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Fostering heat transition in residential building stock: An integrated perspective on policy instruments, digital technologies, and risk management

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von

Jakob Rockstuhl (geb. Ahlrichs)

aus

Höxter

Dekan:	Prof. Dr. André Meyer
Erstberichterstatter:	Prof. Dr. Jens Strüker
Zweitberichterstatter:	Prof. Dr. Björn Häckel
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> “The earth has a fever. And the fever is rising.”
>
> (Al Gore, 2007)

Mit Abschluss dieser Dissertation möchte ich mich bei allen Weggefährt:innen der letzten Jahre bedanken und blicke auf eine sehr lehrreiche und prägende Zeit zurück. In Zeiten des fortschreitenden, menschengemachten Klimawandels war und ist es mir ein persönliches Anliegen, einen kleinen Teil zur Eindämmung dieser globalen Herausforderung zu leisten und so den Planet Erde für die jetzige und auch kommende Generationen zu erhalten. Der Klimawandel und die daraus resultierenden Folgen ist die Kernherausforderung der jetzigen Generationen und es muss das Interesse aller sein, die Folgen abzumildern.

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Copyright statement

The following sections are partly comprised of content taken from the five research articles in this thesis. To improve the text's readability, I have omitted the standard labeling of these citations.

Abstract

Climate change is an escalating existential global challenge resulting from human activities and is approaching a critical tipping point, beyond which global warming's negative impacts become potentially irreversible. In line with the Paris Climate Agreement, Germany has committed to achieving climate neutrality by 2045, with residential buildings as a cornerstone. As a large proportion of buildings were constructed before the introduction of thermal building codes, and the majority have not been sufficiently retrofitted, they are mostly energy-inefficient. To meet climate targets, extensive emission-reducing measures such as building retrofitting and transitioning to renewable energy sources are necessary. However, the retrofitting rate remains too low, with only 1% of buildings undergoing retrofits annually against a target of 2% to 4% per year. This cumulative dissertation seeks to foster heat transition in residential building stock by examining two aspects. The first aspect examines how policymakers can increase environmental policies' attractiveness by considering uncertainty, stakeholders' perspectives, and regional differences in their instruments. The findings reveal that, for owner-occupied residential buildings, energy efficiency insurances mitigate risks and offer a cost-efficient alternative to subsidies. For rented buildings, the results indicate that a building's efficiency standard and the amount invested in energy efficiencies influence fair rental increases and that the current regulations are unfair to both landlords and tenants. Further, for both owner-occupied and rented buildings, local circumstances in buildings' energy efficiency and socio-economic factors should be reflected in policy instruments. The second aspect investigates decision support for individuals to encourage them to invest in emission-reducing measures. The knowledge gained can serve as a basis for both support tools and policy instruments. This dissertation reveals that those focused on energy bill risk invest 20% more than those focused on investment risk. This insight can be used to develop instruments such as specific information campaigns to nudge individuals toward energy-efficient investments. Further, six design principles for a digital product passport are developed to support decision-makers who are considering a change to a hydrogen-powered heating system. In sum, this cumulative dissertation provides insights from five research articles and aims to foster heat transition in the residential building sector.

Keywords: Energy Efficiency, Environmental Policy, Risk Management, Digital Technologies, Energy Informatics

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I Introduction

I.1 Motivation

Climate change is a pressing existential global issue that is rapidly approaching a critical tipping point, beyond which global warming's negative impacts may become irreversible (van Zalinge et al., 2017). Recognizing the urgency of the situation, governments worldwide have begun to implement environmental programs and policies to foster a more sustainable future (Mercure et al., 2021). One significant milestone in the international efforts to address climate change is the Paris Climate Agreement, which was ratified in 2015 (Pye et al., 2017; Savaresi, 2016). This is the first global and legally binding climate pact with the primary objective of combatting climate change (Savaresi, 2016). It seeks to limit the increase in average global temperature to well below 2°C above pre-industrial levels, with a temperature rise of 1.5°C (Rogelj et al., 2016). In alignment with the Paris Climate Agreement and the urgent need for concerted action, several European governments such as that of Germany have set ambitious climate neutrality targets by 2045 or 2050 (German Federal Government, 2021; Mercure et al., 2021). The goal of climate neutrality entails balancing the amount of greenhouse gases emitted with an equivalent amount removed from the atmosphere. It requires the collective effort to combat climate change by means of coordinated actions by governments, businesses, and individuals (Pye et al., 2017; Rogelj et al., 2016). Transitioning to low-carbon economies, increasing renewable energy generation, promoting energy efficiency, implementing sustainable land-use practices, and adopting eco-friendly technologies are among the key strategies to mitigate climate change's dramatic consequences and ensure a sustainable future for generations to come (Bogdanov et al., 2019; Da Graça Carvalho, 2012; Newman, 2023; Roelfsema et al., 2020).

In this vein, one of many necessary elements is the residential building sector (Ahlrichs et al., 2020; Roelfsema et al., 2020). Against the background of approximately 19 million residential buildings in Germany, more than 12 million were built prior to 1979, prior to the first German Thermal Insulation Ordinance (German Energy Agency, 2018). Unless retrofitted in the interim, most of these buildings are not sufficiently energy-efficient (Bürger et al., 2017). In 2022, residential buildings in Germany, for instance, accounted for more than a quarter of the country's total energy consumption (German Energy Agency, 2023) – and therefore approximately 27% of Germany's greenhouse gas emissions (German Environment Agency, 2023). For residential buildings, heat generation (66%) and hot water production (16%) account for the largest share of energy consumption and emissions (German Energy Agency, 2023).

There are similar figures for many other industrialized countries (Cao et al., 2016). Given that more than 80% of today's building stock is projected to also exist in 2050 (Bürger et al., 2017), the current (residential) building stock will persistently account for a significant portion of energy consumption and greenhouse gas emissions in the future (Fylan et al., 2016). Ambitious climate targets demand therefore extensive emission-reducing measures, such as the retrofitting of buildings or switching to renewable energy sources (Achtnicht & Madlener, 2014; Ahlrichs et al., 2020). Nonetheless, and despite a multitude of measures, implementations of emission-reducing retrofits lag behind, and the retrofit rate (the percentage of buildings that undergo retrofitting per year) remains too low (1%), given a target of 2% to 4% per year (Behr et al., 2023).

To combat these problems, further measures must be taken to foster heat transition in residential building stock using policy instruments, digital technologies, and risk management.

I.2 Research objectives

In research, under-investment in building retrofits as a special energy efficiency investment type is generally known as the *energy efficiency gap* (Jaffe & Stavins, 1994a). This term describes how individuals refuse to implement energy efficiency projects even though they would be financially profitable (Gerarden et al., 2017). Many studies have examined the causes of these investment barriers, categorizing them into two primary types: structural and behavioral barriers (Brown, 2001; Häckel et al., 2017; Hirst & Brown, 1990; Shogren & Taylor, 2008; L. Weber, 1997).

Structural barriers are mostly beyond the control of individuals and stem from actions by public and private organizations (Hirst & Brown, 1990). They can be categorized as market and nonmarket failures. Market failures occur when perfect market conditions deviate (Häckel et al., 2017), including imperfect information (Allcott & Greenstone, 2012; Howarth & Andersson, 1993; Linares & Labandeira, 2010), externalities (Brown, 2001; Gillingham et al., 2009; Jaffe et al., 2004), innovation market failures (Coltrane et al., 1986; Jaffe & Stavins, 1994a), and imperfect capital markets (Blumstein et al., 1980; Brown, 2001; Gillingham et al., 2009). Nonmarket failures pertain to barriers that rationalize suboptimal behaviors among energy users (Brown, 2001; Häckel et al., 2017; Hirst & Brown, 1990; Jaffe & Stavins, 1994b), with the main concerns being risks associated with energy efficiency investments (Hassett & Metcalf, 1993; Metcalf, 1994; van Soest & Bulte, 2001) and barriers within institutions and organizations (Brown, 2001; DeCanio, 1993; Groot et al., 2001; Hirst & Brown, 1990; L. Weber, 1997).

Besides structural barriers, behavioral barriers contribute to the energy efficiency gap (Häckel et al., 2017); these can be categorized into efficiency behaviors (promoting energy efficiency) and curtailment behaviors (reducing energy consumption) (Barr et al., 2005; Gardner & Stern, 1996). They arise from factors such as social influences (i.e. individuals who seek guidance on what is considered acceptable or desirable), emotional and moral motivations (i.e. individuals who are driven by personal values, environmental concerns, or a sense of responsibility), and decision heuristics by bounded rationality (i.e. individuals who refrain from making investments owing to limited cognitive abilities, information overload, or time constraints) (Häckel et al., 2017; Wenninger, 2022; Wilson & Dowlatabadi, 2007). This dissertation focuses mainly on structural nonmarket failures.

Addressing these barriers and their impacts on retrofit behavior is a crucial part of closing the energy efficiency gap and meeting the set climate goals in the residential sector. A broad mix of measures already exist, from policy instruments to digital technologies for decision support. To foster heat transition in residential building stock and to derive guiding knowledge, this doctoral thesis has two research objectives:

(1) Examine how policymakers can effectively promote emission-reducing measures in residential building stock.

(2) Investigate decision support for individual homeowners and subsequent instruments to encourage investment in emission-reducing measures in residential building stock.

These two research objectives differ: Research Objective #1 analyzes environmental policy and its instruments, while the Research Objective #2 analyzes individual decision-making and the measures that build on them to support individual decision-making. The knowledge gained regarding the Research Objective #2 can serve as a basis for policy instruments analyzed in Research Objective #1.

