0.208	0.122	0.974	5.64
HDD	1 x 402	Measure for heating needs [-]	3,546	291	2,916	4,508	1.77
Inverse density	1 x 402	County area [m^2]/household	13,077	10,763	424	57,929	2.40
Welfare recipients	1 x 402	Social welfare recipients/household	0.171	0.075	0.038	0.423	1.59
PV systems	15 x 402	Annual adoption rate [-]	0.0020	0.0021	0.0000	0.0157	2.02

[21] The variance inflation factor (VIF) is based on the square of the multiple correlation coefficients resulting from regressing a predictor variable against all other predictor variables. A VIF greater than 10 signals a collinearity problem in the model.

5 Empirical estimation and results

5.1 Static and dynamic panel model results

As a benchmark, a pooled OLS regression is estimated (cf. Table 2, all variables are standardized to improve comparability of coefficients). Collinearity causes instability in parameter estimation and must be avoided. It is tested using the variance inflation factor (VIF) (cf. Table 1). As household size, single-family houses, detached houses and owner-occupied houses are highly correlated only one variable is used. As household size entails the highest explanatory power, the corresponding results are shown. To investigate the null hypothesis that regional and time FE are jointly insignificant, Breusch-Pagan type Lagrange-Multiplier tests are performed. The hypothesis of insignificance of regional FE is rejected. Likewise, the insignificance of time FE is rejected and the influence of time FE seems to be bigger.[22] The used variables seem to account for a larger share of regional characteristics than year-specific information.[23] This indicates that given the used dataset it is more important to include time FE than regional FE. Also, a practical aspect supports the use of time FE: Since MAP supported ST installations are considered, annual changes or announcements regarding the MAP funding rates may lead to time FE. A regional, a time and a two-way FE model are yet specified to compare results (cf. Table 2). As explained earlier, the RE model is not appropriate in this study. Yet, it is estimated and a Hausman specification test is performed to check that FE models provide a better fit to the data than the RE model.

In panel estimations, different R^2 can be defined. The shown within R^2 (cf. Table 2) represents the proportion of the within variance in ST uptake explained by the independent variables for a given FE, e.g. a NUTS3 region.[24] It can be used to compare the model fit of two regional FE models, but is inappropriate to compare the fit of different model types (e.g. a regional and a time FE model). The overall R^2 describes the proportion of the total variance in the dependent variable that is predictable from the independent

[22] Test regional FE: chisq = 1,806, df = 1, p<0.001; test for time FE: chisq = 76506, df = 1, p-value<0.001.
[23] By regressing the resulting 402 regional FE of the regional FE estimation with the variables HDD, household size, inverse population density and benefits, an R^2 of 70% is obtained.
[24] Here, the total sum of squares (TSS) for the regional FE model is defined as $TSS = \sum_{i=1}^{N}\sum_{t=1}^{T}(y_{it} - \bar{y}_i)^2$ with $\bar{y}_i = \frac{1}{T}\sum_{t=1}^{T} y_{i,t}$. For the time FE TSS is calculated with $\bar{y}_t = \frac{1}{N}\sum_{i=1}^{N} y_{i,t}$. R^2 is then defined as usual: $1 - \frac{RSS}{TSS}$ with RSS being the residual sum of squares.

variables and the fixed effects and can be used to compare different model types.[25] In addition, a between R^2 is computed by regressing the means of the ST uptake in a NUTS3 region (over the 15 year period) on the means of the individual independent variables. It amounts to 0.79, indicating that regional differences in ST uptake are explained quite well with the used variables.

Table 2 Estimation results of static panel models

	OLS (pooled)	Regional FE	Time FE	Two-way FE
Profitability index	0.4359***	0.4130***	0.9144***	0.7507***
	(0.0098)	(0.0095)	(0.0405)	(0.0617)
New buildings	-0.2727***	-0.3606***	-0.1425***	-0.1581***
	(0.0110)	(0.0145)	(0.0100)	(0.0136)
Income	-0.1101***	-0.1112***	-0.0685***	-0.1572***
	(0.0148)	(0.0265)	(0.0132)	(0.0291)
Green	0.0813***	0.4182***	0.0040	-0.0226
	(0.0102)	(0.0225)	(0.0091)	(0.0281)
EEWärmeG	-0.4154***	-0.4754***		
	(0.0104)	(0.0119)		
Household size	0.5021***		0.4354***	
	(0.0169)		(0.0149)	
Heating degree days	0.1637***		0.1642***	
	(0.0106)		(0.0089)	
Inverse population density	0.0878***		0.0654***	
	(0.0118)		(0.0100)	
Benefits	-0.2137***		-0.1411***	
	(0.0142)		(0.0134)	
Within R^2	0.5844	0.4763	0.5545	0.0473
Overall R^2	0.5844	0.7103	0.7085	0.8020
AIC	11836.14	10457.27	9727.96	8191.51
BIC	11909.89	13192.71	9888.87	11020.81

Note: the values in parentheses are standard errors
*** Significance level at 1%.
** Significance level at 5%
* Significance level at 10%

The ST uptake within a region is likely to depend on the previous adoptions in this region (e.g. because of peer effects), which may lead to autocorrelation in the static panel models. In fact, Wooldridge's test for serial correlation in FE panels (Wooldridge 2002) points to serial correlation in the estimated FE specifications which might bias results. One remedy is to include a lagged dependent variable, leading to a dynamic model

[25] Here, TSS is defined as $TSS = \sum_{i=1}^{N}\sum_{t=1}^{T}(y_{it} - \bar{y})^2$ with $\bar{y} = \frac{1}{N \cdot T}\sum_{i=1}^{N}\sum_{t=1}^{T} y_{i,t}$. Wooldridge terms the within R^2 “centred” and the overall R^2 “uncentred” (Wooldridge 2002.)

(cf. section 3). Hence, we include solar thermal uptake of the previous year as a predictor for ST uptake in a region (cf. Table 3). However, introducing a lagged dependent variable takes out a lot of variance and reduces the impact of other explanatory variables. Also, results must be regarded in face of potential "Nickell bias" as our panel is rather short (Nickell 1981). Comparing the static(cf. Table 2) and the dynamic estimation results (cf. Table 3), the coefficients' signs do not change, indicating robust estimation results when introducing the lagged dependent variable. Yet, as expected, coefficients are generally smaller. Notably, the introduction of time lagged ST uptake enhances the model fit of each FE specification, indicated by higher within and overall R^2 as well as by the Akaike information criterion (AIC) and the Bayesian information criterion (BIC). So even model specifications including time FE are further enhanced by an autocorrelation term which indicates the relevance of a time-lagged imitation or peer-group effect. Wooldridge's tests further show a reduced serial correlation, as expected.

Table 3 Estimation results of dynamic panel models

	OLS (pooled)	Regional FE	Time FE	Two-way FE
Profitability index	0.4370***	0.4369***	0.4789***	0.6295***
	(0.0082)	(0.0088)	(0.0348)	(0.0579)
New buildings	-0.1039***	-0.2112***	-0.0610***	-0.0987***
	(0.0097)	(0.0144)	(0.0085)	(0.0129)
Income	-0.0727***	-0.1642***	-0.0455***	-0.1723***
	(0.0123)	(0.0247)	(0.0110)	(0.0272)
Green	0.0229***	0.1796***	-0.0009	-0.0589**
	(0.0085)	(0.0224)	(0.0076)	(0.0263)
EEWärmeG	-0.3860***	-0.3988***		
	(0.0086)	(0.0114)		
Household size	0.2632***		0.2101***	
	(0.0148)		(0.0132)	
Heating degree days	0.0864***		0.0761***	
	(0.0089)		(0.0076)	
Inverse population density	0.0307***		0.0244***	
	(0.0098)		(0.0083)	
Benefits	-0.0886***		-0.0623***	
	(0.0120)		(0.0113)	
Lag of ST uptake (tau)	0.4819***	0.3274***	0.5418***	0.3431***
	(0.0093)	(0.0111)	(0.0106)	(0.0122)
Within R^2	0.7127	0.5469	0.6900	0.1648
Overall R^2	0.7127	0.7493	0.7970	0.8264
AIC	9614.96	9587.76	7544.65	7399.52
BIC	9695.42	12329.90	7712.27	10235.53

Note: the values in parentheses are standard errors
*** Significance level at 1%.
** Significance level at 5%
* Significance level at 10%

Looking at the results of the different FE specification, the following aspects are worth noting. Overall R^2 and AIC point out that the two-way FE performs best, as it includes regional and time FE. However, the impact of several time invariant predictor variables cannot be evaluated, as they are implicitly included in the individual intercepts u_i (cf. section 3). It is hence not possible to derive implications on which regional characteristics drive regional ST uptake. However, as these (time-variant) regional characteristics are of special interest in this study, the time FE model is favoured. Also, the model fit of the time FE comes close to the fit of the two-way FE in terms of overall R^2 and AIC. If the number of estimated parameters (including FE) is strongly penalized as done in the BIC, the time FE even renders the best result. Subsequently, the focus of the analysis is hence on the time FE model results and only selected findings of other specifications are used to complement the analysis. It is worth noting that the estimated coefficients have the same sign and significance in all (static and) dynamic FE specifications, except the coefficient for Green voters (addressed in the next paragraph).

