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Data-driven Analysis of Energy Policy Instruments to Advance Energy Efficiency and Energy Flexibility

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von

Sebastian Lukas Harding

aus

München

Dekan: Prof. Dr. André Meyer

Erstberichterstatter: Prof. Dr. Jens Strüker

Zweitberichterstatter: Prof. Dr. Björn Häckel

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Copyright Statement

The following sections are partly comprised of content taken from the research articles included in this thesis. To improve the readability of the text, I omit the standard labeling of these citations.

Abstract

The transition from conventional and fossil energy sources to renewable energy in the form of wind and solar poses major challenges to the energy system. These are largely rooted in energy availability. Although theoretically sufficient to meet all of the planet's energy needs, wind and solar are not always available in the desired amounts and locations due to their dependence on the weather. This change in the supply side of energy requires the demand side to adapt in two ways. First, the demand side must become more efficient, especially during periods of low renewable availability. Second, the demand side must become more flexible to take advantage of periods of high energy availability. Against this background, the aim of this thesis is to overcome existing barriers to the expansion of energy efficiency and energy flexibility and to provide guidance to policy makers on three levels: (1) At the residential level, it analyzes energy policy instruments that promote efficiency, particularly in the residential sector, as current retrofitting rates, e.g. in Germany, fall drastically short of climate targets. In this sense, the thesis examines a key investment barrier - the financial risk associated with retrofitting - through an illustrative field experiment and shows a dichotomy in risk perception that influences decision-making. The results suggest that promoting an energy bill perspective on efficiency increases investment. Furthermore, the paper shows that energy efficiency insurances are another effective instrument to reduce the perceived financial risk and increase the expected cost savings associated with retrofits in owner-occupied buildings. For rental buildings, the current regulations in Germany on retrofitting fees are unfair in terms of the max-min fairness scheme and represent a further regulatory barrier to necessary investments. Introducing a retrofitting fee based on the efficiency standard of the building before the retrofit would result in a fair rent increase for both the landlord and the tenant. (2) The second level shifts the focus from the residential to the industrial sector. In this sense, the thesis shows how dynamic electricity tariffs can overcome existing economic and regulatory barriers and enable flexible industrial consumers to achieve cost reductions and emission reductions. It also focuses on the recent European energy market crisis and illustrates how the relative cost reductions in 2021 and 2022 are up to twelve times higher than in the pre-crisis years. This shows policy makers how electricity tariffs can encourage investment in energy flexibility by enabling flexible consumers to save costs and emissions and be resilient to market crises. (3) At the system level, the thesis illustrates how policy makers can evolve the existing energy system and overcome outdated regulations by deploying residential microgrids and local electricity markets. In doing so, the results show how the interconnection of multiple residences with certain energy flexibility potentials and renewable production can increase the overall efficiency. In summary, this thesis provides insights using data-driven analysis to better understand effective energy policy instruments for enhancing energy efficiency and energy flexibility, thereby providing guidance to policy makers to pave the way towards a sustainable energy system.

Keywords: *Energy efficiency; Energy flexibility; Greenhouse gas emissions; Energy policy; Retrofitting; Microgrids; Financial risk; Max-min fairness; Data analytics*

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1. Introduction

1.1 Motivation

As I write this introduction (end of 2023), society has encountered the year with the highest global temperature since 1850 accompanied by a series of extreme weather events, such as heatwaves, floods, droughts and wildfires (Climate Change Service 2024). As a result, concerns about climate change, accelerated by human-induced global warming, are driving discussions, and pushing for greater sustainability across all sectors. In this sense, the Paris Agreement, established in 2015, involves almost all nations worldwide in shaping a more climate-friendly global economy (Savaresi 2016) and more recently, the "Fit for 55" package, introduced by the European Union, aims to cut greenhouse gas emissions across Europe by 55% by 2030 compared to 1990 levels (European Commission 2021). Despite these global alliances to address climate change and temporary reductions in emissions during the COVID-19 pandemic, the necessary long-term investments in decarbonization to effectively address and reduce global warming are falling short, resulting in a significant emissions gap estimated to be between 22.4 and 28.2 $GtCO_2eq$ by 2030 when considering optimal pathways to achieve the Paris 2°C and 1.5°C goals (Roelfsema et al. 2020).

To reduce greenhouse gas emissions, it is imperative to decarbonize energy systems in order to achieve ambitious climate goals. This transformation includes a significant shift towards renewable energy sources, such as wind and solar power plants (Hansen et al. 2019). In response to Russia's invasion of Ukraine and natural gas shortages, the EU Commission has even increased its renewable energy expansion targets in the REPowerEU plan (European Commission 2022). Despite high initial investments these sources offer low marginal costs and can directly contribute to an affordable and secure energy supply, reducing dependence on foreign energy such as Russian gas (Madler et al. 2023). However, the transition to an energy system that relies heavily on renewables poses significant challenges due to the volatile and partially uncertain energy supply (Pape 2018). In this context, innovative technological solutions and energy policies are needed to reshape the demand side so that it can effectively align with the increasing volatile and decreasingly controllable supply side, thereby ensuring a secure energy supply. In this sense, energy efficiency and energy flexibility are two promising approaches that can help consumers adapt to the evolving supply side of the energy system. On the one hand, since wind and solar energy are not available in the desired amounts at any given time and place, there is an urgent need to increase the efficiency of energy use. On the other hand, energy flexibility allows consumers to adjust their energy demand to the unpredictable supply of renewable energy sources (Bichler et al. 2022).

Despite the need for a transition to greater energy efficiency and flexibility, outcomes have fallen short of policy goals, representing significant policy failure on a national and global level (McConnell 2015). For example, in the area of energy efficiency, the retrofitting rate in Germany, which represents the share of buildings that are retrofitted annually, has stagnated at around 1%. However, a much higher rate of up to 4% is essential to meet the EU's target of climate neutrality by 2050 (Behr et al. 2023; European Parliament 2023). The picture is similar for energy flexibility. Here, the technological potential, e.g. in (energy-intensive) industry (Kopernikus project SynErgie 2021), would already be significant, but is being used far below its potential, with an inadequate regulatory framework being a key obstacle (Leinauer et al. 2022). In Germany, for example, electricity prices are distorted by various surcharges, such as levies, taxes and grid fees, which undermine the steering effect of prices and hinder the adoption of energy flexibility and thus the progress of the energy transition (Hanny et al. 2022).

1.2 Research aim

Given the urgency of ongoing climate change and the pressure to act quickly, a wide range of policy instruments have already been used by governments and intercontinental associations. In their developed classification, Bergek and Berggren (2014) show the wide range of policy instruments with general economic (e.g., emissions taxes, emissions trading), general regulatory (emissions regulation), technology-specific economic (subsidies for specific technologies), and technology-specific regulatory instruments (emissions regulations for specific technology sectors). In this sense, it is imperative for research to intensively investigate the design, application, and effectiveness of energy policy instruments. Existing studies in this area include Peñasco et al. (2021), who develop and implement a framework for systematically assessing and consolidating the effects of ten decarbonization policy instruments. Another work that summarizes different policy instruments to promote energy efficiency is of Labandeira et al. (2020), who quantify the effects of several energy efficiency policy instruments in a meta-analysis. An example of the existing literature on policy instruments to promote energy flexibility is the work of Hanny et al. (2022), which focuses on the influence of network charges on the use of energy flexibility and provides an outlook on what small and large regulatory changes policy makers need to make.

Despite initial political efforts and the existing range of literature, several barriers for necessary investments in energy efficiency and energy flexibility remain. In the case of energy efficiency, this is illustrated, among other things, by the low retrofitting rate in Germany (German Energy Agency 2021). Weber (1997) classified the barriers to energy efficiency into four different categories: institutional barriers, obstacles conditioned by the market (i.e. economic barriers), organizational barriers, and behavioral barriers. While Weber (1997) states that this should not to be interpreted as a definitive typology, but rather as a representation of each barrier encompassing its institutional, economic, organizational, and behavioral dimensions, these four categories delineate the wide range of barriers found in the literature. Institutional barriers include distortionary fiscal and regulatory policies (Brown 2001) and misaligned incentives (Brown 2001). Economic barriers include low energy cost savings, externalities, or price distortions due to fixed surcharges on market prices (Jaffe and Stavins 1994; Brown 2001; Hanny et al. 2022) and imperfect market information (Linares and Labandeira 2010;

Allcott and Greenstone 2012). Organizational barriers comprise characteristics of companies (Groot et al. 2001) and behavioral barriers address barriers inside individuals including social influences (Frederiks et al. 2015; Allcott 2011) or risk perception and aversion (Hirst and Brown 1990; Allcott 2011). Related to the latter, studies have found that private decision makers use implausibly high internal rates of return for energy efficiency investments, suggesting an unusually high perception of investment risk compared to other investments (Dubin and McFadden 1984; Min et al. 2014). An additional barrier that deserves special emphasis and is particularly relevant for energy efficiency investments in rental housing is the so-called "landlord-tenant dilemma". This dilemma arises from the situation where, on the one hand, the tenant pays energy bills based on consumption in addition to the rent and, on the other hand, the landlord supervises the dwelling and the installed appliances (Ástmarsson et al. 2013). In the case of retrofitting, the landlord makes the investment, but the tenant benefits from reduced energy costs (Charlier 2015).

As with energy efficiency, several barriers to the deployment of energy flexibility exist. A comprehensive overview of the barriers already found in the literature is provided by the work of Leinauer et al. (2022). They categorize the barriers similarly to energy efficiency into: economic, regulatory, technological, organizational, information, behavioral and competence. Economic barriers include internal factors such as high investments that would be required (Albadi and El-Saadany 2008; Alcázar-Ortega et al. 2015; Olsthoorn et al. 2015) and external factors such as price spreads on electricity markets that are too small (Alcázar-Ortega et al. 2015; O'Connell et al. 2014). Regulatory barriers can be the general complexity of energy market regulation (Olsthoorn et al. 2015; Warren 2014) or specific regulations, such as the regulation of network charges (Richstein and Hosseinioun 2020; Hanny et al. 2022), that inhibit the use of energy flexibility. Technological barriers refer to technical requirements of production processes (Lund 2007; Grein and Pehnt 2011; Heffron et al. 2020) or disproportionately high IT requirements (Cappers et al. 2012; Shoreh et al. 2016). Organizational barriers include obstacles that exist within the organization, such as internal policies (Leinauer et al. 2022) or cumbersome project decision-making processes (Vine et al. 2003; Wohlfarth et al. 2020). Behavioral barriers can be lack of acceptance or general skepticism about energy flexibility (Vine et al. 2003; Bradley et al. 2013; Annala et al. 2018). Information barriers include uncertainty about future energy prices (Cappers et al. 2013; Goulden et al. 2018), and thus financial savings from flexibility and uncertainty about future regulation (Alcázar-Ortega et al. 2015; Olsthoorn et al. 2015). Finally, competence barriers address the lack of internal resources and knowledge about the energy market and how to properly market energy flexibility (Grein and Pehnt 2011; Alcázar-Ortega et al. 2015).