For Research Objective #1, the following considerations are key: As noted, several policy instruments are already available today to incentivize individuals to implement emission-reducing measures (Ahlrichs et al., 2020; Bergek & Berggren, 2014). They can be categorized into general economic (CO_2 taxes, emission trading), general regulatory (emission regulation), technology-specific economic (subsidies for specific technologies), and technology-specific regulations (Bergek & Berggren, 2014). However, their success has been limited, as the retrofitting rate remains too low (Achtnicht & Madlener, 2014). Thus, Gerarden et al. (2017) emphasized the importance of prioritizing research that assesses current energy-efficiency policies' effectiveness and explores opportunities for enhancing them to better address under-investment. This doctoral thesis seeks to provide guidance to policymakers for effective policy that increases emission-reducing measures' attractiveness. One starting point is the consideration of uncertainty of future financial and environmental savings in investment decisions, which – as the research has shown – has not yet been sufficiently considered in policy instruments. Mills (2003) emphasized that the financial risks linked to energy savings are a significant obstacle for investment in emission-reducing measures. These risks stem from both external factors such as energy prices and weather conditions as well as internal factors, including occupant behaviors and inadequate calculations (Wilde, 2014). Another obstacle is bridging the landlord-tenant problem in the case of rental properties, since the decision-making landlord does not benefit from savings on their tenants' energy bills. Further, landlords' investment and increased cash flows by increasing the rent as a percentage of the retrofit investment are certain, while tenants face financial uncertainty in their energy bill savings (Ahlrichs & Rockstuhl, 2022; I. Weber & Wolff, 2018). This doctoral thesis examines policy instruments, considering risks and evaluating their resulting influences on investment decisions. Besides considering risks, the research has shown that policy measures' effectiveness can differ, owing to local differences in residential building properties as well as socio-economic factors (Jones et al., 2009; Kastner & Stern, 2015). For instance, in their review of 26 studies, Kastner and Stern (2015) identified more than 700 factors that impact on energy retrofits, with income and place of residence having significant roles, while demographic factors, gender, education, and occupation have limited influences. Druckman and Jackson (2008) detected regional differences in energy consumption based on income, dwelling type, tenure, household composition, and rural/urban location (Druckman & Jackson, 2008). Thus, understanding interdependencies between residential building energy efficiency and these factors is required to improve energy efficiency policies' effectiveness (Fylan et al., 2016; Gerarden et al., 2017; Rosenow & Eyre, 2016). However, the research has been limited to mainly qualitative studies. This doctoral thesis seeks to contribute to the existing research gap, using quantitative approaches based on comprehensive real-world datasets.

Regarding Research Objective #2, i.e. to investigate supporting instruments to encourage individual decision-makers, this thesis addresses both individuals' investment decision-making behaviors and their perceived risks. The knowledge gained can serve as a basis for support tools and policy instruments. In this context, Achtnicht and Madlener (2014) attributed the shortfall in relation to climate targets and low retrofit rates to a lack of understanding of individual investment decisions. Several studies have modeled and analyzed energy efficiency (Allcott, 2011; Blumstein et al., 1980; Brown, 2001; DeCanio, 1993; Häckel et al., 2017; Rockstuhl et al., 2021; L. Weber, 1997) and have tried to explain investment decision-making behaviors, concluding that risks connected to energy efficiency plays an key role (Hassett & Metcalf, 1993; Jaffe & Stavins, 1994b; Rockstuhl et al., 2021; van Soest & Bulte, 2001). Further, the research has shown that effective risk management in investing in building retrofits is important to support individuals in their decision-making (Baltuttis et al., 2020; Jackson, 2010; Mills et al., 2006; Niemierko et al., 2019). This doctoral thesis analyzes risk perceptions in retrofitting decisions and investigates how the derived insights can be used, for instance in policy instruments, to foster heat transition by supporting individuals' decision-making. The findings on individual investment behaviors can be used to overcome structural barriers and to create or improve political measures. A second aspect to answer Research Objective #2 is to mitigate asymmetric information about low-carbon energy sources' greenhouse gas emissions, thereby supporting decision-makers in their buying or investing in emission-reducing measures (Howarth & Andersson, 1993; Velazquez Abad & Dodds, 2020; White et al., 2021). To increase sustainability and corresponding decarbonization efforts in residential building stock, low- or zero-carbon energy sources such as low-carbon hydrogen instead of fossil fuels can be a key solution (Akhtar et al., 2023; Nyrud et al., 2008; Sorgulu & Dincer, 2018). Many countries (e.g. in the EU) are seeking partnerships and build international supply chains, as it requires large amounts of low-carbon energy to produce low-carbon hydrogen and not every location is suitable to produce it (Akhtar et al., 2023; Wappler et al., 2022). To guarantee a sustainable production of the energy carrier, traceability and data-sharing along the supply chain is necessary to verify its contribution to decarbonization (Velazquez Abad & Dodds, 2020). In this way, decision-makers can determine a low-carbon energy carrier's true price/value. Therefore, correct market prices develop and decision-makers are able to decide whether to buy or invest in a low-carbon energy carrier and associated measures (White et al., 2021). The literature has considered digital technologies such as digital product passports (DPPs) as a differentiating and enabling factor to enable traceability and data-sharing along the supply chain (Müller et al., 2023; Saberi et al., 2019). To address the research gap, this doctoral thesis explores how digital technologies enable traceability of sustainability information along international supply chains in order to support individual decision-makers to verify product information and encourage them to buy or invest in emission-reducing measures.

I.3 Structure of the dissertation and embedding of the five research articles

This dissertation is cumulative and comprises five research articles that contribute to the overall research aim, focusing on achieving successful heat transition in the residential building sector. As shown in Figure 1, this dissertation is structured to analyze two primary research objectives: First, an analysis of how policymakers can effectively promote emission-reducing measures; second, an investigation of decision-making and subsequent supporting instruments to encourage individual decision-makers to invest in emission-reducing measures in residential building stock.

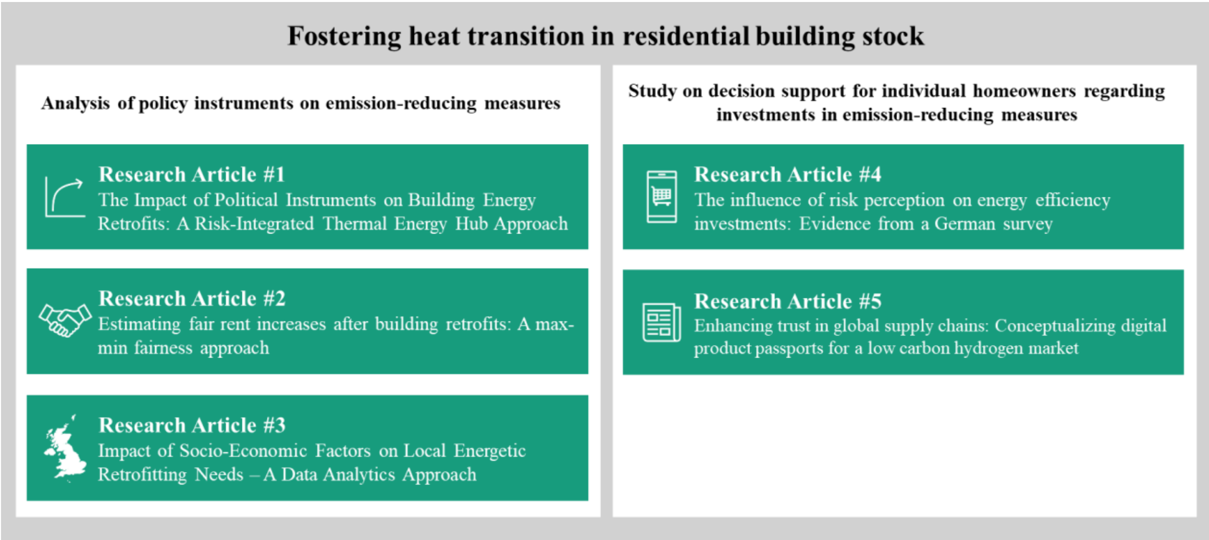

Figure 1: The structure of this dissertation to answer Research Objectives #1 and #2

The remainder of this dissertation is structured as follows: Section II analyzes policy instruments for promoting emission-reducing measures in residential building stock. As emphasized by Gerarden et al. (2017), there is a strong need for the research to assess current energy policies' effectiveness. To comply with this call and to consider the findings on risk as a barrier to investment barrier, Research Article #1 examines policy instruments' impacts on risks and returns on investment in retrofit measures of private residential buildings. The article is based on Geidl et al.'s (2007) Energy Hub and expands this framework to a Risk-Integrated Thermal Energy Hub to model energy flows and uncertainties. Three policy instruments are then analyzed in a case study. Research Article #2 focuses on emission reducing measures in rental buildings and the estimation of fair rent increases by applying Rawls's (1971) max-min fairness scheme. Further, two policy instruments are included in the analysis, and their impacts on fair retrofitting fees is derived. To better allocate scarce financial resources and improve energy efficiency policies, Research Article #3 examines the interdependencies between (regional) building energy efficiencies and influencing socio-economic factors. By applying data-driven methods to publicly available energy performance certification data and socio-demographic data, knowledge and insights are gained for locally tailored policy instruments.

To answer Research Objective #2 and to investigate supporting instruments to encourage individual decision-makers to invest in emission-reducing measures, in Section III, Research Article #4 analyzes the influence of (financial) risks and risk perceptions in individual retrofit decisions. Using Rockstuhl et al.'s (2021) theoretical foundation of two opposing perspectives on risk – the investment risk perspective vs. the energy bill risk perspective – a choice experiment based on a simulated online shop for energy retrofitting was conducted with 174 participants. To obtain transparency not only on future financial savings but also on the carbon footprint of energy carriers such as hydrogen, Research Article #5 applies a multi-step approach with a structured literature review and 13 semi-structured interviews with experts to derive design principles as requirement for a DPP for low-carbon hydrogen. The article presents design principles for data-sharing in form of DPPs, which enables the verifiability of information in globalized supply chains and enables one to establish markets for price premiums of sustainable products. In this way, a low-carbon energy carrier such as low-carbon hydrogen can be priced correctly, and individual decision-makers can be supported in their investment decisions when installing a hydrogen-powered heating system by allowing them to consider their future energy prices.

Section IV of this dissertation draws conclusions from the research findings by presenting a comprehensive summary of all the key findings (Subsection IV.1) and addressing the relevant limitations, offering insights into potential avenues for future research (Subsection IV.2). Subsection IV.3 acknowledges particularly inspiring and related research. Section V presents the references for the thesis, while Section VI – the Appendix – provides additional details on the five research articles in this thesis. Subsection VI.1 provides an overview over the research articles' indexes, while Subsection VI.2 provides a detailed account of the author's contributions to each article. Subsection VI.3 contains all five research articles. The supplementary material not intended for publication contains the full texts of all the articles.

II Policy instruments for investment decisions in emission-reducing measures

II.1 Political instruments' impacts on building energy retrofits

Research Article #1 explores different policy instruments' impacts on mitigating risks associated with building retrofits, as Mills (2003) emphasized that financial risks linked to energy savings are a significant obstacle to investments in emission-reducing measures. To address the intrinsic and extrinsic risks of Wilde (2014), a Risk-Integrated Thermal Energy Hub is developed by extending the original Energy Hub (Fabrizio et al., 2010; Geidl et al., 2007). The Risk-Integrated Thermal Energy Hub computes the mean and variances in the Net Present Value for building retrofits and therefore simultaneously assesses the financial risk and return using a two-dimensional mean-variance representation. By employing this approach, the article estimates Pareto-efficient residential building retrofits and simulates risk-averse individuals' investment decision-making process. When faced with two retrofits with equal expected returns, these individuals prefer the one with lower risk (inspired by Markowitz, (1952).