The effect of previous ST installations in a region is found to be positive in all dynamic specifications. Accordingly, adoption in one region predicts an increased likelihood of similar behaviour in this region. Recurrent visual perception or social contagion might explain the positive time lag as potential adopters follow decisions by peers. The effect of the profitability index conforms with expectations, as the coefficient is positive and indicative of a response of ST adoption to economic viability. Notably, high energy prices and price expectations seem to drive the installation of ST systems. Also higher solar radiation in a region, which implies larger solar yields and superior annuities favours ST uptake. The negative impact of new constructions on ST uptake indicates that the uptake of ST systems is less likely in NUTS3 regions with higher construction rates.[26] Also, the regional FE result implies that within a region, ST uptake is lower in years with high construction rates. This could be a result of financial constraints, which may especially prevail when constructing a house, making households choose comparatively lower priced heating systems. The official MAP evaluation covering the period 2007-2008, before the EEWärmeG was enacted, states that the building stock is accountable for 90% of MAP supported household ST installations (Nast et al. 2009). Also considering this finding, the estimation results show ST systems are easily applied in the building stock and adoption does not depend on new construction.

Household income has a negative impact on residential ST installations, showing that above average household income is no precondition for the adoption of ST systems. Based on the rationale that wealthier areas are more likely to adopt ST systems, this finding is surprising. However, the share of welfare recipients in a region affects negatively ST uptake. Hence, the share of welfare recipients seems to be a suitable negative proxy for wealth and financial capability in a region. It might not be income but rather wealth i.e. accumulated capital, which contributes to different regional ST diffusion levels.

[26] Although the effect of the EEWärmeG is captured in the time FE (or in a dummy-variable for the years 2010-2015 in the regional FE model), the terminated funding of ST systems in new constructions may contribute to this finding.

No impact of Green voters is detected in the time FE model, implying that differences in Green votership do not explain varying ST adoption between regions. Yet, the result of the regional FE model indicates that the development of Green vote shares within a region positively affects ST uptake in a region over time, whereas in the two-way FE model the effect is negative. Hence, the effect of Green voters stays ambiguous.

Next to profitability, especially household size qualifies to explain differences in regional ST adoption levels. It implies that larger households are more inclined to use ST systems. Water and space heating needs increase with the number of persons in a household, which usually increases utilization and efficiency of a ST system leading to higher profitability. As household size is positively correlated with detached houses, single-family houses and owner-occupied housing, the impact of these variables is also implicitly included in the finding. By replacing household size with these variables respectively, estimations show that all three have a positive impact on regional ST uptake.[27] Thus, households living in their own single-family house have a higher propensity to adopt ST systems. Further, results show that less densely populated regions favour ST uptake. Solar collectors need open areas that are clear of obstructions from sunlight; such areas may be more prevalent in less densely populated regions (with higher shares of detached houses and on average larger floor and roof area per dwelling). The coefficient of HDD is positive, which indicates a broader use of ST systems in regions with above average heating demand. This again may be a result of higher utilization of the ST system which positively influences economic viability.

The regional FE estimation results confirm that the EEWärmeG reduces MAP subsidised ST installations (cf. Figure 2). First, this is a direct result of terminating grants for combi-systems in existing buildings starting 2010. Second, the announcement of the EEWärmeG with the prospect of reduced subsidies, could have shifted ST adoptions to the years before the enactment (2008 and 2009), as households wanted to benefit from the higher grants. In addition, uncertain funding conditions mainly due to the temporary

[27] Results are provided upon request. When considering all four variables in a single model (which should not be done because of collinearity), the effect of detached houses, single family houses and owner-occupied houses turns insignificant, while the coefficient of household size (and inverse population density) stays positive and significant. Therefore this variable is retained in the final specification.

suspension in of MAP-grants in 2010 may have led to lacking trust in the MAP, roughly at the same time of the EEWärmeG enactment.

5.2 Spatial model results

If spatial dependence exists in a model, it may suffer from misspecification. To test for spatial correlation, Lagrange Multiplier (LM) tests are carried out for the time FE model (cf. Table 4). In the classical LM tests, the hypothesis of no spatially lagged dependent variable and the hypothesis of no spatially autocorrelated error term are strongly rejected. It seems that although accounting for time FE and a time lag in ST adoptions, spatial spillover in ST uptake is present. Examining the LM tests' robust counterparts, the hypothesis of no autocorrelated error is still rejected. Yet, in presence of a spatially autocorrelated error, no spatially lagged dependent variable is present. Nevertheless, both the SEM and SAR model are estimated.

Table 4 Tests for spatial dependence in the time FE model

Tests	
LM_{lag}	19.44^{***}
LM_{error}	25.21^{***}
rLM_{lag}	2.08
rLM_{error}	7.86^{***}

*** Significance level at 1%

Considering the coefficients of the SAR and SEM with time FE, the detected signs of the predictor variables in the conventional time FE model are (cf. Table 5). A difference to the conventional FE model are slightly different coefficient values in the spatial models. Smaller coefficients indicate that the direct influence of a variable is less pronounced, and that their impact is partly attributable to spatial association.

The SAR model shows the effect of spatial lag in the dependent variable (number of ST systems). The positive and statistically significant estimate of the spatial autoregressive parameter λ reveals a positive correlation between the uptakes of solar collectors in neighbouring regions. According to this model specification, adoption levels in one region may serve to predict an increased likelihood of similar behaviours in neighbouring regions, implying that levels of ST uptake tend to spill over county borders. Recurrent visual perception, intensified social interactions and peer-effects might explain spatial lag as potential adopters follow decisions by actors in the proximity. The positive and statistically significant estimate of the autocorrelation parameter ρ in the SEM indicates spatial dependence in the residuals. According to this model, similar unobserved characteristics hence result in similar decisions in neighbouring regions. A local concentration of craft skills, solar initiatives, local ST supplier activities or advertising campaigns might lead to an accelerated ST diffusion in a region and its surroundings.

The spatial panel models confirm the hypothesis that residential ST systems form geographical clusters in certain regions. Both, the SAR and SEM specification improve the model fit and therefore both types of spatial spillover may be acknowledged when modelling ST uptake. Yet, by taking one type of spatial dependence into account, the explanatory power of the other is reduced drastically. Hence, it is advisable to consider either spatial lag or spatial error dependence in a specification. Addressing regional ST diffusion, overall R^2, AIC and BIC point to the SEM as the preferable specification. This indicates that although spatial lag is present, spatial dependence in the residuals is more influential. Yet, on the basis of the available dataset, which relies on rather large spatial entities, a clear distinction between the two spillover types is challenging and requires further research.

Table 5 Estimation results with spatial interactions for dynamic time FE models

	Time FE	SAR Time FE	SEM Time FE
Profitability Index	0.4789***	0.1627***	0.2921***
	(0.0348)	(0.0333)	(0.0407)
New buildings	-0.0610***	-0.0528***	-0.035***
	(0.0085)	(0.0078)	(0.0084)
Income	-0.0455***	-0.0228**	-0.0309***
	(0.0110)	(0.0102)	(0.0107)
Green	-0.0009	-0.0043	0.0106
	(0.0076)	(0.0070)	(0.0080)
Household size	0.2101***	0.2016***	0.1743***
	(0.0132)	(0.0136)	(0.0130)
Heating degree days	0.0761***	0.0210***	0.0554***
	(0.0076)	(0.0072)	(0.0084)
Inverse population density	0.0244***	0.0562***	0.0442***
	(0.0083)	(0.0090)	(0.0091)
Benefits	-0.0623***	-0.0156	-0.0442***
	(0.0113)	(0.0106)	(0.0107)
Lag of ST uptake (τ)	0.5418***	0.4835***	0.5817***
	(0.0106)	(0.0103)	(0.0104)
Spatial lag (λ)		0.2927***	
		(0.0106)	
Spatial error (ρ)			0.5217***
			(0.0139)
Overall R^2	0.7970	0.8266	0.8528
AIC	7544.65	6596.56	5608.40
BIC	7712.27	6770.88	5782.72

Note: the values in parentheses are standard errors
*** Significance level at 1%.
** Significance level at 5%
* Significance level at 10%

5.3 Sensitivity and robustness results

The aim of this study is not to identify a best model specification but to derive resilient implications regarding the uptake of ST combi-systems building on several estimations. To test whether results are robust against input data variations a sensitivity analysis is performed. First, a constant energy price increase of 3% is employed, instead of expectations formed based on the development over the previous ten years. Also, a sensitivity with a price expectation based on the last three years is tested. The used interest rate is based on the interest of 10-year government securities. As a sensitivity, a constant interest rate of 3% is used throughout. In the base model, the average of oil and gas prices is employed, as these energy sources have the largest shares in the residential building stock. As a sensitivity, gas prices and oil prices are considered separately. The majority of coefficient estimates do not change for the performed input data variations, implying robust results.[28]

Similar to ST collectors, PV panels can also be roof mounted and are a possible competitor for roof area. However, visibility of PV panels in NUTS3 regions may also induce social imitation – including also installations of ST systems. Although ST and PV are very different technologies, they may look similar in a passers-by perspective. Thus, an estimation including panel data on PV installations up to 10 kW as a predictor is performed.[29] Results show that PV installations and ST systems positively correlate in all model specifications (cf. Appendix B, Tables 7-10). This indicates that PV uptake does not negatively affect ST adoption. Rather, imitative purchase behaviour could be present. By the year 2015, the two solar technologies hence do not seem to compete for roof space or possible adopters.

