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Master's Degree
in Sustainable Development

(Joint Degree Programme in Sustainable Development in cooperation
with the University of Graz)

Final Thesis

**Distributional Effects of Climate Policies on German
Households: Incorporating Behavioural Frictions into a
Microsimulation**

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Matriculation Number 904894

Academic Year

2025 / 2026

Abstract

Carbon pricing is widely regarded as an efficient instrument for reducing emissions. However, concerns remain about its distributional effects on low-income households. Current assessments largely assume that households will respond rationally to carbon price signals, potentially overlooking behavioural barriers that influence investment decisions and energy consumption patterns. This thesis investigates how behavioural frictions affect the distributional impacts of the German national emissions trading system (nEHS) in the residential heating sector. To this end, a household-level microsimulation model is extended to incorporate behavioural factors, such as bounded rationality, liquidity constraints, and social-class-related barriers to adopting low-carbon heating technologies. The model evaluates how households respond to rising carbon prices in various policy and behavioural scenarios, including subsidy schemes, credit support measures, and per-capita climate payments. The results indicate that behavioural frictions significantly slow the adoption of low-carbon heating technologies and increase the policy burden on low-income households relative to conventional rational-choice assumptions. Consequently, the regressive effects of carbon pricing are amplified when behavioural barriers are considered. Subsidies and credit support partially mitigate these effects. These findings demonstrate that behavioural frictions are a critical determinant of carbon pricing outcomes and should be incorporated into distributional policy assessments. Failing to consider such factors could result in a systematic underestimation of the social impacts of climate policy and the difficulties experienced by vulnerable households during the transition to a low-carbon economy.

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1. Introduction

The transition to a low-carbon economy is no longer merely a technical or environmental challenge. It is a test of social cohesion and democratic legitimacy. The formation of the Yellow Vest (*Gilets Jaunes*) movement in France is a prime example of the dangers of overlooking the distributional impact of environmental policy. What began as a reaction to a proposed increase in the carbon tax evolved into a nationwide uprising, driven by a widespread perception of “felt unfairness” regarding the burden of the energy transition. As Mehleb et al., (2021) observed, protesters perceived the fuel tax as a disproportionate burden on lower-income and rural residents who rely on diesel vehicles for basic survival, while wealthier demographics continued to enjoy untaxed luxuries like air travel. This perceived class conflict was further intensified by simultaneous changes to the French tax code, particularly the replacement of the solidarity tax on wealth with a more lenient property tax. This led to the widespread belief that the carbon tax was effectively subsidising tax cuts for the wealthy (Douenne & Fabre, 2022).

Resistance to the French carbon tax was not a single economic grievance, but rather the intersection of four distinct ideological oppositions. For some, the tax was a diversionary tactic within a capitalist framework designed to enrich the elite under the guise of ecology. For others, the opposition was not to the environmental goal itself, but to the lack of equitable redistribution. A significant portion of the movement focused on the immediate erosion of purchasing power in regions lacking public transport alternatives, while another group argued that corporations, as the primary drivers of pollution (Wright & Nyberg, 2024), should bear the financial responsibility rather than individual consumers (Mehleb et al., 2021).

The French carbon tax debacle was a critical turning point that highlighted a significant “bias of pessimism” and a breakdown in communication between the state and its citizens. Research by Douenne and Fabre (2022) indicates a substantial gap between objective economic data and consumer perception. Even when policies were designed to be progressive, many citizens, particularly those already distrustful of the government, overestimated their personal losses. This “motivated reasoning” often led to a “boomerang effect¹”, where providing factual information about policy benefits actually increased opposition. Such dynamics suggest that the success of climate policy depends less on its aggregate environmental effectiveness and

¹ The term “boomerang effect” refers to the undesirable outcomes that can arise from climate mitigation or adaption policies. These policies can inadvertently reduce their own effectiveness or even lead to negative reactions (Swatuk et al., 2018).

more on its perceived fairness and the trust placed in the implementing institutions (Lunn, 2024).

The determinants of support for such movements are deeply rooted in social status and the quality of public services (Gugushvill & Otto, 2021). Mayol and Porcher (2025) find that individuals with lower social status, such as blue-collar workers and employees, are significantly more likely to participate in protests, often motivated by rational economic calculations regarding their commuting needs. Conversely, higher satisfaction with local public services, such as transport and waste management, can enhance perceptions of fiscal effectiveness, increasing the social acceptability of ecological levies. Ultimately, the Yellow Vest movement was a manifestation of a “feeling of decline” among the lower-middle class, exacerbated by a top-down policy approach that failed to provide adequate compensation for the vulnerable.

The Yellow Vests protests in France illustrate the social tensions ignited by climate policies that overlook distributional impacts. Enacted in 2018, France’s fuel tax hikes disproportionately burdened low-income households reliant on automobiles for work and daily needs, sparking widespread unrest and eroding public support for the energy transition (Drews & van den Bergh, 2016). This episode illustrates how insufficient attention to distributional equity in sustainability policy design can exacerbate social inequalities and intensify political contestation, potentially undermining the “Just Transition” objectives embedded in frameworks such as the European Green Deal and Germany’s nEHS (Ascari et al., 2025; Burger et al., 2022).

For society, the stakes are immediate. Germany’s nEHS, launched in 2021, imposes carbon prices on heating and transport fuels, imposing additional costs of up to 55€ per tonne CO₂ by 2025 (DEHSt, 2025). Low-income groups, which spend a larger share of their income on energy, face greater regressivity, potentially deepening poverty (Ackermann & Radulescu, 2024). Policymakers must balance emission reductions with social cohesion. Failure invites “yellow vests” scenarios that stall decarbonisation (Driscoll, 2023).

This thesis addresses a significant gap in research. Prevailing microsimulation studies of carbon pricing assume fully rational agents (Maier et al., 2025; Rausch et al., 2011), overestimating adaptation and understating harm to vulnerable groups. By integrating behavioural frictions, such as imperfect information, adjustment delays, limited price responsiveness, liquidity constraints, and barriers to low-carbon technology into an nEHS model, this work reveals

whether low-income households suffer disproportionately compared to higher earners. This approach not only refines distributional incidence estimates and informs compensatory mechanisms such as eco-bonuses, but also advances Just Transition scholarship and policy design in Germany and beyond.

The thesis begins with a theoretical framework that explores the concept of Just Transformation and the reasons underlying carbon pricing, including the institutionalisation of Just Transformation and various justice criteria. Following this, the policy background is detailed, focusing specifically on the European Union Emissions Trading System (EU ETS) and the German national Emissions Trading System (nEHS), as well as its revenue recycling and compensation measures.

The state-of-the-art review evaluates the existing literature on the distributional effects of carbon pricing, introducing cognitive and behavioural frictions, such as loss aversion, imperfect information and status quo bias, that challenge the traditional gap concerning the disconnect between these behavioural frictions and distributional outcomes for low-income households. The thesis outlines a microsimulation methodology. This approach involves simulating the nEHS carbon price shock and comparing rational and behavioural scenarios in order to assess the influence of behavioural frictions on distributional outcomes, adaptive capacity, subsidy effectiveness and the probability of adopting low-carbon heating technologies, such as heat pumps. Additional sensitivity analyses examine the impact of different behavioural parameters and imperfect information on income groups. The final chapters present and summarise the simulation results, focusing particularly on the behavioural amplification of policy burdens, the adoption gap and unequal access to the energy transition. This is followed by a discussion of the findings and a concluding summary.

2. Theoretical Framework

Understanding the distributional impacts of carbon pricing requires a clear conceptual foundation that links climate policy with principles of justice. The concept of a Just Transition (JT) provides this foundation by emphasising that the shift towards a low-carbon economy needs to balance environmental objectives with social equity and fairness considerations. This chapter, therefore, develops the theoretical framework underpinning the thesis, combining insights from Just Transition and economic perspectives on carbon pricing. Its purpose is to define the key concepts and normative criteria that guide the analysis, thereby establishing the basis for evaluating distributional outcomes and behavioural responses in later chapters.

2.1 Just Transformation and Carbon Pricing

The effectiveness of carbon pricing is significantly affected by perceived fairness issues, as these subjective evaluations determine public acceptability, which in turn dictates the political feasibility and long-term stability of climate mitigation efforts (Barrez & Bachus, 2023; Huttarsch & Matthies, 2024; Maestre-Andrés et al., 2019; Pitkänen et al., 2022). Consequently, perceived unfairness is a primary barrier to the implementation of carbon pricing. When the public views a policy as unjust, it often leads to societal resistance that can force governments to suspend or cancel planned measures (Barrez & Bachus, 2023; Huttarsch & Matthies, 2024; Maestre-Andrés et al., 2019; Povitkina et al., 2021). Notable examples include the repeal of carbon pricing in Australia, the rejection of ballot initiatives in Washington State, and the suspension of the French carbon tax following the “Yellow Vest” protests, all of which were rooted in fairness concerns (Barrez, 2024; Huttarsch & Matthies, 2024; Maestre-Andrés et al., 2019; Povitkina et al., 2021). This lack of acceptability frequently results in weak policies with price levels that remain far below those required to meet Paris Agreement targets (Barrez & Bachus, 2023; Maestre-Andrés et al., 2019).

Central to this dynamic is a strong psychological link between a policy’s perceived fairness and its perceived effectiveness (Huttarsch & Matthies, 2024; Maestre-Andrés et al., 2019). This relationship is often conditioned by perceived distributive justice. Individuals who perceive a carbon price as personally or socially unfair, due to high costs or a lack of alternatives, frequently dismiss the policy as ineffective (Barrez & Bachus, 2023; Huttarsch & Matthies, 2024). Such a self-serving bias leads individuals to reject the notion that price increases can effectively change behaviour (Barrez & Bachus, 2023; Dütschke et al., 2023; Huttarsch & Matthies, 2024). In many cases, citizens do not believe carbon pricing will reduce emissions,

viewing it instead as a pretext for the government to raise revenue (Barrez & Bachus, 2023; Dütschke et al., 2023). For example, focus groups in Germany revealed that the majority believe that the demand for fossil fuels is price inelastic (Dütschke et al., 2023). This means that consumption only responds weakly to price changes because households often have limited short-term alternatives for mobility and heating (Díaz & Medlock, 2021). This leads to the perception that the tax is both a “financial penalty” and an ineffective climate tool (Dütschke et al., 2023).

The intended climate mitigation impact of these policies is further undermined by a lack of procedural fairness and political trust (Barrez & Bachus, 2023; Maestre-Andrés et al., 2019; Povitkina et al., 2021). Transparency plays a critical role here: perceived fairness increases when there is dissatisfaction with the provision of government information (Barrez & Bachus, 2023; Huttarsch & Matthies, 2024; Maestre-Andrés et al., 2019). Without transparency, citizens are less likely to recognise the environmental or economic co-benefits of the tax, further weakening their belief in its overall impact (Barrez, 2024; Barrez & Bachus, 2023; Maestre-Andrés et al., 2019).

Additionally, effectiveness is impacted when policies fail to account for horizontal equity, meaning that individuals or groups in comparable circumstances should be treated equally, even if their specific needs differ (Lambert et al., 1995; Pitkänen et al., 2022). Under the “need principle”, policies are viewed as unfair when they burden those who have no choice but to consume carbon-intensive goods, such as rural residents lacking public transport or families living in poorly insulated housing (Pitkänen et al., 2022). If vulnerable groups cannot adapt their behaviour due to these structural constraints, the carbon price fails to incentivise a low-carbon shift and serves only as a regressive financial burden (Dütschke et al., 2023; Maestre-Andrés et al., 2019; Pitkänen et al., 2022).

However, the design can enhance the impact of carbon pricing. Revenue recycling can restore perceived effectiveness by directly addressing fairness concerns (Maestre-Andrés et al., 2019). Environmental earmarking², dedicating revenues to projects like renewable energy or green infrastructure, creates a logical link that counters effectiveness scepticism and increases public support (Maestre-Andrés et al., 2019). Similarly, targeted redistribution to vulnerable or heavily burdened groups, such as social welfare recipients or commuters, increases perceived

² Environmental earmarking is a fiscal mechanism where the revenue generated from “green” taxes is legally or administratively tied to specific environmental expenditures (Soares, 2012).

fairness and helps close the gap between an economically optimal policy and a politically achievable one (Barrez, 2024; Maestre-Andrés et al., 2019). Finally, a gradual implementation of price increases allows for societal learning, in which citizens can experience policy benefits and adapt their behaviour before being hit by full costs, thereby increasing both acceptance and actual emission reductions over time (Barrez & Bachus, 2023; Dütschke et al., 2023).

2.1.1 Reasons for Carbon Pricing

This chapter established the theoretical framework for carbon pricing, transitioning the thesis from climate problem identification to economic intervention. It is positioned here to define the market-based logic required to address the negative externalities of greenhouse gas emissions.

Carbon pricing addresses core market failures in climate policy by internalising the social costs of CO₂ emissions, ensuring emitters bear the full societal burden of climate damages not reflected in fossil fuel market prices. This Pigouvian mechanism³ alters relative prices to favour low-carbon alternatives without mandating specific technologies, compelling firms and consumers to automatically account for global warming effects (Baranzini et al., 2017). Even when determining an “optimal” price proves challenging due to scientific uncertainties and emission-damage lags (Dietz et al., 2021), rough estimates deliver a critical signal for integrating climate costs into economic decisions (Köppl & Schratzenstaller, 2023). In the short run, it incentivises households and firms to cut emissions via the most cost-effective measures, while accommodating emitter heterogeneity to minimise aggregate abatement costs (Baranzini et al., 2017; Boyce, 2018). By decentralising abatement choices, it reduces regulators’ information burdens, harnessing price responsiveness, consumers’ primary driver in purchasing over environmental ethos (Baranzini et al., 2017). Long-term, it delivers a continuous spur to the adoption and innovation of carbon-efficient technologies (Baranzini et al., 2017; Boyce, 2018; Calel & Dechezleprêtre, 2016) and curtails carbon rebound effects. Fundamentally, carbon pricing counters the “tragedy of open access” in climate change, where individuals reap fossil fuel benefits but share infinitesimal costs (Murphy & Murphy, 2012), akin to a command depleted by unchecked use. It establishes property rights over the biosphere’s finite CO₂ absorption capacity, transitioning from unmanaged exploitation to sustainable allocation (Boyce, 2018).

³ Pigouvian mechanisms in climate policy refer to tax instruments that internalise the external costs of greenhouse gas emissions by pricing pollution in proportion to its social damage (van der Ploeg, 2025).

2.1.2 The Concept of Just Transition

Research states that a fundamental transition from fossil fuel energy systems to a low-carbon system is required to address climate change in an effective way (Calvin et al., 2023). However, this shift cannot be reached easily. It requires complicated social and technological changes and is sure to have considerable social impacts (Wang & Lo, 2021). Researchers have found that such a transition needs to be handled carefully to avoid reproducing environmental and socio-economic disparities that are currently embedded in society (Jasanoff, 2018; Winkler, 2020). Within current academic discourse, a universally accepted definition or standardised framework for Just Transformation (JT) has yet to be established (Stark et al., 2023). Despite this lack of consensus, several prominent conceptualisations emerge from the literature, ranging from labour-centric perspectives to broader socio-environmental paradigms (Bennett et al., 2019; Wang & Lo, 2021).

The International Labour Organization (ILO) provides a foundational definition, characterising Just Transformation as a conceptual framework utilised by the labour movement to address the multifaceted complexities inherent in transitioning toward a low-carbon, climate-resilient economy. Central to the ILO's perspective is the strategic use of public policy to mitigate and minimise the hardships experienced by workers and their respective communities during this shift (International Labour Organization, 2015).

Expanding beyond labour dynamics, other organisations and scholars emphasise a more holistic integration of justice. For instance, the Canadian Labour Congress (CLC) explicitly underscores the necessity of achieving both environmental and social justice within the transformative process (Stark et al., 2023). Similarly, McCauley and Heffron (2018) define Just Transformation as a “fair and equitable process of moving toward a post-carbon society.” However, at its most fundamental level, the concept serves as a critical bridge between policy objectives, effectively linking the dimensions of climate action with the requirements of social fairness (Stark et al., 2023).

2.1.2.1 The Evolution of Just Transformation

The lineage of Just Transformation (JT) can be traced back to the American labour movement of the late 20th century, where the term is specifically attributed to the unionist Tony Mazzocchi. It emerged as a pragmatic response to the escalating tension between environmental protection and job security. Mazzocchi advocated for the protection of workers' rights at a time when nascent environmental regulations threatened the viability of high-

polluting industries (Thomas, 2021; Wilgosh et al., 2022). Initially, the concept functioned with a narrow framework of “labour environmentalism.” However, it evolved into a sophisticated political strategy aimed at dismantling the binary “Jobs versus Environment” narrative. This shift allowed for a more integrated discourse where ecological sustainability and labour rights were no longer viewed as mutually exclusive (Cigna et al., 2023; UNRISD & ULIP, 2018).

Historically, the application of Just Transformation was almost exclusively associated with the mining and energy sectors, particularly within major coal-producing regions such as the United States of America, Australia, and Germany. In recent years, however, the scope has expanded significantly (Cigna et al., 2023). The framework is now applied to other high-emitting sectors, such as animal agriculture (Thornton et al., 2025). The broader fields that have been permeated include food justice, green gentrification, and energy sovereignty.