In a case study, 150 possible retrofits for one exemplary house in Germany were analyzed. To this end, real-world building data of 342 one- and two-family houses (to determine different performance gaps), energy price forecasts and future weather scenarios were used to calculate 250 different CO_2-equivalent emissions savings and 12,500 different Net Present Values for each retrofit. Using these results, the mean and variance was determined to evaluate the financial risk and return within a two-dimensional mean-variance portrayal simultaneously. With this portrayal, the article estimates Pareto-efficient residential building retrofits and models the investment decision-making of individuals who act 'rationally.' Further, the research article examines three political instruments' impacts: Pigouvian emission taxes, indirect subsidies on investment costs, and energy efficiency insurances as technology-specific financial instruments.

The findings illustrated in Figure 2 depict a clear connection between the emission savings and the financial risk of a building retrofit: higher emission savings result in higher risk. Pareto-efficient retrofits (predominantly in the top-left corner of the plot) are chosen by the decision-maker. However, investments with high emission savings (i.e. residential building retrofits that exchange the heating system with for instance a heat pump or a pellet heating system) can mainly be found in the bottom right-hand corner. This empirical evidence supports previous studies, including Mills (2003) and Häckel et al. (2017), who identified risk as a significant obstacle to energy efficiency investments. In addition to the higher risk, the emission impacts are not sufficiently reflected in the current market prices, as measures with high emission savings in particular have low returns. Thus, policy interventions are needed to address this.

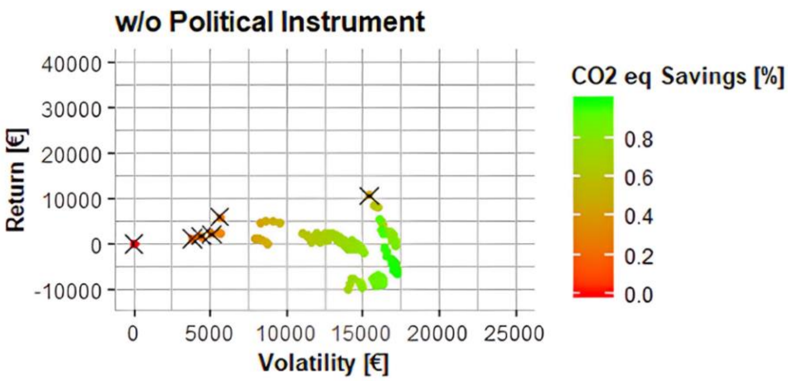

Figure 2: The efficient frontier (highlighted with crosses) of emission-reducing measures (the color of each considered building retrofit indicates the expected emission savings)

To analyze and compare the three political instruments, several design options were applied in the simulation: the percentage of the initial investment that is reimbursed (subsidies), the percentage of the expected energy bill saving that is guaranteed (energy efficiency insurance), and the tax rate (emission taxes). Figure 3 depicts the instruments' effectiveness and costs. Effectiveness is measured by the average emission savings of all Pareto-efficient building retrofits. The costs of political instruments are shared among stakeholders, with subsidies and insurances covered by policymakers and taxes borne by homeowners. The red line represents the anticipated emission savings in the absence of political intervention.

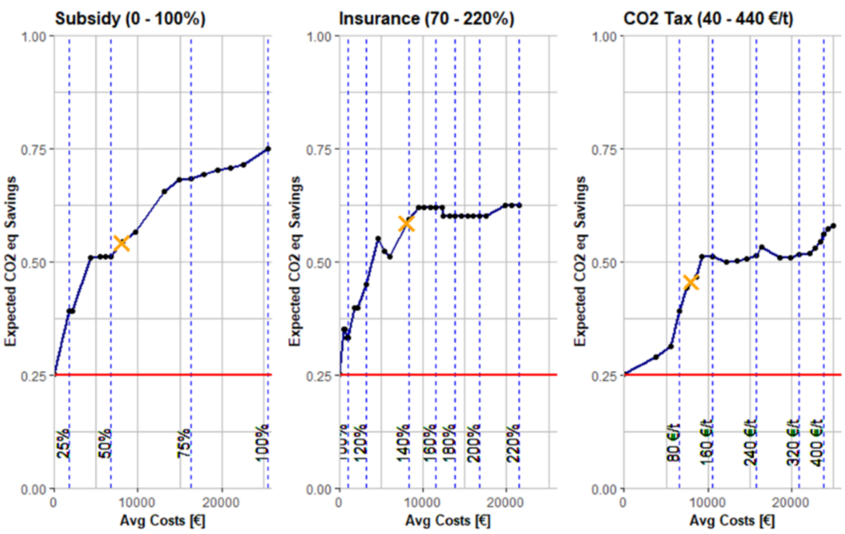

Figure 3: Assigning the incurred costs per building to the three considered instruments' effectiveness (red line = the expected emission savings without any political intervention; X = the designs of instruments that resulted in costs of €8,000[1])

[1] *To better compare the different instruments, the amount of €8,000 was self-selected and has no special meaning.*

Subsidies are found to solely enhance the financial return of building retrofits, potentially resulting in up to 50% reduction in CO_2 emissions (in the case of a 100% subsidy). These findings align with those of Achtnicht and Madlener (2014) – i.e. subsidies, despite their efficiency challenges, can effectively encourage energy efficiency investments in the residential building sector. Further, Research Article #1's results demonstrate the potential of emission taxes as a government instrument without direct costs, which can increase environmentally friendly retrofits' appeal. However, for emission taxes to significantly influence decision-making on building retrofits, they need to be sufficiently high, leading to increased costs for homeowners (see Figure 3). These findings align with Aasness et al. (1996) and Thonipara et al. (2019), who both found that higher emission taxes result in significantly greater reductions in energy consumption compared to lower taxes (Thonipara et al., 2019). Also, the findings show that energy efficiency insurance improves financial return and mitigates risk, since it allows policymakers to bear some of the inherent risk in building retrofit investments. Energy efficiency insurance can therefore enhance the attractiveness of retrofitting efficiency and can potentially reduce emissions by an additional 35% for the sample house when having an insurance of 140%[1]. This finding corroborates the conclusions of Mills (2003) as well as Töppel and Tränkler (2019), who both highlighted energy efficiency insurance's positive impact on investment decisions by mitigating financial risk. Comparing subsidies to insurance, Resarch Article #1 concludes that insurance is generally more efficient when considering environmental impacts and costs, although subsidies are easy to scale up.

Research Article #1's findings offer several recommendations for policymakers:

(1) It reaffirms the trade-off between the environmental and the financial benefits of energy efficiency investments, as emission-reducing measures with high emission savings have lower expetected returns. This is due to the fact that emissions are not suffienctly reflected in current market prices. Policymakers must effectively address this trade-off.

(2) Private households cannot achieve current environmental policy targets without political intervention. The high financial risk of building retrofits, combined with investor loss aversion, poses a significant barrier. Thus, policymakers should design instruments that not only consider the estimated financial return, but also address the

[1] The height of 140% corresponds to 140% of the expected Net Present Value without political intervention. The low-risk decision-maker has still a certainty equivalent of less than the expected Net Present Value, as the expected Net Present Value increases with 140% energy efficiency insurance.

associated risks. Innovative approaches such as the proposed energy efficiency insurance can simultaneously reduce the risks and increase the returns.

(3) The case study highlights the cost implications for policymakers when aiming at ambitious goals, such as the German government's 80% CO_2-equivalent emission savings target, solely relying on existing instruments. Policymakers should explore supporting research for new technologies that are both environmentally friendly and financially beneficial to homeowners.

II.2 Estimating fair rent increases after building retrofits

Besides owner-occupied houses (see Research Article #1), rental buildings are a special case. While here the decision-maker for investments in emission-reducing measures is the landlord, the nonetheless do not directly benefit from saved energy costs after a retrofit, as these are typically paid by tenants. To solve this mismatch in incentives, known as the landlord-tenant dilemma, policy allows a landlord to increase the rent as a percentage of the retrofit investment, i.e. a *percentage-retrofitting-fee* (I. Weber & Wolff, 2018). Germany's government has set a maximum percentage-retrofitting-fee allowed by law (e.g. in Germany, 2022: 8%). The downside of this fee is the tenant's perspective, for whom the energy cost savings are often below the increase in rent (Berger & Höltl, 2019). In contrast, considering the retrofitting rate in Germany, the current design of the percentage-retrofitting-fee specified in law as a fixed maximum seems to be a weak incentive. Also, the financial risks lie not with the decision-making landlord but with the tenant. Whereas a landlord's investment and increased cash flows by increasing the rent as a percentage of the retrofit investment are certain, the tenant faces financial uncertainty in their energy bill savings (I. Weber & Wolff, 2018).

In this vein, Research Article #2 proposes a model that balances these different perspectives and estimates fair percentage-retrofitting-fees. Specifically, it focuses on residential building retrofits as emission-reducing measures that decrease a residential building's thermal energy demand. The model considers economic as well as environmental interests of the tenant, the landlord, and society. The article is based on Rawlsian justice (Rawls, 1971) and derives a max-min fair solution for a percentage-retrofitting-fee (Bonald & Massoulié, 2001; Luss, 1999). First, a general and simple model was developed to demonstrate the different changes in utility caused by a retrofit of a rented house for a tenant, a landlord, and any other individual not involved in the tenancy. This model considers a retrofit's environmental and economic effects. Also, with the help of expected utility theory, the model includes the financial risk caused by uncertain future energy prices. This model is the basis to derive a max-min fair percentage-retrofitting-fee depending on the investment in energy efficiency. The article shows that applying Rawls's theory of justice in the form of max-min fairness results in a single solution, guaranteeing the maximal minimal utility increase for all individuals. Using a case study, considering four representative houses in Germany and 1,080 retrofitting investments in Germany, the article shows how a fair percentage-retrofitting-fee is influenced by a building's efficiency standard and the investment amount. To include uncertainty of future energy prices in the analysis, 1,000 price paths were simulated to derive the expected utility changes caused by energy bill savings.

The results show two clear trends, which are visible in Figure 4. First, higher investments in residential building retrofits result in a lower fair percentage-retrofitting-fee, and vice versa. Second, the lower a building's energy efficiency standard, the higher a fair percentage-retrofitting-fee is. Further, the comparison of the results to the existing 8% fee reveals that, for small retrofitting investments in buildings with low energy efficiency standards, the fair percentage-retrofitting-fee exceeds 8%. The fair percentage-retrofitting-fee is lower than 8% for all other cases and thereby unfair to the tenant. In sum, the results reveal that current regulations concerning percentage-retrofitting-fees are not fair to either landlords or tenants.