Studies suggest that households do not conduct profitability calculations when deciding on energy saving measures (e.g. Zundel and Stieß 2011; Aravena et al. 2016). They exclude certain aspects and are possibly not fully aware of all costs during the purchase stage (Michelsen and Madlener 2012). To test, how the defined profitability index performs, the regression is also done using single variables for system costs (investment costs minus subsidies), solar radiation, interest rate, energy prices and price expectations. Thereby, effects can be singled out and argued whether the decision rather follows a business investment calculus or is driven by one or more single parameters. Results are referred to as the consumer model (cf. Appendix B, Tables 7-10). The estimated coefficients on energy prices, price expectations and solar radiation are positive and indicative of a response to economic viability. ST installations are more likely in regions with higher solar radiation and times with higher prices and price expectations. The impact of investment cost is negative, whereas the effect of subsidies is positive. Again, differences in profitability influence ST adoption. Interest rates seem to positively affect the decision to invest in ST systems, which is surprising from an economic

[28] Results are made available upon request.

[29] In addition, I only included PV system costs, which decreased drastically in the observed period and may have made PV preferable over ST systems for some households. However, PV costs are only available in the time-dimension whereas PV installations are available in panel form, including more information.

perspective. It indicates that households do not consider capital costs for ST investments, which increase with rising interest rate.

In addition, a focus is put on the period until 2009, to exclude the effect of the EEWärmeG and the consecutive changes in the MAP. Some variations regarding the income variable are observed. First, in regional FE models, the income variable turns positive, indicating that until 2009, ST adoptions and income within a region are positively correlated (cf. Appendix B, Table 9 and Table 10). In the time FE models, the income variable is insignificant, entailing no effect of income on different adoption levels between regions. Finally, a different weights matrix is applied (cf. Appendix A, Figure 5). Results are confirmed and seem robust against other NUTS3 neighbourhood structures.

6 Conclusion and Implications

Space heating accounts for a large fraction of the primary energy consumption and CO_2 emissions of residential buildings in Germany. Besides targeting the insulation of homes, renewable-based heating systems offer the potential to reduce conventional energy consumption and move towards a low-carbon building stock. Thus, understanding a broader set of determinants for households' heating system choice becomes increasingly important. This article studies drivers and barriers influencing the spatio-temporal diffusion of solar systems, using panel data, based on NUTS3-year combinations. Besides regional fixed effects and time fixed effects models, spatial panel models are estimated to capture regional clustering of ST adoption. The presented results might be exploited for future policy design or targeted marketing strategies. A few implications are derived here.

Estimation results indicate that ST uptake follows profitability causing differences in ST adoption rates between regions and over time. In particular, differing solar radiation levels and fossil fuel prices drive profitability. It implies that households’ adoption decision can be at least to some extent explained by economic considerations. Thus, policy instruments providing financial support and enhancing economic viability (like the MAP) effectively contribute to ST uptake. However, the lack of cost effectiveness of residential ST heating - even when subsidies are taken into account - is still a major limitation for technology adoption. Additional, price signals for conventional energy sources, e.g. induced by a CO_2-tax, improve economic viability of ST systems and are therefore a policy instrument likely to foster the diffusion of renewable heating systems. Also, the use of ST systems might increase if economies of scale and scope will result in substantial cost reductions, which are not accomplished to date.

A negative impact of new constructions on ST uptake is present in all estimated models. Other (renewable) RHS seem to be preferred and more (cost) attractive in new buildings. Notably, the finding indicates that ST systems are easily applied in the building stock, making it a suitable renewable technology for retrofit activities. Yet, if policy makers intend to increase the share of ST systems in new buildings, their installation needs to be more attractive, e.g. higher funding made available.

The results further show that larger households are more inclined to adopt ST systems, indicating a more efficient use of solar generated heat.[30] In addition, inverse population density increases the propensity to use solar heating. ST adopting households are likely to live in spacious, rural areas, with possibly higher shares of detached single-family houses and large (unshaded) roof space. Further, regional ST installations positively correlate with HDD, indicating that higher heating needs are advantageous for ST systems. The share of green voters does not qualify to explain regional ST adoption levels, as the coefficient is insignificant in the time FE models. Also, disposable household income does not foster ST uptake, as the coefficient shows a negative sign. Based on the rationale that wealthier areas are more likely to be structurally enabled to adopt ST systems, this finding is surprising. However, high shares of social beneficiaries decelerate the regional diffusion of ST system. It might hence not be income but rather wealth i.e. accumulated capital, which contributes to different regional ST diffusion levels. The share of welfare recipients may be the better indicator for wealth or financial capability of a region compared to household income. It implies that ST uptake is constrained in financially disadvantaged regions. If a more evenly distributed spatial diffusion of ST systems is intended, differential NUTS3 level subsidies could be introduced or financially weak regions could be specifically targeted with monetary incentives, which need to be higher than MAP-grants. Delegating the effective design and implementation of instruments to the federal states or counties can be a meaningful strategy to better suit

[30] Further, results suggest that households with ST systems are homeowners and live in detached single-family houses.

regional heterogeneity (Braun 2010). This is already done in Baden-Württemberg, where a state specific law was enacted in 2008.[31]

Besides the impact of the included predictor variables, it is shown that ST uptake follows an autoregressive process, since adoption rates in a region are positively influenced by past adoption decisions in this region. Recurrent visual perception or social contagion might induce potential adopters to follow decisions by actors nearby. As the adoption behaviour of others affects the use of solar heating, highly visible projects may promote diffusion effectively. Moreover, results show that these peer effects are not confined by NUTS3 borders, but are likely to spillover, indicated by spatial lag in ST adoption captured in the SAR model. Spatial model results point to spatial spillover between ST adoption levels in adjacent counties and confirm that residential ST forms local clusters in certain regions. Another and even more important reason for spatial dependence are unobserved spatially correlated effects, indicated by the SEM model. This might be e.g. a regional concentration of craft skills. The uptake of ST devices in an area likely means that neighbouring regions benefit from the technical installation expertise, leading to spillover across NUTS3 borders. Also, information dissemination activities in some regions (e.g. information campaigns, door-to-door energy advice) possibly lead to an accelerated ST diffusion in certain regions and its surroundings.

With the commencement of the EEWärmeG, (MAP subsidised) ST uptake drastically decreased, as funding for standard ST combi-systems in new buildings was discontinued and at the same time support for ST systems for water heating was generally stopped. A further major driver for decreasing ST uptake after 2009, which coincided with the EEWärmeG, may be the temporary suspension of MAP-grants in 2010. This disruption might also have reduced trust in the funding scheme and decreased acceptance. In this respect, it is recommendable to provide stable funding conditions, which was not the case for the MAP in the considered period. Yet, regulatory measures (like renewable use obligations established in the EEWärmeG) help to brake persisting behaviours (Michelsen and Madlener 2013) and increase the share of renewable heating technologies.

[31] Erneuerbare-Wärme-Gesetz (EWärmeG), of november 20th, 2008 (GBl. 19, p. 531), and revised march 17th, 2015 (GBl. 5, p. 151).

A balanced bundle of policy instruments should be established and adverse repercussions prevented.

The present study deepens the understanding on the regional distribution of domestic ST systems. Yet, limitations leave room for further investigations. The variables employed are not the only possible predictors of ST technology use. Studies identifying a richer set of household attributes and preferences and models employing other socio-demographic variables could improve results. Yet, sensitivity analyses show rather robust results regarding the employed variables. Further research is needed to disentangle the sources of peer-effects, spatial dependence and regional clustering. When examining spillover effects, NUTS3 regions are rather large to control for neighbourhood effects and spillover between households. Smaller units could be employed to allow for more specific interpretations. Also, other spatial models, like the spatial Durbin specification could be tested, which includes a spatial lag in the independent variables (Elhorst 2010a). Moreover, the investigated ST sample only covers installations that received a MAP-grant. Until 2009, the majority of ST installations is covered (cf. Figure 2). After that, only half of the installed ST systems received a grant. Extending the sample to all domestic ST installations might enhance results and allow for more general conclusions – yet data is likely to be not available. Alternatively, the study could also be extended to other renewable heating technologies supported under the MAP.