As the term matured, its theoretical foundations expanded to include a tripartite view of justice. The first is Distributional Justice. This dimension focuses on the equitable allocation of the transition’s outcomes, ensuring that both benefits, such as the creation of green jobs, and burdens, e.g., job losses, are shared fairly across society. The second dimension is Recognitional Justice. The framework has evolved to acknowledge and address the concerns of historically marginalised groups, including indigenous peoples, women, and migrant workers. The groups were largely excluded from early, labour-centric discussions. The third dimension is procedural Justice, which emphasises the democratisation of the transition. The approach is about ensuring that diverse stakeholders have a meaningful “seat at the table” and agency within the decision-making process (Shangguan et al., 2024). Currently, organisations such as the Climate Justice Alliance are extending the definition further to encompass racial justice, cultural preservation, and self-determination. This evolution marks a departure from a strictly technocratic or economic placeholder, repositioning Just Transformation as a holistic framework for comprehensive social transformation (Climate Justice Alliance, 2026)

2.1.2.2 Institutionalisation of Just Transformation

The institutionalisation of Just Transformation (JT) within the European Union (EU) has been characterised by the systematic integration of fairness and equity principles into core policy frameworks, legislative acts, and dedicated funding mechanisms. This evolution has transitioned JT from a conceptual ideal to a foundational pillar of the European Green Deal (EDG), operationalising the political commitment to ensure that the transition to climate neutrality is neglecting no one. Launched in 2019, the EDG established Just Transformation as

one of its three primary ambitions, recognising that rapid decarbonisation can exacerbate socio-economic inequalities and thus requires a systematic response to manage inherent trade-offs. This is further supported by the European Pillar of Social Rights (EPSR), proclaimed in 2017, which serves as a “European compass” to ensure that both green and digital transitions remain socially fair. Through its 20 principles, including equal opportunities and social protection, the EPSR provides the necessary framework for a robust “Social Europe”. Additionally, the long-standing EU Cohesion Policy was adapted to address regional imbalances triggered by the green transition, with nearly one-third of the total EU budget for the 2021-2027 period allocated to strengthening territorial cohesion (European Environmental Agency, 2024).

Operationalising these policy goals, the EU has established dedicated financial and legal mechanisms, most notably the Just Transition Mechanism (JTM). This central tool is designed to support the regions most affected by the transition, such as those heavily dependent on fossil fuels. The JTM consists of three distinct pillars: the Just Transition Fund (JTF), which supports economic diversification, labour upskilling, and environmental rehabilitation. The second is the Invest EU “Just Transition” scheme, which finances public and private investments and finally the Public Sector Loan Facility, which mobilises public investment via a combination of grants and loans. Furthermore, the Social Climate Fund (SCF) was established as part of the “Fit for 55” package to mitigate the social impacts of carbon pricing in the buildings and road transport sectors, specifically targeting the reduction of energy and transport poverty. These efforts were reinforced in 2022 by a Council Recommendation on ensuring a fair transition toward climate neutrality, which provides concrete guidance to Member States on supporting employment, education, and social protection systems (European Environmental Agency, 2024).

The institutionalisation of these principles is also reflected in the domestic legislation and regional planning of Member States. Spain has emerged as a frontrunner by approving the Strategic Energy and Climate Framework in 2019, which includes a Just Transition Strategy that mandates the approval of transition plans every five years, a legislative commitment unique in its scale. Similarly, the revised Finnish Climate Act (2022) enshrined the objective of ensuring the “justice of climate measures” into law, specifically recognizing the rights of the indigenous Sámi people and establishing a dedicated Sámi Climate Council. At the regional level, the development for Member States to access JTF funding. These plans ensure that local stakeholders, including social partners and regional authorities, are actively involved in the decision-making process (European Environmental Agency, 2024).

Finally, the EU has developed robust monitoring and governance structures to oversee this progress. The Just Transition Platform (JTP), established in 2020, provides technical support and capacity building while serving as a forum for stakeholders to exchange knowledge. To further formalise this oversight, the European Commission plans to launch a European Fair Transition Observatory in 2025. This body will be responsible for monitoring social and employment issues, ensuring that the institutional framework for Just Transformation remains responsive to the evolving needs of the European population (European Environmental Agency, 2024).

2.1.3 Criteria for Just Transformation

The transition toward a low-carbon, resource-efficient, and resilient economy is fundamentally defined by the pursuit of fairness and inclusivity. According to the United Nations, a Just Transformation must ensure that no one is left behind, necessitating an integrated approach that balances climate action with socio-economic equity (Matei, 2025). This process is guided by three foundational principles: planning for and financing the transition well in advance to allow for stakeholder engagement and workforce reskilling. Ensuring strategies are context-specific to local social, economic, and political systems and maintaining transparency through rigorous measurement and reporting of outcomes (Matei, 2025).

2.1.3.1 Distributive Justice and Vital Needs

A primary criterion for evaluating these transformations is distributive justice, which focuses on the fair allocation of benefits and burdens (Avelino et al., 2024; Tribaldos & Kortetmäki, 2022). At the most basic level, this requires protecting the rights of all people to satisfy universal needs, such as food security, safe drinking water, healthcare, and housing (Tribaldos & Kortetmäki, 2022). Within food systems, this entails ensuring that vulnerable groups have access to nutritious, safe food (Devine & Lawlis, 2019).

Beyond basic needs, distributive justice encompasses economic fairness and labour rights, demanding fair payment and decent working conditions for all workers across value chains, including farmers, fishers, and energy sector employees (Tribaldos & Kortetmäki, 2022). Additionally, a “just” transformation requires a “contraction and convergence” strategy. This necessitates that affluent societies reduce their excessive consumption levels to allow underprivileged communities to increase theirs to meet well-being needs (Kanashiro Uehara, 2024).

2.1.3.2 Procedural and Recognition Justice

Just Transformation requires more than equitable outcomes. They require fair processes and the recognition of marginalised identities (Avelino et al., 2024). Decision-making processes must be transparent and inclusive, providing a fair opportunity for diverse voices, including indigenous, local, and marginalised groups, to be heard without intensifying existing power disparities (Tribaldos & Kortetmäki, 2022).

This dimension also demands a commitment to respectful pluralism, in which transitions reject pluralistic worldviews and traditional knowledge, rather than imposing a single universal trading or technological system (Tribaldos & Kortetmäki, 2022). In specific sectors such as energy, a vital criterion is the right to resistance, ensuring that those affected by new projects have the power to contest decisions and voice opposition (Siciliano et al., 2021).

2.1.3.3 Cosmopolitan and Intergenerational Justice

The impact of transformations must be evaluated across both spatial and temporal scales to ensure global and long-term fairness (Tribaldos & Kortetmäki, 2022). Under the concept of “rooted globalism”, decarbonisation activities in one region must not cause food or economic insecurity elsewhere in the world (Devine & Lawlis, 2019; Tribaldos & Kortetmäki, 2022). This requires trade and policy frameworks that reconcile international agreements with place-based needs, ensuring global rules do not override local strategies (Kanashiro Uehara, 2024). From a temporal perspective, intergenerational equity is a core requirement. Actions taken today to mitigate environmental crises must not undermine the opportunities for future generations to achieve well-being or inherit a functional, healthy ecosystem (Tribaldos & Kortetmäki, 2022).

2.1.3.4 Ecological Integrity and Non-Human Justice

Distinct from traditional sustainability models, Just Transformation explicitly incorporates the rights of the natural world (Gupta et al., 2023). A critical criterion is the adherence to planetary boundaries, ensuring that the use of both biotic and abiotic natural resources stays within limits that maintain climate stability and biodiversity integrity (Steffen et al., 2015). In addition, in sectors such as food systems, justice is extended to non-human animals, respecting their inherent value as living beings rather than treating them merely as sources of emissions or commodities (Tribaldos & Kortetmäki, 2022).

2.1.3.5 Systems-Level and Evaluative Criteria

To avoid the “project mentality” that often hinders large-scale change, transformations must meet broader systemic criteria (Patton, 2019; Singh et al., 2023). This includes cross-sector integration to ensure that progress in finance or energy does not cause unintended harm in agriculture or other areas (Patton, 2019; Pedersen et al., 2021). Additionally, sustainability is viewed as a dynamic characteristic of adaptive resilience (Biggs et al., 2015). Criteria include the stability of systems to be innovative, flexible, and responsive to complexity (Patton, 2019). Finally, a Just Transition is evaluated by its capacity for “prefiguration”, experimenting with alternative ways of organising society in the present to challenge existing power structures (Avelino et al., 2024).

2.1.3.6 The Six Pillars of Just Transition

In addition to the academic sources mentioned earlier, the UN has also set out six criteria to ensure a Just Transition towards sustainability. The practical application of these criteria is organised into six interconnected pillars (Matei, 2025):

- **Social Progress:** Ensuring social equity by redressing pre-existing inequalities, promoting socio-cultural resilience, and practicing restorative justice to address historical harms from extractive industries.
- **Workers’ Protection and Empowerment:** Utilising a tripartite approach between governments, workers, and employers to provide comprehensive support, including retraining and social safety nets for informal and migrant workers.
- **Environmental Consciousness & Responsibility:** Ensuring environmental accountability where polluters bear the costs of remediation, while seeking opportunities to repurpose old infrastructure for renewable energy.
- **Economic Success:** Fostering economic regeneration and diversification by investing in green industries and infrastructure to reduce outward migration.
- **Participatory Governance:** Providing multi-stakeholder governance to co-design strategies and ensuring procedural justice through clear rights for grievance redress.
- **Institutional Support:** Implementing inclusive outreach to marginalised groups and aligning education and vocational training with the needs of the green economy.

Ultimately, a Just Transformation is measured by its support for the capacity building of the least-advantaged actors, providing the skills, technology, and innovation necessary for diverse social groups to respond effectively to transition demands (Tribaldos & Kortetmäki, 2022).

2.1.4 Evaluating Carbon Pricing from a Justice Perspective

Carbon pricing is widely regarded as an efficient instrument for reducing greenhouse gas emissions (Döbbeling-Hildebrandt et al., 2024). However, its effectiveness in practice depends not only on economic efficiency but also on its perceived fairness (World Bank Group, 2017). As outlined in the broader framework of Just Transformation, climate policies need to be assessed by how their impacts are distributed across society.

This subchapter therefore evaluates carbon pricing through a justice perspective, with a specific focus on distributive impacts. The purpose is to establish a normative foundation for the subsequent analysis by clarifying under which conditions carbon pricing can be considered socially just, and where potential tensions between efficiency and equity arise.

2.1.4.1 Distributive Justice

Distributive justice in the context of climate policy concerns the fair allocation of social benefits and burdens. As taxation serves as the primary mechanism for funding the “public costs” of social cooperation, including the protection of both negative liberties (property rights) and positive welfare rights, the implementation of a carbon price must be evaluated through its impact on different socio-economic groups (Farrelly, 2004). While economists frequently present carbon pricing as the most efficient tool for inducing behavioural change (Dietsch, 2024), its alignment with justice depends on the distinction between initial incidence and net impact.

2.1.4.1.1 Initial Incidence and the Regressivity Challenge

A significant hurdle for carbon pricing is the “regressivity challenge”. In developed economies, the initial impact of a carbon price is often regressive, falling disproportionately on low-income households. Although wealthy individuals consume more in absolute terms, they spend a smaller percentage of their total income on carbon-intensive consumption than those in lower-income brackets. Consequently, a flat tax impacts the poor more heavily in relative terms (Feindt et al., 2021).

However, this trend is not a global universal. In many countries in the Global South, the initial effect can be progressive, as carbon-intensive goods like private vehicles are often accessible only to the wealthy. In addition, the effectiveness of a flat tax is challenged by the “price inelasticity” of the rich. Wealthy individuals, who are often the largest polluters (Apeti et al., 2025), may remain insensitive to price increases (Andersson & Atkinson, 2020). From a justice perspective, a tax that fails to curb emissions from the primary contributors, who can easily

afford surcharges for luxury activities such as flying private jets, is frequently viewed as ineffective (Apeti et al., 2025; Linden et al., 2024; Mayer et al., 2021).

2.1.4.1.2 Revenue Recycling and Narrow Justice

Carbon pricing can be rendered distributionally just through revenue recycling (Caron et al., 2018; Mintz-Woo, 2023). By redistributing tax revenues back to citizens, for example, via an equal per-capita rebate, the policy's net effect can become significantly progressive. Many jurisdictions use these rebates to protect vulnerable households, achieving what is described as “justice in a narrow sense” (Reañosa & Angel, 2019). This approach, however, often accepts the existing distribution of wealth as a given baseline. A “broader” view of distributive justice, as suggested by Dietsch (2024), identifies a “blind spot” in these assessments: they often assume the capital spent by the wealthy on carbon-intensive activities was legitimately theirs to begin with, rather than questioning the underlying distribution.

2.1.4.1.3 Progressive Benefits and Co-Benefits for Vulnerable Groups

Beyond financial transfers, carbon pricing generates progressive benefits by alleviating the environmental burdens that disproportionately affect the most vulnerable. Climate change disproportionately harms the Global South and racial minorities (Smith et al., 2022). Therefore, any reduction in emissions provides a progressive benefit.

Additionally, carbon pricing has reduced the emission of “co-pollutants” such as particulate matter and nitrogen oxides from factories and power plants. Data suggest that racial minorities are often disproportionately exposed to these local pollutants (Tessum et al., 2021). In the United States of America, for example, Black Americans are exposed to 38% more polluted air than White Americans and are 75% more likely to live in “fence-line” communities adjacent to industrial facilities. By curbing these activities, carbon pricing provides these specific groups with significant “co-benefits”, improving public health outcomes in historically marginalised areas (Mintz-Woo, 2024).

2.1.5 Distributional effects on Low-Income households

The implementation of carbon pricing mechanisms frequently raises concerns regarding their distributional fairness (Andersson & Atkinson, 2020; Fragkos et al., 2021; Reañosa & Angel, 2019). While intended as a tool for decarbonisation, the financial burden of these taxes often falls disproportionately on low-income households (Berry, 2019; Jacobs et al., 2022; Mengesha & Roy, 2025), who face regressive financial burdens and structural barriers (Lackner & Nabernegg, 2026). Computable general equilibrium models reveal that CO₂ pricing yields the

highest negative consumption impacts on low-income groups due to their reliance on inefficient energy sources, but through per-capita revenue recycling (e.g., climate bonuses) and social transfers, these impacts can be mitigated and even render them net beneficiaries (Hübler et al., 2024). Absent targeted lump-sum or income-tested rebates, such measures risk deepening energy poverty in this demographic (Vandyck et al., 2023). This subchapter examines the mechanisms that drive these regressive outcomes, focusing on consumption patterns, the scope of economic analysis, and the influence of national income levels.

2.1.5.1 Carbon-Intensive Consumption Patterns

The primary argument for the regressive nature of carbon taxes lies in the specific expenditure patterns of low-income households in developed nations. For these populations, a significantly larger share of total consumption is dedicated to basic necessities, specifically heating, cooking, and lighting (Jacobs et al., 2022). Since these essential services are highly energy-dependent, they are directly susceptible to carbon pricing. When the price of carbon increases, the cost of maintaining a home and meeting basic energy needs rises. For lower-income households, this represents a more severe contraction in disposable income than for wealthier households, who spend a smaller fraction of their earnings on such essentials (Jacobs et al., 2022; Mengesha & Roy, 2025).

2.1.5.2 Characteristics of affected Low-Income Households

Low-income households exhibit heightened vulnerability to carbon pricing and energy transition policies due to a confluence of housing tenure patterns, institutional constraints, and concentrated exposure to energy-inefficient stock, distinguishing them from higher income counterparts. Affected low-income households are divided between homeowners, who disproportionately occupy single-family houses, and tenants in multi-family dwellings. Single-family homeowners incur greater burdens from policy-induced renovations, as these structures require higher per-square-meter investment than apartments, driven by greater envelope surface area and dispersed heating systems (Lackner & Naberneegg, 2026). Higher income households, conversely, benefit from economies of scale in multi-unit ownership and superior liquidity for upfront costs (Köppl & Schratzenstaller, 2023).

Lackner & Naberneegg (2026) found that low-income tenants in Austria cluster in pre-1945 rent-controlled or municipal housing, where the principal-agent problem manifests as split incentives: landlords forgo energy retrofits due to uncovered costs under rent caps, imposing regressive energy bill escalation to rents. Shifting focus back to Germany, dwellings occupied

by low-income households are disproportionately older and more in need of upgrades (Römer, 2022). This empirical pattern interacts with the landlord-tenant (user-investor) dilemma, a principal barrier to building-sector decarbonisation: tenants pay energy bills and carbon charges while landlords make capital-investment decisions, so landlords do not fully capture the returns from energy-efficiency investments. Rent regulation and limited cost-recovery options further weaken landlords' incentives to retrofit. Although German law allows a partial pass-through of modernisation costs to tenants via the modernisation levy, this mechanism can raise housing costs and produce regressive outcomes for low-income households. Consequently, carbon pricing alone transmits a deficient investment signal to property owners, reducing retrofit uptake in rental housing, precisely where low-income households are concentrated, and thereby exacerbating inequalities in energy expenditure and decarbonisation burdens (George et al., 2023).