In this context, the primary objective of this thesis is to overcome some of these barriers and to make a meaningful contribution to the advancement of energy efficiency and flexibility, which are essential requirements for the ongoing energy transition. In this context, data-driven methods such as simulations and optimizations have become established methods for analyzing the complexity of investment decisions and energy systems in general. The results of this thesis should provide a basis for efficient policy instruments at three different levels. Specifically: (1) At the residential level, to illustrate how policy instruments can help overcome the economic and behavioral barriers of low financial savings and risk aversion to energy efficiency in owner-occupied housing, and the regulatory barriers of the landlord-tenant dilemma in rental housing. (2) At the industrial level, analysis of how future dynamic electricity tariffs can increase the attractiveness of energy flexibility by overcoming the economic and regulatory barriers of low cost savings and an outdated electricity tariff structure. (3) At the system level, to illustrate how policy makers can evolve the existing energy system to overcome economic and regulatory barriers and promote energy efficiency and flexibility through residential microgrids and local electricity markets.

1.3 Structure of the thesis and embedding of the research articles

This thesis presents a composite framework consisting of six research articles that collectively address the stated research objectives. The overall structure, shown in Figure 1, is based on the barriers and levels described in Section 1.2 It shows how each research article is incorporated into the dissertation's context based on its level, the barriers it aims to overcome, and its emphasis on either energy efficiency or energy flexibility.

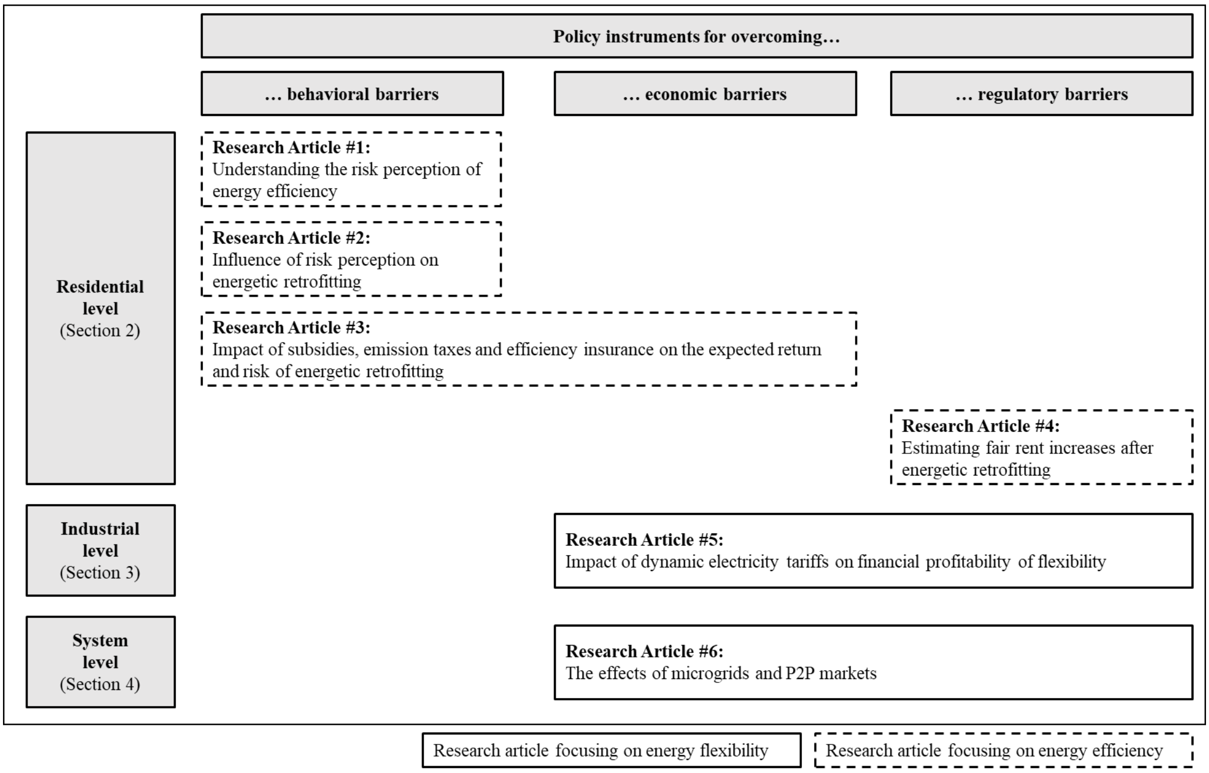

Figure 1: Structure of the doctoral thesis and embedding of research papers

The following sections of the thesis are organized as follows: After this introductory section, Section 2 delves into an analysis of energy policy instruments designed to increase efficiency, particularly in the housing sector. In this context, the section first examines the barrier of financial risk associated with energy efficiency. In this context, Research Article #1 lays the groundwork by reviewing the existing literature on decision-making in energy efficiency investments, with a particular focus on the impact of associated risks. The review reveals two distinct conclusions from previous studies. First, from an investment perspective, the research highlights investment risk arising from unpredictable future energy cost savings as a significant barrier to energy efficiency investments. Second, from an energy bill perspective, studies suggest that energy efficiency measures mitigate exposure to energy price fluctuations, resulting in an overall risk reduction that supports investment. This divergence in risk perception is then further explored through both a theoretical model and a case study using data from the German retrofit market. Research Article #2 builds on these findings by developing and implementing a field experiment in the form of an online store that presents energy efficiency investment alternatives either from an investment perspective or from an energy bill perspective to different treatment groups. In the second part of Section 2, Research Article #3 illustrates how subsidies, emission taxes, and efficiency insurances affect the financial risk and increase the expected cost savings associated with retrofits in owner-occupied buildings. This expands the focus from behavioral barriers to energy efficiency to economic barriers and how policy instruments can overcome them. Concluding Section 2, Research Article #4 focuses on regulatory barriers and rental buildings to achieve a holistic analysis of the residential housing sector. In this context, the paper examines the current regulations in Germany on retrofitting fees (rent increases after retrofitting rental housing), shows that these are unfair in terms of the max-min fairness scheme, and suggests how policy could introduce fair regulations on retrofitting fees.

Moving from the residential to the industrial level, Section 3 of the thesis shifts its focus. In this context, Research Article #5 within the thesis demonstrates how the implementation of dynamic electricity tariffs can effectively overcome prevailing economic and regulatory barriers. This strategy enables flexible industrial consumers to not only achieve cost reductions, but also to contribute to emission reductions. Using data from the German day-ahead spot market for the years 2019 to 2022 as the basis for the construction of a dynamic tariff structure, the article focuses on the recent upheaval in the European energy market. It illustrates how the integration of dynamic pricing mechanisms can empower flexible consumers, especially in unique market scenarios such as the current crisis. Using a linear programming model, the study quantifies the cost and GHG emission differences between industrial processes that lack flexibility and those that have it. This analysis underscores that significant reductions in energy costs are achievable when energy flexibility is coupled with a market-driven dynamic tariff. Importantly, these reductions are even more pronounced in times of market crisis. Furthermore, the article finds a remarkable positive correlation between electricity costs and associated emissions. This correlation implies that the incorporation of flexibility through market-based dynamic electricity tariffs has the potential not only to minimize electricity costs, but also to reduce emissions at the same time, thus providing a double benefit.

Section 4 of the thesis turns to the systemic level, exploring how policy makers can evolve the current energy system and overcome outdated regulations through the implementation of residential microgrids and local electricity markets. It also analyzes how microgrids reduce costs for all participants through the efficient use of renewable energy, thereby helping to overcome economic barriers. In this context, Research Article #6 contributes to the existing literature by providing a real-world implementation study that advances the understanding of the field. To achieve this goal, the article introduces a multi-agent model that serves as a tool for validating results with real-world data. The model focuses on microgrid performance in the context of residential energy systems. It quantifies a comprehensive set of metrics that includes economic, technical, and ecological dimensions. This holistic simulation incorporates the latest research standards and features self-interested, independent agents, each characterized by specific load profiles, renewable energy generation, and certain flexibility potentials. The model is also equipped to replicate a local electricity marketplace where agents engage in electricity trading. The paper then demonstrates the validity of the model through an illustrative case study in a medium-sized German city.

Section 5 provides a comprehensive overview of the primary findings, accompanied by relevant limitations and avenues for future research. The section also discusses previous, related work that was available at the time this thesis was written.

Section 6 lists the references used throughout the thesis. In Section 7, an appendix provides additional details on the six research articles incorporated into the thesis. In addition, my contributions to each of these research articles are detailed.

2. Analysis of energy policy instruments on a residential level

2.1 Understanding the risk perception of energy efficiency investments: Investment perspective vs. energy bill perspective

Energy efficiency, especially in the residential sector, is a key element for a sustainable future. In this context, a comprehensive understanding of homeowners' investment decision-making is crucial for assessing and designing effective policy instruments that can overcome existing barriers to investment. Therefore, Research Article #1 focuses on how homeowners perceive risk associated with energetic retrofitting and how to overcome behavioral barriers to investment. This forms the basis for the following sections of the article.

Generally, energetic retrofitting necessitates an initial investment aimed at enhancing a building's energy efficiency, resulting in decreased energy consumption. Consequently, this leads to a long-term reduction in energy costs, which depend on future energy prices, weather conditions, the technical performance of the retrofit, and the behavior of the occupants, introducing uncertainty into the investment. Here, two different perspectives on this uncertainty and its impact on the investment decision have emerged in the literature. One line of research argues that the energy cost savings resulting from reduced energy consumption can be understood as uncertain cash flows subsequent to the initial investment (Häckel et al. 2017). These savings are susceptible to the described uncertainty, leading to a perceived risk associated with the investment and thus a behavioral barrier to energy efficiency adoption (Mills 2003). As a result, the level of risk increases with the size of the investment and the corresponding energy cost savings. Given risk aversion, homeowners tend to invest less in energy retrofits because larger investments are associated with greater variability in energy cost savings. This perspective, defined by Research Article #1, is referred to as the "investment perspective". Conversely, a second line of research focuses not on energy cost savings, i.e. the reduction of energy costs, but on the residual energy costs themselves. These costs also depend on the uncertainty of weather conditions, price fluctuations, etc., even in the absence of energy retrofits. In other words, when considering energy efficiency, the individual is not choosing between doing nothing and an uncertain investment, but between two different uncertain cash flows: the cash flow of energy costs with the investment and the cash flow of energy costs without the investment (Thompson 1997). As a result, larger investments lead to more stable future cost flows due to reduced exposure to the sources of uncertainty, such as price fluctuations (Buhl et al. 2018). This perspective is referred to as the "energy bill perspective," as defined in Research Article #1. Note that the presence of these two perspectives may create the illusion that there are distinct categories of risk associated with energy efficiency. However, because the underlying sources of risk - such as uncertain energy prices - remain consistent regardless of the perspective, these two perspectives do not represent different forms of objective risk. Figure 2 provides a visual illustration of these perspectives.