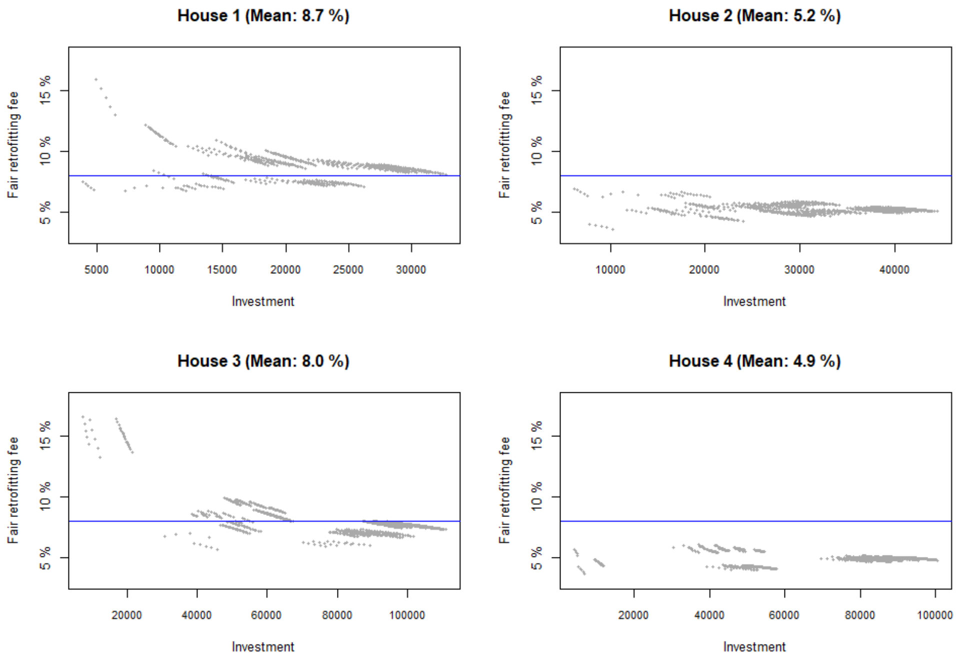

Figure 4: Fair percentage-retrofitting-fees dependent on the investment amount for exemplary houses (the blue line = the law in Germany)

To examine policy instruments' impacts on investment decisions while considering risks in rental buildings, the article further analyzes how subsidies and emission taxes affect the fair percentage-retrofitting-fee. Both instruments would have only limited success if they are not adapted to tenancy. First, since the retrofitting fee is a percentage of the investment amount, reducing this investment amount with subsidies would be offset by reduced absolute rent increases. Second, emission taxes that increase the energy prices of fossil energy sources would concern only a tenant when they pay their energy bill. The decision-maker in retrofits (the landlord) would not be affected by both political instruments. To transfer the effect, adaptations of the prescribed percentage retrofitting fees are necessary. The results show that the fair percentage-retrofitting-fee increases with either the height of the subsidies or the height of the tax rate. Thus, the fair percentage-retrofitting-fee of buildings with low energy efficiency standards increases more than for buildings with high energy efficiency standards. One potential reason in the context of emission tax may be that emission tax savings of residential building retrofits to buildings with low energy efficiency standards are higher than for buildings that already have fairly high energy efficiency standards. Thus, the increase in utility for tenants caused by emission tax savings is higher, also allowing for a higher fair percentage-retrofitting-fee. Adapting the percentage-retrofitting-fee in parallel to the implementation of certain environmental policy instruments, as proposed in the article, would promote green investment and would be fair to all individuals, simultaneously. Without this adaptation, environmental instruments would not affect tenancies and would be much less effective.

Research Article #2's results lead to several proposals for policymakers:

(1) A fixed retrofitting fee limit can be unfair. For especially small investments in residential building retrofits of rented buildings with low energy efficiency standards, the fair fee is higher than the current legal fee, disadvantaging landlords. Investments in retrofits for buildings with fairly high energy efficiency standards disadvantage tenants. Thus, a retrofitting fee should at least depend on the building's efficiency standard, as this has strongly impacts on a fair retrofitting fee. Nonetheless, notably, based on the results, this would result in high fees for buildings with low energy efficiency standards, and vice versa. This could be problematic, especially given the relationship between low energy efficiency standards and the probable low ability of the tenant to pay for high retrofitting fees. It is therefore better to implement a retrofitting fee that depends on the expected energy bill savings, as proposed in the model. For instance, this could be established by making the determination of a fair retrofitting fee part of energy consulting (Michelsen & Madlener, 2012).

(2) The article shows that especially for buildings heated by volatile energy sources and occupied by risk-averse tenants, the uncertain energy bill savings after the retrofit strongly influence a fair retrofitting fee. Thus, after implementing a fair retrofitting fee,

policymakers should introduce suitable models to include financial risks in the calculations. Studies, such as that of Niemierko et al. (2019), can help to establish models as realistic as possible.

(3) The retrofitting fee needs to be adapted if environmental policy instruments such as subsidies or environmental taxes are in place. Otherwise, environmental instruments would not affect the attractiveness of retrofitting rented buildings and would be less effective in general. The article shows how policymakers should change regulations concerning retrofitting fees parallel to an emission tax implementation. Further, the applied retrofitting fee should consider the specific subsidy for the investment.

II.3 Socio-economic factors' impacts on local energetic retrofitting needs

In addition to analyzing different policy instruments, considering different risk types and whether a building is owner-occupied or rented, the research has shown that policy measures' effectiveness can vary. One reason for this may be that policy instruments are often designed as scattershot approaches without considering local circumstances, such as socio-economic factors or building characteristics (Jones et al., 2009; Kastner & Stern, 2015). In this sense, and as many studies have shown, the impacts of socio-economic factors and barriers on building retrofit decisions (Achtnicht & Madlener, 2014; Druckman & Jackson, 2008; Kastner & Stern, 2015; Wilson et al., 2015), the research has highlighted the need for locally tailored policy instruments that consider these factors, rather than national policies (Morton et al., 2018). Given that local authorities already provide a range of energy services, are committed to reducing greenhouse gas emissions (Comodi et al., 2012; Wade et al., 2020), and are responsible for coordinating policies and measures to reduce residential energy use (Morris et al., 2017), it is crucial to examine socio-economic factors' influences on building energy efficiency at the local level. However, it is not yet fully understood what local differences exist in building characteristics and building energy efficiencies, and how these are influenced by socio-economic factors. To this end, and to improve environmental policies' effectiveness by deriving locally tailored policy measures, Research Article #3 analyzes whether there are local differences in the retrofitting needs of the residential building stocks in England, Scotland, and Wales.[1] It also explores the socio-economic factors that could potentially account for these regional differences.

[1] The article focuses on England, Scotland, and Wales rather than Germany, owing to data availability.

Research Article #3 used a data-driven approach based on an extensive real-world dataset of more than 10.5 million Energy Performance Certificates of residential buildings in England, Scotland, and Wales, as well as additional socio-demographic data from the 2011 Census. In a first step, $\chi 2$-independence tests were performed to reveal regional differences in the energy efficiency of the analyzed residential building stocks in England, Scotland, and Wales. Using a random forest classifier, k-Means algorithm and a second $\chi 2$-independence test, archetypes with specific building retrofit needs of the residential building stock were derived and tested for local differences. Last, to identify socio-economic factors that influence energy efficiency, the article employs several Random Forest Regressions on different quantiles of the local authorities' energy efficiency.

The results show that, overall, the energy efficiency and the density of the seven derived building archetypes with their various energetic retrofitting needs differ locally at a 5% significance level. Six of the seven archetypes have a specific retrofitting need, i.e. the archetype is characterized by at least one building characteristic, which indicates the need for a retrofit. Figure 5 displays the archetypes and their characteristics.

Archetype	Energy Efficiency Score [1-100]	Hot Water Efficiency Label [1-5]	Share of Low Energy Lighting [%]	Living Area [m²]	Window Performance [%]	Roof Performance [%]	Walls Performance [%]
1: Lukewarm-Shower-Polluter	47.94	1.68	45.05	90.87	53.86	87.47	57.44
2: Villa	61.16	3.57	43.29	198.30	56.93	88.96	61.11
3: Allrounder-with-Torches	67.68	3.92	23.38	88.28	59.76	89.35	82.73
4: Straw-Roof-Building	51.60	3.58	39.93	101.78	49.73	7.94	40.89
5: Cardboards-Building	58.59	3.90	46.10	89.46	56.93	86.94	23.55
6: Building-with-Window-Cracks	54.61	3.64	41.70	97.09	9.44	86.12	40.42
7: Eco-House	71.75	3.92	85.74	88.28	66.93	91.27	83.29

Figure 5: Using the averages of key buildings properties and of the Energy Efficiency Score, the seven building archetypes are named

In the vein of the influencing socio-economic factors on energy efficiency, Figure 6 shows the overall weighted importance of the superordinate domains[1] of the socio-economic factors, and the findings reveal that the correlation of socio-economic factors with building energy efficiency varied, depending on the energy efficiency level. When excluding the extreme 1% and 99% quantiles, clear trends emerged regarding different domains' importances. The importance of employment and housing domains diminish as buildings' energy efficiency increase, declining from 22% to 14% and 26% to 12%, respectively. Also, there is a slight decrease in demographics' importance. Conversely, the socio-economic and economic domains

[1] The naming of these superordinate domains and the assignment of each socio-economic factor originated from the 2011 Census. *Socio-economic* is both an individual superordinate domain and the generic term for all factors.

became more important as energy efficiency improves. The overall importance of household composition remained fairly consistent, with a slight increase from 16% to 20% at the 90% quantile. Notably, these trends do not hold for the 1% and 99% quantiles, which represent the most extreme cases where varying outcomes are expected. Further, the findings provide more details on specific socio-economic factors' impacts, for instance, how rural a region is. In general, factors relating to the employment domain exhibit greater importance. Other major influences include *share of vacancy*, *living rent-free*, *residents above the age of 60*, and *travel to work*. Further, two illustrative locally tailored policy measures were developed to exemplify how the findings can be used to improve residential buildings' energy efficiency.