2.1.5.3 Short-term vs. Long-term Analysis: Direct and Indirect Effects

The perceived impact of carbon taxes can vary significantly depending on whether an analysis accounts for indirect effects. These represent the price increases of non-energy goods and services that utilise energy as a primary production input.

Research indicates that excluding these indirect effects can distort the tax's true burden. In many countries, the cumulative impact of price hikes across the wider economy is usually much greater than the direct effect of the energy bill tax alone (Gugler et al., 2023). Therefore, a comprehensive understanding of the distributional impact on the poor requires looking beyond immediate utility costs to the long-term shifts in the general basket of goods. The relationship between income and the distributional impact of carbon pricing is not uniform across the globe. Research by Dorband et al. (2019) introduces a "turning point" theory based on national income thresholds. This theory posits an inverse U-shape relationship between energy expenditure and income levels. Carbon pricing is often found to be progressive in countries where the annual per capita income is below 15.000\$. Once a country surpasses this 15.000\$ income threshold, the tax tends to become regressive. This suggests that as countries grow wealthier, the proportion of income spent on carbon-intensive necessities shifts in a way that makes the poor more vulnerable to climate policy costs than their counterparts in lower-income nations (T. T. H. Nguyen & Song, 2021).

2.1.6 Revenue Recycling

In order to mitigate the inherent regressive nature and potential negative economic impacts of carbon taxation, policymakers primarily utilise revenue recycling, the process of earmarking and returning tax proceeds back to society (Beiser-McGrath & Bernauer, 2019; Berry, 2019; Pomerleau & Asen, 2019). Without such interventions, carbon taxes disproportionately affect lower-income households, as these households spend a larger share of their budgets on energy-intensive goods and services. This disparity not only reduces the purchasing power of the most vulnerable but also exacerbates the crisis of fuel poverty, in which households are unable to afford basic energy needs (Berry, 2019).

2.1.6.1 Mechanisms for Direct Compensation and Social Equity

One of the most prominent strategies for addressing these distribution imbalances is the use of direct transfers. Lump-sum rebates, often called “climate dividends”, involve distributing tax revenues equally among all households. This approach significantly increases the progressivity of the tax code, as the uniform payment represents a much larger percentage increase in after-tax income for poorer households than for richer ones (Malerba et al., 2022; Pomerleau & Asen, 2019). Although this approach is popular due to its perceived fairness, some scholars have noted that it may negatively affect overall economic output and employment because it does not reduce other distortionary taxes (Pomerleau & Asen, 2019).

As an alternative, revenues could be channelled into targeted transfers specifically aimed at the bottom 15% to 30% of income earners. This has been identified as the most efficient way to reduce fuel poverty (Berry, 2019). Specific instruments, such as France’s “energy cheque”, provide dedicated financial support for energy bills, directly offsetting the price spikes triggered by the carbon tax. Beyond simple income-based targeting, adjustments can also be made for factors such as household size and geographic location. This acknowledges that individuals in suburban or isolated areas often face higher costs due to car dependency and a lack of public infrastructure (Berry, 2019).

2.1.6.2 Beyond Equity: Behavioural Steering and Structural Investment

While direct and targeted compensation mechanisms prioritise immediate social equity, the architecture of revenue recycling often encompasses broader macroeconomic and behavioural objectives. Rather than viewing compensation solely as a tool for financial fairness, contemporary public finance literature highlights a dual-track logic where revenue is split between immediate household relief and clean-energy subsidies (Brzezinski & Kaczan, 2025).

Clean-energy subsidies differ fundamentally from cash transfers. Rather than reimbursing static household expenditure retrospectively, they actively reduce the capital cost of adopting lower-carbon technologies. This enables carbon taxation to transcend its purely punitive fiscal role and become a mechanism that influences long-term consumer behaviour and finances the structural changes needed for decarbonisation. Ultimately, the decision to fund either direct rebates or clean-energy investments cannot be made in isolation. The optimal recycling design depends heavily on prevailing macroeconomic conditions and specific overarching policy objectives, rather than equity criteria alone (Brzezinski & Kaczan, 2025).

2.1.6.3 Empirical Implementations and Outcomes across Europe

European nations have served as the primary empirical laboratories for these recycling configurations. Their approaches range from pure efficiency-driven fiscal reforms to highly targeted socio-environmental welfare frameworks.

2.1.6.3.1 The Tax-shifting and Fiscal Reform Models: Germany, Sweden, and Finland

Unlike household-centric rebate models, early environmental tax reforms (ETR) in Northern and Central Europe prioritised macroeconomic efficiency (EEA, 2025). Germany is a prime example of the “tax-shifting” paradigm, in which revenues from environmental and carbon taxes were explicitly channelled into the wider fiscal system to reduce labour costs by subsidising public pension contributions (Andersen, 2010; Bach et al., 2019). The underlying objective was to minimise market distortions and improve employment incentives, positioning the mechanism as an instrument of broader economic reform rather than targeted social compensation. However, this model has a distinct structural vulnerability: it is not automatically progressive. Its ultimate equity outcomes are highly regressive or neutral, depending entirely on which income cohorts benefit most from the corresponding labour tax cuts (Andersen, 2010).

Following a similar Nordic trajectory, Sweden and Finland implemented carbon pricing as a mechanism for systemic fiscal restructuring, opting for this approach over direct household reimbursement. The Swedish model is based on a general tax-reduction framework that uses carbon revenues to offset sharp reductions in other economy-distorting levies, such as income tax (Andersen, 2010; Nurhayati et al., 2024). This empirical precedent is often used in public finance literature to demonstrate that robust, high-rate carbon taxation can successfully coexist with a low overall national tax burden if the revenues are recycled back into the broader economy efficiently (Andersen, 2010).

Finland mirrored this approach, incorporating carbon proceeds into the general tax system to maximise institutional efficiency and facilitate tax reform (Nurhayati et al., 2024), rather than implementing specific low-income support measures (Andersen, 2010). Consequently, in both Sweden and Finland, the net distributive outcome is decoupled from the carbon tax itself and remains entirely dependent on the progressive or regressive nature of the wider, pre-existing national tax system (Andersen, 2010).

2.1.6.3.2 The Mixed Model: Denmark

Denmark represents a distinct variation of the Nordic approach by employing a mixed-recycling framework that explicitly seeks to reconcile environmental and social priorities (Eriksson et al., 2023; OECD, 2019). Rather than adhering strictly to a single efficacy or rebate track, the Danish policy design combines carbon pricing with wider energy-tax adjustments and climate-focused public expenditures (OECD, 2019). Denmark's design works by layering carbon pricing onto a broader, preexisting energy tax system, then softening the fiscal burden through targeted public spending and selective relief measures (Batini et al., 2020). In practice, the state does not rely on a standalone carbon tax alone. Instead, it established a comprehensive carbon-pricing architecture that simultaneously combines domestic carbon taxes, the EU ETS, energy-tax adjustments, sector-specific exemptions, and a substantial climate investment fund (OECD, 2019).

The operational functionality of this package relies on carbon pricing signals, including domestic taxes and EU ETS coverage, to raise the cost of emissions across various economic sectors. Alongside this price signal, coordinated energy-tax adjustments are utilised so that higher carbon taxes are intentionally offset by strategic reductions in traditional energy taxes within specific sectors, keeping the overall tax burden at a politically acceptable level. Additionally, capital yields are directly channelled into public spending, most notably through a dedicated Green Fund valued at approximately 7.2 billion €. Slated to support climate investments from 2024 to 2040, this fund directly finances large-scale decarbonisation infrastructure, including offshore wind energy and carbon capture storage (CCS) technologies. Finally, to manage competitiveness risks and technical constraints in politically sensitive areas, specific industries, such as cement production, fisheries, and international transport, receive tailored exemptions or reduced tax rates (OECD, 2026).

Consequently, the Danish approach is best understood as a mixed recycling model rather than a pure dividend system. Revenue is not simply returned to households. It is actively reinvested into national climate infrastructure while mitigating distributional and competitiveness

concerns through targeted relief (OECD, 2019). Empirical evaluations indicate that this multifaceted deployment is highly tethered to public acceptance. Danish citizens exhibit a clear preference for revenue-recycling strategies that simultaneously advance national climate mitigation goals and protect baseline principles of social fairness (Hedegaard & Kongshøj, 2024). The underlying policy logic is twofold: first, emissions are made expensive enough to fundamentally shift market behaviour. Second, political resistance is minimised by recycling a portion of the burden through lower energy taxes, visible climate spending, and temporary exemptions. OECD and Nordic policy literature further highlights that this evolutionary trajectory represents a structural shift from a system historically reliant on narrow energy taxes toward a broader, integrated carbon-pricing framework (OECD, 2019). Ultimately, the Danish reform operates as much as a systemic tax restructuring as a climate policy, successfully balancing environmental ambition with public and institutional acceptability.

2.1.6.3.3 The Targeted Welfare Model: Ireland

In direct opposition to the efficiency-driven tax reforms of its northern peers, Ireland provides one of the most explicit examples in Europe of a highly targeted compensation strategy (Callan et al., 2009; ESRI et al., 2020). The Irish state rigidly ring-fences its carbon tax proceeds to fortify the domestic welfare apparatus. Revenues are explicitly reallocated to fund increases in social welfare payments, expanded fuel allowances, and progressive household energy-retrofitting schemes (ESRI et al., 2020). By concentrating fiscal returns on economically vulnerable populations, the Irish framework directly offsets regressive price spikes of carbon pricing, successfully merging short-term social protection with the long-term capital injections needed to alleviate structural fuel poverty (ESRI et al., 2020).

2.1.6.4 Strategic Trade-Offs in Public Acceptance and Efficiency

The divergent empirical outcomes across Europe confirm that no single revenue recycling strategy can simultaneously maximize all political and economic variables (OECD, 2019). Instead, policymakers face an institutional trilemma where the optimal choice is entirely contingent upon the specific evaluative metric prioritised by the state.

From a political economy perspective, the literature underscores that revenue recycling operates most effectively when it is simple, highly visible, and easily communicated to the public. Prominent revenue returns, such as lump-sum dividends or visible rebates, allow citizens to directly associate the fiscal benefit with the carbon tax, thereby mitigating the political resistance often fatal to climate pricing policies (Dominioni & Heine, 2019). This creates a distinct friction between political survival, social equity, and economic optimisation.

As synthesised across the public finance literature, the strategic trade-offs inherent to revenue recycling can be categorised across three distinct institutional vectors:

- For equity: Targeted transfers or lump-sum dividends consistently yield the most progressive outcomes, safeguarding low-income households from energy shocks (Monar, 2024).
- For political Acceptability: Visible revenue earmarking and clear, climate-linked public spending generate the strongest public trust and policy longevity (Maier et al., 2025).
- For economic efficiency: The reduction of distortionary taxes (such as labour and income taxes) remains the superior method for boosting macroeconomic output and employment incentives (OECD, 2019).

Ultimately, the European experience suggests that rather than searching for a single, universally superior recycling blueprint, effective carbon tax governance requires a context-specific policy mix tailored to a jurisdiction's specific institutional capacity, macroeconomic baseline, and socio-political climate (Andersen, 2010).

2.1.6.5 Balancing Economic Efficiency and Progressivity

Beyond direct transfers, revenue recycling can be used to reform existing tax structures, creating a “double dividend” of environmental protection and economic growth. Reducing distortionary taxes, such as payroll or capital income taxes, can boost output and employment. For instance, cutting employee-side payroll taxes helps low- and middle-income workers while stimulating the labour market (Pomerleau & Asen, 2019). In contrast, lowering capital income or corporate tax rates tends to maximize long-run welfare and GDP growth, though it risks making the tax code less progressive since the benefits primarily accrue to high-income earners (Fried et al., 2021; Pomerleau & Asen, 2019).

Research suggests that the approach that maximises welfare involves a “policy mix” that balances efficiency with equity. Some models recommend an optimal split, with approximately two-thirds of the revenue used to reduce distortionary capital taxes to foster investment, and the remaining third is dedicated to increasing labour-tax progressivity for low-wage earners (Fried et al., 2021). This approach ensures that the tax system remains progressive while simultaneously supporting macroeconomic stability.

2.1.6.6 Structural Support and International Competitiveness

A comprehensive revenue recycling strategy extends beyond domestic considerations to include structural investments and international factors. Earmarking funds for energy efficiency, dwelling retrofitting, and renewable energy infrastructure provides a more permanent solution to fuel poverty than short-term financial support (Berry, 2019). Additionally, funding public transport, such as expanding railway networks, can increase public acceptance of higher carbon prices (Beiser-McGrath & Bernauer, 2019).

In order to protect domestic industries and prevent “carbon leakage”, whereby production shifts to countries without carbon constraints, policymakers may implement border carbon adjustments. This ensures that the tax is applied to carbon-intensive imports while providing credits for exports, thus maintaining a focus on domestic consumption (Pomerleau & Asen, 2019). Additionally, the political feasibility of high carbon taxes is closely tied to international cooperation. Public support increases significantly when citizens believe that other industrialised nations are adopting similar policies, thereby maintaining a level playing field and preventing job losses (Beiser-McGrath & Bernauer, 2019). In low- and middle-income countries, these revenues could be used to expand existing social assistance programmes, protecting the vulnerable people from price shocks while reducing overall inequality (Malerba et al., 2022). Ultimately, a well-designed policy package can ensure that carbon pricing not only drives decarbonisation and enhances the welfare of the most vulnerable households, potentially reducing poverty to levels lower than those seen before the tax was implemented (Berry, 2019; Fried et al., 2021).

2.2 Policy Background

Carbon pricing is frequently referred to as a cost-effective tool for reducing greenhouse gas emissions (Tvinnereim & Mehling, 2018). The World Bank Group defines carbon pricing as “an instrument that captures the external costs of greenhouse gas (GHG) emissions [...] and ties them to their sources through price [...]” (World Bank Group, 2017). The pricing tools encompass carbon taxes and emissions trading systems. Carbon taxes impose a fixed price per ton, offering price certainty but uncertain emission reductions, as outcomes depend on behavioural responses (Goulder & Schein, 2013). Emission Trading Systems impose a declining cap on total emissions with tradable allowances, guaranteeing emissions cuts while prices vary by market dynamics (Asuene, 2025).

In order to assess the distributional and behavioural impacts of carbon pricing, it is first essential to understand the institutional and policy frameworks within which these instruments operate. This thesis focuses on Emission Trading Systems within the European Union, more specifically in Germany. Carbon pricing here is mainly implemented through the national Emission Trading System (nEHS) in combination with the EU ETS I. This subchapter, therefore, outlines the key policy mechanisms relevant to this thesis, particularly the EU ETS and German nEHS, to provide the necessary context for the subsequent analysis. Establishing this background is crucial, as the specific design features of these instruments directly shape both their economic incentives and distributional consequences.

2.2.1 EU ETS

The European Union Emissions Trading System (EU ETS I), launched in 2005, is a cornerstone of the Union's climate policy and a market-based environmental instrument designed to mitigate greenhouse gas emissions. While originally conceived as a classic cap-and-trade system, the ETS has evolved through several distinct phases into a sophisticated hybrid model that seeks to balance ambitious environmental targets with the need to protect industry (European Commission, 2016).

At its core, the mechanism requires regulated participants to surrender one tradable permit for every ton of carbon dioxide (or equivalent greenhouse gas) emitted annually. The system's flexibility derives from two primary features: trading and banking. If a regulated entity reduces its emissions below its allocated limit, it may sell its surplus permits to other participants in the carbon market. Alternatively, firms have the option of "banking" these permits for future use, providing a buffer against periods of higher emissions or rising permit costs (European Commission, 2016; Verbruggen et al., 2019).

In its implementation, the EU ETS attempts to reconcile two primary and often conflicting objectives, frequently categorised as the "Atmosphere-goal" (A-goal) and the "Profit-protection-goal" (π -goal). The A-goal prioritizes atmospheric stability, aiming for a near-zero emission level, specifically an 80-95% reduction, by 2050. Achieving this target relies on maintaining sufficiently high carbon prices to incentivise industrial innovation and structural change. Conversely, the π -goal focuses on safeguarding the economic welfare and global competitiveness of EU industries. The central concern of this objective is the prevention of "carbon leakage", a phenomenon wherein high carbon costs drive energy-intensive industries

to relocate their operations to jurisdictions outside the EU with less stringent environmental regulations (Verbruggen et al., 2019).

The distribution of emission permits is managed through two primary methods: auctioning and free allocation. Under the auctioning system, public authorities sell a determined annual quota of permits through competitive bidding (European Commission, 2016). This method has gained prominence over time. By the third phase of the ETS (2013-2020), approximately half of all permits were distributed via auction. In contrast, free allocation involves granting permits at no cost, often based on historical emissions or specific product benchmarks, a practice known as “grandfathering” (Knight, 2013). This approach is strategically employed for Emission Intensive, Trade Exposed (EITE) sectors as a primary defence against carbon leakage (Verbruggen et al., 2019).

Throughout its history, the system has undergone significant adaptations to improve its efficacy, including the 2019 introduction of the Market Stability Reserve (MSR). This mechanism was designed to regulate the surplus of permits in the market, thereby stabilising prices and ensuring a more predictable investment environment. While evidence suggests the EU ETS has been highly successful in achieving its profit-protection goals, notably through the documented absence of carbon leakage in EU industrial activities, it has faced academic and political criticism. Specifically, historically low and volatile permit prices have led some scholars to argue that the system has at times failed to drive the “disruptive innovation” required to achieve the long-term objective of a carbon-free economy (Marcu et al., 2025; Verbruggen et al., 2019).