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Appendix A: Input data

There are different options to define the spatial weights matrix W based on concepts of contiguity and distance; or a combination of both (Anselin and Bera 1998). The used inverse-distance matrix is defined as:

$$w_{i,j} = \frac{1}{d_{i,j}};\ w_{i,j} = 0, if\ d_{i,j} > 65\ \text{km}$$

By convention, the diagonal elements of the weights matrix ($w_{i,i}$) are set to zero as no spatial unit is viewed as its own neighbour and row elements are standardized such that they sum to one. NUTS3 centres are used to calculate distances. As the effect of spatial units on the entity of interest is expected to decrease with distance and eventually vanish, a cut-off distance at 65 km is introduced. Thereby each region has at least one neighbour.

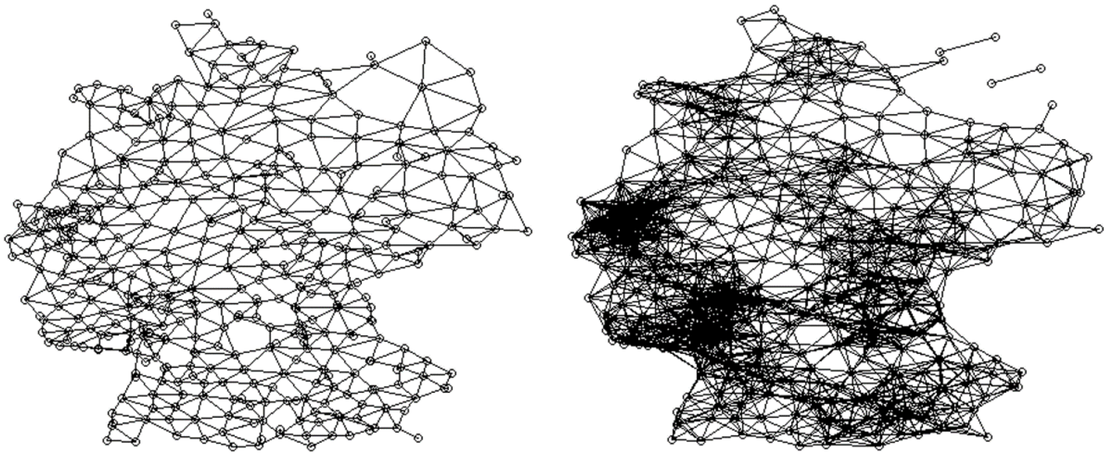

Figure 5 Neighbourhood structure of queen contiguity spatial weights matrix (left) and inverse distance spatial weights matrix with cut-off distance at 65 km (right) of German NUTS3 regions

There are different options to define the spatial weights matrix W based on concepts of contiguity and distance; or a combination of both (Anselin and Bera 1998). The used inverse-distance matrix is defined as

Additional information on investment costs

Major driver of system costs are collectors, which are subject to the cost of primarily used materials like copper and aluminium. Besides production costs, system costs are determined by costs for marketing, retail etc. Cost developments of ST systems showed a steady decrease up to 2002. Since then, prices of some components increased and hence solar system prices remained constant or even went up (BSW – Bundesverband Solarwirtschaft e.V. 2012). According to the official evaluation of the MAP, no distinct explanation, e.g. like shortages, could be derived from discussions with industry representatives. However, some producers (with delays) presumably considered increased commodity prices of previous years, especially after high turnovers in 2007 and 2008 (Langniß et al. 2011). Although producers of flat plate collectors claimed to have reduced production costs and due to price competition are forced to pass on price reduction to sales and distribution, these price reductions did not pass on to consumer prices. Somewhere in the distribution chain (wholesale, sale, installation) price reductions have been lost or even surpassed. Langniß et al. (2011) suggests that cost reduction potentials in the installation business are not realised by artisans. Due to high utilization, installers and plumbers do not perceive the need to reduce installations costs of ST systems (Langniß et al. 2011). In the ST data (cf. section 4.1), a wide spread between investment costs is present. One reason can be the use of different components (e.g. collectors with and without expensive antireflexion coating) or distinct system hydraulics (Stuible et al. 2016). Also, installation circumstances and profit margins of installers vary. Average specific investment costs in relation to average collector area for combi-systems subsidised under the MAP reveal that prices do not fall over the years (cf. Figure 6). Average costs lie between 671 and 983 €/m^2 and average sizes between 14.7 and 11.9 m^2.

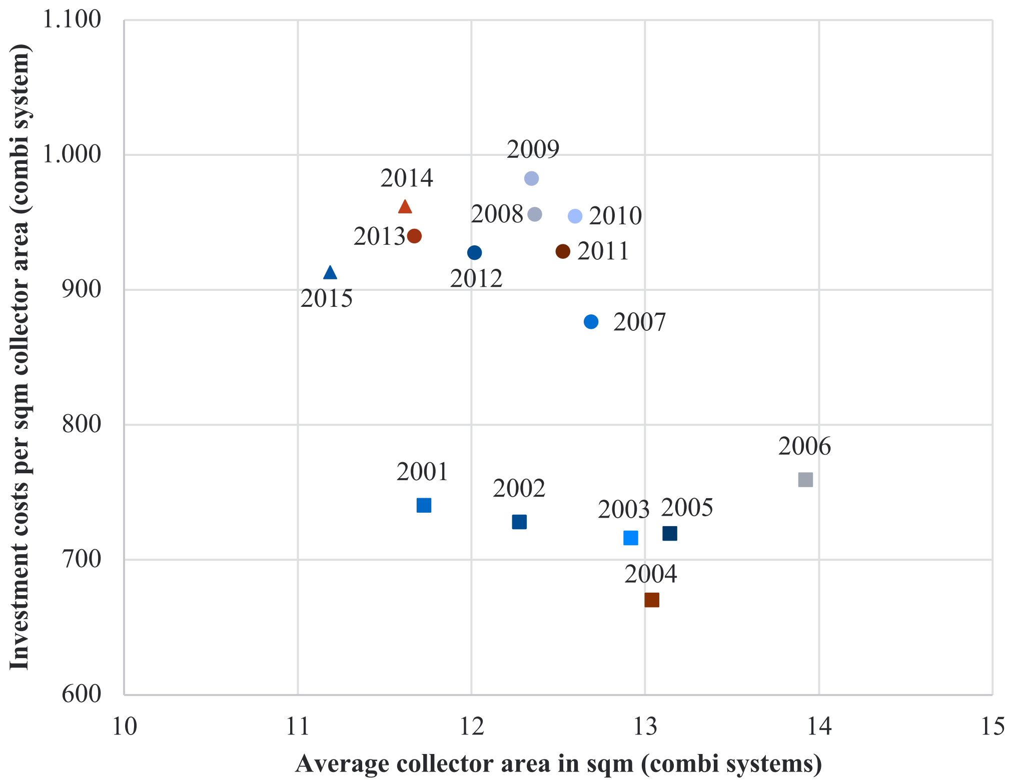

Figure 6 Collector area and specific investment costs of subsidised solar thermal Combi-systems; own illustration based on data from solaratlas.de

Usually, specific investment costs decrease with rising collector area. This is visible comparing costs of combi-systems and water heating systems, which usually have smaller collector sizes around 6 m^2. Offering turnkey-ST-systems with a smaller collector area in order to provide low-priced products might increase specific investments costs. However, average collector area of combi-systems did not change much between 2001 and 2015 (cf. Figure 6). Thus, specific cost increases are not due to smaller systems. Price increases are especially visible from 2006 to 2007. During the year 2007, in addition to the basic subsidy, a bonus was introduced in the MAP. It was paid for the supplementary installation of high efficient pumps or the replacement of the existent heating systems. Due to this linkage of other measures with ST systems, the declared investment costs turn out to be higher for the subsequent years, which is not only due to increasing system prices. Also, after 2007 subsidies in the used data are slightly higher than standard MAP-grants. As there is no itemization for investment costs in (BSW 2017) (i.e. solar thermal system, storage, heating boiler, pumps, hydraulic compensation), interpretation is rather difficult.