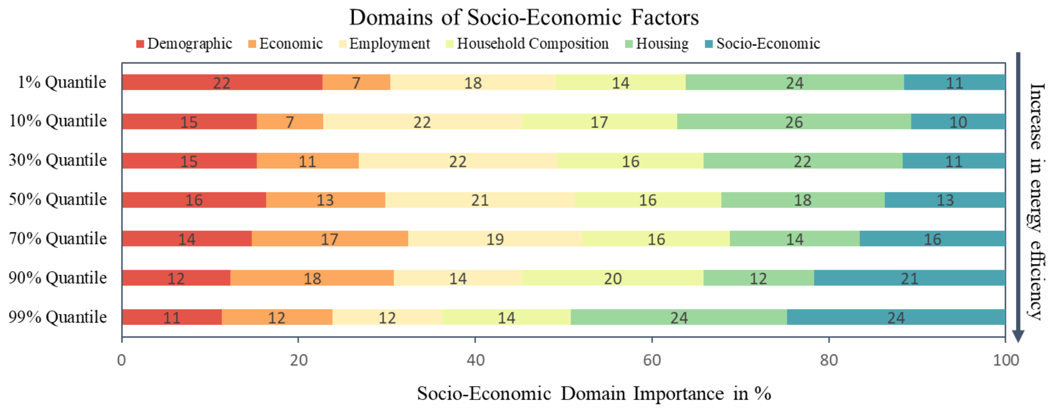

Figure 6: Comparison of the importance of the different socio-economic domains shows how the domains' influences shift with different levels of local energy efficiency

Research Article #3's results lead to several policy implications:

(1) The analyses provide compelling evidence that there are significant regional differences in the energy efficiencies and building stocks in England, Scotland, and Wales. As a result, environmental policies should be tailored to the local context if they are to achieve maximum effectiveness. Policymakers are encouraged to use available data, even at a more granular level that provides greater detail, to design tailored policies that meet specific needs.

(2) By deriving building archetypes, it becomes possible to prioritize essential retrofits for residential building stock within a local authority, providing valuable guidance on the most suitable instruments to implement.

(3) When implementing measures, policymakers should consider the local population, including their various socio-economic factors, as well as the desired target in terms of current and future energy efficiency levels. It is important to maximize the resource allocation's effectiveness. Even when addressing the same retrofitting need in two areas, there may be varying socio-economic factors that influence the outcomes.

III Decision support for individual investments in emission-reducing measures

III.1 Risk perceptions’ influences on energy efficiency investments

To answer research objective 2 and to investigate supporting instruments to encourage individual decision-makers to invest in emission-reducing measures, Research Article #4 analyzes decision-makers’ risk perceptions. As noted, financial risk is a key factor in investment decisions for emission-reducing measures. This risk stems from uncertainty about future financial and energy savings and raises concerns among decision-makers (Mills et al., 2006). Here, risk connected to energy efficiency investment as an emission-reducing measure is perceived from two contrary perspectives (Rockstuhl et al., 2021). From an *investment perspective*, the perceived risk acts as a barrier to making economically and ecologically beneficial energy efficiency investments owing to risk aversion among decision-makers (Farsi, 2010; Hirst & Brown, 1990; Mills, 2003). This phenomenon has led to the term *energy efficiency gap* (Jaffe and Stavins 1994; Gerarden et al., 2017). However, from an *energy bill perspective*, energy efficiency is perceived as an insurance, reducing energy price exposure (Buhl et al., 2018; Naumoff & Shipley, 2007; Thompson, 1997). Thus, the risk of high energy bills in future decreases with higher investments, adding additional benefits for risk-averse decision-makers. These two opposing perceptions indicate a strong potential for supporting decision-makers when they seek to invest in emission-reducing measures. However, both perspectives have only been studied theoretically in the literature in modeling decision-making and simulation-based case studies (Buhl et al., 2018; Jackson, 2010; Rockstuhl et al., 2021).

To this end, Research Article #4 applies these two opposing risk perceptions in a choice experiment to evaluate the potential of nudging risk-averse investors toward greater investment in energy efficiency. Thereby, several energy efficiency investments in the contexts of the investment perspective and of the energy bill perspective were presented to evaluate whether there are significant differences in investment decision-making, through a choice experiment in the form of an energy efficiency online shop with different displayed information corresponding to these two risk perception perspectives. As online applications are typical for finding information about energy efficiency investments (Fraunhofer IBP, 2021), the choice experiment was designed as an online shop that offers various real-world energy efficiency retrofitting measures for participants to purchase for their (imaginary) houses. Further, the 174 participants were divided into three treatment groups (treatment 1: investment risk; treatment 2: energy bill risk; treatment 3: both risk perspectives). In a first step, an introductory video was presented, and each participant was asked to imagine that they are the owner of a single-family house and to think about possible retrofitting options. Each participant was then asked to click through the online shop, which displayed information specific to the treatment group and interacts with them as if they were browsing for retrofits for their home. After choosing their preferred set of retrofitting measures, each participant was asked to rate the importance of the key figures in the online shop, respective to their treatment group in an additional questionnaire. Figure 7 illustrates the survey procedure.

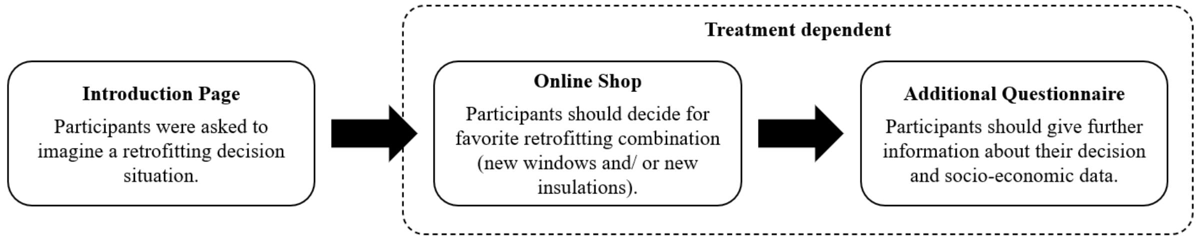

Figure 7: The three-step survey procedure

Research Article #4's result show that displaying retrofitting measures with key figures of the resulting energy bill increases investment in energy efficiency by about 20%. The effect is significant at the 5% significance level (see Table 1). Thus, there is a significant difference in the investment decision-making between an online shop that displays information from the investment perspective and an online shop that displays information from the energy bill perspective. Treatment group 1 (the investment perspective) invested only €13,022.88, and treatment group 2 (the energy bill perspective) €15,541.99. This means that displaying figures relating to energy bills led to increased investment of around €2,500. The results also show that the differences in decision-making are not only significant but also substantial, as the 20% increased investment in energy efficiency translates into reduced emissions and helps avert climate change's damaging effects.

A further conducted cluster analysis for treatment group 3 (both risk perspectives) – using the k-Means and the Elbow method (resulting into three clusters) – provides two crucial insights into the decision-making behaviors (see Figure 8).

Attribute	Expression
average investment in the online shop with displayed information in an investment perspective (treatment group 1)	€13,022.88
average investment in the online shop with displayed information in an energy bill perspective (treatment group 2)	€15,541.99
average investment in the online shop with displayed information in both perspectives (treatment group 3)	€14,349.91
p-value of Mann-Whitney U-test for alternative hypothesis (H1): *investment in treatment group 2 > investment in treatment group 1*	0.0007
p-value of Mann-Whitney U-test for alternative hypothesis (H2): *investment in treatment group 3 > investment in treatment group 1*	0.037
p-value of Mann-Whitney U-test for alternative hypothesis (H3): *investment in treatment group 2 > investment in treatment group 3*	0.049

Table 1: Results of Mann-Whitney U-test to compare average investment in different displayed information setups in the online shop

First, confronted with both perspectives, the participants weighed both perspectives differently while deciding. Clusters 1 to 3 were respectively characterized by an exclusive¸ a strong and a balanced consideration of the investment perspective. In turn, this results in increasing energy efficiency investment from cluster 1 to cluster 3. Second, the results show an overall dominance of the investment perspective, as 40 of the 55 participants chose the investment perspective over the energy bill perspective. This should be considered by stakeholders who seek to achieve a more sustainable future, highlighting the necessity of setting the proper context for energy efficiency.

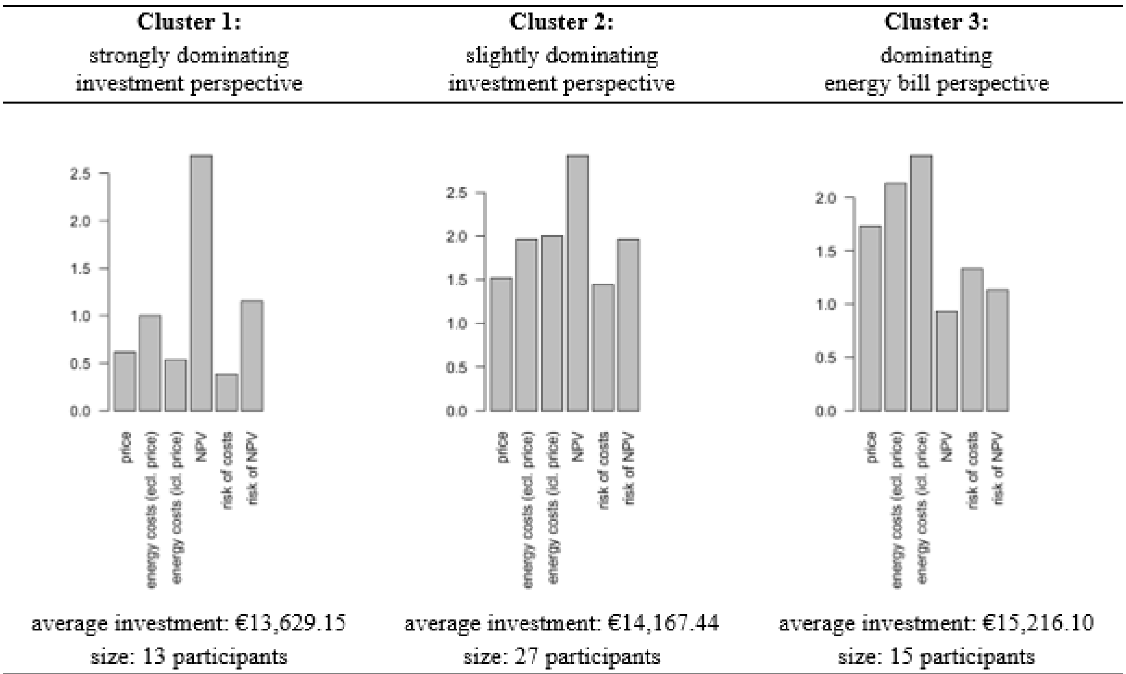

Figure 8: Different clusters of decision-makers in treatment group 3

Research Article #4's findings illustrate how supporting instruments can effectively promote individual investment decisons in emission-reducing measures:

(1) Information and awareness campaigns, as supportive instruments, guide decision-makers such as homeowners in their energy efficiency investment decisions. In this context, more attention should be paid to the energy bill perspective as well as to the risk reduction potential of energy efficiency. Existing subsidy programs and information campaigns can provide more detailed information on the potential for risk reduction to create stronger incentives for sustainable investment.