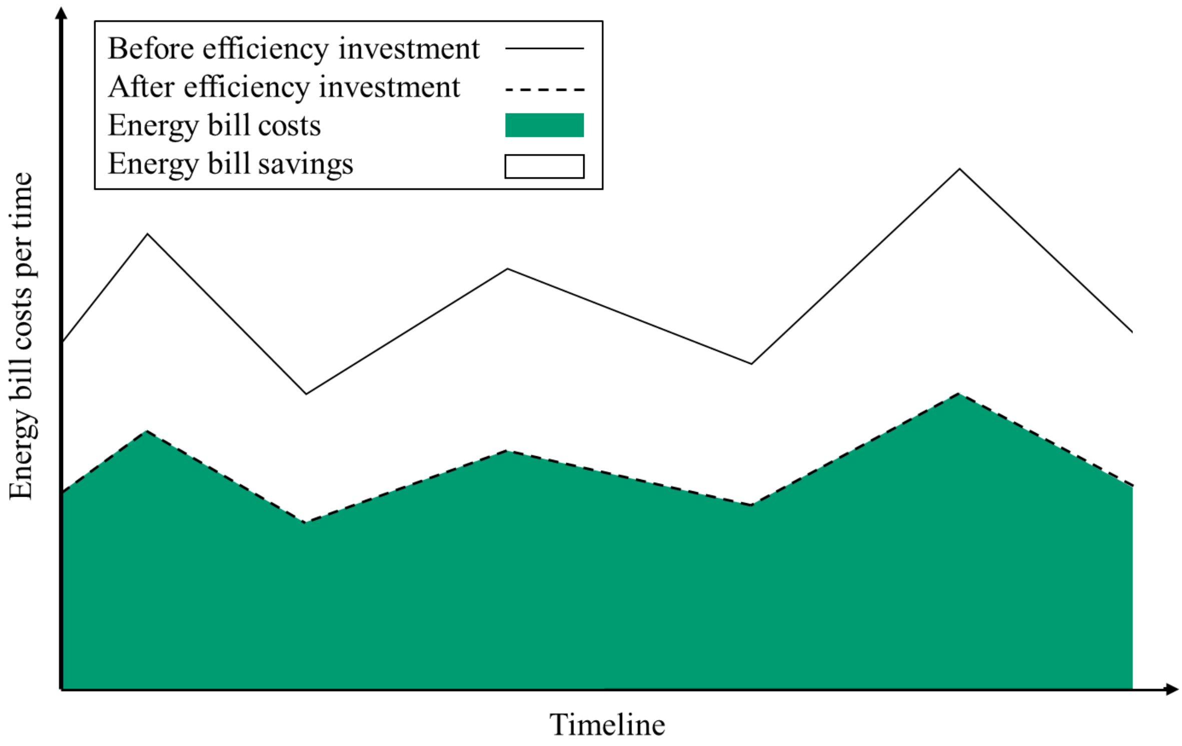

Figure 2: Different risk perceptions: investment perspective (white area) vs. energy bill perspective (green area)

With the help of the Expected Utility Theory (Bernoulli 1954) Research Article #1 illustrates and analyzes these two different in a case study with market data on energetic retrofitting. The theoretical and empirical results indicate that there are differences in investment levels depending on risk perception and that risk perception from an energy bill perspective leads to higher investment. Here, the exemplary case study revealed a 175% difference in investment between homeowners who evaluate energy retrofits from an energy bill perspective and homeowners who evaluate energy retrofits from an investment perspective.

The results have two main implications for policy makers. First, recognizing that decision makers value energy efficiency from different perspectives has implications for evaluating and designing effective policy instruments. For example, the effectiveness of conventional policies such as carbon taxes or subsidies depends on the decision maker's perception of risk. Both strategies are designed to increase the expected return on energy efficiency investments. However, decision makers evaluating from an investment perspective may seek reduced financial risk and call for different policy instruments, such as efficiency insurances (see Section 1.3). Second, the theoretical framework that encompasses the investment and energy bill perspectives provides opportunities for policy makers to promote the energy bill perspective and convince decision makers that energy efficiency serves to reduce uncertainty about their future energy costs. Policy instruments that build on the findings of Research Article #1 could include, for example, information campaigns or guidance for retailers of energy efficiency measures on how to promote the energy bill perspective. Nevertheless, the hypothesis that the energy bill perspective promotes investment in energetic retrofitting requires empirical validation in real-world scenarios.

2.2 The influence of risk perception on energy efficiency investments: Evidence from a German survey

Research Article #2 complements the theoretical insights in Research Article #1 by conducting a field experiment through an online survey. The survey simulates an energy efficiency decision-making problem through an online store showcasing a range of retrofitting measures, such as different types of insulation and windows. There are three treatment groups in the study. The first group is exposed to the increasing risk of energy bill savings deviation as the investment increases, emphasizing the investment perspective. The second group encounters the decreasing risk of energy bill fluctuation after the investment, highlighting the energy bill perspective. The third group experiences a comprehensive display of risk from both perspectives through the online shop interface. In this context, the research question seeks to determine if a significant difference exists in investment decision-making between the investment perspective and energy bill perspective (i.e., the different treatment groups), established in Research Article #1. The purpose of answering this research question is to demonstrate, for policy and practice, if and how promoting the energy bill perspective can serve as an effective nudge towards greater investments in energy efficiency.

The term " nudge" in this article refers to the work of Münscher et al. (2016), where they describe nudging as a technique for influencing decision-making by adjusting how choices are presented. This concept builds upon earlier research that differentiates between intuition and reasoning (Jacoby and Dallas 1981; Epstein 1994). These cognitive processes were designated as System 1 and System 2 by Stanovich and West (2000). System 1, the intuitive mode, operates quickly, in parallel, automatically, and effortlessly, while System 2, the reasoning mode, functions slowly, sequentially, with control, and requires effort. Within System 1, impressions of attributes related to specific objectives take shape. Consequently, System 1 generates prompt solutions and judgments based on intuition, while System 2 supervises System 1 and aids with problems lacking immediate solutions (Moxley et al. 2012). Decision-making in matters of energy efficiency typically falls under System 2, particularly decisions involving risk. This is because uncertainty is not well-handled by intuition (Kahneman 2003). The nudging technique introduced in this article engages both System 2 and System 1. Regarding the approach discussed here, the crucial aspect of System 1 is its inclination to ignore alternatives. Thus, when provided with contextual information in an online store, System 1 is unlikely to consider other potential contexts in which the decision-making process could take place. Although System 2 primarily processes energy efficiency decisions, System 1 establishes the decision's context by shaping a perception of the situation. If this perception (context) is reasonable for System 2, alternative contexts are overlooked in favor of the decision at hand. This, in theory, effectively guides individuals towards one of the two outlined perspectives on energy efficiency.

The online survey consists of a structured three-step process. Firstly, participants are asked to imagine themselves as owners of a single-family home, aided by a concise, informative, and animated video. In this phase, all three treatments are the same. Next, participants are directed to the webpage of the online store. Within this virtual store, participants can choose from three distinct insulation options and three different window choices for their hypothetical house. Participants also have the option to choose no investment in new insulation or windows, resulting in a total of 16 potential investment combinations. The online store displays the costs of the selected retrofitting measures and provides additional information specific to the treatment group. An illustrative segment of the online store interface appears in Figure 3. In the third and final step, participants are asked to evaluate the importance of the information provided on the online store.

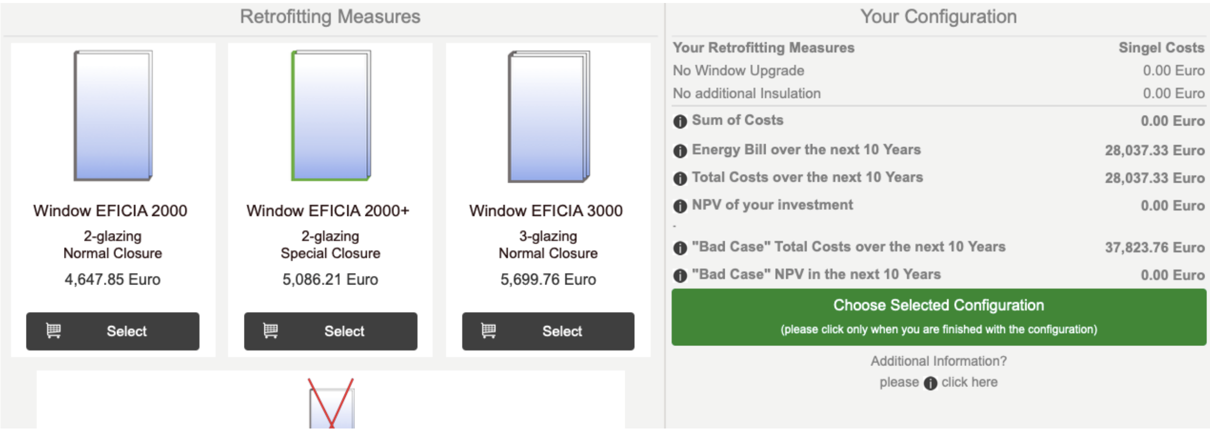

Figure 3: Translated exemplary excerpt from the online shop of treatment group 3 – language in the online shop was originally German

The recruitment for the choice experiment involved distributing invitations via an energy market newsletter and the authors' networks, resulting in a sample size of 174 participants. The results show that presenting retrofitting options within the context of the accompanying energy bill and the associated energy bill risk (energy bill perspective) results in a 20% increase in investments toward energy efficiency. This effect demonstrates statistical significance at the 5% level.