Profitability index

Table 6 Interest rates, energy prices and price expectations for the base profitability index

Year	Interest rate	Average gas price	Average oil price	Gas price increase	Oil price increase
2001	4.98%	4,84	3,87	3.84%	3.17%
2002	4.92%	4,53	3,54	3.74%	2.39%
2003	4.29%	4,76	3,67	3.94%	2.99%
2004	4.23%	4,82	4,09	5.81%	3.11%
2005	3.45%	5,34	5,40	9.34%	4.37%
2006	3.87%	6,33	5,97	8.63%	6.55%
2007	4.31%	6,51	5,91	8.24%	6.43%
2008	4.16%	7,10	7,77	13.32%	7.29%
2009	3.59%	6,98	5,39	7.26%	7.53%
2010	2.97%	6,36	6,60	4.85%	4.92%
2011	2.84%	6,66	8,22	7.82%	3.23%
2012	1.65%	7,03	8,95	9.72%	4.48%
2013	1.69%	7,13	8,41	8.64%	4.11%
2014	1.23%	7,14	7,75	6.60%	4.01%
2015	0.53%	7,06	5,96	1.00%	2.83%

Appendix B: Sensitivity analyses

Table 7 Sensitivity estimations for the time fixed effects spatial lag model

	Base model	No time lag	PV install.	Till 2009	Cons. model	Distance W.
Profitability index	0.1627***	0.4563***	0.1503***	0.2507***		0.1830***
	(0.0333)	(0.0381)	(0.0336)	(0.0422)		(0.0345)
Solar radiation					0.0015	
					(0.0077)	
Energy price					0.0996***	
					(0.0293)	
New buildings	-0.0528***	-0.1216***	-0.0527***	-0.0665***	-0.0494***	-0.0500***
	(0.0078)	(0.0091)	(0.0078)	(0.0097)	(0.0079)	(0.0080)
Income	-0.0228**	-0.0367***	-0.0218**	0.0147	-0.0183*	-0.0290***
	(0.0102)	(0.0121)	(0.0103)	(0.0113)	(0.0103)	(0.0105)
Green	-0.0043	-0.0007	-0.0047	-0.0066	-0.0037	-0.0156**
	(0.0070)	(0.0083)	(0.0070)	(0.0084)	(0.0070)	(0.0072)
Household size	0.2016***	0.3943***	0.1912***	0.2080***	0.1907***	0.2109***
	(0.0136)	(0.0136)	(0.0128)	(0.0148)	(0.0124)	(0.0125)
HDD	0.0210***	0.0828***	0.0220***	0.0317***	0.0155**	0.0211***
	(0.0072)	(0.0084)	(0.0072)	(0.0089)	(0.0073)	(0.0075)
Inverse pop. density	0.0562***	0.1006***	0.0562***	0.0661***	0.0567***	0.0523***
	(0.0090)	(0.0090)	(0.0078)	(0.0096)	(0.0078)	(0.0079)
Benefits	-0.0156	-0.0714***	-0.0137	-0.0118	-0.0266**	-0.0179*
	(0.0106)	(0.0124)	(0.0106)	(0.0128)	(0.0111)	(0.0109)
Lag of ST uptake	0.4835***		0.4751***	0.5545***	0.4888	0.5022***
	(0.0103)		(0.0106)	(0.0136)	(0.0103)	(0.0104)
PV installations			0.0289			
			(0.0098)			
Lambda	0.2927***	0.3695***	0.2880***	0.2572***	0.3051***	0.3321***
	(0.0106)	(0.0121)	(0.0107)	(0.0133)	(0.0106)	(0.0134)
Overall R^2	0.8266	0.7618	0.8267	0.8430	0.8268	0.8180
AIC	6596.56	8510.39	6595.31	3608.08	6593.39	6890.13
BIC	6770.88	8678.00	6776.34	3731.95	6774.41	7064.45

Note: the values in parentheses are standard errors
*** Significance level at 1%.
** Significance level at 5%
* Significance level at 10%

Table 8 Sensitivity estimations for the time fixed effects spatial error model

	Base model	No time lag	PV install.	Till 2009	Cons. model	Distance W.
Profitability index	0.2921***	0.5807***	0.2659***	0.3192***		0.3312***
	(0.0407)	(0.0492)	(0.0407)	(0.0502)		(0.0441)
Solar radiation					0.0583***	
					(0.0110)	
Energy price					0.0858***	
					(0.0283)	
New buildings	-0.035***	-0.1185***	-0.0316***	-0.0554***	-0.0349***	-0.0376***
	(0.0084)	(0.0102)	(0.0084)	(0.0102)	(0.0084)	(0.0090)
Income	-0.0309***	-0.0520***	-0.0259**	0.0007	-0.0324***	-0.0345***
	(0.0107)	(0.0502)	(0.0107)	(0.0116)	(0.0107)	(0.0110)
Green	0.0106	0.0239**	0.0113	0.0071	0.0103	0.0072
	(0.0080)	(0.0098)	(0.0079)	(0.0095)	(0.0080)	(0.0085)
Household size	0.1743***	0.4159***	0.1502***	0.1882***	0.1757***	0.1804***
	(0.0130)	(0.0151)	(0.0135)	(0.0156)	(0.0131)	(0.0135)
HDD	0.0554***	0.1295***	0.0565***	0.0585***	0.0577***	0.0611***
	(0.0084)	(0.0102)	(0.0084)	(0.0103)	(0.0086)	(0.0087)
Inverse pop. Density	0.0442***	0.1039***	0.0451***	0.0483***	0.0457***	0.0371***
	(0.0091)	(0.0111)	(0.0091)	(0.0110)	(0.0092)	(0.0091)
Benefits	-0.0442***	-0.1136***	-0.0372***	-0.0427***	-0.0394***	-0.0511***
	(0.0107)	(0.01301)	(0.0107)	(0.0127)	(0.0111)	(0.0111)
Lag of ST uptake	0.5817***		0.5620	0.6668***	0.5814***	0.5783***
	(0.0104)		(0.0108)	(0.0135)	(0.0104)	(0.014)
PV installations			0.0687***			
			(0.0107)			
Rho	0.5217***	0.4993***	0.5205	0.5215***	0.5251***	0.5815***
	(0.0139)	(0.0143)	(0.0139)	(0.0180)	(0.0139)	(0.0173)
Overall R^2	0.8528	0.7750	0.8538	0.9215	0.8528	0.8398
AIC	5608.40	8167.77	5570.90	2958.71	5612.98	6118.28
BIC	5782.72	8335.39	5751.92	3119.75	5794.00	6292.59

Note: the values in parentheses are standard errors
*** Significance level at 1%.
** Significance level at 5%
* Significance level at 10%

Table 9 Sensitivity estimations for the regional fixed effects spatial lag model

	Base model	No time lag	PV install.	Till 2009	Cons. model	Distance W.
Profitability index	0.1238***	0.0907***	0.1151***	0.1285***		0.1419***
	(0.0073)	(0.0072)	(0.0075)	(0.0101)		(0.0086)
Invest. cost					-0.1299***	
					(0.0121)	
Subsidy					0.1151***	
					(0.0092)	
Interest					0.1445***	
					(0.0150)	
Price expectation					0.0824***	
					(0.0147)	
Energy price					0.1553***	
					(0.0233)	
New buildings	-0.0871***	-0.1497***	-0.0757***	-0.1124***	-0.0940***	-0.0932***
	(0.0101)	(0.0100)	(0.0102)	(0.0128)	(0.0104)	(0.0107)
Income	-0.0813***	-0.0499***	-0.0685***	0.0464*	-0.0234	-0.0949***
	(0.0172)	(0.0177)	(0.0173)	(0.0279)	(0.0213)	(0.0183)
Green	-0.0301*	0.0696***	-0.0570***	-0.0513**	-0.0447***	-0.0309*
	(0.0158)	(0.0153)	(0.0162)	(0.0255)	(0.0162)	(0.0166)
EEWärmeG	-0.0976***	-0.1135***	-0.1190***		-0.0120	-0.1093***
	(0.0087)	(0.0088)	(0.0091)		(0.0164)	(0.0097)
Lag of ST uptake	0.1673***		0.1547***	0.1999***	0.1880***	0.1827***
	(0.1674)		(0.0088)	(0.0120)	(0.0095)	(0.0094)
PV installations			0.0686***			
			(0.0096)			
Lambda	0.6231***	0.6664***	0.6142***	0.5507***	0.6025***	0.6970***
	(0.0111)	(0.0110)	(0.0113)	(0.0156)	(0.0118)	(0.0116)
Overall R^2	0.8686	0.8613	0.8692	0.8870	0.8702	0.8540
AIC	5695.90	6019.49	5666.54	3195.97	5629.30	6325.71
BIC	8444.75	8761.63	8422.09	5729.18	8404.97	9074.56

Note: the values in parentheses are standard errors
*** Significance level at 1%.
** Significance level at 5%
* Significance level at 10%

Table 10 Sensitivity estimations for the regional fixed effects spatial error model

	Base model	No time lag	PV install.	Till 2009	Cons. model	Distance W.
Profitability index	0.3162***	0.2871***	0.3109***	0.2915***		0.4532***
	(0.0158)	(0.0179)	(0.0156)	(0.0159)		(0.0218)
Invest. cost					-0.0654***	
					(0.0248)	
Subsidy					0.1950***	
					(0.0227)	
Interest					0.2201***	
					(0.0353)	
Price expectations					0.3083***	
					(0.0254)	
Energy price					0.1249***	
					(0.0291)	
New buildings	-0.0696***	-0.1283***	-0.0559***	-0.1185***	-0.0649***	-0.0800***
	(0.0107)	(0.0412)	(0.0110)	(0.0131)	(0.0108)	(0.0116)
Income	-0.0714***	-0.0437	-0.0827**	0.2280***	-0.0579**	-0.0906**
	(0.0262)	(0.0282)	(0.0262)	(0.0333)	(0.0271)	(0.0276)
Green	0.0549**	0.0968***	0.0474	0.0603*	0.0018	0.0359
	(0.0252)	(0.0273)	(0.0251)	(0.0365)	(0.0253)	(0.0277)
EEWärmeG	-0.2680***	-0.2766***	-0.2830***		-0.0323	-0.4035***
	(0.0177)	(0.0110)	(0.0175)		(0.0353)	(0.0239)
Lag of ST uptake	0.3471***		0.3308***	0.3746***	0.3220***	0.3485***
	(0.0117)		(0.0119)	(0.0144)	(0.0119)	(0.0117)
PV installations			0.0822***			
			(0.0127)			
Rho	0.6751***	0.6987***	0.6858***	0.6356***	0.6400***	0.7284***
	(0.0113)	(0.0108)	(0.0111)	(0.0155)	(0.0119)	(0.0114)
Overall R^2	0.8764	0.8599	0.8770	0.9396	0.8769	0.8615
AIC	5324.96	6077.62	5298.03	2776.62	5308.63	6010.02
BIC	8073.81	8819.76	8053.58	5309.83	8084.29	8758.87