2.2.1.1 European ETS I

The EU ETS 1 is the existing framework that has served as the primary instrument of European climate policy for over two decades. Its sectoral scope is specifically tailored toward large-scale, stationary installations, primarily covering combustion emissions from the power sector and energy-intensive industrial plants. A defining characteristic of the EU ETS 1 is its “downstream” regulatory structure: the firms participating in the allowance market, such as utility companies and manufacturers, are typically the same entities making the actual technical and operational abatement decisions. This direct link ensures that the financial signal of the carbon price is felt by the same actors who have the immediate capacity to invest in cleaner technologies or adjust production processes. Since these costs are largely contained within industrial and energy supply chains, the immediate financial impact on the general public is

often indirect, reflected primarily through fluctuations in electricity prices or the cost of manufactured goods (Günther et al., 2025).

Since the implementation of the EU ETS 1, a 37% reduction in emissions has been achieved. If British emissions are also considered, which were part of the EU ETS until 2021, a 44% reduction was achieved (Rickels et al., 2024). In comparison, emissions outside the EU over the same timeframe have only declined by around 13% (Rickels et al., 2024). However, a comparison is difficult to make at this point, considering different political and environmental shifts.

The European Union Emissions Trading System (EU ETS) is currently undergoing a transformative period of recalibration. As of early 2026, the system is transitioning from a sectoral carbon market into a comprehensive economy-wide instrument. This evolution is driven by the need to align with the EU's net 90% greenhouse gas (GHG) reduction target for 2040, which requires a fundamental revision of the system's architecture to ensure long-term market stability and social equity.

A primary focus of the 2026 revisions is adjusting the Linear Reduction Factor (LRF). Without a strategic increase in the LRF, the market faces an “endgame” scenario where the supply allowances could reach zero prematurely, causing extreme price volatility (Hernández, 2026). In order to prevent this while maintaining decarbonisation momentum, the EU is shifting toward a dual-system approach:

- ETS1: Continues to regulate heavy industry, energy, aviation, and maritime sectors. By 2024, these sectors had already achieved a 50% reduction in emissions compared to 2005 levels (Hernández, 2026).
- ETS2: A separate, parallel system for road transport and buildings is scheduled for implementation in 2028 (Günther et al., 2026). This expansion is particularly relevant for the study of distributional effects, as these sectors directly impact household expenditures on heating and mobility (Claudia et al., 2022).

The scope of the EU ETS is expanding both geographically and technically to include previously peripheral emission sources (Günther et al., 2026). The first one is aviation and maritime. Since January 2025, the EU has monitored non-CO₂ effects in aviation (e.g., contrails). Depending on the assessment of the global CORSIA measure, international flights may be fully integrated by 2027. Similarly, the maritime sector began surrendering allowances for methane and nitrous oxide in early 2026, with feasibility studies underway for smaller

vessels (400-5000 gross tonnage). The second one is municipal waste. By July 2026, a report will determine the inclusion of municipal waste incineration (MWI) and landfills, with potential surrendering requirements starting in 2028 (Federation of European Waste-to-Energy Companies, 2024). A critical technical hurdle, however, for the 2026 revision is the accounting of Carbon Dioxide Removals (CDR). This includes permanent solutions like Direct Air Capture (DAC) and non-permanent Carbon Capture and Utilisation (CCU) for synthetic fuels (Hernández, 2026).

2.2.1.2 European ETS II

Scheduled for launch in 2027, the EU ETS 2 is a separate system designed to cap emissions from sectors previously excluded from the original framework, specifically buildings, road transport, and small industrial plants (Claudia et al., 2022). Unlike its predecessor, the EU ETS 2 utilises an “upstream” regulatory structure, creating a fundamental dichotomy between the regulated entities and the actual emitters. In this model, the firms required to purchase and surrender allowances are fuel distributors rather than the end-consumers. However, the day-to-day abatement decisions, such as choosing to drive less or upgrading a home heating system, remain with the individual drivers and homeowners.

In order to manage the heightened sensitivity of these sectors, the EU ETS 2 features an elaborate price-stability mechanism designed to dampen sharp cost increases. For example, during its initial years, the carbon price exceeded 45 EUR/tCO₂ for two consecutive months, a “price trigger” released up to 40 million additional allowances into the market. Further protections allow for the release of 50 million or 150 million allowances if prices increase by certain multiples (1.5x, 2x, or 3x) relative to the preceding six-month average. These safeguards are essential because the EU ETS 2 directly targets heating and transport fuels, making carbon prices far more salient to citizens than the industrial costs of the EU ETS 1. While these two systems are currently operated and modelled independently, research suggests they may eventually be linked, potentially leading to a convergence of prices across the European economy (Claudia et al., 2022; Günther et al., 2025).

2.2.2 The German nEHS

Germany has committed to substantial greenhouse gas (GHG) emissions reductions by 2030 (OECD, 2022), specifically aiming to cut emissions by at least 65% from 1990 levels (UBA, 2025). However, the reduction has been modest so far, particularly within the German road transport sector (Torkayesh & Venghaus, 2024). In response, the German government

concluded in 2019 that a CO₂ pricing mechanism was necessary for sectors currently operating outside the scope of the European Union Emissions Trading System (EU ETS) (ICAP, 2025). This resulted in the creation of the national emissions trading system for fuels (nEHS) (Wendl-Damerius, 2021).

2.2.2.1 Legal Foundation

The primary legal basis for this system is the Fuel Emissions Trading Act (Brennstoffemissionshandelsgesetz – BEHG), which came into force in December 2019. The overarching purpose of the BEHG, as defined in Section 1, is to introduce certificate trading for fuel emissions (BMVJ, 2026). This market-based instrument serves two main functions: providing a steering effect to meet climate targets via a price-based incentive and generating revenue to refinance climate measures, such as the Energy and Climate Fund and renewable energy costs. For the period from 2021 to 2024, revenues were estimated at approximately 40 billion euros (Wendl-Damerius, 2021).

Administrative oversight and responsibility for implementing the BEHG lie with the German Environment Agency (Umweltbundesamt – UBA) and the German Emissions Trading Authority (DEHSt). Unlike traditional systems with fixed caps for individual participants, the nEHS relies on a price-based steering effect, in which any entity intending to emit CO₂ through the combustion of fuels must acquire the relevant emission rights (Wendl-Damerius, 2021).

2.2.2.2 Designs of the nEHS

The nEHS is designed as an “upstream” system, meaning it targets fuel distributors rather than the end-users (emitters). This approach was chosen because directly linking the system to individual emitters in the heat and transport sectors is not practically feasible, given the sheer number of participants. Instead, the BEHG considers the potential emissions of fuels at the point of market placement, with the expectation that costs are passed down the value chain to the final customers (Wendl-Damerius, 2021).

2.2.2.2.1 Scope and Fuel Coverage

The scope of the nEHS includes all fuels listed in Annex 1 of the BEHG, as well as products whose combustion can cause CO₂ emissions. This list corresponds largely to the energy products defined in the German Tax Act (Energie StG). While biomass is technically included, a zero-emission factor is applied to sewage sludge and biogenic fuels, provided they meet specific sustainability criteria under Section 7 (4)(2) BEHG (BMVJ, 2026).

The obligation to participate is triggered when fuels are “placed on the market”, which aligns with the chargeable event defined in energy tax law:

- Standard fuels: For products like petrol or heating oil, the responsible party is typically the owner of the tax warehouse from which the fuel is removed.
- Natural Gas: The responsible party is the energy-taxable supplier delivering to the end-user.
- Coal: This was introduced to the system later, starting in 2023, with specific deviations regarding the determination of the responsible debtor.

Fuels subject to a tax suspension or tax exemption do not trigger a BEHG obligation. In addition, the system includes provisions for tax relief to prevent multiple reporting or surrender obligations when energy tax might be incurred multiple times for the same fuel (Wendl-Damerius, 2021).

2.2.2.2.2 Avoidance of Double Charging

A significant design challenge involves the intersection of the “upstream” nEHS and the “downstream” EU ETS. The upstream nEHS for heating and transport fuels prices CO₂ at the point at which fuels are placed on the market (i.e., importers/distributors). By contrast, the downstream EU ETS prices emissions at the installation level (i.e., at the level of operators of EU ETS-covered facilities). In instances where fuel designated for an EU ETS installation is priced below the nEHS, both the distributor (nEHS surrender) and the installation operator (EU ETS allowances) effectively incur costs for the same CO₂, resulting in double charging of the fuel. German legislation addresses this overlap through Section 7(5) and Section 11(2) of the BEHG: distributors may be exempt from surrender obligations if direct delivery to an EU ETS installation can be demonstrated, and installations may later claim compensation when supply-chain tracing is infeasible, thereby preventing duplicate CO₂ payments. These safeguards have been designed to reduce misaligned incentives and administrative burdens, yet their effectiveness is contingent upon the reliability of traceability mechanisms and the timely compensation of losses (ICAP, 2024; Wendl-Damerius, 2021).

2.2.2.2.3 Heating Sector

In the industrial context, evidence suggests that the nEHS significantly increases the costs associated with fossil-based heat supply. This price enhances the financial attractiveness of investments in energy efficiency and waste heat recovery. However, case studies indicate that while the nEHS provides a necessary push, the additional economic incentive specifically for

waste heat utilization remains relatively small when considered in isolation from other support mechanisms (Möhren et al., 2021). For Germany to achieve its climate neutrality targets, scenarios consistently emphasise a substantial transition away from traditional gas and oil boilers. A fundamental shift towards heat pumps, solar thermal energy, and the electrification of district heating is considered essential for meeting energy and climate goals in the building sector (Bauermann, 2016; Merkel et al., 2017; Ruhnau et al., 2019; Schlemminger et al., 2025). Within this transition, carbon prices under the nEHS act as a critical driver for two primary developments:

- **Industrial Process Heat:** A marked decline in fossil-based process heat, replaced by increased direct electrification (Wiese et al., 2022).
- **Power-to-Heat Expansion:** The accelerated development of Power-to-Heat technologies in both individual household systems and large-scale district heating networks. This shift is expected to significantly increase national electricity demand as thermal energy production is integrated into the power sector (Bloess, 2019; Kröger et al., 2023; Naegler et al., 2021; Ruhnau et al., 2019)

2.2.2.2.4 Transport Sector

The transport sector remains a significant challenge for German climate policy, often described as a laggard in the energy transition. Unlike other sectors, transport emissions have remained largely stagnant, hovering near 1990 levels (Canzler & Wittowsky, 2016; Hainsch, 2023). Modelling suggests that while carbon pricing in the transport sector can significantly reduce long-term emissions and influence broader energy system dynamics, the magnitude of these effects depends heavily on policy synergy (Canzler & Wittowsky, 2016).

Research indicates that the greatest emission reductions occur when carbon pricing is coupled with demand-side management and “modal shift” policies, such as reducing total passenger-car kilometres and expanding public transport and rail infrastructure (Canzler & Wittowsky, 2016; Thema, 2024). Long-term scenarios for 2050 anticipate a heavy reliance on the electrification of passenger vehicles. For heavy-duty vehicles, where direct electrification faces greater technical hurdles, these scenarios anticipate that electrification will be supplemented by electricity-based synthetic fuels, such as Power-to-Liquid and Power-to-Gas (Bartholdsen et al., 2019; Ruhnau et al., 2019; Wulff et al., 2025).

2.2.2.3 Revenue Use and Compensation Measures

The revenues generated by the national fuel emissions trading system (nEHS) are legally earmarked for the Climate and Transformation Fund (Vella et al., 2026). By design, these proceeds are not treated as general tax revenue for the federal budget but are instead strategically allocated to support climate policy objectives (UBA, 2026). This mechanism aims to mitigate the economic burden imposed by CO₂ pricing through flanking measures, thereby preserving the overall competitiveness of the national economy (Bach et al., 2025; UBA, 2026).

These revenues primarily support private households, particularly those in the transport and building sectors (Bach et al., 2025). A portion of the nEHS proceeds is utilised for transport-related mitigation measures, such as the adjustment of commuter tax allowances (Pendlerpauschale) and investments in public transport and cycling infrastructure. Additionally, the extra heating costs incurred by the nEHS surcharge on heating oil, natural gas, and other fuels are integrated into the calculation of housing benefits and heating costs coverage under basic social security, ensuring that vulnerable populations are financially buffered through existing welfare frameworks (UBA, 2026; Vella et al., 2026).

Moreover, these revenues serve to stimulate climate-friendly capital investment. A significant share of the nEHS inflows is directed into support schemes for energy efficiency, building retrofitting, and renewable heating systems, most notably through KfW and BAFA subsidy programs for heat pumps and the replacement of heating systems. Consequently, nEHS revenues function not merely as a relief mechanism but as a transformation fund, facilitating the structural transition from fossil-fuel-based technologies toward decarbonised energy systems (BAFA, 2024; UBA, 2026).

Finally, these funds are allocated to address distributional concerns. For instance, expert assessments consistently recommend a targeted, incremental relief strategy for lower-income households, such as subsidised fares, mobility passes or tiered energy assistance, to counteract the regressive nature of CO₂ pricing. In this context, the utilisation of nEHS revenues is conceptualised as a mechanism for “socially equitable compensation” and effectively bridging the gap between ambitious climate protection and social distributive justice (Peterson & Maamoun, 2025; Vella et al., 2026).

2.2.2.4 Performance Review 2025

The empirical evaluation of the German National Emissions Trading System (nEHS) for the year 2025, as reported by the German Environment Agency (UBA), provides a critical

framework for analysing the system's maturity and fiscal impact (Umweltbundesamt (UBA), 2026). During this period, the nEHS demonstrated robust growth in financial performance, generating over 16 billion € in total revenue. This represents a significant increase over the 13 billion € earned in 2024, despite a marginal decrease in the total volume of national emissions certificates (nEZ) sold, from 294.7 million in 2024 to just over 294 million in 2025.

The 2025 vintage certificates were issued at a fixed price of 55€ per nEZ (Burret, 2024). Market activity was notably concentrated in the final quarter of the year, which accounted for approximately 13.6 billion € in revenue through the sale of 246.6 million certificates. November 2025 emerged as the most active month in the system's history, recording a monthly volume of 186.1 million nEZ. A significant peak in demand occurred on November 20, 2025, with a record-breaking single-day sale of over 65.9 million certificates.

The market structure in 2025 also indicated a shift toward broader participation and reduced concentration. A total of 196 distinct buyers engaged in the primary market, with 222 participants authorised for direct access and over 1900 registry accounts utilising intermediaries for indirect access. While the annual average attendance per sales session was 22 buyers, this figure rose to 32 during the high-intensity fourth quarter. Additionally, market concentration among the top ten buyers decreased from 45% in 2024 to 42% in 2025, suggesting a more distributive market environment. A key operational feature of the 2025 period was the "repurchase rule" (Nachkaufregel), which permitted participants to acquire 2024 vintage certificates at the previous year's price of 45€. Of the 27 million certificates eligible under this rule, participants purchased approximately 12 million, representing 63% utilization rate of the allowed volume.

In 2026, the nEHS transitioned its sales mechanism towards a more market-driven approach. The UBA report outlines an auction phase scheduled between July and November 2026, during which certificates will be traded within a price corridor of 55€ to 65€. Following the auction period, the system will return to a fixed-price phase at 68€ per nEZ. The total auction volume for 2026 is estimated to be approximately 195 million nEZ. These evolving price benchmarks and volume constraints are essential parameters for the microsimulation of behavioural frictions and the resulting distributional effects on low-income households (Umweltbundesamt (UBA), 2026).

2.3 Alternative Heating Systems

In the context of this study, heat pumps serve as the primary technological paradigm for high-efficiency, renewable heating. They represent the primary alternative to conventional fossil-fuel systems in the microsimulation model. Since the revenues of the nEHS is partially used for providing subsidies and funding for households to switch to heat pumps (BAFA, 2024), they were chosen to be further analysed in the scope of this thesis⁴.

2.3.1 Operational Efficiency and Technical Performance

The thermodynamic efficacy of a heat pump is determined by its seasonal performance factor (SPF or JAZ). Empirical field studies demonstrate that air-to-water heat pumps in existing building stocks achieve average SPF⁵ values ranging from 3.0-3.6 (Dr. Kjell et al., 2023; ISE, 2025). This efficiency translates directly into operational cost reductions. Under current price regimes (averaging 36 ct/kWh for electricity), these systems yield heating cost savings of 30-40% compared to natural gas systems. Within the microsimulation, these parameters serve as the baseline for calculating household-level utility expenditures.

2.3.2 The Federal Subsidy for Efficient Buildings (BEG)

The “Bundesförderung für effiziente Gebäude – Einzelmaßnahmen” (BEG EM) is a funding program managed by the Federal Ministry for Economic Affairs and Climate Action (BMWK). Its primary objective is to incentivise investments in individual measures that increase energy efficiency and the share of renewable energies used for heating and cooling in German buildings, thereby reducing CO2 emissions in the building sector (BAFA, 2024).