Additionally, within treatment group 3, an analysis of the third step of the online survey indicated that when participants were exposed to both perspectives, most focused on the investment perspective. This implies that the positive impact of energy efficiency on risk may be consistently underestimated and that risk aversion serves as a significant barrier to investing in energy efficiency.

These results indicate to policy makers that dissemination of information and awareness campaigns are essential. They should convey to decision makers that energy efficiency assessments involve not only an investment perspective but also an equally crucial energy bill perspective. By effectively conveying this, energy efficiency can be perceived as a means of mitigating risk, thus stimulating investments in energy-efficient retrofitting measures in Germany, as well as broader-scale energy efficiency investments.

2.3 The impact of political instruments on building energy retrofits: A risk-integrated thermal energy hub approach

While Research Article #1 and Research Article #2 focus on understanding individuals' risk perception during decision-making for energy efficiency investments, Research Article #3 addresses the gap in research on evaluating the impact of political instruments on the financial risk of energy efficiency investments. To that end, the article develops a method for incorporating risk into the financial evaluation of thermal building retrofits. To demonstrate the developed method, the Risk-Integrated Thermal Energy Hub, and provide guidance for policy makers, we analyze the impact of various political instruments, such as emission taxes, subsidies, and energy efficiency insurances for homeowners.

Geidl et al. (2007) introduced the concept of the Energy Hub, a framework that found application in various studies for simplifying the modeling of energy systems (Fabrizio et al. 2010). Research Article #3 builds upon this concept by introducing a derivative, the Thermal Energy Hub, which is designed to optimize thermal energy systems. It divides energy systems into three parts: the desired space heating energy as the output (Q^{out}), a collection of energy carriers such as electricity or gas forming the input vector (Q_1^{in} ... Q_n^{in}), and a conversion vector ($\varepsilon_{K_1}/\eta_{K_1}$ ... $\varepsilon_{K_n}/\eta_{K_n}$) dictating the proportion of the input converted into the output. The incorporation of risk is dealt with based on the research of Mills et al. (2006). They present five distinct risk categories: economic, contextual, technological, operational, and measurement and verification risks. In addition, the article differentiates between intrinsic and extrinsic risks. Based on these different types of risks, the Risk-Integrated Thermal Energy Hub is derived (refer to Figure 4). It comprises input, conversion, and output, which are affected by different types of risks, namely price risk (economic), weather risk (contextual), equipment performance (technology) and personal behavior risk (operation). The article adheres to the perspectives of Töppel and Tränkler (2019) and does not factor in risk associated with measurement and verification.

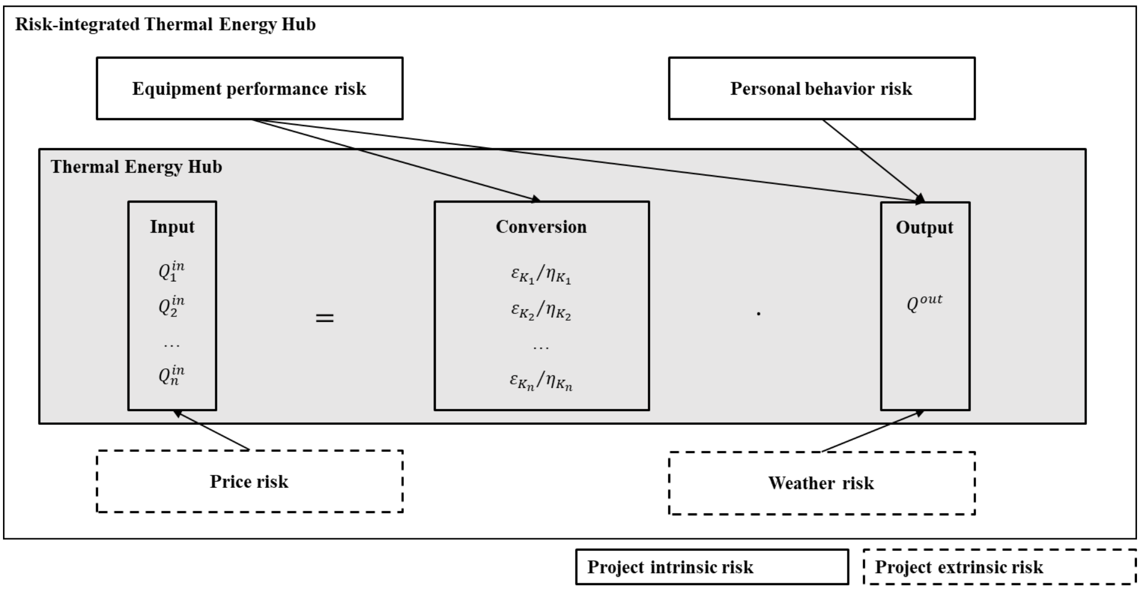

Figure 4: The Risk-Integrated Thermal Energy Hub

After developing the Risk-Integrated Thermal Energy Hub, this article illustrates the method through a case study on a two-story, single-family home in Germany, using a Monte Carlo Simulation. The simulation is based on 12,500 combinations of price and weather developments, deviations in expected equipment performance, and 150 different retrofitting investments used as input for the Energy Hub. The simulation generates 12,500 distinct net present values for each of the 150 retrofits, which are presented as a mean-variance portrayal. This illustration offers a means of estimating Pareto-efficient thermal building retrofits and thereby models investment decision-making of rational individuals. Furthermore, the Risk-Integrated Energy Hub method permits calculation of emission savings for each analyzed retrofit. The case study shows that retrofits offering greater emission savings coincide with increased financial risk and reduced financial returns for homeowners. This result is in line with previous research (Mills 2003; Häckel et al. 2017). In addition, the study evaluates the effectiveness of emission taxes, initial investment subsidies, and energy efficiency insurance, which guarantees a certain level of energy bill savings after an investment in a building retrofit. The subsidies and insurances are assumed to be paid for by policy makers. Furthermore, the article analyzes the comparative costs of implementing a particular policy instrument for policy makers (subsidy, insurance) and homeowners (taxes). The results indicate that subsidies contribute positively to the financial returns of thermal building retrofits. Additionally, they demonstrate how energy efficiency insurances improve financial returns while reducing associated risks. The incorporation of such insurances allows policy makers to assume a share of the underlying risks associated with investments in thermal building retrofits. Consequently, energy efficiency insurances have the potential to impact retrofitting incentives and reduce emissions by an additional 35% for the examined example home. Based on a comparison of subsidies and insurances, the study concludes that insurances are more efficient overall in terms of ecological impact and costs. It is noteworthy that emission taxes must be substantial, at approximately 140€ per ton, to significantly affect decision-making regarding thermal building retrofits.

The research article's findings offer three proposals for policy makers. Firstly, they reveal a discrepancy between the financial and ecological benefits of energy-efficient investments. Secondly, to attain present ecological policy goals, political intervention is crucial because private households are unable to attain these targets by themselves, due to the high monetary risk involved in thermal building retrofits and investors' risk aversion. Thus, policymaking should not rely solely on estimated financial returns when designing instruments; the element of risk must also be acknowledged. Additionally, the study emphasizes that substantial emission taxes affecting ecological investments could burden private homeowners. For example, in the case study, an emission tax leading to a projected 50% emission reduction would result in an additional annual cost of 1,000€ for the homeowner. This suggests that policy makers should consider strategies to alleviate the public's burden after the enforcement of steep emission taxes.

2.4 Estimating fair rent increases after building retrofits: A max-min fairness approach

Research Article #1, Research Article #2, and Research Article #3 center their attention on the energy efficiency of buildings occupied by their owners. It should be noted, however, that a substantial number of buildings in Germany are rented rather than owned (Destatis 2023). As a result, Research Article #4 places a specific emphasis on investment barriers to energy efficiency within this particular category of housing. Here, the landlord is responsible for making investment decisions regarding retrofitting measures. However, the landlord does not immediately benefit from reduced energy costs following a retrofit, as those expenses are typically covered by the tenant. To resolve the landlord-tenant dilemma, policies have been created that allow for landlords to increase rent by a certain percentage of the investment, also known as a retrofitting fee (Weber and Wolff 2018). The drawback associated with this fee pertains to the tenant's standpoint, as the financial benefits gained from energy cost reductions frequently fall short of offsetting the rise in rent (Berger and Höltl 2019). This becomes particularly concerning in regions characterized by strained housing conditions. On the contrary, when examining the rate of retrofitting, particularly in the context of rented buildings, the existing regulation of the percentage-based retrofitting fee, appears to lack a robust incentive and a barrier for sufficient investment remains. Therefore, Research Article #4 puts forth a model that strikes a balance among diverse perspectives and proposes fair retrofitting fees contingent upon the scale of investment in building retrofitting measures and the building's efficiency standard.

Like for owner-occupied buildings, uncertainty remains a crucial factor in energy-efficient investments for rental housing. While landlords can rely on certain cash flows subsequent to investment due to the fixed retrofitting fee, tenants, conversely, confront financial uncertainty regarding their potential energy bill savings (Weber and Wolff 2018). For instance, fluctuations in energy prices have a direct impact on the energy bill savings for tenants, which affects profitability (Töppel and Tränkler 2019; Ahlrichs et al. 2020). While there has been substantial investigation of energy efficiency risks in literature of owner-occupied buildings (see Research Article #1), there has been little focus on estimating fair retrofitting fees following building retrofits, taking both risk and return into consideration. Hence, the article introduces a risk-integrated approach for estimating such fees, grounded in the expected utility which is substantially influenced by risk of the tenant and the landlord. Additionally, the model incorporates a third-party, a member of society not directly engaged in the tenancy, to address society's interest in reducing emissions and mitigating climate change.

Various interpretations of fairness exist and general theories have shaped fairness schemes in literature (Bertsimas et al. 2011). Early notions trace back to Aristotle and his "equity principle", which advocates for resource allocation based on preexisting claims (Bertsimas et al. 2011). Bentham (1996) introduced the utilitarian principle, emphasizing maximizing overall utility, the sum of individual utility. Additionally, Nash's comparison standard suggests that transfers are fair when the recipient's increase in utility percentage outweighs the donor's decrease, known as "proportional fairness" (Kelly et al. 1998). Despite these early schemes for fairness, Research Article #4 bases its proposal for a fair retrofitting fee on the latest and widely established interpretations of fairness: The “Max-min fairness," rooted in Rawlsian justice (Rawls 1999). This approach prioritizes maximizing the lowest utility among individuals first, followed by raising the second lowest, and so on. Its ultimate goal is to ensure that even the least well-off participants experience improved welfare, and it implicitly rejects outcomes where only the "rich" benefit at the "poor's" expense (Bertsimas et al. 2011). When an efficient allocation leads to equal utilities, the approach results in a convergence to that equilibrium. When someone can enhance utility without reducing the minimum levels of others, max-min fairness can efficiently boost their utility by optimizing a novel shared minimum (Bertsimas et al. 2011).