Note: the values in parentheses are standard errors
*** Significance level at 1%.
** Significance level at 5%
* Significance level at 10%

5 Conclusion and outlook

Related to long-lasting concerns about energy security and environmental degradation and in the course of the discussions about climate change, Germany has developed several energy policies to lower its energy demand and associated carbon emissions. With the *Energiewende* decisions, the country has emphasized the need for a reorganisation of its energy sector towards efficiency and renewable generation. As the household sector accounts for around one quarter of final energy demand, a major transformation in household energy supply and demand is required. Yet, the development of household energy use in the last decade is unsatisfying, as demand still is predominantly provided by fossil fuels. The change in energy usage in this sector is of utmost importance for national greenhouse gas reductions and the overall success of the *Energiewende*. Building components and household technologies installed today have a potential lifetime of up to 40 years and shape a household's ecological impact for the following decades. The choice of the insulation level sets boundaries for heating energy demand and the heating system choice determines the primary energy source and resulting CO_2 emissions (Bauermann 2015). Path dependence and technological lock-in are powerful forces to contend with. Thus, it is important to provide incentives for investments with the potential to reduce energy demand and decarbonise supply (energetic refurbishments, solar thermal heating, photovoltaic systems) as soon as possible. To determine promising measures, it is a prerequisite to explore household decisions and to examine drivers and barriers related to energy efficient and sustainable investments. The overarching objective of this thesis has been to better understand and to statistically analyse the decision-making of households, which has been pursued by addressing the five research questions posed in Section 1.5.

Chapter 2 presents the results of interviews with independent energy advisers and demonstrates the link between drivers and barriers at various stages of the decision-making process. The descriptive analysis of the decision-making process of households regarding energetic refurbishments establishes the first element of this thesis. Here, the individual interactions between households and energy advisers as a personal and trustworthy source of information are investigated. Chapters 3 and 4 address interactions between households within larger regional entities, namely NUTS3 regions, which also affect individual adoption decisions. By extending conventional econometric models with spatial interaction effects, cross-regional spillover is considered as a decision determinant. Chapter 3 elaborates on the main drivers for households' photovoltaic adoption, which seem to be solar radiation, the share of detached houses, electricity demand and inverse population density. In addition, spatial dependence is found to be a relevant determinant for regional patterns of PV adoption. Chapter 4 is concerned with household solar thermal adoptions in the period between 2001 and 2015. Results indicate that differences in profitability influence the spatial and temporal patterns of uptake. Regional diffusion is mainly induced by solar radiation, whereas the development of fossil fuel prices is accountable for different adoption rates over time. New constructions do not seem to foster solar thermal use, indicating that solar heating does not depend on new buildings and is easily applied in the building stock.

The following sections (5.1 and 5.2) condense the findings and highlight the contributions to the main research questions. The thesis concludes by pointing at alternative policy interventions (5.3) and promising avenues for future research (5.4).

5.1 Drivers and barriers for energy efficient and sustainable household decisions

Households' implementation of energy efficiency measures and adoption of renewable based generation technologies is crucial for German climate protection targets. Chapter 2 presents findings on energy-related household decision-making. Research questions A) and B) relate to these findings and are answered in the following, recurring also partly to results from Chapters 3 and 4:

A) How can the complexity of individual decision-making and its interactions with policy interventions be conceptualized adequately?

Most attempts to reconstruct energy efficient and sustainable retrofit decisions are guided by the presupposition that financial advantages and energy cost savings motivate households to implement these measures. Efficiency measures are presumed to be profitable, meaning over the lifetime of a component, households are able to recoup upfront costs by reduced energy expenses. Also, households would be deterred from undertaking measures by capital constraints and uncertainties regarding profitability. These explanation attempts mainly focus on the economic rationale as the decision to refurbish is interpreted as an investment decision (Kastner and Stern 2015). Against the background of findings in Chapter 2, the decision-making regarding energy efficient and sustainable products is not sufficiently explained when treated as ordinary investment decision. To households, the dwelling is the focal point of private life and a place to feel comfortable and safe (Wilson et al. 2015; Gram-Hanssen et al. 2007). Energy efficiency decision are hence characterised by a high degree of involvement that emerges from households' strong emotional bonds towards their home. Further, efficiency measures provide several useful services that households "consume" in their daily life or the utilisation phase of efficient and sustainable technologies.

Hence, the decision-making clearly deviates from financial investment calculus and for an improved understanding the conceptualization as environment-related strategic consumer decisions (Bodenstein et al. 1997), associated with extensive problem solving (Kroeber-Riel et al. 2011), is helpful. In this vein, the decisions can be framed in a consumer decision process model, which encompasses the stages: stimuli and problem recognition, information search and evaluation of alternatives, choice and implementation, usage and assessment. With regards to these decision stages, subsequently the main results of Chapter 2 are summarized and selectively complemented by findings of Chapters 3 and 4 in answer to research question B).

B) What motivates or prevents households to invest in energy efficient and sustainable technologies? Which influences foster or impede the adoption decision?

Since need recognition is a precursor to action, it is fundamental to understand what initiates the decision to invest in energy efficient and sustainable products. Two aspects produce serious impediments for need recognition. First, salience of energy consumption and energy expenditures is rather low. Even though maintaining a warm house has become more expensive over the years, it is often not putting enough pressure on households to consider reducing energy consumption. Nonetheless, the findings of Chapter 4 indicate that solar thermal uptake follows somewhat oil and gas prices. As a consequence, observed and future expected fossil fuel price increases have the potential to trigger decisions. Second, households regard their homes as ideal and durable. Hence, they tend to be at ease with domestic energy consumption and do not request any changes.

Notably, a decision-making process is hardly ever initiated unless households are confronted with “salient events”.

Salient events may consist of technical failures, structural deterioration or biographical changes. The decision process often literally starts with problem recognition, with observed deficiencies ranging from a sordid façade over damp walls to faulty heating systems. This kind of need recognition most likely leads to actually implementing measures, as households no longer want to bear the situation and thus, a decision and implementation is forced. In addition, the readiness to deal with energy-related decisions and the willingness to spend money is higher in two transition periods in a household lifecycle: One is the first purchase or inheritance of own property by young couples or families. A turnover offers the occasion to assess the building quality and plan efficiency and sustainability measures. New owners want to guarantee a comfortable home and are willing to retrofit the entire building but due to budget constraints conduct stepwise refurbishments: They start with the most important measure and postpone the rest, while keeping the final efficiency standard in mind. The second transition period arises with settled households who want to adapt their living conditions to changed circumstances (e.g. children moving out) or are eager to update the dwelling before retirement. They live in their own single- or double-family house and are financially well off. The results of Chapters 3 and 4 support this finding: A certain non-urban, settled lifestyle manifesting in higher electricity demand, larger households, lower population density and detached housing seems to favour solar installations. In comparison to younger homeowners, settled households are often only planning single measures (like the adoption of photovoltaic panels) and not an extensive refurbishment.

After need recognition, households search for adequate measures and evaluate alternative efficient and/or sustainable products. In most decisions, monetary aspects are essential determinants. However, the main concern is not profitability but financial feasibility. The households’ objective is not to choose the product with the highest net present value, but they focus on which alternative is sufficiently cost effective.[1] In particular, investment costs are the main barrier for extensive measures. This is

[1] According to Simon, individuals tend to make decisions by satisficing (a combination of sufficing and satisfying) rather than optimizing (Simon 1956). Hence, households often choose an alternative that is simply good enough in light of the costs and other constraints involved.

exacerbated by the fact that households are often not willing to take a loan. Yet, non-monetary criteria have the potential to upstage monetary aspects and enhance the willingness to spend money on energy efficient and sustainable options: First, comfort losses like air draught, problems with cold indoor temperatures or enhanced demand for thermal comfort; second, visibility of refurbishment activities (e.g., new windows or solar systems), which embellish the building's appearance and symbolise wealth; third, interest in and fascination with new technology.