The administrative framework of the BEG EM is split between two major institutions: as of January 1, 2024, the KfW (Kreditanstalt für Wiederaufbau) manages the administration of subsidies for heat generators, while the BAFA (Bundesamt für Wirtschaft und Ausfuhrkontrolle) remains responsible for specific infrastructure projects, such as the construction, expansion, or conversion of building networks and the subsequent connection of residences to these systems.

A critical element of the BEG EM is the “Einkommensbonus” (income bonus), a targeted social component designed to support lower-income households. Eligibility for this bonus is restricted

⁴ This thesis focuses on air-to-water heat pumps, since they are the most prominent ones in Germany (Marek, 2026)

⁵ The Seasonal Performance Factor (SPF) is the ratio of total heat energy delivered by a heat pump to the electrical energy consumed over an entire heating season or annual cycle (Eurostat, 2024)

to private individuals who are owners of the subsidised property, specifically within homeowners' associations, and who occupy the residence as their primary or sole home. The qualifying threshold is defined by a maximum taxable annual household income (zu versteuerndes Haushaltsjahreseinkommen) of 40.000€. To verify this, applicants have to submit official income tax assessment notices (Einkommenssteuerbescheide) for the second and third years preceding the main application, accounting for all contributors to the household income.

Table 1: Heat Pump Subsidy Structure in Germany based on (BAFA, 2024; KfW, 2026)

Bonus Type	Subsidy	Eligibility & Conditions
Basic Subsidy	30%	Available to all private homeowners and non-profits for any eligible heat pump.
Income Bonus	30%	For owner-occupiers with a taxable annual household income of 40.000€.
Climate Speed Bonus	20%	For replacing a functioning fossil fuel heating system (oil, coal, or gas/biomass > 20 years old) in owner-occupied homes.
Efficiency Bonus	5%	For heat pumps using a natural refrigerants or geothermal / water / waste-water as a heat source.
Emission Bonus	flat 2.500€	Applicable specifically to biomass systems with very low dust emissions.
Maximum subsidy possible	70%	

Beyond income-specific bonuses, the program dictates that all subsidised measures must demonstrably improve the energetic level of the building and be implemented within the territory of the Federal Republic of Germany. While the BEG EM allows combining these grants with other credit or subsidy programs, it strictly prohibits double funding of the same measure by both KfW and BAFA, ensuring that cumulative aid remains within established expenditure limits (BAFA, 2024; KfW, 2026).

2.3.3 The KfW-BEG EM Integrated Financing Structure

The KfW heat-pump credit operates strictly as a supplementary promotional loan that must be used in tandem with the “Bundesförderung für effiziente Gebäude – Einzelmaßnahmen (BEG

EM) heating grant, meaning a standalone application is not permitted (KfW, 2024). Mechanistically, households must navigate a two-step application process: they first secure a grant approval via the KfW platform, and only after receiving a formal commitment letter can they apply for the complementary loan through their regular commercial bank, which acts as the on-lending intermediary (KfW, 2024). This credit facility can finance up to 100% of the remaining eligible project costs, including the heat pump unit, installation, and associated building modifications (KfW, 2024; Tower Renewal Partnership, 2017). Structural loan conditions are highly favourable, offering terms up to 35 years with a 10-year fixed interest rate period and options for penalty-free early repayment (KfW, 2024). Additionally, interest rates are preferential and income-dependent, such as households with an annual taxable income below or equal to 90.000€ receive rates significantly below market averages, hovering around an effective 2.21% in 2024 (KfW, 2024). Moreover, components of the principal can be converted into non-repayable grants if the property meets predetermined energy-performance standards, thereby reducing the total debt burden (Tower Renewal Partnership, 2017). Ultimately, funds are disbursed post-installation following strict verification of project completion (KfW, 2024).

3. Current state of Art

In order to develop a comprehensive understanding of the distributional effects of carbon pricing, it is necessary to engage with the existing body of empirical and modelling literature. Previous research has extensively analysed the impact of carbon pricing on different income groups, highlighting both its potentially regressive short-term effects and the crucial role of policy design, in particular revenue recycling, in determining overall outcomes.

The aim of this chapter is to review the current state of the art, identifying key findings, methodological approaches, and remaining limitations in the literature. This foundation is necessary in order to position this thesis within the academic debate and to justify the inclusion of behavioural frictions as an addition to existing approaches.

3.1 Distributional Effects of Carbon Pricing

The implementation of carbon pricing, particularly through mechanisms such as Germany's national Emissions Trading System (nEHS), is a critical pillar of modern climate policy within the framework of Sustainable Development. However, the ultimate success of such policies depends heavily on their distributional equity and the extent to which they account for the

unique vulnerabilities of low-income households. The primary challenge regarding carbon pricing lies within the immediate regressivity of its consumption effects. Since low-income households typically spend a larger share of their total budget on essential energy-intensive goods such as heating, electricity, and transport, the direct price signals of carbon taxes often result in a higher percentage loss of disposable income of the poor than for the wealthy (Berry, 2019; Jacobs et al., 2022; Mengesha & Roy, 2025). This phenomenon is particularly acute in the housing sector; for example, microsimulation data from France indicates that higher carbon taxes on fuels significantly increase both the risk and depth of fuel poverty unless robust compensation mechanisms are in place (Berry, 2019).

In the context of German transport, the distributional picture is nuanced. While the current petrol taxation system is clearly regressive, diesel taxation tends to be more progressive. Research suggests that while a separate carbon tax on fuels is neither clearly progressive nor regressive on average, a harmonized carbon-based fuel tax could actually become mildly progressive (Jacobs et al., 2022). This highlights that carbon pricing does not operate in a vacuum but reshapes the entire economy through indirect and factor-income effects. Computable General Equilibrium (CGE) models, such as those applied to the Austrian economy, reveal that households earn income from various “production factors”, primarily labour such as wages and salaries, and capital, which include profits, interest, and rents. When a carbon price is introduced in non-ETS sectors, it triggers a structural reallocation of sectoral output. High-carbon sectors like gas, oil refining, and certain transport industries shrink, while less carbon-intensive sectors such as services, trade, construction, and district heating expand.

This economic shift generates what is known as the “factor-income effect”, which refers to the impact of these sectoral changes on household incomes from labour and capital. In the Austrian case, this reallocation raises wide labour demand and alters returns to capital across different sectors. Since lower-income households in Austria rely relatively more on labour income and less on capital income than richer households, they tend to gain proportionally more from higher consumer prices. When decomposing the total impact, the regressive consumer price effect, driven by higher energy and transport costs, is actually dominated by these progressive factor-income shifts in welfare terms. Consequently, even without targeted compensation, carbon pricing on non-ETS emissions can be slightly progressive. When the improved provision of public goods is also factored in, low-income households may even find themselves better off than in a baseline scenario without the policy (Mayer et al., 2021).

However, results can vary by geography and policy design. An extended GEM-E3-FIT model for the EU warns that climate-neutrality policies could modestly increase inequality if revenues are not recycled, as low-income households face the most significant negative impacts in a non-recycled scenario (Fragkos et al., 2021). The design of revenue recycling is therefore the most decisive factor in determining the social outcome of the nEHS. When carbon revenues are directed toward lump-sum transfers or used to cut social security contributions, they can transform a mildly regressive transition into a progressive one, while simultaneously boosting employment (Fragkos et al., 2021). Comparative analysis of recycling options suggests that while labour-tax cuts perform best on combined economic and equity criteria, per-capita transfers, often called an “eco-bonus”, are the most clearly equity-enhancing choice, whereas untargeted uses or VAT cuts remain less progressive (Mayer et al., 2021). A global assessment of eight different models confirms that while ambitious climate policy may raise inequality in the short run, equal per-capita recycling can more than offset this burden, lowering the Gini index by almost two points and improving social inclusion (Emmerling et al., 2024).

Beyond simple income metrics, regional and sectoral inequalities play a significant role in how carbon pricing is experienced. Rural or peripheral households that are car-dependent often face much higher costs than urban households at the same income level (Jacobs et al., 2022; Mayer et al., 2021). In addition, the interaction between housing policy and carbon pricing is critical. Market-based insulation schemes can disadvantage low-income tenants who cannot control the energy efficiency of their buildings, yet well-designed eco-taxes and transfers can actually support redistribution by lowering the utility costs for these households (Schaffrin, 2013). These structural realities feed into the normative and political dimensions of climate policy. From a philosophical standpoint, carbon pricing is not inherently unjust. When paired with progressive recycling and the recognition that climate damages fall most heavily on the poor, it becomes a tool for distributional justice (Mintz-Woo, 2024). Ultimately, public support for the nEHS is tied to perceived fairness. The perceived distributional consequences, alongside procedural fairness and the perceived effectiveness of the policy, are the primary drivers of whether the public views carbon pricing as a legitimate and acceptable tool for sustainable development (Huttarsch & Matthies, 2024).

3.1.1 Distributional Effects of the nEHS in Germany

The German national emissions trading scheme (nEHS) serves as a central pillar of national climate policy, yet its implications raise significant concerns regarding social equity. When considered in isolation, the nEHS exerts a primarily regressive effect on income distribution

(Schrems et al., 2022). This implies that while higher income households consume roughly three times as much fossil energy in absolute terms as the poorest 10%, the financial weight of the CO₂ price is felt more heavily by those with lower incomes. In 2022, the average burden of CO₂ pricing was 0.33% of net household income, but this impact was unevenly distributed across income groups. Households in the lowest income decile spent approximately 0.6% of their net income on nEHS-related costs, whereas the middle-income deciles faced a burden of roughly 0.4%, and the highest income class saw costs accounting for only 0.2% of their net income (Schrems et al., 2022).

The 2024 analysis of the nEHS provides a more detailed look at these dynamics under a CO₂ price of 45€ per tonne. This more recent data confirms the regressive trend, with the first decile facing a gross burden of only 0.25% (Bach et al., 2025). The regressive effect arises specifically because household income increases much faster across these deciles than energy consumption. In absolute terms, the distribution is reversed: the average monthly burden for the bottom decile is under 10 euros, while the top decile pays roughly 18 euros (Schrems et al., 2022). Despite the lower absolute costs for the poor, the nEHS leads to a slight increase in broader income inequality, reflected in a 0.09% rise in the Gini coefficient and a 0.71% increase in the poverty risk rate (Bach et al., 2025).

The severity of these distributional effects varies significantly depending on the type of energy used and specific household circumstances. For instance, the regressive effect is more pronounced for heating fuels than for motor fuels. While wealthier households often have larger homes, they frequently possess better energy efficiency, meaning their heating costs do not scale directly with income. Conversely, the burden for transport fuels like diesel is almost proportional because wealthier households tend to own more vehicles and drive longer distances (Schrems et al., 2022). Geographic and technical factors also play a role: Households in rural areas face higher transportation burdens, and those using oil heating are burdened significantly more than gas users because nEHS charges for heating oil are roughly 50% higher per heating value than for gas (Bach et al., 2025; Schrems et al., 2022).

A critical factor in mitigating these burdens for low-income tenants is the CO₂-Kostenaufteilungsgesetz (CO₂ Cost Allocation Act). This law mandates that landlords bear a share of heating costs based on building efficiency. In 2024, landlords are estimated to bear 45% of CO₂ heating costs, totalling approximately 740 million euros (Bach et al., 2025). This measure specifically benefits low-income households, who are more likely to live in rented

accommodations and in buildings with poor energy efficiency. In addition, for those in the bottom two income deciles, the regressive effects are largely compensated by established social mechanisms. For recipients of basic social security (Grundsicherung), the state generally covers the increased heating costs as part of the “costs of accommodation”, which primarily stabilizes the first income decile. Additionally, recent reforms to the housing benefit (Wohngeld) in 2021 and 2023 added climate components that provide relief primarily in the second decile and extend into the lower-middle class. As a net result of these measures, the average burden for those in the bottom 20% remains proportional to that of the rest of the population, at roughly 0.4% of net income (Bach et al., 2025; Schrems et al., 2022).

Beyond these targeted social supports, broader policy instruments can further counteract or even reverse the regressive nature of the nEHS. Lowering the EEG levy (renewable energy surcharge) has a progressive effect because electricity consumption is relatively similar across income groups, making the savings a larger percentage of income for poorer households. Even more effective would be a uniform per-capita payment, often referred to as a climate dividend or “Klimaprämie”. A payment of 100 euros per person would make the overall nEHS policy clearly progressive by significantly overcompensating households in the lowest decile while resulting in only minimal net burdens for the wealthiest (Schrems et al., 2022).

However, “average” burdens often mask significant internal variations and specific “hardship cases”. About 31% of households in the lowest two deciles still face a net burden exceeding 0.5% of their income, and 11% face a burden exceeding 1% (Bach et al., 2025). These vulnerabilities are often tied to specific socio-economic traits, such as families with two or more diesel cars used for commuting. Additionally, low-income households face structural barriers to transitioning away from fossil fuels, such as the “landlord-tenant dilemma” and high capital requirements. Historically, building energy subsidies (BEG) have been used mostly by high-income households in the 10% (Bach et al., 2025). Low-income households often lack the savings or access to credit to invest in heat pumps or electric vehicles, even with subsidies available. While the current price of 45€ is manageable for many due to existing relief measures, the transition to EU ETS 2 in 2027 could create social hardships for these vulnerable groups if prices are much higher. This could be avoided if a broader compensation scheme, such as a “climate premium” (Klimageld), were to be implemented (Bach et al., 2025).

3.2 Revenue Recycling and Social Compensation

Research on the possibilities of revenue recycling and social compensation has proposed multiple strategies on how to combat the distributional effects of the nEHS. The option involves a per-capita reallocation in the form of Lump-Sum Transfers, returning revenues to all citizens as a uniform annual payment. Lump-Sum Transfers are considered progressive because low-income households benefit more relative to their incomes than wealthy households do. Since energy costs do not increase in proportion to the number of members, larger households would benefit more from this reallocation. However, this strategy would entail high transaction and bureaucracy costs that could absorb a large portion of the revenues. In addition, it might not fully compensate poor households that own cars and thus face higher mobility costs (Fronzel & Schubert, 2021). Another strategy analysed by Fronzel & Schubert is the reduction of electricity prices to the EU minimum rates. This is supposed to have negligible transaction costs compared to the per-capita transfers. The Electricity Tax Cut supports “sector coupling” by making renewable electricity more competitive against fossil fuels. The paper argues that the electricity tax is increasingly obsolete, since the electricity sector is already covered by the European ETS. However, when it comes to distributional effects on households, the Tax Cut would offer more benefits to wealthy households in absolute terms, since wealthier households consume more electricity (Fronzel & Schubert, 2021). Nevertheless, targeted financial aid promises the most effective outcomes. By directly supporting vulnerable consumers, the burden on poor households is alleviated. Additionally, it requires relatively small monetary resources (Fronzel & Schubert, 2021).

The social and political viability of the German nEHS is intrinsically linked to the transparent recycling of its revenues to mitigate the disproportionate burden on low-income households. Currently, revenues from national carbon pricing are directed into the Energy and Climate Fund (EKF). In 2021, approximately 40% of these funds were utilised to reduce the renewable energy levy (EEG-Umlage), a share planned to decrease 32% in 2022 (Roelfs et al., 2021). While lowering electricity prices benefits households and supports sector coupling by making renewable electricity more competitive, this measure is less targeted toward the poor. Since wealthier households consume more electricity, they receive greater absolute benefits, even though electricity costs represent a larger share of income for poorer households. Reducing electricity prices to EU minimum rates is noted for having negligible transaction costs compared to other measures, but its regressive nature in absolute terms remains a challenge for vertical equity (Fronzel & Schubert, 2021).

To address the distributional effects of carbon pricing, research highlights the distinction between vertical equity, which focuses on impacts across income groups, and horizontal equity, which addresses impacts based on CO₂ intensity, such as rural commuters or those with oil heating. Equal-per-capita payments, or lump-sum transfers, are identified as having the greatest relief effect on low-income households, as they provide a net gain for the poorest 20% of the population. Since energy costs do not increase in proportion to household size, larger households benefit significantly from these uniform annual payments. However, implementing such transfers involves high transaction and bureaucracy costs and may not fully compensate poor households with high mobility needs.

In contrast, hardship-based compensation specifically targets horizontal inequality by assisting vulnerable groups with high CO₂ costs, such as long-distance commuters. While these measures reduce the burden on specific high-intensity users, they provide the least overall relief to the general low-income population compared with other strategies. Targeted financial aid, however, promises highly effective outcomes by directly supporting vulnerable consumers, thereby alleviating the burden on poor households while requiring relatively small amounts of money.

Other popular relief options show limited effectiveness for the most vulnerable. For instance, a landlord-pay regime, whereby landlords are responsible for 50% of heat-related carbon costs, was found to be relatively ineffective compared with alternative options. This may be explained by the fact that not all low-income households are tenants, and that heat-related costs do not represent the largest expense, meaning that they are only able to address a “fraction of the burden” (Roelfs et al., 2021). Similarly, raising the commuting allowance has not been shown to have a substantial relieving effect on poorer households (Puentes & Roberto, 2008). Ultimately, a pragmatic solution involves combining equal-per-capita payments with targeted hardship compensation. This balanced approach ensures that revenues from household carbon pricing are returned directly to citizens, minimising variability in the financial burden across different household types while ensuring that low-income households are positioned better under the carbon pricing regime (Roelfs et al., 2021).