(2) Reaching every decision-maker requires individual solutions instead of scattershot approaches. As decision-makers weight certain metrics differently, the relevant metrics from both perspectives should be presented in an understandable, descriptive way for the greatest possible transparency.

III.2 Enhancing trust in global supply chains

Besides investments in energy efficiency retrofits, low-carbon energy carriers are considered as an emission-reducing measure and therefore a solution for decarbonizing the residential sector (Akhtar et al., 2023; Nyrud et al., 2008; Sorgulu & Dincer, 2018). A key energy carrier is low-carbon hydrogen. It is regarded as an instrument to substitute fossil fuels, which cannot be replaced by electricity alone (Seo et al., 2020) . However, this can only be accomplished if the hydrogen has been produced in a low-carbon process with electrolysis powered only by renewable energy sources (Velazquez Abad & Dodds, 2020). Yet since this type of production requires large amounts of renewable, low-carbon energy, and not every location is suitable to produce low-carbon hydrogen. As a result, many countries (e.g. in the EU) are seeking partnerships to expand their hydrogen economy, build international supply chains, and import hydrogen from more suitable locations (Akhtar et al., 2023; Wappler et al., 2022). Recent studies points out that, to reduce greenhouse gases along the supply chain, consumers are willing to pay a premium for guaranteed low-carbon hydrogen (White et al., 2021). However, if buyers do not know how carbon-friendly the hydrogen is produced, a market failure for price premiums occurs owing to asymmetric information. The market for low-carbon hydrogen will not emerge, since buyers cannot be sure whether the premium price is justified. For this reason, certifications help to reduce information asymmetries, provide transparency in the supply chain, and are a cornerstone for the development of a market for low-carbon hydrogen (Velazquez Abad & Dodds, 2020; White et al., 2021). In the energy transition, this means that, among other things, manufacturers can demand price premiums for their environmentally friendly production methods, or that decision-makers in the residential building sector can consider future energy prices when taking investment decisions on new hydrogen-powered heating systems.

Against this background, Research Article #5 paves the way for traceability of emissions along supply chains in the form of DPPs for low-carbon hydrogen. DPPs are a digital solution for sharing product-specific information along the supply chain to any (including end-) customers. While studies have analyzed the suitability of specific technologies for supply chain traceability (Bodkhe et al., 2020; Liu et al., 2021; Saberi et al., 2019), researchers and practitioners are still searching for applicable solutions.

To address this research gap, Research Article #5 develops six design principles for a hydrogen DPP that enables verification in complex hydrogen supply chains and that makes allowances for the concerns and challenges of different stakeholders regarding data-sharing. The article follows a multi-step approach with a structured literature review followed by 13 semi-structured interviews with experts and qualitative content analysis for a synthesis of design principles. The approach is based on the Design Cycle Research of Hevner et al. (2004) and covers especially the first steps of that procedure. In the literature review, the existing knowledge base and specific challenges of supply chain transparency were studied. Initially, the search resulted in a total of 448 research articles. After screening their content and conducting a forward/backward search, the final 29 articles were analyzed to identify challenges and derive meta-requirements. An initial set of design principles was formulated based on these findings. While the derived meta-requirements are use-case-agnostic, the first draft of the design principles had a broader foundation and was specifically applied to the hydrogen context. This application was facilitated by incorporating general background information about hydrogen supply chains and certification. Following the initial development of the design principles, we evaluated these in 13 semi-structured interviews with experts, following Schultze and Avital (2011). In a last step, the author’s team discussed the feedback of the two previous process iterations in detail and finalized six design principles.

Research Article #5’s findings, thus of the literature rewiew, revealed nine challenges to the use of DPPs in the hydrogen supply chain (lack of transparency, privacy concerns, loss of control, system vulnerability, threat of data misuse, lack of trust; data integrity, lack of interoperability, and data processing). After identifying these challenges, three meta-requirements were derived as the basis for the design principles:

- *Enable traceability and efficient data processing along the entire supply chain.*
- *Ensure sufficient confidentiality and meet the sovereignty requirements of stakeholders.*
- *Ensure the reliability and trustworthiness of the shared data.*

The final set of six design principles for a DPP in hydrogen supply chains, following the 13 semi-structured interviews with experts from practice and academia, are:

Holistic Data Capture: This design principle ensures comprehensive data collection across the entire hydrogen supply chain to enable traceability and accurately assess its environmental impact (Velazquez Abad & Dodds, 2020; White et al., 2021). By capturing data at a detailed level, it avoids inaccurate estimations and ensures the effectiveness of a DPP in enhancing sustainability within supply chains.

Data Privacy: This design principle addresses the concerns of supply chain stakeholders regarding data control and information disclosure (Liu et al., 2021; Saberi et al., 2019). As stated, core function of a DPP is traceability. The need for sustainability disclosure for decarbonizing hydrogen supply chains is the main driver for developing a DPP that enables verification of hydrogen origins and usage. Complex hydrogen supply chains result in a high amount of different stakeholders in an ecosystem using DPPs. The design of a DPP must incorporate privacy-preserving measures that ensure that stakeholders are willing to share data within the DPP but keep sovereignty over their data.

Decentralized Data Administration: In order to avoid a central authority that has to be trusted by all stakeholders of the DPP, the research illustrates that a decentralized data administration should be reflected in the design of a DPP. A decentralized data administration ensures collaboration without agreeing on a central entity for data administration and can address the vulnerability of systems. It prevents single-point failures since an attack or technological failure at one point does not lead to an entire failure of the DPP infrastructure.

Forgery-Proof Data: The research illustrates that data integrity is indispensable to ensure a DPP's usefulness and applicability (Bodkhe et al., 2020; Zhao et al., 2019). Hence, this design principle is essential to enable verification along the hydrogen supply chain. A tamper-proof architecture ensures stakeholders' trust in a DPP system and reduces the fear of data misuse.

In order to achieve forgery-proof data, one could include the use of cryptographic or decentralized approaches to ensure tamper-proof data input and transfer.

Automated Passport Processing: Processing a DPP along the entire supply chain is complex, as the supply chain is globally meshed. Therefore, an automated processing of information shared within the DPP is necessary to ensure an efficient data management on the stakeholders' side. This also includes the option to aggregate DPPs with different supply chain histories in the sense of cross-organizational collaboration across different domains.

Interoperability: A DPP is especially useful and realizable when it can be used with already existing systems. On the one hand, this includes technical interoperability. This means that data from different systems can be used and incorporated into the DPP. On the other hand, a DPP should be interoperable with various existing certifications and sustainability standards. For global verification of hydrogen, DPPs must function across existing certification standards and reporting requirements. Therefore, DPPs must be designed interoperable.

In sum, a DPP for low-carbon hydrogen can be used to reduce information asymmetries and to enable a standardized market with price premiums. In this way, low-carbon hydrogen can be priced correctly. In the building sector, individual decision-makers are supported in their investment decisions for installing hydrogen-powered heating systems. This support stems from the ability to consider future energy prices. Further, in municipal district heating or gas supply, decision-makers can use the resulting market prices to determine the optimal use of low-carbon hydrogen in the energy mix considering both economic and environmental factors.

Research Article #5's findings illustrate how digital technologies can be used to promote individual investment decisions in emission-reducing measures. However, currently, the industry is still far away from implementing and using solutions such as DPPs.

(1) Both the literature review and the semi-structured interviews with the experts called for sharing environmental data along the entire supply chain in order to trace and verify information on emissions and product sustainability. Only in this way is it possible to price products correctly and therefore enable targeted sustainability measures. This requires cross-organizational and cross-national cooperations and the use of digital technologies, which must be actively promoted by leading stakeholders.

(2) Further, policymakers and the industry must tackle obstacles to realizing a DPP and execute necessary actions in the areas of 1) infrastructure and technology adoption, 2) governance and regulation, and 3) initiation and functionality to pave the way for a hydrogen DPP. For instance, in area 1, a digital infrastructure and interfaces must be built. To progress in area 2, a clear regulatory framework must be developed and the policy must incentivize the implementation of a DPP. In area 3, minimal standards must be defined and a demonstrator must be developed.

IV Conclusion

IV.1 Summary

The pressing existential threat of climate change is reaching a critical tipping point, after which the irreversible consequences of global warming become unavoidable. In response to this urgency, governments worldwide are taking proactive measures to introduce environmental initiatives and policies aimed at promoting a sustainable future (Mercure et al., 2021). In this vein, and to advance decarbonization, the residential sector has a critical role. In Germany, for instance, residential buildings account for about 28% of total energy consumption and about 27.1% of the greenhouse gas emissions in 2020. Despite intense efforts by policymakers and researchers to address various aspects of heat transition and to develop a wide range of policies, the set climate targets in this sector are not being met – not even close. One major obstacle is the so-called energy-efficiency gap: decision-makers refuse to carry out emission-reducing measures, although these would be economically and ecologically sensible. Given this context, the primary objective of this dissertation is to stimulate heat transition in the residential building sector. First, it is examined how policymakers can effectively promote emission-reducing measures in the residential building stock. Second, it is investigated how supporting instruments can encourage individual decision-makers to invest in emission-reducing measures.

Against this background, the results concerning objective 1 show how policymakers can increase the attractiveness of environmental policies by considering uncertainty, stakeholders' utility, and regional differences in their instruments. Considering findings on risk as investment barrier, Research Article #1 examines policy instruments' impacts on the risks and returns on investments in retrofit measures for residential buildings. The basis is the extension of Geidl et al.'s (2007) Energy Hub to a Risk-Integrated Thermal Energy Hub as a framework to model energy flows and uncertainties. The findings reveal that retrofits with higher emission savings have a higher risk and are not Pareto-efficient and are therefore not chosen by risk-averse decision-makers. Against this background, energy efficiency insurances mitigate risks and encourage emission-reducing measures, offering a relatively cost-efficient alternative to subsidies. This article also suggests that emissions taxes must exceed €140 per CO_2 ton if they are to have a significant impact on investment decisions. Regarding uncertainty and owing to the high percentage of rental housing, Research Article #2 focuses on retrofitting rental housing. To overcome the landlord-tenant problem and increase the attractiveness of retrofits, the article derives a model for estimating fair retrofit-percentage-fees considering tenants' risk of uncertain energy bill savings after the retrofit using expected utility theory. The results indicate that a building's efficiency standard and the investment amount in energy efficiency influence the fair percentage-retrofitting-fee. The findings reveal that current regulations concerning percentage-retrofitting-fees are not fair to either landlords or tenants. Further, the fair percentage-retrofitting-fee increases with either the height of the subsidies or the height of an emission tax rate. While it does not consider financial uncertainty in policy instruments, addressing regional differences and socio-economic factors instead, Research Article #3 provides insights into tailored local policies. In this context, unsupervised machine learning methods reveal clear evidence of regional differences in residential energy efficiency and retrofitting needs across England, Scotland, and Wales. Further socio-economic factors show a strong correlation to a building's energy efficiency, with the correlation varying depending on different degrees of this condition. The article claims that local circumstances in buildings' energy efficiency and socio-economic factors should be reflected in policy instruments.