Households usually do not reflect on reduced CO_2 emissions or environmental benefits and at most perceive it as a nice co-benefit. Notably, the share of Green voters seems to be irrelevant for regional solar technology uptake, as indicated by the findings of Chapters 3 and 4. Hence, political activities and campaigns aiming at the promotion of general green attitudes are likely to have only limited impact. Nonetheless, some households are ecologically motivated (often reflected in their entire lifestyle). Households are willing and ready to use wood pellet or solar systems, but are prevented from adopting those by financial restrictions and often stick to incumbent technologies.

5.2 Adequate methods to empirically investigate energy efficient and sustainable household investments

The decision to invest in energy efficient refurbishments and sustainable technologies is subject to personal and contextual influences. Different internal and external forces interact and affect households' problem recognition and evaluation of alternative measures. Besides individual motives and circumstances, general regional conditions influence the choice of sustainable technologies. Chapter 3 and 4 evaluate spatial influences, which go beyond individual dwellings or households. Furthermore, spatial interactions between regional entities are addressed. The related research questions C) and D) are answered in the following:

> **C)** What empirical evidence exists on regional drivers and spatial adoption patterns of energy efficient and sustainable investments?

By investigating the diffusion of solar photovoltaic and solar thermal systems at a regional level, findings demonstrate the emergence of solar clusters. These clusters spread across delimited spatial units. This is partly due to geographical similarities between adjacent regions (e.g. solar radiation or income), which foster or impede the uptake of solar technologies. In particular, higher economic viability increases the propensity to adopt solar systems. Regional diffusion is driven by solar radiation levels, leading to superior profitability. In addition, the development of fossil fuel prices is accountable for adoption rates over time. This result implies that households' adoption decision can be at least to some extent explained by economic considerations. Admittedly, a fundamental result of Chapter 2 is that the decision-making deviates from a financial investment calculus, as other determinants are (equally) important. Yet, the findings are not mutually exclusive, as either indicates that economic and financial aspects are relevant, but not sufficient to explain energy-related strategic household decisions.

Besides differences in profitability, region specific characteristics lead to varying adoption rates of solar technologies. Detached houses in spacious regions offer favourable conditions for the adoption, likely because of larger unshaded roof areas and better accessibility for installation work. Also, households owning their dwelling (owner-occupiers) have an increased propensity to adopt photovoltaic systems, as the installation decision as well as the allocation of subsequent benefits is straightforward in contrast to rented dwellings, where information asymmetries and principal-agent problems between landlords and tenants may arise (Jaffe and Stavins 1994). Remarkably, high rates of new construction do not explain solar thermal uptake, implying that solar technology adoption does not prevail in new buildings. This could be a result of financial constraints (cf. Chapter 2), which may especially prevail when constructing a house, making households choose comparatively lower priced heating systems. The finding further implies that solar systems are easily applied in the building stock, making it a suitable renewable technology for retrofit activities. Findings of Chapter 2 add that because of financial restrictions, households often stick to single retrofit measures, like the installation of a solar thermal system. In addition, households with higher electricity demand are more likely to adopt photovoltaic panels and larger households are more inclined to use solar thermal systems. Both findings can be attributed at least in part to higher economic viability: Higher electricity consumption induces generally a higher share of self-consumed PV generation, which substitutes purchases of electricity. Those purchases are paid a far higher price than is currently paid for PV infeed into the grid (BNetzA 2017;

EEG 2017). Larger households obviously also consume more heat, notably for hot tap water. This increases the useable yield of solar thermal systems, particularly during the summer months.

Disposable household income does not qualify to explain higher levels of solar adoption. Based on the rationale that wealthier areas are more likely to adopt solar systems, this finding is surprising. Yet, the share of welfare recipients in a region is found to have significant negative impact on the diffusion of solar technologies. The share of welfare recipients seems to be a suitable negative proxy for wealth and financial capability in a region. Hence, it might not be income but rather wealth i.e. accumulated capital, which contributes to different regional diffusion levels. Certainly, to derive implications for individual households from regional (NUTS3 regions) characteristics is prone to misinterpretation. Still, a result of Chapter 2 is that, given the unwillingness to take a loan, upfront costs are an important barrier for energy-related investments. These measures are rather financed by financial savings. Income obviously has an impact on financial wealth, but other factors (e.g. property or inheritance) also largely contribute.

Ecological attitude (measured by votes for the Green party) shows inconclusive results in the estimations of Chapters 3 and 4 and does not seem to facilitate higher levels of solar adoption. Admittedly, the use of other indicators for environmental awareness than Green party voters might induce different results. Yet, results of Chapter 2 confirm that households only perceive environmental benefits of energy efficiency measures as a nice co-benefit. In this vein, energy-related household decisions are not primarily motivated by ecological considerations. Further, no support can be given to a supposed specific East German mind-set, which would impede the adoption of innovative solar technologies.

To conclude, simple economic causalities do not sufficiently explain regional differences in solar technology adoption. In fact, a certain non-urban, settled lifestyle manifesting in lower population density, larger households and detached housing is an important driver for solar installations and energy efficient and sustainable products in general. In addition, a strong enabling factor for the emergence of regional solar clusters is spatial dependence. The methodological contribution of the thesis, i.e. including spatial spillover in statistical analyses, is established in answer to research question D).

D) Does spatial spillover between adjacent regions affect adoption and how can spatial dependence be modelled adequately?

The results of Chapter 3 and 4 show that traditional regression models addressing solar technology uptake need to be extended with spatial interaction effects. Three types of spatial interactions may be considered: (i) spatial lag, where the dependent variable in a region is affected by dependent variables in neighbouring regions; (ii) exogenous spatial lag, where the dependent variable in a region depends on independent explanatory variables of neighbouring units; (iii) spatial error correlation, where similar unobserved characteristics result in similar decisions. Different model specifications, i.e. including different spatial interactions, are tested in Chapters 3 and 4, and the positive and statistically significant estimates of spatial parameters show a strong spatial correlation between adoption levels in adjacent regions. Even after controlling for geographic suitability (e.g. solar radiations) and socio-economic characteristics, findings indicate regional clustering of solar technology installations. It implies that solar uptake tends to spill over NUTS3 borders and households' propensity to adopt solar technologies increases with diffusion levels in neighbouring regions.

Given the analysis of Chapters 3 and 4, two forms of spatial interactions are identified. First, spatial lag, which is incorporated in the spatial autoregressive model (SAR): The presence of solar installations on rooftops is conspicuous, induces knowledge of these innovations and entails information externalities from adopters. Besides recurrent visual perception, intensified social interactions and peer-effects lead to local reinforcement of technology uptake and drive potential adopters to follow decisions by actors in the proximity. The second type of spatial spillover is spatial error correlation, captured in the spatial error model (SEM): Similar unobserved characteristics result in similar decisions in neighbouring regions. Presumably, a concentrated expertise of artisans, regional solar initiatives, local PV supplier activities or advertising campaigns lead to an accelerated diffusion in a region and its surroundings. These (in the dataset of Chapters 3 and 4) non-observed regional characteristics are difficult to measure and hard to obtain, but would possibly improve model interpretations.

Notably, both types of spatial spillover may be acknowledged when modelling solar technology uptake. Yet, by taking one type of spatial dependence into account, the explanatory power of the other is reduced drastically. Hence, it is advisable to only consider spatial lag or spatial error dependence in a specification. Addressing regional solar photovoltaic diffusion, the SEM model performs best (cf. Chapter 3). This indicates that although spatial lag is present, spatial dependence in the residuals is more influential. Spatial spillover may not mainly be driven by social imitation but by other regional characteristics not included in the model. In the same vain, results of Chapter 4 indicate that the SEM is the superior model to interpret the diffusion of solar thermal systems, when controlling for time fixed effects. Thus, social imitation seems to be less relevant than spatial knowledge spillover and similar, not directly observable effects. Consequently, on the basis of the available dataset, which relies on rather large spatial entities, a clear distinction between the two spillover types is challenging and rather questionable when it comes to individual households. Here, further in-depth analysis is needed in order to provide policy makers with a better understanding of the "soft factors" that facilitate the energy transformation at the scale of private households.

5.3 Implications for policies targeting household decision-making

With one quarter of final energy consumption, the German household sector is in the focus of policies to implement the *Energiewende* towards a low carbon society. Against the backdrop of mediocre effectiveness of present instruments and the impending breach of climate protection agreements, this thesis also provides insights to policy makers and practitioners concerning the design of policy instruments to activate energy efficient and sustainable household investments. Research question E) is addressed in the following:

E) What can be inferred from more sophisticated models of households' energy-related decision-making for energy policy formulation? Can more adequate and efficient policy measures be identified that enable a better target achievement?

A general policy finding related to the obtained results is that recent interventions seem to be inappropriate to make the majority of households adopt refurbishment measures, photovoltaic systems and renewable heating systems. Admittedly, energy policy is committed to multiple targets, must consider many factors and address multiple barriers whilst avoiding overspending and conflicts with stakeholders (Connor et al. 2013). However, if residential buildings are to be decarbonised, stronger policy signals and incentives will be necessary. Relying on households to do the right thing is unlikely to succeed (Curtis et al. 2018). To increase the refurbishment rate and to foster the diffusion of sustainable energy generation technologies, the following suggestions are worth considering.