The determination of reasonable retrofitting costs includes three separate groups: tenants, landlords, and a member of society not participating in tenancy, who hold considerable significance due to ambitious energy policy goals. The model factors in ecological and financial benefits, as well as financial losses. All three groups experience benefits from improved building efficiency following the retrofit, resulting in reduced greenhouse gas emissions. Ecological benefits increase with higher retrofitting fees, motivating landlords to prioritize energy efficiency, thereby driving more retrofits. In terms of finances, elevated fees benefit landlords by expediting investment return, while tenants suffer from increased rental costs. However, tenants also benefit from reduced energy expenses. Research Article #4 demonstrates that the application of Rawls' justice theory through max-min fairness results in a unique solution that maximizes the increase in minimal utility for all parties. A case study further investigates four representative German homes and 1,080 possible retrofit investments, revealing the impact of building efficiency and investment size on fair retrofitting fees. To account for uncertainty in upcoming energy prices, the article rans 1,000 varied price scenarios to simulate potential changes in expected utility resulting from varying energy bill savings. The results presented two distinct trends: Firstly, an increase in retrofitting investments led to a reduction in fair fees, and conversely, a decrease in retrofitting investments correlated with higher fair fees. Secondly, buildings with lower energy efficiency standards correlated with higher fair retrofitting fees. When compared to the current 8% fee outlined in German law (§559 BGB), the data shows that only minor retrofit investments in low-energy standard buildings exceed this threshold. On the other hand, in other cases, the fair retrofit fee remains below 8% and is therefore unfair from the tenant’s perspective.

Based on its results, Research Article #4 proposes three policy suggestions. Firstly, it argues that uniform limits on retrofitting fees are unfair, and instead suggests that fees should be related to building efficiency or estimated energy bill savings. Secondly, it proposes that fees should consider uncertain energy bill savings, particularly in light of volatile energy sources and risk-averse tenants. Thirdly, it recommends aligning fees with subsidies and ecological policies to enhance the appeal and effectiveness of retrofitting.

3. Analysis of energy policy instruments on an industrial level

3.1 Unleashing the economic and ecological potential of energy flexibility: Attractiveness of real-time electricity tariffs in energy crises

The focus of Research Article #5 transitions from examining political instruments at the residential level to an exploration of the industrial level. Here, energy flexibility is a promising approach for helping industrial consumers to better align their energy demand with the unpredictable supply of renewable sources (Bichler et al. 2022). Given that industrial electricity consumption represents a significant portion of the total demand in developed nations (e.g., approximately 44% in recent years in Germany according to the Ministry for Economic Affairs and Climate Action Germany (2021)), the significance of addressing energy flexibility in industries is underscored (Sauer et al. 2022). However, the benefits of energy flexibility are primarily achieved through favorable electricity tariffs, such as time-varying dynamic tariffs, which enable consumers to react to market dynamics and reduce costs by shifting consumption to periods of lower prices (Schreiber et al. 2015). Nevertheless, these dynamic tariffs are currently not widely offered and adopted by electricity consumers. Thus, the key to promoting the adoption of dynamic tariffs and energy flexibility is to showcase their potential benefits for future policies and practical implementation.

The Russian-Ukrainian conflict, resulting natural gas shortages, and issues with French nuclear power plants had a significant impact on European energy markets recently, underscoring the need for a flexible and sustainable energy system. These events caused substantial hikes in electricity costs throughout Europe, both regarding average and volatility. Visualized in Figure 5, the evolution of the electricity market, as shown through EPEX SPOT hourly Day-Ahead price distributions for the Germany/Luxembourg bidding zone, exemplifies this situation. This context has posed and continues to pose significant challenges for all stakeholders, significantly impacting industrial competitiveness (Mastini et al. 2021). As a result, the industry is required to improve its resilience against future market scenarios by adopting energy flexibility.

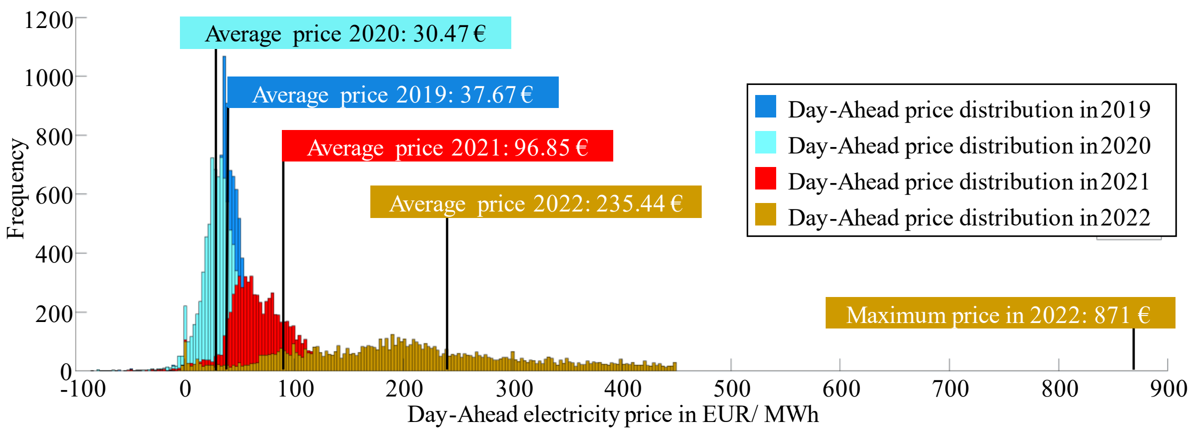

Figure 5: Frequency of EPEX SPOT hourly Day-Ahead prices for BZN|DE-LU between 2019 and 2022

Against this background, Research Article #5 explores the economic and ecological benefits of energy flexibility under market-driven dynamic tariffs, particularly in the context of market crises similar to the recent European experience. The study examines a dynamic tariff corresponding to Day-Ahead prices. To assess the economic and ecological benefits, we use a mixed-integer linear programming model to analyze different categories of industrial flexibility. This model calculates cost and emission reductions based on market data from 2019 to 2022. However, it is important to note that the model has the sole optimization goal of minimizing costs, regardless of potential emission reductions, and thus assumes that companies make decisions based solely on financial considerations. The results show that a market-based dynamic tariff led to a significant increase in the potential for reducing electricity costs through energy flexibility in Q3 2021. This potential continued to remain high as the electricity price volatility increased. In this period, cost reductions averaged five times higher than the average reduction in 2019-2020 due to the increased volatility in Day-Ahead market prices, which were captured by the dynamic tariff. Additionally, the study shows that the use of the dynamic pricing tariff resulted in both cost savings and a decrease in emissions. This is due to the established correlation between electricity costs and the greenhouse gas intensity of the energy mix. The study's findings have three implications for energy policy. Firstly, the research demonstrates how energy flexibility can act as a financial insurance against energy market volatility within the context of a market-based dynamic electricity tariff. This highlights the need for policy makers to incentivize utilities to adopt dynamic tariffs and encourage investment in energy flexibility. This forms part of a comprehensive risk management strategy for industrial energy consumers. As the energy market moves towards complete renewable energy usage, heightened volatility in power generation is expected. This could lead to repeated market disruptions, such as those experienced by industries in 2021 and 2022. Therefore, policymaking concerning future electricity rates must prioritize guiding industrial consumers to adopt a range of risk mitigation measures to maintain competitiveness. Additionally, the ecological consequences of energy flexibility, as uncovered in the study, should prompt policy makers to endorse market-based dynamic tariffs. These tariffs show a positive correlation with the greenhouse gas intensity of electricity generation, allowing flexible consumers to reduce costs and emissions simultaneously. As a result, investments in energy flexibility enable companies to contribute to ecological goals while succeeding in a future-proof energy environment. Third, the positive correlation observed between economic and ecological benefits of energy flexibility under market-based dynamic electricity prices may face challenges in certain market scenarios. For example, during the European market crisis in Germany, the prevalence of cheap yet high-emission electricity from coal-fired plants disrupted the correlation between Day-Ahead prices and emissions. In the long term, policy makers must establish favorable conditions for cost and emission reductions to progress together. This requires going beyond the implementation of dynamic and market-based electricity tariffs, and ensuring emissions are adequately considered in wholesale electricity pricing to enhance the efficiency of market-driven tariffs. An effective measure to accomplish this is to incorporate higher emissions pricing into future electricity tariff designs.

4. Analysis of energy policy instruments on a system level

4.1 A multi-agent model of urban microgrids: Assessing the effects of energy-market shocks using real-world data

In addition to the residential and industrial level, Research Article #6 explores the system level. As the proportion of renewable energies grows, the energy system must undergo significant changes. It is shifting from a centralized, top-down controlled structure, which creates regulatory barriers for expanding renewable energy, to a decentralized, bottom-up structure centered on smart energy grids (Colak et al. 2016; Abrishambaf et al. 2019). In this context, microgrids are of particular relevance. They consist of localized areas with a shared energy network that includes renewable generators, prosumers, and consumers. These microgrids can be isolated or connected to the public grid, making them highly interesting (Zhang et al. 2018; Wang et al. 2018; Jabeur et al. 2022). However, current studies on microgrids are mainly theoretical and lack real-world validation (Abrishambaf et al. 2019). To close this divide, Research Article #6 presents a pioneering multi-agent model designed to handle real-world data. It evaluates microgrid efficiency by analyzing a dataset from an actual mid-sized German city, making significant strides towards practical application. Furthermore, the article specifically examines microgrid performance during the recent European energy crisis, which was also the subject of Research Article #5.

Abrishambaf et al. (2019) classify microgrids as one of four transactive energy layers: (1) Regional layer, which connects conventional generation, grid-scale renewable energy, and energy-intensive industrial consumers through transmission system operators. (2) Local layer, managed by distribution network operators, enables electricity transmission from the transmission network to small-scale industrial, commercial, and residential consumers. (3) The microgrid layer, beginning after the point of connection to the distribution network, includes a variety of commercial and residential customers who share a local grid (microgrid) with small-scale renewable generation. (4) The residential layer, a subset of the microgrid, denotes a small-grid segment specific to residential customers. In microgrid modeling, multi-agent modeling is the dominant method in existing literature. It focuses on residential consumers and prosumers who have self-generation capabilities, including often PV, energy storage, and demand response potential. Microgrid models also often involve local electricity trading and electric vehicles (Kahrobaee et al. 2014; Reis et al. 2021a; Reis et al. 2021b). Research Article #6 encompasses all these aspects into a cohesive model, consistent with established models in the field. Furthermore, the article improves standard local electricity market modeling by approximating local demand and supply curves per time step. It determines the corresponding local electricity price to maximize turnover value. For validation, previous studies mostly use synthetic data for load profiles and PV generation under various electricity tariffs. Notably, Research Article #6 extends this literature by incorporating real-world data from a mid-sized German city. Figure 6 illustrates the multi-agent model's architecture.