The results regarding Research Objective #2 reveal insights into how to support individuals to invest in emission-reducing measures. A key aspect is to understand individuals' risk perceptions, as there is a major barrier to investment. Research Article #4 analyzes the influences of two opposing perspectives on investment in emission reducing measures: the investment perspective and the energy bill perspective. The results show that decision-makers in the experimental online shop with the energy bill risk perspective invested about 20% more than those with the investment risk perspective. Further, the results show an overall dominance of the investment perspective, as participants weighted the investment perspective over the energy bill perspective. These findings provide a new way to nudge individuals toward energy efficiency investments, which is particularly important for policymakers. Thus, it is recommended to actively use the risk-reducing potential of the energy bill perspective when promoting emission-reducing investments. Besides retrofitting residential buildings to reduce energy demand, the decarbonization of the energy carrier can be an emission-reducing measure. Research Article #5 provides insights into how to design a DPP for low-carbon hydrogen. Based on the literature and semi-structured interviews with experts, challenges and meta-requirements for supply chain traceability were identified. The article illustrates that a DPP must collect data comprehensively and automatically, must process them in a decentralized and tamper-proof way, must protect stakeholders' privacy and sovereignty, and must ensure interoperability. The results provide new insights into supply chain traceability and provide a starting point for realizing a DPP in hydrogen supply chains, to enable low-carbon markets, supporting decision-makers in their investment decision for installing a hydrogen-powered heating system by allowing them to consider their future energy prices.

IV.2 Limitations and future research

Naturally, like any research endeavor, the results of this dissertation are accompanied by certain limitations, which open new avenues for future research. Instead of delving into the limitations and prospects for further research of each individual research article, the following section presents an overarching view of the limitations and future exploration areas in this doctoral thesis. Specific information regarding the limitations of each article can be found in the supplementary material.

First, the research designs and methodologies in all the ariticles limit this doctorial thesis's results. Research Articles #1 and #2 for instance used a case study research design, thereby simplifying the real world by using assumptions among others relating to costs, financial benefits, and environmental benefits. Further, only a set of exemplary retrofitting investments and a low number of different houses were used to explore the different effects of policy instruments (Research Articles #1 and #2). Thus, the findings may not be easily generalized owing to the specific nature of each case. To this end, the articles and their findings were evaluated in the context of the literature. Nonetheless, researchers may validate the results through alternative research methods, or may validate the assumptions or limitations. Further, Research Article #3 used a data-driven methodology with CRISP-DM (Cross Industry Standard Process for Data Mining). Owing to this set research design, the findings only show correlations but do not allow statements about causality. To overcome this limitation, future work may use other research methodologies such as experiments or interviews with homeowners to find causalities and clarify the found results on correlations between socio-economic factors, energy efficiency retrofits needs, and regional differences. Research Article #4 is limited owing to its set research design. The participants in the field experiment had to imagine a situation where they needed to choose retrofitting measures for their imaginary homes. These imagined scenarios can differ from reality and may therefore distort the results. Future research could additionally analyze how the approach performs in de facto retrofitting decision processes. For instance, studies could collaborate with energy consultants to validate how the energy bill perspective and the investment perspective influence individuals in consultations.

Second, the results of all the research articles and thus this dissertation rely on the underlying data and their quality and availability. As noted, Research Articles #1 and #2 used a case study approach with forecasted energy prices and weather scenarios based on real-world historical data. Further, Research Article #1 used real-world data of 20,000 one- and two-family houses in Germany to model the performance risks. These data were collected by energy consultants and therefore depend on their conscientiousness in collecting the building characteristics. In this vein, data quality is a limiting factor in Research Article #3, as Energy Performance Certificates are the foundation of the article. A significant number of research papers have revealed quality problems in these certicificates (Hardy & Glew, 2019). Further, Research Article #3's results are limited owing to data availability, as aggregated information of local authorities for the socio-economic factors had to be used, because Energy Performance Certificates contain no information about residents. In turn, this aggregated information limits the article's informative value. Future research may use socio-economic data at a more granular level, preferably at the household level, to obtain a deeper understanding of socio-economic drivers of and barriers to energy efficiency. This would allow for the identification of socio-economic factors' influences on individual behaviors and decision-making for or against retrofitting. In Research Article #4, data availability was also a limiting factor. The participant sample in the field experiment was relatively small and potentially biased. Future research into effective nudging strategies should include a broader and more representative sample. The same holds for Research Article #5, as the evaluation was limited to 13 semi-structured interviews with experts from academia and practice. Although the interviewees represented a valuable sample of experts in digital traceability solutions, data-sharing, and hydrogen stakeholders, more interviews with representatives of the hydrogen economy with different background knowledge on certification and data-sharing challenges may have provided more insights into the needs and requirements of the various supply chain stakeholders.

Third, Kahneman and Tversky (1979) showed that individuals tend to perceive risk irrationally. In Research Articles #1 and #2, these findings were neglected in the case studies to propose a solution for 'rational' individuals. Future research could also elaborate on 'irrational' individuals. Further, not all risk types were included. Besides the considered financial risks owing to uncertain energy prices, the risks of changing lending rates or the occurrence of construction defects were omitted. In Research Article #2, one crucial source of uncertainty was neglected: tenant behaviors. In this vein, the so-called *rebound effect* after the implementation of a building renovation should be mentioned. Owing to a building's increased efficiency standard, the residents become less careful in their efficiency behaviors. Future studies should include more sources of risk so as to carefully investigate their impacts on decision-making or policy instruments. Further, we assumed different stakeholder risk perceptions. For instance, in Research Article #1, to compare the different instruments' costs, a risk-neutral policymaker was assumed. This is especially important for insurance analysis. Here, the policymaker takes over the individual's risk. Assuming the same risk aversion for the policymaker as for the individual investor would mitigate an energy efficiency insurance's benefits. In Research Article #2, the function used to model changes in utility caused by financial benefits and losses was based on Gandelman and Hernández-Murillo (2014), who observed 0.66 as the parameter for relative risk aversion. Future studies could apply different risk aversions to analyze their impacts on decision-making and their consequences on policy instruments.

Fourth, the approaches of Research Articles #1, #2, and #4 neglect the efforts and costs that would be needed to collect all the needed information and calculate the key figures such as Net Present Value, fair rent increase, or energy bill savings for each retrofit. Nonetheless, at least in Germany, as noted, most people consult energy consultants before retrofitting a building (Michelsen & Madlener, 2012). During these consultation meetings, the necessary energy information about the residential building and the retrofit are collected. Future research could focus on how to use the theoretical models in the research articles and to design digital applications for energy consultancies that can easily derive key figures with the information about the building that is already collected anyway and the current energy price (forecasts).

Fifth, this dissertation focuses on the residential building sector, aiming to understand the impacts on investment decision of energy efficiency investment and emission-reducing measures in this specific context. However, future research could expand the scope and investigate the findings in other domains, such as commercial buildings and manufacturing facilities, as well as broader studies on energy efficiency investments. Examining the energy efficiency and decision-making would be an essential extension of this research. For instance, commercial buildings encompass various types of structures, including office buildings, shopping centers, hotels, and hospitals. Analyzing the energy efficiency investment patterns and identifying effective emission-reducing strategies in these settings could yield valuable insights for reducing environmental impacts and operational costs.

In conclusion, as successful heat transition in the residential building sector requires the utilization of various strategies, researchers, practitioners, and policymakers will encounter interdisciplinary challenges as they work toward achieving climate goals and decarbonication.

IV.3 Acknowledgment of previous and related work

All these research projects were co-authored in close collaboration or benefited from fruitful discussions and inspiration with colleagues from the Business & Information Systems Engineering department of the Fraunhofer Institute for Applied Information Technology and the FIM Research Center for Information Management in Augsburg and Bayreuth.

Further, work by Achtnicht and Madlener (2014), Buhl et al. (2018), Häckel et al. (2017), and Mills (2003) formed the basis for this dissertation and specifically for Research Article #1 by discussing various aspects of risk in retrofitting decision-making. Research Article #2 was a continuation and was also inspired by Berger and Höltl (2019) as well as I. Weber and Wolff (2018). For Research Article #3, Pasichnyi et al. (2019), Druckman and Jackson (2008), Tziogas et al. (2021), and Magnani et al. (2020) formed the basis by proposing to use data to derive environmental policy instruments and by examining local differences and circumstances in national residential building stock. By analyzing the risk perceptions of energy efficiency investments, Rockstuhl et al. (2021) provided the template for Research Article #4. Finally, Research Article #5 were inspired by Velazquez Abad and Dodds (2020) and their call for research into consistent rules and regulations for guarantees of origin schemes globally.

With this work, I strongly encourage researchers, practitioners, and policymakers to gain an integrated perspective on policy instruments, digital technologies, and risk management, so as to stimulate heat transition in residential building stock.

Please note that I have used different writing assistance software programmes (ChatGPT, DeepL & Grammarly) and also professional proofreading to improve the language and readability of this work. However, I take full responsibility for the content of this work and have reviewed and edited the material as necessary.

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VI Appendix

VI.1 Index of research articles

Research Article #1: The Impact of Political Instruments on Building Energy Retrofits: A Risk-Integrated Thermal Energy Hub Approach

Rockstuhl, J.[1]; Harding, S.[2]; Tränkler, T.; Wenninger, S. (2020). “The Impact of Political Instruments on Building Energy Retrofits: A Risk-Integrated Thermal Energy Hub Approach”. In: *Energy Policy*. DOI: 10.1016/j.enpol.2020.111851 (VHB-JQ3 Category: B)

Research Article #2: Estimating fair rent increases after building retrofits: A max-min fairness approach

Rockstuhl, J.[1] and Harding, S.[2] (2022). “Estimating fair rent increases after building retrofits: A max-min fairness approach”. In: *Energy Policy*. DOI: 10.1016/j.enpol.2022.112923 (VHB-JQ3 Category: B)

Research Article #3: Impact of Socio-Economic Factors on Local Energetic Retrofitting Needs – A Data Analytics Approach

Rockstuhl, J.[1]; Wenninger, S.; Wiethe, C.; Häckel, B. (2022). “Impact of Socio-Economic Factors on Local Energetic Retrofitting Needs – A Data Analytics Approach”. In: *Energy Policy*. DOI: 10.1016/j.enpol.2021.112646. (VHB-JQ3 Category: B)

Research Article #4: The influence of risk perception on energy efficiency investments: Evidence from a German survey

Harding, S.[2]; Wenninger, S.; Wiethe, C.; Rockstuhl, J.[1] (2022). “The influence of risk perception on energy efficiency investments: Evidence from a German survey”. In: *Energy Policy*. DOI: 10.1016/j.enpol.2022.113033 (VHB-JQ3 Category: B)

Research Article #5: Enhancing trust in global supply chains: Conceptualizing digital product passports for a low-carbon hydrogen market

Heeß, P.; Rockstuhl, J.; Körner, M.; Strüker, J. (2024). “Enhancing trust in global supply chains: Conceptualizing digital product passports for a low-carbon hydrogen market”. Accepted in *Electronic Markets*. DOI: 10.1007/s12525-024-00690-7 (VHB-JQ3 Category: B)

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[1] Due to the marriage-related name change of Jakob Rockstuhl (born Ahlrichs) the author’s name differ in the published version of the article.