3.3 Behavioural Frictions and Carbon Pricing

Standard economic theory often assumes that carbon pricing operates within a vacuum of perfect rationality, where price signals lead directly to optimal emission reductions. However, several strands of research highlight that carbon pricing does not behave as early as these

models predict. Significant frictions arise at three primary levels: individual cognition, social and fairness preferences, and political decision-making. These distortions mean that the mere existence of a carbon price, such as the nEHS, is often insufficient to trigger the necessary lifestyle and technological shifts without complementary policy interventions (Gsottbauer & van den Bergh, 2025; Stoll & Mehling, 2021a; van der Ploeg, 2025).

A fundamental barrier to effective carbon pricing is the existence of bounded rationality, imperfect optimisation, and inattention. Real-world households do not continuously optimise their consumption. Instead, they rely on heuristics, suffer from myopia, and face significant information overload. This weakens the intended response to price signals (Gsottbauer & van den Bergh, 2025). Additionally, households require supportive regulation and infrastructure, such as viable low-carbon mobility and housing options, to translate price signals into meaningful lifestyle changes. Without these structural supports, potential emission cuts remain unrealised because consumers face low adaptive capacity and are essentially “locked in” to their current routines (Dubois et al., 2019). The following subsections focus on behavioural frictions particularly relevant for low-income households and for the microsimulation framework employed in this thesis.

3.3.1 Bounded Rationality, Inattention, and Carbon Lock-Ins

The complexity of choice plays a significant part in how households respond. The variety of products and overlapping policies involved in decisions leads people to use “rules of thumb” rather than full optimisation, making it difficult to predict exactly how a population will react to a specific carbon price (Gsottbauer & van den Bergh, 2025; Stoll & Mehling, 2021). This is exacerbated by the “salience effect”. Carbon pricing embedded in upstream prices or complex utility bills can suffer from a lack of visibility, leading to dampened behavioural responses and low demand elasticities. For instance, field experiments show that when taxes are not clearly displayed in the posted price, consumers significantly underreact. Research by Chetty et al. (2009) demonstrated that displaying tax-inclusive prices cut demand by 8%, proving that non-salient taxes lead to low demand elasticities. While visibility is often thought to increase effectiveness, highly salient carbon taxes can sometimes produce paradoxical results like moral licensing, where explicitly itemising a tax gives some consumers a “moral self-boost” that can actually encourage more consumption of the carbon-intensive good (Hartmann et al., 2023).

Short-run rigidity and habit formation further distort the impact of carbon pricing. Energy demand is notoriously price-inelastic in the short run because habits, technologies, and housing

structures are fixed. Larger behavioural responses only emerge over time as individuals gradually switch equipment or fuels, resulting in delayed adaptation (Csereklyei, 2020). At the household-level, additional barriers such as limited cognitive capacity, limited knowledge, low self-efficacy, and a default bias toward carbon-intensive routines further impede the transition (Dubois et al., 2019; Stankuniene et al., 2020). These cognitive limitations, along with housing and mobility lock-ins, directly contribute to low price elasticity and sticky consumption patterns.

3.3.2 Status Quo Bias and Loss Aversion

The Status Quo Bias (SQB) and loss aversion fit naturally together to explain why households resist switching technologies, underinvest in heat pumps, and show a reluctance to bear upfront costs. SBQ represents a non-rational or biased preference for the current state of affairs, characterised by an individual's tendency to remain inactive or maintain previous decisions even when an alternative choice would be more beneficial (Blascha & Daminatob, 2020; Godefroid et al., 2022). One of the most tangible consequences of this bias is the persistent “energy-efficiency gap”, where individuals forgo economically viable investment in green technology. Biased individuals frequently fail to replace inefficient appliances, opting to keep old, energy-intensive durables until they are completely broken rather than upgrading. Research indicates that households heads exhibiting this bias are 4 percentage points more likely to own appliances older than 10 years (Blascha & Daminatob, 2020). In addition, SBQ contributes to the over-consumption of energy services through the sunk-cost fallacy, as individuals feel a psychological commitment to “mentally amortise” the initial cost of an appliance, leading to an estimated 5.4% higher consumption of energy services (Blascha & Daminatob, 2020). This behavioural friction also contributed to “fuel poverty” among low-income individuals by preventing them from switching to more favourable energy tariffs, leaving them trapped with disproportionately high costs for efficient energy (Godefroid et al., 2022).

This inertia is deeply rooted in loss aversion, as defined in prospect theory, the idea that people are more sensitive to losses than to gains of the same magnitude relative to a subjective reference point (Homar, 2023; Knobloch et al., 2019). Research suggests that this asymmetry is significant, with the pain of losses being psychologically twice as powerful as the enjoyment of commensurate gains (Tversky & Kahneman, 1992). This reference dependence means that individuals evaluate choices in terms of changes relative to a status quo or currently owned technology, leading to a strong reluctance to replace appliances due to fear of upfront

investment. For the design of climate policies like the nEHS, these insights have significant implications. Due to the weighted impact of immediate losses, which are more heavily weighted by loss-averse consumers than future energy savings, upfront subsidies can be highly effective because they directly reduce the size of relative losses, such as high initial costs for new technology, thereby reducing perceived losses and helping to close the adoption gap (Knobloch et al., 2019).

3.3.3 Imperfect information and Unequal Access to the Low-Carbon Transition

The efficacy of climate policies is significantly mediated by the availability and processing of information among economic agents, serving as a critical justification for behavioural heterogeneity assumptions by income. Within the context of energy transition and carbon pricing, consumers' responses to price signals are frequently hampered by imperfect information. This friction often manifests as biased reasoning, where consumers tend to underestimate potential energy savings, leading to suboptimal investment decisions and delayed responses (Austin, 2012). Unlike theoretical models, in which fiscal shocks might have an immediate impact, real activity indicators show minimal movement initially. This is because agents must decipher the nature of policy changes through “noisy signals”, resulting in sluggish information shocks (Corrado & Silgado-Gómez, 2023).

The role of information is particularly critical regarding the adoption of sustainable technologies, such as heat pumps. Experimental evidence suggests that providing consumers with transparent data regarding operating and investment costs significantly increases their willingness to pay (WTP) for renewable systems compared to fossil-based alternatives (Eßer, 2025). Many households are simply unaware of the long-term cost advantages of renewable heating, and uncertainty about future carbon prices and fluctuating energy costs further complicates the ability to calculate long-term savings. Given that heating systems have been used for decades, addressing these information gaps is essential to prevent short-sighted decisions that keep households dependent to fossil-fuel systems for over 20 years (Eßer, 2025).

For low-income households in Germany, the intersection of imperfect information, liquidity constraints, and the current subsidy landscape under the Building Energy Act (GEG) creates an unequal adaptive capacity and a substantial barrier to the heat pump transition. While the framework offers a tiered grant system through BAFA that can cover up to 70% of investment costs, combining 30% income-based bonus for owner-occupiers with a taxable annual income below 40.000€ (BAFA, 2024), the complexity of these stackable incentives can often lead to

information overload (Briganti et al., 2023). For vulnerable, low-income households, the difficulty of accurately calculating the net present value of such an investment, together with uncertainty about future nEHS carbon price trajectories and the inability to pre-finance investments, often leads to a “wait-and-see” approach. Consequently, even when the state significantly de-risks upfront costs to as little as 30% of the total price, imperfect information regarding eligibility and long-term savings acts as a behavioural friction that neutralises the distributive intent of the policy and widens the adoption gap (Eßer, 2025).

3.3.4 Political and Institutional Constraints on Carbon Pricing

Finally, political and institutional distortions shape the level and timing of carbon pricing. Because carbon taxes are highly visible and often unpopular, fairness concerns strongly influence policy design (Stoll & Mehling, 2021a; van der Ploeg, 2023). Public acceptance is largely mediated by perceived personal burdens and distributional consequences, fuelled by the widespread belief that “carbon taxes hurt the poor” (Huttarsch & Matthies, 2024). Because the impacts of carbon pricing are highly heterogeneous, affecting groups such as rural, car-dependent households and low-income families living in poorly insulated housing particularly severely, policymakers face intense electoral pressure (Antosiewicz et al., 2022; Berry, 2019; Mayer et al., 2021). This political resistance limits carbon price levels, encouraging governments to keep prices artificially low, grant exemptions, or rely on subsidies and compensation schemes to bypass public opposition and manage distributional anxieties (van der Ploeg, 2023).

3.3.5 Implications for the Microsimulation Framework

The behavioural frictions reviewed in this chapter provide the theoretical and empirical foundation for the parameter assumptions and structural design of the microsimulation framework used in this thesis. Rather than assuming uniform, perfectly rational responses to the German nEHS, the simulation explicitly operationalises these frictions to capture realistic distributional outcomes and unequal adaptive capacities across income deciles.

The table below outlines how these theoretical frictions translate directly into specific model implementations:

Table 2: Model implications stemming from behavioural frictions

Behavioural frictions	Model implementation
Inattention / Habits	Delayed adjustment parameter
Imperfect Information	Lower subsidy uptake rates
Status Quo Bias	Lower technology adoption probability
Loss aversion	Reduced investment willingness for upfront costs
Lock-Ins (Housing)	Lower short-run price elasticity

In corporate and household micro-modules, these behavioural parameters vary systematically by income. Low-income households are assumed to face significantly stronger frictions. This income-based parameter heterogeneity is justified by the compounding effects of tighter liquidity constraints, lower information access, rental housing market failures (owner-tenant dilemmas), and an inability to pre-finance high upfront investment costs. By modelling these frictions explicitly, the microsimulation avoids underestimating the regressive impacts of carbon pricing, demonstrating how behavioural barriers can amplify the energy-efficiency gap and lock vulnerable households into long-term carbon liabilities.

3.4 Focus on Germany

Recent Research on the distributional effects of Germany's national emissions trading system (nEHS) for buildings and transport highlights its regressive tendencies on low-income households, who face disproportionate energy cost burdens relative to income, often 3.5%-11% of consumption expenditure (Kalkuhl et al., 2022), due to higher reliance on fossil fuels for heating and mobility. Studies incorporating behavioural frictions, such as loss aversion, reveal that revenue recycling via lump-sum dividends or tax cuts mitigates inequality but is blunted by reduced tax bases and weakened incentives for emission reductions, dropping political support from 60% to 30% without hybrid measures (Ackermann & Radulescu, 2024; Tovar & van der Ploeg, 2021).

Advanced models account for frictions like limited energy-saving responses among low-income renters and peripheral households, where carbon pricing elevates consumption prices more sharply without targeted retrofits. Experimental evidence confirms that nEHS prompts fuel consumption cuts, yet liquidity constraints and information gaps hinder full adjustment,

thereby amplifying net burdens in the absence of dynamic relief such as per-capita payments (Hübler et al., 2024; Kettner et al., 2026). The state of the art emphasizes hybrid recycling for equity-efficiency balance, but longitudinal data on nEHS implementation remains sparse, with calls for friction-aware simulations tailored to Germany's housing stock (Ackermann & Radulescu, 2024)

4. Research Gap

The preceding review of the literature on carbon pricing, the German National Emissions Trading System (nEHS), and behavioural economics reveals several critical gaps. While the distributional impacts of carbon taxes and the existence of behavioural frictions are well-documented as isolated phenomena, their intersection remains under-researched, particularly in the German context.

4.1 Disconnect between Behavioural Frictions and Distributional Outcomes

A primary limitation in current research is the frequent decoupling of behavioural components from distributional analysis. While many studies utilise high-quality microdata to investigate the impacts of carbon pricing on households (Gordon et al., 2015; Rausch et al., 2011), they often do so without accounting for behavioural components or irrational decision-making. Conversely, a growing body of research identifies how carbon responses are influenced by behavioural frictions, such as bounded rationality, inattention, and the “salience effect”, but these studies often lack a direct link to quantified distributional outcomes (Marcos et al., 2022; Stoll & Mehling, 2021).

Moreover, while some research explores the modelling of non-optimal behaviour in energy transitions, these studies often focus on specific regions like the UK and do not relate their findings to other countries (Li, 2017a). Most existing cases have not yet quantified how these frictions specifically exacerbate the financial burden for different income classes.

4.2 Incomplete Representation of Household Heterogeneity

Existing studies also tend to focus on narrow household demographics or broad national averages that mask internal disparities. For example, while research has explored the economic impact of carbon pricing on single and childless households (Cui et al., 2025), these analyses are frequently not categorised by income class. Similarly, European-wide studies that analyse carbon taxes on transport and heating fuels, and the subsequent impact of lump-sum refunds (Rüb, 2024), often fail to take behavioural frictions or “irrational” consumer behaviour into

account (Caron et al., 2018; Mathur & Morris, 2014). This oversight is also evident in a “blind spot” in which the actual lived experience of the energy transition for low-income households is obscured by models that assume perfect rationality (Berry, 2019; Gordon et al., 2015; Rausch et al., 2011). In an effort of representing household heterogeneity, the role of job loss and labour-market dynamics within the distributional analysis has been explored in other contexts like Poland (Antosiewicz et al., 2022), but remains under-analysed in Germany.

4.3 Energy Efficiency Barrier for Low-Income Households

The persistent discrepancy between the theoretical potential for energy savings and the actual adoption of energy-efficient technologies is particularly pronounced among low-income households. While neoclassical economic models suggest that households should adopt efficient appliances if the long-term energy savings outweigh the initial investment, empirical evidence from regions like Hong Kong reveals a far more complex reality. For these households, the adoption of green technology is hindered by a multifaceted interplay of financial, structural, and cognitive barriers that collectively render “economically rational” choices inaccessible.

The most immediate obstacle to energy efficiency in low-income settings is the significantly higher upfront cost, or “first cost”, associated with efficient appliances. Although these models offer lower operating costs over their lifecycle, capital-starved households operating on precarious budgets are often unable to bridge the initial price gap. Research by Gibb and Chu (2026) highlights a stark sensitivity to initial pricing: low-income respondents were generally willing to pay only a 5-10% premium for energy-efficient models. Given that the actual market price premium for high-efficiency technology frequently exceeds this threshold, these households are effectively priced out of the market. This financial constraint forces a focus on immediate liquidity rather than on long-term utility maximization, a phenomenon exacerbated by the “scarcity mindset,” in which urgent daily needs take precedence over future savings (Gul & Pesendorfer, 2004).

Beyond direct financial constraints, structural market failures, specifically the principal-agent problem, create a significant barrier for the high proportion of low-income individuals living in rental accommodations. In these scenarios, there is a clear “split incentive” (Gillingham & Palmer, 2014): the landlord (the agent) is responsible for purchasing and installing major appliances but typically selects the cheapest, least-efficient models to minimise capital expenditure. Conversely, the tenant (the principal) is responsible for the monthly energy bills

but has no control over the energy performance of the provided hardware. Data suggests that nearly half of renters believe their landlords would refuse to replace a malfunctioning appliance with a more expensive, efficient alternative (Gibb & Chu, 2026). This structural entrapment ensures that those with the least ability to pay are often burdened with the highest operating costs due to inefficient infrastructure they do not own.

Finally, the energy efficiency gap is widened by cognitive frictions and varying levels of financial literacy. Low-income households often exhibit high implicit discount rates, estimated at approximately 30%, meaning they heavily devalue future savings in favour of immediate cash preservation (Gibb & Chu, 2026). This short-termism is often not a choice but a survival strategy. Furthermore, significant information gaps persist regarding energy consumption patterns. For instance, in the Hong Kong context, only 65% of households correctly identified the air conditioner as the primary energy consumer, despite it being the most energy-intensive appliance in a typical home (Gibb & Chu, 2026). Without clear, accessible information on where energy is being consumed, households cannot effectively prioritise investments or behavioural changes.

In summary, the barriers facing low-income households are not merely a result of insufficient capital, but a systemic failure where financial scarcity, lack of agency in rental markets, and information asymmetries converge. For policies like the German nEHS to be effective without causing social harm, they must move beyond carbon pricing alone and address these specific “frictions” that prevent the most vulnerable from responding to price signals.

4.4 Neglected Dimensions of Just Transformation

Finally, there is a notable absence of studies that evaluate how pricing instruments and climate policies affect households in distributional terms. There is research on how consumers’ response to carbon pricing is affected by behavioural frictions (Marcos et al., 2022; Stoll & Mehling, 2021b). However, current research lacks quantified results on households, even though lessons from other highly regulated sectors, such as the role of behavioural frictions in health insurance marketplace enrolment, suggests that these factors are critical to policy success (Domurat et al., 2021). By ignoring these frictions in the context of carbon pricing, current literature risks overestimating the effectiveness of the nEHS while underestimating the “distributional” and “recognition” justice requirements for vulnerable groups who may be disproportionately affected by poverty and inequality.

In summary, the specific research gap addressed by this thesis is the lack of a quantified, microdata-driven link between behavioural frictions and the distributional outcomes of the German nEHS. While current literature acknowledges that consumers often act “irrationally” (e.g., due to status quo bias or inattention) and that carbon pricing is regressive in developed economies, these two realities are rarely modelled together. This study fills this void by analysing how cognitive and institutional barriers prevent different income classes from responding to nEHS price signals, thereby potentially worsening inequality. By integrating behavioural economics into a Just Transformation framework, this research moves beyond the idealised “rational consumer” to provide a more accurate assessment of the social risks inherent in Germany’s energy transition.