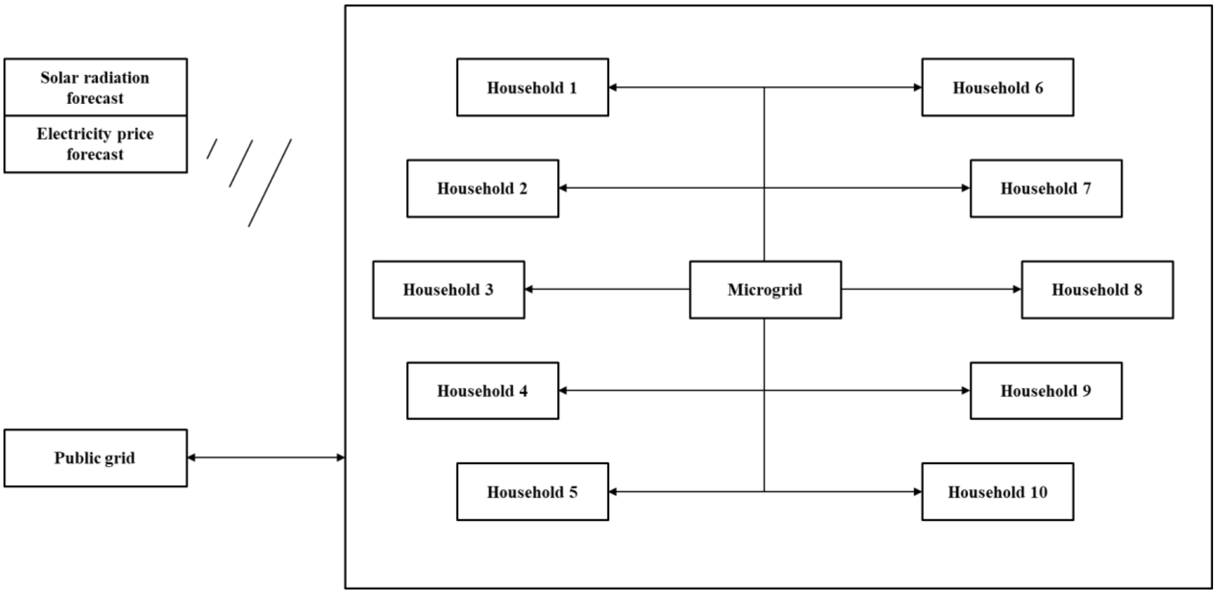

Figure 6: Exemplary microgrid architecture; note that the model can include any number of households, and the real-world data set in the article actually includes twelve households.

The article utilizes a multi-agent model to quantitatively explore the electricity costs, public grid interaction, and emissions of twelve households that have partially onsite renewable electricity production, home energy storage, and bidirectional charging electric vehicles. The study compares various scenarios to evaluate the performance of a microgrid infrastructure and a local electricity market implementation. Additionally, the model was based on data from before and during the recent European energy crisis, which enables assessment of the impact of energy market shocks on microgrid performance.

The article presents four essential discoveries that provide policy makers with insights into the advantages and difficulties connected with deploying microgrids. Firstly, a microgrid utilizing 35% of the possible solar energy generated by households can export electricity to the grid, thereby functioning as a power generator for the public grid based on rooftop PV usage. Secondly, by introducing dynamic electricity pricing within the microgrid, household energy costs decrease by 44.69%, while the interaction between the microgrid and public grid remains consistent. Thirdly, incorporating local electricity trading significantly lowers microgrid costs (average decrease of 108.91%), with prosumers (households with onsite production) benefiting twice as much as consumers (households without onsite production). Local electricity trading reduces microgrid emissions by an average of 15.81%. A comparison of microgrid performance between normal market situations and energy market crises reveals the following insights: (1) Energy crises impact microgrid consumers through public electricity price spikes. (2) High prices on public markets lead to high prices at the local electricity market, which boosts prosumer income, leading to greater inequality. (3) Despite energy market shocks, the ecological performance of microgrids remains consistent.

5. Conclusion

5.1 Summary

The dependence of wind and solar on weather patterns means that they are not always available in the desired amounts and areas. As a result, switching from conventional and fossil fuel energy sources to renewable sources such as wind and solar poses significant challenges to the energy system. The change in energy supply dynamics requires corresponding adjustments on the demand side. First, the overall efficiency must be improved, particularly during periods of limited renewable energy availability. Second, the demand side should become more adaptable to exploit periods of high energy generation from renewables. Given these circumstances, the primary goal of this thesis is to overcome existing barriers that impede the expansion of energy efficiency and flexibility. Furthermore, it aims to provide policy makers with guidance on three clear levels: residential, industrial, and systemic.

On the residential level, this thesis investigates energy policy instruments that aim to enhance efficiency, with a specific emphasis on the housing sector. The objective of the analysis is to address current retrofitting rates, which have resulted in countries such as Germany, falling considerably short of climate targets. Within this context, the thesis examines the financial risks associated with retrofitting projects and uncovers a divergence in risk perception. The decision-making process for investments in energy efficiency is explored from two distinct perspectives. Firstly, the investment perspective frames risk as "investment risk," arising from uncertain future energy cost savings. This form of risk is identified as a key impediment to energy efficiency investments. Secondly, analyses conducted from an energy bill perspective argue that energy efficiency measures decrease vulnerability to energy price fluctuations, which can be considered an investment-promoting factor. The results recommend that promoting the energy bill perspective fosters investment in energy efficiency. To empirically test this hypothesis, we conducted a field experiment. The findings confirm that participants, who are making decisions on retrofitting measures in an online shop that presents energy bill risks, invest about 20% more as compared to participants using the same online shop in an investment risk context. Furthermore, the thesis highlights the efficacy of energy efficiency insurances as an additional tool to mitigate the perceived financial risk of retrofitting projects and increase expected cost savings associated with such undertakings in owner-occupied buildings. Additionally, when analyzing typical policy measures designed to enhance residential energy efficiency, the thesis finds that subsidies would result in greater expenses for policy funding when opposed to efficiency insurances, despite generating similar investment outcomes. Moreover, the thesis underscores that emission taxes would have to be significant, at approximately 140€ per ton, to notably impact decision-making concerning thermal building retrofits. For rental properties, the current German regulations on retrofitting fees are considered unfair based on the principle of max-min fairness. As a result, these regulations pose a hurdle to required investments. To achieve fair rent increases for both landlords and tenants following the implementation of energy efficiency measures, it is recommended to apply a retrofitting fee that is anchored on the building's efficiency standard pre-retrofitting.

On an industrial level, this thesis demonstrates that dynamic electricity tariffs have the potential to overcome current economic barriers. Notably, market-based dynamic tariffs have a direct link to the greenhouse gas intensity of electricity generation. This link empowers flexible consumers to lower their costs and emissions simultaneously. Consequently, investing in energy flexibility allows companies to make a significant contribution to ecological goals and gain a competitive edge. However, it is important to note that the results of this thesis also showed that there are certain market situations in which the observed positive correlation between economic and ecological benefits of energy flexibility in the context of market-based dynamic electricity prices might be reduced. For example, during the market crisis in Europe, coal-fired plants in Germany provided inexpensive yet high-emission electricity that disrupted the previously established relationship between Day-Ahead prices and emissions. Additionally, the thesis demonstrates that the cost reductions seen in 2021 and 2022 resulting from market-based dynamic electricity tariffs and energy flexibility were significantly greater than those before the crisis. This highlights to policy makers the potential for energy flexibility to function as a means of financial protection against the volatility of the energy market.

On the system level, the thesis demonstrates how policy makers can evolve the existing energy system and surpass outdated regulations by deploying residential microgrids and local electricity markets. These measures can integrate and balance decentralized renewable electricity supply with an increasingly demand for power, heat, and transportation, while reducing costs and emissions. To achieve this objective, the thesis introduces a multi-agent simulation model to evaluate the microgrid's real-world performance based on economic, technical, and ecological metrics. The model's holistic approach enables accurate and comprehensive simulation of microgrid behavior. Following the state-of-the-art research, the model encompasses self-interested, autonomous agents with unique load profiles, renewable generation, and demand-response potential. The model can simulate a peer-to-peer marketplace in which electricity is exchanged between agents. The thesis provides policy makers with insights regarding the use of microgrid implementation as a system-level instrument. To begin with, a microgrid could serve as a dependable source of energy when supplemented with on-site renewable generation. Second, by implementing dynamic electricity pricing, the microgrid has the potential for significant cost reductions for all participants within the microgrid. Third, local electricity trading within the microgrid also leads to substantial cost savings, although prosumers benefit more than consumers. Lastly, the microgrid's performance during the recent European energy crisis demonstrated notable changes: it affected consumers with public electricity price spikes, exacerbated income inequality among participants due to high local electricity market prices, yet retained ecological stability despite market fluctuations.

Figure 7 presents a conclusive summary of the policy implications derived from this thesis. It expands on the structure presented in Figure 1, illustrating effective policy instruments at different levels and for the relevant barriers under examination.