First, household decisions on energy efficient and sustainable technologies are, at least to some extent, subject to economic considerations. Results of Chapter 4 indicate that higher fossil fuel prices and price expectations increase the propensity to adopt solar thermal systems. Hence, additional price signals might be effective to foster energy-related household decisions and decrease the use of fossil fuels. In principle, taxes on energy use or related emissions provide an economic incentive both to retrofit existing buildings and to install efficient or low-carbon technologies (Schuler et al. 2000). Since current (heating) energy prices do not reflect environmental externalities, it is recommendable that politics consider the implementation of a CO_2 price by taxes or tradable emission permits, to internalize harmful impacts from CO_2 emissions. Especially in times of low energy prices, this additional economic incentive might be fruitful to trigger energy-related household investments. Yet, a CO_2 price encompassing the heating market is currently not planned in Germany. The government rather tries to simplify and unify regulation with respect to energy use in buildings by introducing the *Gebäudeenergiegesetz* (GEG), which is supposed to merge the *Energieeinsparverordnung* (EnEV) and the *Erneuerbare-Energien-Wärmegesetz* (EEWärmeG).

Second, policy interventions aimed at reducing financial barriers are key to promote investments (e.g. *Marktanreizprogramm)*. Financial capability is a prerequisite to implement refurbishment activities. In general, grants are preferred over loans, as many households want to avoid getting indebted. However, bureaucratic impediments sometimes discourage households to apply for financial support (Vom Hofe 2018). Also, the application for funding often is only possible for measures requiring extensive structural and financial efforts, which sometimes overwhelm households. To enhance acceptance of funding measures, providers should simplify application guidelines and lower requirements. It could be considered to make financial support available for low-investment measures, if transaction costs (for bureaucratic procedures) are acceptable. Thereby, small-scale measures can be fostered and implemented without overstraining households regarding the structural efforts and financial expenses. In particular, the successful outcome of these measures has the potential to incentivise broader actions.

Third, policy makers should acknowledge that decisions on sustainable and energy efficient measures do not rely on economic considerations alone. Hence, strategies that only address economic viability may not suffice and guiding attention towards increased thermal comfort or the use of innovative technologies might be more rewarding in incentivizing investments. Besides notifying about e.g. energy cost savings or amortisation times, communication strategies by energy advisers or consumer organisations should stress improved comfort or enhanced independence from fossil fuels and suppliers. Information strategies may further take into account results of Chapter 2 and systematically target households in biographical phases with an increased willingness to spend money on energy efficiency measures. In addition, defined areas like urban neighbourhoods seem to be well suited to approach households. Information campaigns could be specifically designed for the district level and include personalised letters, complimentary energy advice and information events. Specifically, information may include success stories and positive testimonials of individual households (in the neighbourhood) which are well suited to illustrate benefits of energy efficiency measures (Vom Hofe 2018). Since households are not well informed about their energy consumption, the (co-)benefits of efficiency and sustainability investments, market ready technologies and available subsidies, the importance of chimney sweeps, plumbers and other artisans as an information source should be noted (Curtis et al. 2018).

Fourth, even if households are aware of energy efficient and sustainable products and these products improve and costs decrease, these may not provide sufficient adoption incentives to households (Curtis et al. 2018). Here, regulatory measures can brake persisting behaviours. Yet, the control of enacted regulations is an important aspect if the regulations are to become effective (Schuler et al. 2000). The regulations therefore need to be supplemented by appropriate control mechanisms. The current practice that the EnEV and the EEWärmeG apply to existing buildings only in the cases of major refurbishments, considerably delays the effect of these regulations. If policy makers wish to pursue the current regulatory strategy (i.e. the GEG), they might consider to extend renewable use obligations and efficiency requirements to the building stock. Yet, this proves difficult, as those affected (building owners) should not be financially overloaded and distributional effects of this measure need to be taken into account. Alternatively, policy makers could consider to impose or extend the ban of certain (out-dated) fossil heating systems. Still, subsidies are available to support the adoption of condensing oil and gas boilers (MAP). In the long term, funding in the residential sector should be directed towards the electrification with heat pumps (cf. sector coupling). In addition, to promote the electrification of household energy consumption, the current system of electricity tax, energy tax (on gas and oil products), levies and shared contributions (concession fee, EEG costs etc.) should be modified (Agora Energiewende 2017).

Fifth, the adoption of energy efficient and sustainable products differs regionally across Germany, with higher technology diffusion in South Germany (cf. Chapter 3 and 4 as well as Energiewende-Barometer (KfW 2018)). The regional differences imply that benefits of national policies are unevenly distributed. If a more uniform spatial diffusion is intended, policy makers need to target efforts in regions where the uptake is currently underperforming, i.e. introduce regionally differing subsidy levels. This would require a delegation of the design and implementation of instruments to the federal states or counties (Braun 2010). Yet it is questionable whether this would increase the economic efficiency of support mechanisms.

5.4 Limitations and suggestions for future research

This thesis has combined different methods to investigate household decisions to invest in energy efficient and sustainable technologies and thus has improved existing knowledge. Yet, the limitations of this work make way for additional research. The qualitative study of Chapter 2 relied on energy advisers as the information source. In future research, households could be interviewed to further analyse the dynamics of these decisions. Further, groups of households could be separated: households who have conducted measures recently; households who considered measures but decided against it; and households who so far have not engaged in any thoughts about retrofit measures. Especially the last two groups could provide insights into barriers to energy efficient and sustainable investments. In contrast to interviews, a broader empirical basis could be gathered by large (written) surveys and would be an alternative for future research. Questions could be differentiated between homeowners and tenants. In addition, the sample could be controlled for other socio-demographic characteristics as opposed to the used variables in this work. E.g. Ramos et al. (2016) find that Spanish households with older members are less likely to invest in energy efficiency, while higher education levels pay more attention to energy efficiency.

With regards to spatial effects and the findings of Chapter 3 and 4, more research should be conducted as spatial dependence in residuals hints at unobserved drivers for regional uptake. E.g. editing data on local solar initiatives and taking them as a predictor variable might account for some of the spatial error correlation. New insights could be gained by investigating smaller spatial units, either postcode districts, neighbourhoods or even individual households. The spatial units used in this thesis seem rather big to investigate social interactions between households. However, data availability at a postcode or household level is limited. The present study focussed on solar technologies to identify spatial dependence in adoption decisions. The method could be applied to other energy efficient and sustainable products that are visible to passers-by, e.g. newly insulated roofs or electrical vehicles.

As this thesis has shown the importance of household decisions, future research could target household behaviours. As illustrated in the introduction, besides the installed technology, the use of this technology drives domestic energy consumption. Research in this respect has been conducted by Sunikka-Blank and Galvin (2012), who found that the impact of behavioural change is underestimated, has the potential to lower energy consumption and is important to decarbonise the household sector. To incentivise behavioural change, visibility and awareness of energy consumption has to be raised. Additional research could focus on feasible quality standards for heating bills to increase awareness and motivate energy reduction behaviours. As of today, heating bills in Germany are often incorrect and unclear (VZ 2018).

A representative survey conducted by the KfW in 2018 shows that 90% of German households support the *Energiewende*, but only 23% adopted a so-called *Energiewende technology* (solar thermal, photovoltaic, heat pump, electric vehicle, battery storage, co-generation) (KfW 2018). Adopting households name “contribution to climate protection” as the main motive to adopt sustainable energy technologies, ranking slightly ahead of "cost reductions" (KfW 2018). This shows the large and still untapped potential for these technologies. The survey results also reveal the existence of the "attitude-action gap" (see e.g. Lane and Potter 2007) which implies that environmental attitudes are not necessarily translated into real actions. Even among environmentally conscious households, strong policy incentives are necessary to encourage the adoption of low-carbon technologies. Future research therefore needs to identify efficient and effective policy measures.

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Own contribution

Title: **A consumer decision-making process? Unfolding energy efficiency decisions of German owner-occupiers**

Authors: Jan Paul Baginski and Christoph Weber

Authors Contribution: Jan Paul Baginski conducted the interviews, transcribed and coded the interview material and prepared the majority of the manuscript. Prof. Christoph Weber supervised the building of the decision framework, edited and reviewed the manuscript. All authors read and approved the final manuscript.

Title: **Coherent estimations for residential photovoltaic uptake in Germany including spatial spillover effects**

Authors: Jan Paul Baginski and Christoph Weber

Authors Contribution: Jan Paul Baginski executed the data research, the model implementation and the model computation. Christoph Weber participated in the data selection and interpretation of estimation results. The manuscript was drafted by Jan Paul Baginski and reworked and expanded by Christoph Weber. All authors read and approved the final manuscript.

Title: **Spatio-temporal diffusion of residential solar thermal systems in Germany: A spatial panel data analysis**

Author: Jan Paul Baginski

Authors Contribution: Jan Paul Baginski is the sole author of this paper.

(Ort, Datum, Christoph Weber) (Ort, Datum, Jan Paul Baginski)

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Jan Paul Baginski