Therefore, this thesis addresses the following questions:

- I. Does accounting for behavioural frictions reveal stronger regressive effects of carbon pricing on low-income households in the German nEHS?
- II. To what extent does incorporating behavioural frictions into a microsimulation model change the estimated distributional effects of carbon pricing on low-income households in Germany?

5. Description of Data

This chapter describes the datasets used to develop and calibrate the microsimulation model. The analysis relies on a combination of survey-based microdata, behavioural parameters, and secondary statistical sources. These datasets provide the empirical foundation for modelling heterogeneous agents and their energy consumption behaviour. Integrating information on socio-demographic characteristics, energy use, a price shock and behavioural responses, the data enables a representation of decision-making processes within the simulation framework.

The primary sources include:

- A representative survey on individual resource consumption in Germany (Kleinhüchelkotten & Moser, 2016)
- Price shock modelled after the nEHS, Germany (Wendl-Damerius, 2021)
- Model calibration and behavioural parameter data from the BLUE energy system model (Li, 2017a)

- Empirical and econometric evidence on energy demand elasticities and household heterogeneity (Priesmann & Praktiknjo, 2025)
- Conceptual and modelling insights on behavioural dynamics in energy systems (Li, 2017a, 2017b)
- Costs and operating costs of gas heating and heating pumps
- Parameter and conditions for modelling the credit extension (KfW, 2025)
- Destatis housing survey for owner-occupier share for the credit extension (Destatis, 2021)

5.1 Survey Data on Resource and Energy Consumption

The core empirical dataset used in this study is derived from a representative survey on per-capita resource consumption in Germany. The survey was conducted as a face-to-face study between March and April 2014 and included 1.012 individuals aged 18 and above living in private households. The sampling strategy ensures that the dataset is representative of the German-speaking residential population.

The survey collects detailed information on individual consumption behaviour across multiple domains. These include household energy use (such as heating, hot water, lighting, and appliance use), mobility-related energy consumption (including daily travel and holiday trips), and broader consumption activities such as food and clothing. In addition, respondents provided information on ownership of energy-related technologies, such as renewable energy systems, and on their willingness to engage in climate-related actions, such as carbon offsetting.

Alongside consumption data, the survey contains a rich set of socio-demographic variables, including income, education, age, gender, household size, and regional location. Moreover, attitudinal variables were collected to capture environmental awareness and behavioural preferences. Based on these variables, individuals can be grouped into different social milieus, reflecting shared lifestyles and value systems.

Using the collected data, individual-level energy consumption CO₂ emissions are derived. For multi-person households, total household consumption is allocated to individuals using equivalence scales and weighting approaches. This allows for consistent comparison for per-capita consumption across different household types. The resulting dataset provides a detailed and heterogeneous picture of energy use at the micro level.

5.2 Behavioural Parameters and Model Calibration

Representing decision-making processes within the microsimulation model, behavioural parameters are incorporated based on the BLUE model framework (Li, 2017a). These parameters capture deviations from purely cost-optimising behaviour and allow for the modelling of heterogeneous agent responses.

Key parameters include price elasticities, which measure the sensitivity of energy demand to price changes, and market heterogeneity parameters, which reflect the extent to which agents deviate from strict cost-optimisation (Li, 2017a). Additional parameters account for intangible costs, representing non-monetary barriers to adopting new technologies, as well as hurdle rates, which describe agents' sensitivity to upfront investment costs.

These behavioural parameters vary across sectors such as residential, commercial, industrial, and transport. This sectoral differentiation reflects the fact that decision-making processes and constraints differ significantly across contexts. For example, households typically face different investment barriers and behavioural biases compared to firms or transport operators. The inclusion of these parameters enables the model to move beyond the assumption of fully rational agents and instead simulate more realistic behavioural patterns, including inertia, bounded rationality, and heterogeneous preferences.

5.3 Energy System and Cost Data

In addition to micro-level survey data and behavioural parameters, the model incorporates stylised representation of the energy system. Energy service demands are calibrated using base-year data derived from official statistics, expressed in consistent energy units such as petajoules (Li, 2017b). These values serve as the starting point for the simulation and ensure that the model reflects realistic baseline conditions.

Fuel prices and emission factors are also included as key inputs. Fossil fuel prices are modelled dynamically based on projections and uncertainty ranges, while emission intensities are derived from established statistical sources. This allows the model to capture both economic and environmental dimensions of energy use. The energy system representation is intentionally simplified to ensure computational tractability while retaining the key relationship between energy demand, costs, and emissions. This balance is particularly important in microsimulation models, where computational complexity increases rapidly with the number of agents and variables.

5.4 Elasticity Estimates and Empirical Evidence

Informing the modelling of behavioural responses further, the study draws on empirical literature on energy demand elasticities (Priesmann & Praktiknjo, 2025). Price elasticity of demand describes how energy consumption responds to changes in energy prices, while income elasticity captures the effect of household income on energy demand. Empirical studies show that these elasticities vary significantly across households, depending on socio-economic and demographic characteristics such as income, household composition, and age. The heterogeneity implies that policy measures, such as price-based instruments, may have different effects across population groups.

Moreover, energy demand responses differ between the short run and the long run. In the short run, households are constrained by existing technologies and infrastructure, limiting their ability to adjust consumption. In the long run, however, households can adapt through investment in energy efficiency or by switching energy carriers. These dynamics are particularly relevant for microsimulation models, which aim to capture both immediate and gradual behavioural changes.

5.5 Price Shock: nEHS, Germany

The German national emissions trading system (nEHS), introduced under the BEHG, constitutes an exogenous price shock to fossil fuel and electricity consumption. The system prices CO₂ emissions upstream, at the level of fuel distributors, who pass the costs on to end users, thereby increasing retail fuel prices in a predictable, policy-driven manner (Wendl-Damerius, 2021).

Table 3: nEHS-Induced Price Shock on selected fuels (2021-2025) based on (Wendl-Damerius, 2021)

Year	CO2 Price (€/tCO ₂)	Gasoline (ct/l)	Diesel (ct/l)	Heating Oil (ct/l)	Natural Gas (ct/kWh)
2021	25	6	7	7	0.5
2022	30	7	8	8	0.5
2023	35	8	10	10	0.6
2024	45	11	12	12	0.8
2025	55	13	15	15	1.0

Note: Values indicate additional price components induced by the nEHS carbon pricing mechanisms. Prices are rounded and exclude VAT and other surcharges.

5.6 Data and Parameters for Heating System Costs

The modelling of heating costs and the transition to efficient technology relies on a comparative analysis between traditional gas heating and heat pumps. To accurately reflect the financial reality of German households, the model integrates specific technical parameters and current energy pricing.

5.6.1 Operating Costs and Energy Pricing

The operating costs for both systems are calculated as the sum of annual energy consumption and fixed maintenance fees.

- Energy prices: The baseline energy price for 2025 is set at 39.3 ct/kWh, following BDEW data (BDEW, 2026)
- Maintenance: Annual maintenance is estimated at 130€ for gas heating and 240€ for heating pumps (co2online, 2026)
- Technical efficiency: For heating pumps, the seasonal performance factor (JAZ) is assumed to be 3.0, which significantly reduces the electricity required to meet the household's heating demand (Dr. Kjell et al., 2023).

5.6.2 Investment and Government Funding

The transition to sustainable heating involves a high initial investment (I_0), which is a primary barrier for low-income deciles. The model uses a base price of 22.500€ for an air-source heat pump (co2online, 2026). The model also incorporates BAFA funding mechanisms. This funding is designed to lower the entry barrier based on the household's prior heating system and the speed of investment (see Table 1).

5.7 Integration of Data into the Microsimulation Framework

The different data sources are integrated within the microsimulation model to represent heterogeneous agents and their decision-making processes. The survey data provides the basis for defining agent characteristics, including socio-demographic attributes and consumption patterns. Behavioural parameters determine how agents respond to changes in price, policies, and other external factors. Energy system data defines the technological and economic environment in which agents operate, while elasticity estimates inform the calibration of behavioural response.

The integrated approach allows the model to simulate complex interactions between individual behaviour, economic conditions, and policy interventions. In particular, it enables the analysis

of distributional effects, behavioural heterogeneity, and dynamic adjustment processes, which are often overlooked in aggregate modelling approaches.

5.8 Limitations

Despite the comprehensive nature of the datasets, several limitations should be taken into account. First, survey-based data may be subject to self-reporting bias. Particularly in areas such as energy use, behavioural parameters are partly based on assumptions or stylised representations, rather than direct observation.

In addition, combining data from different sources may raise comparability issues, as datasets may differ in definitions, time periods, and geographical coverage. Nevertheless, the integration of multiple data sources provides a robust foundation for the microsimulation model and allows for a detailed representation of energy consumption behaviour.

6. Methodology

6.1 Characterisation of Household Budgets

To evaluate the distributional impacts of the nEHS, the microsimulation begins by establishing four representative household archetypes based on stratified consumption patterns shown in the calibration table (see Annex A). The following will discuss lower and higher income classes. This refers to the two lower or two higher income classes. The baseline energy profiles ($C_{i,0}$) are calibrated using representative survey data from the German Environment Agency (UBA), which provides annual energy consumption for heating, electricity, and mobility across different income classes. As shown in the empirical data, a distinct positive correlation exists between net equivalent income and absolute energy use: households in the lowest income class (under 1000€) consume approximately 12.664,0 kWh per person annually, whereas those in the 2000 to 2999€ income class consume 18.207,8 kWh.

These baseline budgets are further characterised by their specific carbon intensities to calculate the initial emissions burden. For the lowest income class, this corresponds to an average footprint of 4.183,9 kg CO₂ per person, while the highest income class reaches 5.968,1kg CO₂ per person. By mapping these consumption columns to the nEHS price schedule, which rose to a fixed price of 55€/t CO₂ in 2025, the model establishes the “Static effect”. This effect represents the immediate financial shock ($\Delta P \times C_{i,0}$) experienced by the household prior to any behavioural or technological adaption.

A critical component of this characterization is the integration of income-specific response parameters. Following the findings of Priesmann and Praktiknjo (2025), the model assigns differentiated price elasticities (ε) to each household archetype. For instance, the short-run elasticity for car fuels is significantly higher for low-income households (-0,47) than for high-income groups (-0,15), reflecting the fact that poorer households often face more immediate pressure to reduce consumption despite limited alternatives.

Finally, to move beyond the “rational actor” model, each household archetype is assigned behavioural friction parameters derived from the BLUE model framework. Low-income households are characterised by higher subjective hurdle rates (r_i), which represent the significant capital constraints and heightened risk aversion that prevent the adoption of efficient technologies. This is complemented by a replacement rate (b) that accounts for the natural inertia of investment cycles, such as the 15–20-year lifespan of heating systems. These parameters ensure that the simulation captures why price signals may fail to trigger investments in low-income deciles, even when such investments appear economically optimal in a frictionless environment.

6.2 The Microsimulation

The microsimulation model analyses the distributional effects of the German nEHS across representative household income groups. By combining household-level energy expenditure data with behavioural-economic mechanisms, the model evaluates how carbon pricing influences energy costs, technology adoption, and policy burdens under different behavioural and policy scenarios. Particular emphasis is placed on imperfect information, investment frictions, and heterogeneous adaptive capacity across income groups.

6.2.1 Modelling the nEHS Price Shock

The primary exogenous variable in the microsimulation is the “price shock” generated by the phased implementation of the German National Emissions Trading System (nEHS). This shock is defined as the absolute increase in energy costs (ΔP) resulting from the transition from a zero-carbon-price baseline to the fixed-price regime established between 2021 and 2025. In the simulation, this price impulse is applied to the initial annual energy consumption ($C_{i,0}$) of each household archetype to determine the immediate, non-adapted financial burden.

The magnitude of the price shock is determined by the CO₂ price trajectory, which rose from 25€ / CO₂ in 2021 to a fixed price of 55€/t CO₂ in 2025. For the 2025 reporting year, this

carbon price translates into specific cost surcharges across all major energy carriers used by households. According to Wendl-Damarius (2021), the 2025 price of 55€/t CO₂ results in an additional cost of 1 cent per kWh for natural gas.

In the mathematical framework of the model, this shock is represented as:

$$\Delta P_t = P_{nEHS,t} \times \text{Emission Factor}$$

The emission factor is obtained from the German Federal Government (BAFA, 2025) and determined as *Emission Factor* = 0.201.

6.2.2 Subsidy schedule and Net Investment Cost

The microsimulation contains a subsidy-information regime $a \in \{aware, unaware\}$, where the latter captures households that do not internalise the available subsidy in their investment calculation. The awareness regime is simulating the behavioural of imperfect information. The gross investment cost of a heat pump is denoted by I_0 .

The subsidy rate is:

$$(1) \sigma_i^{(a)} = 0.70^6, \text{ if } a = \text{aware and } Y_i < 27.000^7$$

$$(2) \sigma_i^{(a)} = 0.50, \text{ if } a = \text{aware and } Y_i \geq 27.000$$

$$(3) \sigma_i^{(a)} = 0.50, \text{ if } a = \text{unaware}$$

Following, the investment costs given the subsidy rate and awareness are defined as:

$$(4) I_i^{(a)} = I_0(1 - \sigma_i^{(a)})$$

⁶ The BAFA grants a maximum of 70% of subsidy for low-income households for Heat-pumps, even if a higher subsidy would have been achieved, when all subsidy rates are combined. For this reason, the model considers a subsidy rate of 70% for low-income households (BAFA, 2024).

⁷ To align the simulation with the German federal subsidy guidelines (Bundesförderung für effiziente Gebäude), a threshold for the low-income “Klimabonus” was established. While the official policy grants the additional 30% subsidy to households with a taxable income (zu versteuerndes Einkommen) below 40.000€ (BAFA, 2024), the microsimulation utilises net income data. To bridge this gap, the 40.000€ taxable income limit was converted into a net income equivalent using a standard tax calculator for Tax Class I (Steuerklasse I). This resulted in an operationalised threshold of 27.000€ net annual income, ensuring that eligibility for the higher subsidy rate is accurately reflected within the household data used in this study.

The microsimulation evaluates household heating choices based on the discounted lifetime costs of gas heating and heat pumps. Operating expenditures, investment costs, and annualised capital costs are incorporated through a net-present-value framework with income-specific hurdle rates.

6.2.3 Operating Costs of Gas Heating and Heat Pumps

$$(5) G_{i,t}^{SR,s} = G_{i,t}^{SR,s} p_t^{g,s} + m^g$$

$$(6) G_{i,t}^{LR,s} = G_{i,t}^{LR,s} p_t^{g,s} + m^g$$

$$(7) C_i^{hp} = C_{i,0}/J$$

$$(8) H_{i,t} = C_i^{hp} p_t^e + m^{hp}$$

6.2.4 Discounting, Net Present Values and Annualised Capital Costs

The effective discount rate depends on the behavioural regime:

$$(9) r_i^{(m)} = 0 \text{ if } m = R; \text{ and } r_i^{(m)} = r_i \text{ if } m = B$$

Households evaluate heating technologies based on discounted lifetime costs using a Net Present Value (NPV) framework:

$$(10) NPV_{i,t}^{hp,(m,a)} = I_i^{(a)} + \sum_{\tau=1} T \left[\frac{H_{i,t}}{(1+r_i^{(m)})^\tau} \right]$$

The switch to an alternative heating technology requires an upfront investment denoted here as I_0 (10).

$$(11) NPV_{i,t}^{g,(s,a)} = \sum_{\tau=1} T \left[\frac{G_{i,t}^{LR,s}}{(1+r_i^{(m)})^\tau} \right]$$

Since gas heating is expected to be in place, the formula for gas heating (11) involves only operating costs over time. To make investment costs comparable to annual operating costs, they are transformed using an annuity formula:

$$(12) A_i^{(m,a)} = \frac{I_i^{(a)}}{T}, \text{ if } r_i^{(m)} = 0$$

$$(13) A_i^{(m,a)} = I_i^{(a)} \left[\frac{r_i^{(m)}}{1-(1-r_i^{(m)})^{-T}} \right], \text{ if } r_i^{(m)} > 0$$

Economically, a higher hurdle rate increases the annualised cost, making capital-intensive technologies less attractive. The hurdle rates are household-income-specific and based on Priesmann & Praktijnjo (2025).

6.2.5 Investment Probability and Adoption

In the rational scenario, switching is deterministic. Households choose the cost-minimising technology and switch as soon as:

$$(14) \quad q_{i,t}^{(s,R,a)} = 1[NPV_{i,t}^{hp,(R,a)} < NPV_{i,t}^{g,(s,R)}]$$

Otherwise, households remain with gas heating. In the behavioural scenario, switching is probabilistic and follows a logistic function:

$$(15) \quad q_{i,t}^{(s,B,a)} = \frac{1}{\{1 + \exp[v_i \lambda (NPV_{i,t}^{hp,(B,a)} - NPV_{i,t}^{g,(s,B)})]\}}$$

Equation (15) implies that even if heat pumps are economically advantageous, households may not switch due to behavioural frictions such as imperfect information or risk aversion.