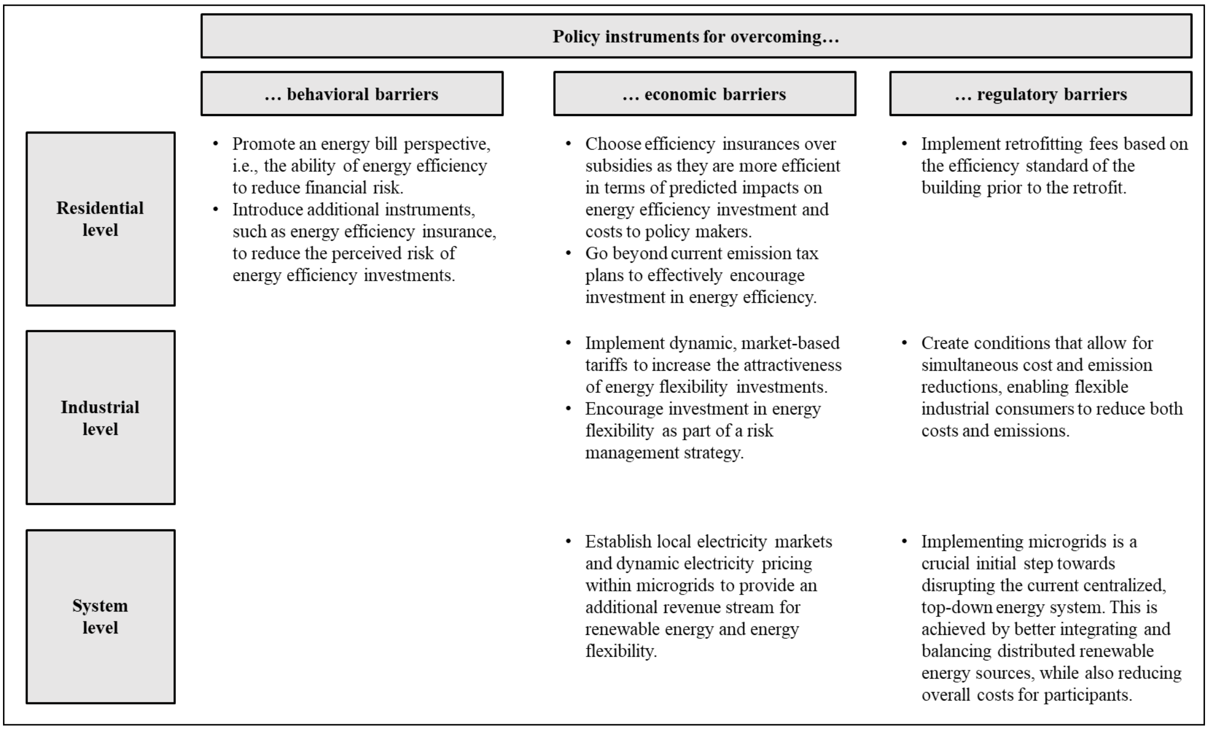

Figure 7: Summary of policy implications for advancing energy efficiency and energy flexibility

5.2 Limitations and future research

Like any research, this thesis has limitations that can serve as the foundation for future research. Specific limitations for the various research articles can be found in the papers themselves. The following section provides general limitations for the entire thesis and specific limitations for the three levels being considered.

(1) The several research articles incorporate data-driven simulations and case studies. These studies have certain inherent limitations regarding data selection and quality. Specifically, all datasets are obtained solely from Germany and cover particular building types (Research Article #1, Research Article #3, Research Article #4, Research Article #6) or targeted market segments (Research Article #5). Furthermore, Research Article #2 involved only German participants who were relatively young and highly educated. As a result, differences in outcomes and potential policy implications may arise when using diverse datasets from different locations, with different types of buildings, market segments, or participant demographics in the experimental field. Given this context, it is essential for future research to use the theoretical frameworks introduced in the various research articles as a basis for further validation utilizing datasets from different countries, a broader range of building types, and diverse market segments.

(2) Another limitation worth noting is the temporal scope of the research articles. The energy sector's regulatory landscape and market dynamics are undergoing significant changes, particularly within the context of the energy transition. A recent example is the energy market disruption in Europe caused primarily by Russia's invasion of Ukraine, leading to natural gas shortages and volatile energy prices. This highlights the abrupt and significant changes that can take place in energy markets. Thus, it is vital for future research to reassess the findings and discoveries put forth in this thesis. Furthermore, given the rising effects of climate change and the growing demand for more decisive government responses, novel policy tools to tackle these issues are likely to arise and be executed on a broader scale. Consequently, it is essential for future research to utilize the methodologies developed in this thesis such as the Risk-Integrated Thermal Energy Hub. This will help assess the effectiveness of potentially new and promising policy tools in the evolving ecological policy landscape.

(3) The research articles relied on the assumption of rational decision-making and risk aversion in their models and simulations. Therefore, individuals and companies base their decision-making on factual data and financial considerations. The objective is to increase financial gains while reducing financial risks. However, education is critical for individuals to navigate and distinguish between accurate information and misinformation, including fake news, especially in the field of energy-related decisions (Pop and Ene 2019). Considering this, future research should further investigate the insights presented in this thesis by exploring irrational behaviors and how they affect policy instruments for improving energy efficiency and flexibility. A pertinent example of such research can be found in the work of Häckel et al. (2017), where they developed a model that incorporates irrational decision-making principles rooted in Cumulative Prospect Theory (Kahneman and Tversky 1979).

(4) At the residential level, research articles primarily focus on space heating, which accounts for a substantial 70% of final energy consumption in German buildings (Destatis 2022). However, it is important to recognize that other energy sectors, such as the mobility sector, also play a crucial role in achieving a successful energy transition within the residential domain. Therefore, future research should explore the principles and insights derived from Research Article #1, Research Article #2, and Research Article #3 to include various energy sectors, such as mobility. In this regard, studies could determine whether the energy bill viewpoint is a persuasive argument to encourage more sustainable and energy-efficient modes of mobility. Furthermore, the concept of a Risk-Integrated Thermal Energy Hub can be adapted into a Risk-Integrated Mobility Energy Hub. This allows for evaluating the effectiveness of measures such as efficiency insurances, subsidies, emission taxes, and other policy instruments on investments regarding sustainable mobility.

(5) Within the industrial sector, this thesis focuses on one specific approach for promoting energy flexibility: utilizing dynamic electricity tariffs based on the Day-Ahead market. However, it is important to note that there are other strategies for promoting energy flexibility, each with the potential to impact investment decisions. In addition to price-based commercialization, which includes dynamic electricity

tariffs, there is also the possibility of incentive-based commercialization (Jordehi 2019). Incentive-based use of flexibility involves offering flexibility resources in balancing markets. Under this framework, electricity consumers receive direct compensation for either reducing or increasing their electricity consumption at specific times as required to stabilize the grid (Albadi and El-Saadany 2008). Therefore, forthcoming research should supplement the findings derived from Research Article #5 by considering the viewpoint of incentive-based commercialization. This may entail scrutinizing whether these methods provide risk-reduction potential in times of energy market turmoil and allow adaptable consumers to simultaneously lower energy expenses and emissions.

(6) Finally, this thesis, on the system level, primarily delves into highlighting the advantages and challenges associated with microgrids and local electricity markets. However, the thesis does not give guidance on how to structure the shift from a centralized energy system to a decentralized one. Given the numerous advantages of microgrids and local electricity markets for both residents and the broader energy system outweigh potential challenges, the next avenue of research should now concentrate on crafting a transition plan that is socially acceptable and economically sustainable while ensuring uninterrupted energy availability.

Despite these limitations I am confident that the analysis, conclusions, and policy recommendations presented in this thesis serve as a valuable foundation for enhancing energy efficiency and energy flexibility and for shaping a climate-neutral future.

5.3 Acknowledgement of previous and related work

In all of my research articles, I have worked closely with colleagues in the Branch of Business & Information Systems Engineering at the Fraunhofer Institute for Applied Information Technology (FIT) and the FIM Research Center in Augsburg and Bayreuth. This work builds upon previous research conducted at these institutions and elsewhere.

For the first three research articles, namely #1, #2, and #3, the foundation laid by respected scholars such as Töppel and Tränkler (2019), Mills (2003), Buhl et al. (2018), and Häckel et al. (2017) was built upon. These studies informed the examination of different aspects of risk in energy efficiency decision making, as well as initial explorations of the concept of energy efficiency insurances. Regarding Research Article #4, the research team was inspired by Bertsimas et al.'s (2011) work on fairness schemes, which laid the foundation for the presented max-min fairness model. Additionally, the contributions of Berger and Höltl (2019) led to the concept of applying a fairness scheme to retrofitting fees. Regarding Research Article #5, it was not based on a specific previous research article but rather emerged from the collaborative efforts within the Kopernikus-project SynErgie, which is funded by the Federal Ministry of Education and Research (SynErgie 2024). This project focuses on industrial energy flexibility. Finally, Research Article #6 was inspired by multiple preceding multi-agent models, including works by Reis et al. (2021a) and Kahrobaee et al. (2014), among others.

Please note that I utilized ChatGPT and DeepL to enhance the language and readability of this work. However, I take full responsibility for the content of this thesis, and I reviewed and edited the material as necessary.

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7. Appendix

7.1 Research articles relevant to this doctoral thesis

Research Article #1: Understanding the risk perception of energy efficiency investments: Investment perspective vs. energy bill perspective

Rockstuhl, S.[1]; Wenninger, S.; Wiethe, C.; Häckel, B. (2021). "Understanding the risk perception of energy efficiency investments: Investment perspective vs. energy bill perspective". In: Energy Policy. DOI: 10.1016/j.enpol.2021.112616

(VHB-JQ3 Category: B)

Research Article #2: The influence of risk perception on energy efficiency investments: Evidence from a German survey

Rockstuhl, S.[1]; Wenninger, S.; Wiethe, C.; Ahlrichs, J. (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 #3: The impact of political instruments on building energy retrofits: A risk-integrated thermal energy hub approach

Ahlrichs, J.; Rockstuhl, S. [1]; 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 #4: Estimating fair rent increases after building retrofits: A max-min fairness approach

Ahlrichs, J.; Rockstuhl, S. [1]; (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)

[1] Due to my name change in 2023, the article was published under my birth name Sebastian Rockstuhl

Research Article #5: Unleashing the economic and ecological potential of energy flexibility: Attractiveness of real-time electricity tariffs in energy crises

Förster, R.; Harding, S.; Buhl, H.; (2024). "Unleashing the economic and ecological potential of energy flexibility: Attractiveness of real-time electricity tariffs in energy crises". In: Energy Policy. DOI: 10.1016/j.enpol.2023.113975

(VHB-JQ3 Category: B)

Research Article #6: A multi-agent model of urban microgrids: Assessing the effects of energy-market shocks using real-world data

Madler, J.; Harding, S.; Weibelzahl, M.; (2022). "A multi-agent model of urban microgrids: Assessing the effects of energy-market shocks using real-world data". In: Applied Energy. DOI: 10.1016/j.apenergy.2023.121180

(VHB-JQ3 Category: -, Impact Factor (2023): 11.2)

I also collaborated on additional research articles within the dissertation, but they are not included in this doctoral thesis. Below are the articles published prior to the submission of the doctoral thesis.