[2] Due to the marriage-related name change of Sebastian Harding (born Rockstuhl) the author’s name differ in the published version of the article.

VI.2 Individual contributions to the research articles

This cumulative dissertation comprises five research articles that comprise the main body of work. All articles were developed in teams with multiple co-authors. This section details the various research settings and highlights the authors' individual contributions to each article:

Research Article #1, *The Impact of Political Instruments on Building Energy Retrofits: A Risk-Integrated Thermal Energy Hub Approach*, was co-authored by a team of four. The responsibility for the initial idea and for analyzing the results was shared among all co-authors. Further, all authors jointly wrote the initial and revised manuscript. I was responsible for preparing the data as well as writing the theoretical background.

Research Article #2, *Estimating fair rent increases after building retrofits: A max-min fairness approach*, was co-authored by a team of two. As the leading author, I had the initial idea and contributed most to the evaluation and the analysis of the results. Further, I conducted the literature review on current policies and derived policy implications for fair retrofitting fees. Together with my co-author, we jointly wrote the initial and the revised manuscript.

Research Article #3, *Impact of Socio-Economic Factors on Local Energetic Retrofitting Needs – A Data Analytics Approach*, was written by a team of four. The writing responsibilities for the initial and the revised versions of the article were shared among three authors, including myself. The fourth author had a subordinate role; his main responsibility was to provide feedback. My contributions were the initial idea, the development of the method, and the implementation.

Research Article #4, *The influence of risk perception on energy efficiency investments: Evidence from a German survey*, was co-authored by a team of four. One of the authors had a lead role, while the remaining three authors, including myself, had lesser roles. I helped prepare the data and interpret the derived results. I also drafted the revised manuscript with the co-authors.

Research Article #5, *Enhancing trust in global supply chains: Conceptualizing digital product passports for a low-carbon hydrogen market*, was co-authored by a team of four. The responsibility for the initial idea and conceptualization of the paper was shared. Further, the author team formulated the initial set of design principles, discussed the feedback from the process iterations in detail, and finalized the artifact. The initial and revised manuscript was written jointly by all the authors.

VI.3 Research Article #1: The Impact of Political Instruments on Building Energy Retrofits: A Risk-Integrated Thermal Energy Hub Approach

Authors[3]: Jakob Rockstuhl, Sebastian Harding, Timm Tränkler, and Simon Wenninger

Published in: *Energy Policy* (2020)

Abstract: Thermal building retrofits are one of the key approaches to mitigate greenhouse gas emissions. Nevertheless, the current rate of retrofits in Germany is around 1%, and the building sector lags behind environmental goals of saving damaging emissions. A potential reason inhibiting investments is the financial risk connected to thermal building retrofits. While recent research focuses on various political instruments to promote environmental investments, their influence on the financial risk of energy efficiency investments has scarcely been considered. In this study, a method to include risk in the financial evaluation of thermal building retrofits is developed. With this method, named as the Risk-Integrated Thermal Energy Hub, the impact of various political instruments such as emission taxes, subsidies, and energy efficiency insurances on investment decisions of homeowners is analyzed. Based on real-world data of 342 one and two-family houses in Germany, this study illustrates how political instruments influence the financial risk and return of example building retrofits. The findings reveal the effectiveness of energy efficiency insurances in mitigating risk, by promoting environmentally friendlier investments relatively cost-efficient compared to subsidies. Further, this case study indicates that emission taxes need to exceed 140€ per CO_2 ton to significantly impact investment decisions.

Keywords: Thermal Building Retrofit; Energy Efficiency Investment; Greenhouse Gas Emissions; Environmental Policy; Pareto Analysis; German Energy Transition

[3] Due to the marriage-related name changes of Jakob Rockstuhl (born Ahlrichs) and Sebastian Harding (born Rockstuhl), the author names differ in the published version of the article.

VI.4 Research Article #2: Estimating fair rent increases after building retrofits: A max-min fairness approach

Authors[1]: Jakob Rockstuhl and Sebastian Harding

Published in: *Energy Policy* (2022)

Abstract: Residential building retrofits are one crucial instrument to reduce greenhouse gas emissions. Due to the high proportion of rental dwellings in Germany, one particular focus is on rental building retrofits. To increase the attractiveness of retrofits, landlords can charge a certain percentage of the investment amount in retrofitting on top of the current rent, i.e., a percentage-retrofitting-fee. This study applies a max-min fairness scheme to derive a model from estimating fair percentage-retrofitting-fees, including tenants, landlords, and society's environmental and economic interests. Additionally, this model includes the tenant's risk of uncertain energy bill savings after the retrofit, using expected utility theory. Further, two policy instruments, subsidies and environmental taxes, are included in the analysis and their impact on fair percentage-retrofitting-fees is derived. The results of a case study on the German retrofitting market show how the efficiency standard of the building and the investment amount in energy efficiency influence the fair percentage-retrofitting-fee. This study reveals that current regulations concerning percentage-retrofitting-fees are not fair for either the landlord or the tenant. Above that, we illustrate that the fair percentage-retrofitting-fee increases with either the height of the subsidies or the height of an emission tax rate.

Keywords: Rental Building Retrofit; Energy Efficiency Investment; Max-min Fairness; Expected Utility Theory; Environmental Policy

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VI.5 Research Article #3: Impact of Socio-Economic Factors on Local Energetic Retrofitting Needs – A Data Analytics Approach

Authors[1]: Jakob Rockstuhl, Simon Wenninger, Christian Wiethe, and Björn Häckel

Published in: *Energy Policy* (2022)

Abstract: Despite efforts to increase energetic retrofitting rates in the residential building stock, greenhouse gas emissions are still too high to counteract climate change. One barrier is that policy measures are mostly national and do not address local differences. Even though there is plenty of research on instruments to overcome general barriers of energetic retrofitting, literature does not consider differences in local peculiarities. Thus, this paper aims to provide guidance for policy-makers by deriving evidence from over 19 million Energy Performance Certificates and socio-economic data from England, Scotland, and Wales. We find that building archetypes with their respective energetic retrofitting needs differ locally and that socio-economic factors show a strong correlation to the buildings' energy efficiency, with the correlation varying depending on different degrees of this condition. For example, factors associated to employment mainly affect buildings with lower energy efficiency whereas the impact on more efficient buildings is limited. The findings of this paper allow for tailoring local policy instruments to fit the local peculiarities. We obtain a list of the most important socio-economic factors influencing the regional energy efficiency. Further, for two exemplary factors, we illustrate how local policy instruments should consider local retrofitting needs and socio-economic factors.

Keywords: Energy Efficiency; Local Environmental Policy; Residential Building Stock; Socio-Economic Effects; Data Mining; Environment; England; Scotland; Wales; Energy Performance Certificates; Socio-Economic

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VI.6 Research Article #4: The influence of risk perception on energy efficiency investments: Evidence from a German survey

Authors[1]: Sebastian Harding, Simon Wenninger, Christian Wiethe, and Jakob Rockstuhl

Published in: *Energy Policy* (2022)

Abstract: Energy efficiency investments are typically based on either one of two opposing perspectives on financial risk. This study conducted a choice experiment based on a simulated online shop for energetic retrofitting. Here, the resulting financial risk of retrofitting was presented in different treatment groups from these two perspectives. In this vein, participants in the first treatment group were confronted with the resulting risk of deviating energy bill savings (investment risk perspective), which increases with the investment. In the second treatment group, participants were confronted with resulting risk of deviating energy bills after the investment (energy bill risk perspective), which decreases with investment. In the third treatment group, we displayed risk from both perspectives. We found that participants deciding on retrofitting measures within the online shop displaying energy bill risk invested about 20% more than participants in an online shop displaying the investment risk, tested for significance. These findings establish a new way of nudging individuals towards energy efficiency investments, which is especially important for energy policymakers. We, therefore, recommended actively leveraging the risk-reducing potential under the energy bill perspective when promoting energy efficiency investments.

Keywords: Nudging; Green IS; Energy Efficiency; Decision-making; Retrofitting; Choice Experiment

[1] Due to the marriage-related name changes of Jakob Rockstuhl (born Ahlrichs) and Sebastian Harding (born Rockstuhl), the author names differ in the published version of the article.

VI.7 Research Article #5: Enhancing trust in global supply chains: Conceptualizing digital product passports for a low-carbon hydrogen market

Authors: Jakob Rockstuhl, Paula Heeß, Marc-Fabian Körner, and Jens Strüker

Accepted in[1]: *Electronic Markets* (2024)

Abstract: Industries and energy markets around the world are facing mounting pressure to decarbonize, prompting them to transform processes and supply chains towards sustainability. However, a lack of credible sustainability data proves to be a considerable barrier for emerging markets for sustainable products: Against the background of complex and globalized supply chains, it is necessary to verify the sustainability claim of products in order to demand price premiums for sustainable products in the long run. To enable this, it is necessary that stakeholders in globalized supply chains are willing to share relevant data along the entire supply chain for increasing traceability and reducing information asymmetries. Using the example of international hydrogen supply chains, we study how data can be shared between different stakeholders using digital product passports while addressing stakeholders' concerns about data privacy and disclosure. In our work, we develop design principles that provide insight into how a digital product passport should be designed to verify the hydrogen's carbon footprint in a reliable way and to ensure the willingness of stakeholders to share their data. We follow a multi-step approach with a structured literature review followed by expert interviews and qualitative content analysis for a synthesis of design principles. Our research illustrates that a digital product passport must collect data comprehensively and automatically, process it in a decentralised and tamper-proof manner, protect privacy and sovereignty of stakeholders, and ensure interoperability.

Keywords: Data Economy; Decarbonization; Digital Product Passports; Hydrogen; Supply Chains; Verification

[1] At the time of writing, this research article has been accepted for publication but has not been published.