- Rusche, S.; Rockstuhl, S.[1]; Wenninger, S. (2021). "Quantifizierung unternehmerischer Nachhaltigkeit in der Fertigungsindustrie: Entwicklung eines zielorientierten Nachhaltigkeitsindex". In: Zeitschrift für Energiewirtschaft. DOI: 10.1007/s12398-021-00312-1.
- Mijatovic, L.; Rockstuhl, S.[1]; Wagon, F.; (2022). "Diversifikation des marktlichen Risikos bei der Vermarktung industrieller Energieflexibilität im Kontext von Demand Response". In: Zeitschrift für Energiewirtschaft. DOI: 10.1007/s12398-022-00318-3

[1] Due to my name change in 2023, the article was published under my birth name Sebastian Rockstuhl

7.2 Individual contribution to the research articles

This doctoral dissertation is cumulative, comprising six research articles that form the main body of work. All articles were developed in teams and have multiple co-authors. This section provides specific information on the research settings and my contributions to each article.

Research Article #1, titled “Understanding the risk perception of energy efficiency investments: Investment perspective vs. energy bill perspective”, was co-authored by a team of four. Three authors, including myself, were jointly responsible for writing the text of the originally submitted version and the revised versions of the article. As a team, we agreed that two of the co-authors and I should assume the roles of lead authors of the research article. The other co-author contributed as a subordinate author, mainly in the form of feedback during the submission and review process and in his role as a scientific supervisor and mentor. All lead authors jointly elaborated on the methodological approach to analyze how the investment and energy perspective influence decision-making with a theoretical model and a case study based on real-world data of the German retrofitting market. Further, all lead authors contributed equally to the evaluation and analysis of the results and the derivation of policy measures promoting the energy bill perspective for higher investments in energetic retrofitting. In the case study conducted, I was particularly responsible for the development of the initial idea and modelling of the two perspectives.

Research Article #2, titled “The influence of risk perception on energy efficiency investments: Evidence from a German survey”, was co-authored by a team of four. All authors, including myself, were jointly responsible for writing the text of the originally submitted version of the article. As a team, we agreed that I should assume the role of the sole lead author of the research article. The other co-authors contributed as subordinate authors, mainly in the form of writing the manuscript, graphical visualizations, and literature work. In particular, I was responsible for the supervision and management of the research project, the conception of the field experiment, the development and implementation of the online shop, the evaluation and interpretation of the results, and the revision of the article.

Research Article #3, titled “The impact of political instruments on building energy retrofits: A risk-integrated thermal energy hub approach”, was co-authored by a team of four. All co-authors were jointly responsible for writing the text of the originally submitted version and the revised versions of the article. All co-authors worked jointly on the analysis and interpretation of the case study results conducted. In addition, all co-authors contributed equally to the evaluation and analysis of the results and to the derivation of policies for risk-mitigating energy efficiency insurances, which are relatively inexpensive compared to subsidies. In the research project, I was particularly responsible for the development and implementation of the Monte Carlo Simulation.

Research Article #4, titled "Estimating fair rent increases after building retrofits: A max-min fairness approach", was co-authored by a team of two. Both co-authors were jointly responsible for writing the text of the original submitted version and the revised versions of the article. As a team, we agreed that my co-author should assume the role of sole lead author of the research article. Therefore, he contributed most to the evaluation and analysis of the results and to the derivation of policy implications for fair retrofitting fees that should be related to building efficiency. My main contribution to the research project was the analysis of the existing literature on fairness and the application of the max-min fairness scheme to retrofitting fees.

Research Article #5, titled “Unleashing the economic and ecological potential of energy flexibility: Attractiveness of real-time electricity tariffs in energy crises”, was co-authored by a team of three. Two authors, including myself, were jointly responsible for writing the text of the originally submitted version and the revised versions of the article. As a team, we agreed that one of the co-authors and I should assume the roles of lead authors of the research article. The other co-author contributed as a subordinate author, mainly in the form of feedback during the submission and review process and in his role as a scientific supervisor and mentor. All lead authors jointly elaborated on the methodological approach to analyze financial and ecological benefits of a market-based electricity tariff for flexible industrial consumers. Further, all lead authors contributed equally to the evaluation and analysis of the results and the derivation of policy implications on future electricity tariffs. I was particularly responsible for the analysis of existing literature.

Research Article #6, titled “A multi-agent model of urban microgrids: Assessing the effects of energy-market shocks using real-world data”, was co-authored by a team of three. Two authors, including myself, were jointly responsible for writing the text of the originally submitted version and the revised versions of the article. As a team, we agreed that one of the co-authors and I should assume the roles of lead authors of the research article. The other co-author contributed as a subordinate author, mainly in the form of feedback during the submission and review process and in his role as a scientific supervisor and mentor. All lead authors jointly elaborated on the development of the multi-agent model analyze the microgrid performance. Further, all lead authors contributed equally to the evaluation and analysis of the results and the derivation of implications on general benefits and challenges of microgrids. In particular, I was responsible for developing the local electricity market mechanism.

7.3 Research Article #1

Title	Understanding the risk perception of energy efficiency investments: Investment perspective vs. energy bill perspective
Authors[1]	Sebastian Harding; Simon Wenninger; Christian Wiethe, Björn Häckel
Published in	Energy Policy (2021)
Abstract	Promoting energy efficiency is an important element of environmentally friendly energy policy and necessary to avert climate change. In this context, understanding the investment decision-making of individuals is important to develop and implement effective policy instruments. Literature analyzing decision-making of energy efficiency investments and especially the influence of connected risk finishes with two different conclusions, i.e., analyzes risk from two different perspectives. First, studies within the investment perspective describe investment risk, caused by volatile future energy bill savings, as a key barrier for energy efficiency investments. Second, studies within the energy bill perspective argue that energy efficiency is reducing energy price exposure and the resulting decrease of overall risk is described as investment promoting. This dichotomy in risk perception is the focus of our study. With the help of a theoretical model as well as a case study based on real-world data of the German retrofitting market, we analyze how the contrary perspectives influence expected utility, i.e., decision-making. Thereby, we find that decision-makers invest more in energy efficiency when evaluating from the energy bill perspective and derive important implications for environmentally friendly energy policymaking.
Keywords	Energy efficiency; Risk evaluation; Expected utility theory; Case study

[1] Due to my name change in 2023, the article was published under my birth name Sebastian Rockstuhl

7.4 Research Article #2

Title	The influence of risk perception on energy efficiency investments: Evidence from a German survey
Authors[1]	Sebastian Harding; Simon Wenninger; Christian Wiethe, 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; Energy efficiency; Decision-making; Retrofitting, Choice experiment

[1] Due to the name changes of myself and Jakob Rockstuhl, the article was published under our birth names Sebastian Rockstuhl and Jakob Ahlrichs.

7.5 Research Article #3

Title	The impact of political instruments on building energy retrofits: A risk-integrated thermal energy hub approach
Authors[1]	Jakob Rockstuhl, Sebastian Harding, Timm Tränkler, 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

[1] Due to the name changes of myself and Jakob Rockstuhl, the article was published under our birth names Sebastian Rockstuhl and Jakob Ahlrichs.

7.6 Research Article #4

Title	Estimating fair rent increases after building retrofits: A max-min fairness approach
Authors[1]	Jakob Rockstuhl, 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

[1] Due to the name changes of myself and Jakob Rockstuhl, the article was published under our birth names Sebastian Rockstuhl and Jakob Ahlrichs.

7.7 Research Article #5

Title	Unleashing the economic and ecological potential of energy flexibility: Attractiveness of real-time electricity tariffs in energy crises
Authors	Robert Förster, Sebastian Harding, Hans Ulrich Buhl,
Published in	Energy Policy (2024)
Abstract	The European energy crisis in 2021 and 2022 emphasized the importance of energy flexibility to mitigate price peaks and manage increased market volatility. Dynamic electricity tariffs are key to unlocking the potential of energy flexibility, as they incentivize flexible consumers to reduce their costs by shifting their load to periods of low prices. We quantify the potential of dynamic tariffs and focus on their economic and ecological potential particularly in energy crises. Using German Day-Ahead spot market data covering 2019 to 2022 as basis for a dynamic tariff, we determine the cost and emission spread between non-flexible and flexible industrial processes. Our results show that energy flexibility together with the real-time electricity tariff lead to energy cost reductions, with relative cost reductions of flexible loads being up to 12 times higher in the energy crisis. Moreover, pre-crisis electricity costs and associated emissions were highly positively correlated, implying flexibilities in real-time electricity tariffs may minimize electricity costs while simultaneously reducing emissions. Based on our results, we conclude that real-time electricity pricing provides a suitable instrument to (1) incentivize necessary investments in energy flexibility, especially in energy crises, and (2) facilitate flexible consumers to reduce costs and emissions at the same time.
Keywords	Demand Side Management; Dynamic tariffs; Decarbonization; Energy flexibility; Renewable energy; Energy crisis

7.8 Research Article #6

Title	A multi-agent model of urban microgrids: Assessing the effects of energy-market shocks using real-world data
Authors	Jochen Madler, Sebastian Harding, Martin Weibelzahl
Published in	Applied Energy (2023)
Abstract	The shift towards renewable energy sources (RES) in energy systems is becoming increasingly important. Residential energy generation and storage assets, smart home energy management systems, and peer-to-peer (P2P) electricity trading in microgrids can help integrate and balance decentralized renewable electricity supply with an increasingly electrified power, heat, and transport demand, reducing costs and CO_2 emissions. However, these microgrids are difficult to model because they consist of autonomous and interacting entities, leading to emergent phenomena and a high degree of complexity. Agent-based modeling is an established technique to simulate the complexity of microgrids. However, the existing literature still lacks real-world implementation studies and, as a first step, models capable of validating the existing results with real-world data. To this end, we present an agent-based model and analyze the corresponding microgrid performance with real-world data. The model quantifies economic, technical, and environmental metrics to simulate microgrid performance holistically and, in line with state-of-the-art research, consists of self-interested, autonomous agents with specific load profiles, RES generation, and demand-response potential. The model can simulate a P2P marketplace where electricity is traded between agents. In the second part of the paper, we validate the model with data from a medium-sized German city. In this case study, we also compare microgrid performance in 2022, during the energy market crisis in Europe, with historical data from 2019 to assess the effects of energy market shocks. Our results show how microgrids with P2P trading can reduce electricity costs and CO_2 emissions. However, our trading mechanism illustrates that the benefits of energy-community trading are almost exclusively shared among prosumers, highlighting the need to consider distributional issues when implementing P2P trading.
Keywords	Microgrids; Local electricity markets; Peer-to-peer energy trading; Agent-based modeling