Replacement friction is regime-specific:

$$(16) \quad h_i^{(m)} = 1 \text{ if } m = R; \text{ and } h_i^{(m)} = \frac{1}{T} \text{ if } m = B$$

$$(17) \quad \alpha_{i,t}^{(s,m,a)} = 1(t \geq 2021)h_i^{(m)}q_{i,t}^{(s,m,a)}$$

$$(18) \quad S_{i,t}^{(s,m,a)} = S_{i,t-1}^{(s,m,a)} + [1 - S_{i,t-1}^{(s,m,a)}]\alpha_{i,t}^{(s,m,a)}$$

For the sake of convenience, it is assumed that the heat pump stock is 0 for the microsimulation prior to the implementation of the nEHS and the subsidy opportunities:

$$(19) \quad S_{i,2020}^{(s,m,a)} = 0$$

6.2.6 Expected energy expenditure and distributional outcomes

$$(20) \quad E_{i,t}^{(s,m,a)} = S_{i,t}^{(s,m,a)}(A_i^{(m,a)} + H_{i,t}) + [1 - S_{i,t}^{(s,m,a)}]G_{i,t}^{SR,s}$$

$$(21) \quad \Delta E_{i,t}^{(m,a)} = E_{i,t}^{(pol,m,a)} - E_{i,t}^{(np,m,a)}$$

$$(22) \quad XS_{i,t}^{(m,a)} = E_{i,t}^{(pol,m,a)} / Y_i$$

Equation (23) measures the additional financial burden imposed by the policy as a share of household income and allows for distributional comparisons across income groups.

$$(23) \quad B_{i,t}^{(m,a)} = \Delta E_{i,t}^{(m,a)} / Y_i$$

This financial burden is calculated for seven different scenarios, which are further explained in Chapter [6.3, Definition of different scenarios](#).

6.2.7 Modelling Imperfect Information and Perceptual Frictions

In order to refine the behavioural scenario, an “imperfect information” layer is integrated into the decision-making framework. This captures the reality that households may not fully internalise subsidies or respond immediately to price changes. This regime modifies the inputs for both the investment calculation and the operating cost projections through three mechanisms:

1. Inattention to subsidies vs. Binary awareness

The model distinguishes between two types of information deficits. While the subsidy-information regime determines whether a household is fundamentally knowledgeable about the subsidy, the inattention share (α_i) represents a behavioural friction where even “aware” households fail to fully internalize the net investment benefits in their mental accounting. The inattention share is defined as:

$$(24) \quad \alpha_i = \frac{\text{inattention rate}_i}{100}$$

In the behavioural branch, the perceived investment cost becomes a weighted average of the net cost and the gross cost:

- For “aware” households: (25) $I_i^{behav} = (1 - \alpha_i) \cdot I_i^{(\alpha)} + \alpha_i \cdot I_0$
- For “unaware” households: (26) $I_i^{behav} = I_i^{(\alpha)}$

(where $I_i^{(\alpha)}$ already equals a higher cost due to the ignored subsidy)

For the lowest income class, a α value of 0.40 implies that despite being “aware” of the policy, 40% of the gross cost remains the psychological benchmark, significantly diluting the subsidy’s incentive effect.

2. Delayed Price Perception

Rather than responding to real-time market prices, households exhibit a perception delay (λ_i), where:

$$(27) \lambda_i = \frac{\text{adjustment delay months}_i}{12}$$

The perceived gas price ($\tilde{p}_{t,i}$) used in the household's evaluation is a weighted combination of current and previous price levels:

$$(28) \tilde{p}_{t,i} = (1 - \lambda_i)p_t + \lambda_i p_{t-1}$$

For households with a 12-month delay ($(\lambda - 1)$), the perceived price at time t is effectively the price from $t-1$, delaying the investment signal generated by the nEHS price shock.

3. Post-Friction heating-demand response

The actual short-run consumption adjustment is modelled using the perceived price ($\tilde{p}_{t,i}$) and the income-specific post-friction heating elasticity (ϵ_i):

$$(29) q_{i,t} = \max \left[q_{0,i} \left(1 + \epsilon_i \frac{\tilde{p}_{t,i} - p_0}{p_0} \right), 0.05 q_{0,i} \right],$$

where $q_{0,i}$ is the baseline heating demand, and p_0 is the 2020 baseline price.

These parameters directly alter the Net Present Value (NPV) calculation. In the behavioural switching probability formula, the model now utilizes I_i^{behav} and operating costs derived from ($\tilde{p}_{t,i}$). This ensures that even if a heat pump is economically advantageous in a frictionless environment, the combination of high hurdle rates, inattention to subsidies, and lagged price signals may prevent adoption.

Definition of Symbols

i	Representative household group	$\varepsilon_i^{SR,h}$	Long-run heating-price elasticity
t	Year	J	Seasonal performance factor of the heat pump, set to 3
s	Price regime, with <i>pol</i> for the policy path and <i>np</i> for the no-policy counterfactual	r_i	Household-specific hurdle rate in the behavioural scenario
m	Behavioural regime, with <i>R</i> for rational and <i>B</i> for behavioural		
a	Subsidy-information regime, with <i>aware</i> and <i>unaware</i>	T	Replacement horizon, set to 15 years
Y_i	Representative annual household income	v_i	Market heterogeneity parameter
$C_{i,0}$	Baseline annual heating demand	λ	Scaling parameter in the behavioural logistic function for perception delay
$CO_{2,i,0}$	Baseline annual CO2 emissions	g	Baseline gas-price growth rate, set to 0.01
I_0	Gross heat-pump investment cost, set to 22.500€	$q_{i,t}^{(s,m,a)}$	Switching probability before replacement friction is applied
$\sigma_i^{(a)}$	Subsidy rate	$\alpha_{i,t}^{(s,m,a)}$	Annual adoption probability
$I_i^{(a)}$	Net heat-pump investment cost	$S_{i,t}^{(s,m,a)}$	Cumulative heat-pump stock share
m^g	Annual maintenance cost of gas heating, set to 130€	$E_{i,t}^{(s,m,a)}$	Expected annual household energy expenditure
m^{hp}	Annual maintenance cost of the heat pump, set to 240€	$\Delta E_{i,t}^{(m,a)}$	Incremental policy cost
$p_t^{g,s}$	Gas price in year t under regime s	$XS_{i,t}^{(m,a)}$	Expenditure share
p_t^e	Electricity price in year t	$B_{i,t}^{(m,a)}$	Policy burden ratio
κ_t	Carbon price in year t	$\varepsilon_i^{SR,h}$	Short-run heating-price elasticity
φ	Implied gas-related emissions intensity per kilowatt-hour	τ_t	nEHS gas-price surcharge

6.3 Definition of Different Scenarios

Table 4: Definition of modelling scenarios⁸

Scenario	Behavioural frictions	Subsidies	Credit support	Ownership restriction
Baseline carbon pricing	No	No	No	n.a.
Rational adoption	No	Yes	No	n.a.
Behavioural, no subsidy	Yes	No	No	n.a.
Behavioural, with subsidy	Yes	Yes	No	n.a.
Behavioural, income-specific frictions	Yes, income-specific	Yes	No	n.a.
Credit case with ownership restriction	Yes, income-specific	Yes	Yes, credit with frictions	Yes
Credit sensitivity without ownership restriction	Yes, income-specific	Yes	Yes, credit with frictions	No

The table shows the different scenarios that are modelled during the microsimulation. Since the subsidy offered by the BAFA is a compensation measure financed by the nEHS revenue, it is assumed that the subsidy would not be available without the nEHS policy implemented⁹.

6.3.1 Temporal Scope

The microsimulation analyses the period from 2021 to 2025, covering the introductory fixed-price phase of the German nEHS. The year 2020 serves as the pre-policy baseline, while 2025 represents the primary evaluation year, as it captures both the full carbon-price increase and the cumulative effects of delayed technology adoption under behavioural frictions. This temporal framework allows the analysis to distinguish between immediate price effects and medium-term adoption dynamics.

6.4 Credit-Support Extension

The credit extension builds directly on the existing microsimulation framework and therefore retains the same four representative households' income groups, the same nEHS price trajectory, and the same behavioural-friction structure as the baseline model, while adding financing access as an additional policy channel. Conceptually, the KfW supplementary credit is not treated as a direct compensation mechanism for carbon pricing, but rather as a financing

⁸ An extended table including the main purpose of each scenario can be found in the Annex A.

⁹ This is an oversimplified assumption that would not necessarily be true in practice.

instrument that reduces the upfront investment barrier for replacing fossil heating systems with heat pumps.

Methodologically, the extension introduced a cash flow affordability test. For each household archetype and simulation year, annual energy-cost savings from switching to a heat pump are compared with annual loan annuity payments. A heat-pump investment is considered financially self-sustaining if annual operating-cost savings exceed annual loan payments. The financed amount is defined as the residual investment cost after subsidy deduction rather than the full gross investment cost. In the current specification, the gross heat-pump investment cost is assumed to be 22.500€, from which applicable subsidies are deducted before calculating the potential KfW loan amount.

Loan repayments are calculated using a standard annuity formula with a modelling assumption of 2% annual interest rate and a 20-year maturity. The model further incorporates key institutional constraints of the KfW supplementary credit scheme, including the requirement of an existing subsidy approval, programme availability from January 2024 onward, a maximum credit volume of 120.000€ per dwelling, and the 90.000€ income threshold associated with programme 358 (KfW, 2025).

As the underlying microsimulation¹⁰ does not directly observe tenure status, owner-occupier shares are approximated using the 2018 Destatis housing survey (Destatis, 2021) differentiated by monthly household net income. These shares are mapped onto the household income classes through proportional overlap between the survey income brackets and the model income classes.

Table 5: Estimated owner-occupier shares by monthly household income group used in the credit-extension analysis

Income classes	Owner-occupier Share (%)
Less than 1.000€	17.89
1.000 - 1.999€	28.91
2.000 - 2.999€	43.85
More than 3.000€	61.77

¹⁰ The baseline microsimulation does not account for renter-occupier status due to limitations in the available household data. This distinction is only introduced in the credit-extension analysis, where housing tenure must be considered because access to the KfW supplementary credit is restricted to owner-occupiers.

Credit accessibility is modelled separately from financial affordability. Even if a heat-pump investment is economically viable, not all households are assumed to access or utilise the financing instrument. Therefore, the model combines owner-occupier shares with existing imperfect-information parameters in order to approximate realistic programme take-up probabilities across income groups. To reflect different institutional environments, three cases are distinguished: a baseline scenario without credit access, a “credit with frictions” scenario, and a “high -access credit” scenario. This extension allows the analysis to distinguish between the technical feasibility of repaying heat-pump investments through energy-cost savings and the broader distributional question of whether lower-income households can actually access the financing mechanism required for the investment.

Mathematical framework:

Loan annuity formula:

- (1) $s_i = 0.5 + 0.2 * 1(Y_i < 27.000)$
- (2) $Sub_i = I_0 * s_i$
- (3) $L_i = \min(I_0 - Sub_i, 120.000)$

where $I_0 = 22.500$ denotes gross heat – pump investment costs

- (4) $s_t^{nEHS} = 0.201 * \frac{CP_t}{1000}$
- (5) $p_t^{gas,policy} = p_t^{gas,nopolicy} + s_t^{nEHS}$
- (6) $q_{i,t} = \max \left\{ q_{0,i} \left[1 + \varepsilon_i \frac{p_t - p_0}{p_0} \right], 0.05 q_{0,i} \right\}$
- (7) $p_{i,t}^{perc} = (1 - \lambda_i) p_t + \lambda_i p_{t-1}$
- (8) $S_{i,t} = C_{i,t}^{gas,policy} - C_{i,t}^{hp}$
- (9) $N_{i,t} = S_{i,t} - A_i$

Credit-supported investment is considered affordable if:

- (10) $N_{i,t} \geq 0$
- (11) $\frac{S_{i,t}}{A_i}$
- (12) $B_{i,t}^{stay} = C_{i,t}^{gas,policy} - C_{i,t}^{gas,nopolicy}$
- (13) $\Delta B_{i,t} = B_{i,t}^{stay} - B_{i,t}^{switch}$
- (14) $BR_{i,t}^{stay} = \frac{B_{i,t}^{stay}}{Y_i}$
- (15) $BR_{i,t}^{switch} = \frac{B_{i,t}^{switch}}{Y_i}$
- (16) $Access_i = \min\{\theta_i(1 - \iota_i)m_c E_i, \theta_i$

Where θ_i denotes the owner-occupier ceiling ι_i , the inattention share, m_c the credit-access multiplier, and E_i the income-eligibility indicator.

L_i	Residual loan amount after subsidy deduction
A_i	Annual annuity loan payment
r	Loan interest rate
n	Loan repayment horizon
$N_{i,t}$	Net annual cashflow after loan payment
$Access_i$	Household-specific credit accessibility share
θ_i	Owner-occupier ceiling parameter
ι_i	Behavioural inattention share
m_c	Credit-access multiplier
E_i	Income-eligibility indicator

7. Results

The results of the microsimulation reveal the complex interplay between carbon pricing, financial incentives, and household decision-making. By comparing a “rational” benchmark against a “behavioural” scenario, the simulation highlights how behavioural frictions alter technology adoption and household expenditure burdens.

7.1 Baseline Distributional Effects of Carbon Pricing

The introduction of the national emissions trading system (nEHS) carbon price exerts an immediate regressive pressure on German households. In the baseline year 2025, assuming a projected carbon price of 55€/tCO₂, energy expenditure shares and policy burden ratios vary significantly across income groups. In the behavioural scenario, the lowest income class earning under 1.000€ monthly allocates approximately 36.1% of its net income to heating and energy costs. Conversely, the highest income class, earning above 3.000€, spends only 7.5% of its income on these identical services.

The policy burden ratio, which measures the additional energy cost relative to income, indicates this regressive trend. Since lower-income households allocate a substantially larger share of their income to energy consumption, the relative financial pressure remains disproportionately higher for them. Even when subsidies are incorporated into the model, carbon pricing disproportionately impacts households with limited income and smaller financial buffers, demonstrating that it is inherently regressive and imposes the highest relative financial burden on the lowest income groups.

7.2 Behavioural Frictions and Distributional Outcomes

7.2.1 Rational vs. Behavioural scenarios

Comparing rational and behavioural modelling assumptions demonstrates that behavioural frictions substantially amplify the regressive effects of the nEHS over time. Across all scenarios, policy burden ratios increase continuously between 2021 and 2025 due to rising carbon prices. However, behavioural scenarios consistently yield higher relative burdens than rational benchmarks, with the gap between low- and high-income households widening steadily. For households earning less than 1.000€ per month, behavioural frictions, such as limited financial flexibility, investment barriers, and delayed adaptation, weaken the capacity to respond efficiently to price incentives. While subsidies reduce the overall burden in both modelling approaches, they fail to fully compensate for these behavioural constraints, leaving vulnerable households significantly more exposed to rising carbon costs.

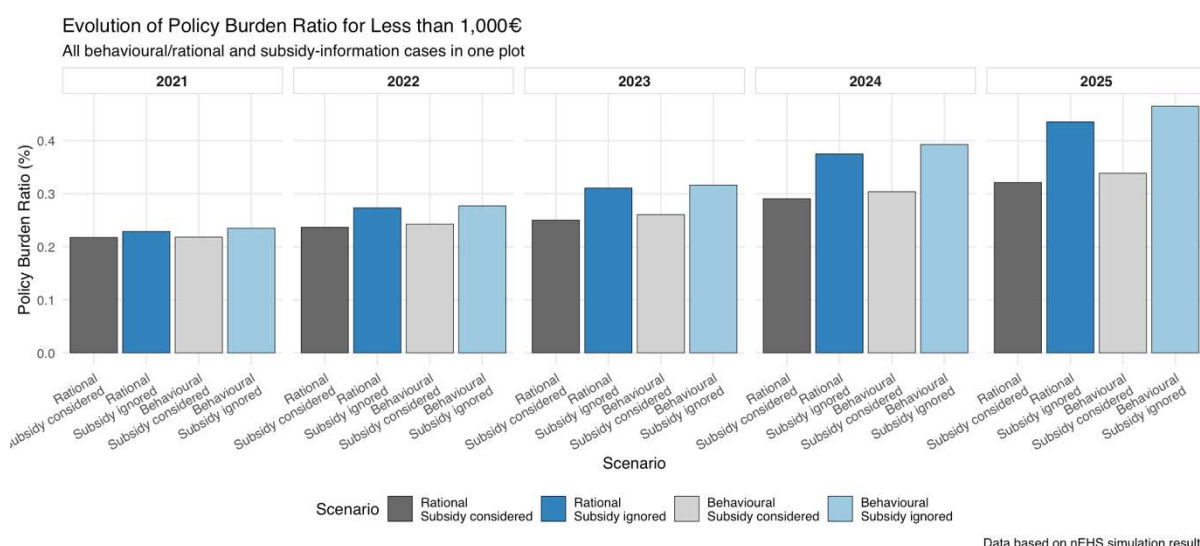


Figure 1: Evolution of policy burden Ratio for income classes "Less than 1.000€"

The deviations between rational and behavioural outcomes become less pronounced with increasing income. Higher income households experience systematically lower burden ratios and smaller deviations between modelling assumptions, indicating greater financial resilience and adaptive capacity. Middle-income households¹¹ exhibit similar structural patterns, but the overall burden declines systematically as income rises.

¹¹ The results for the middle-income households can be found in Annex B.

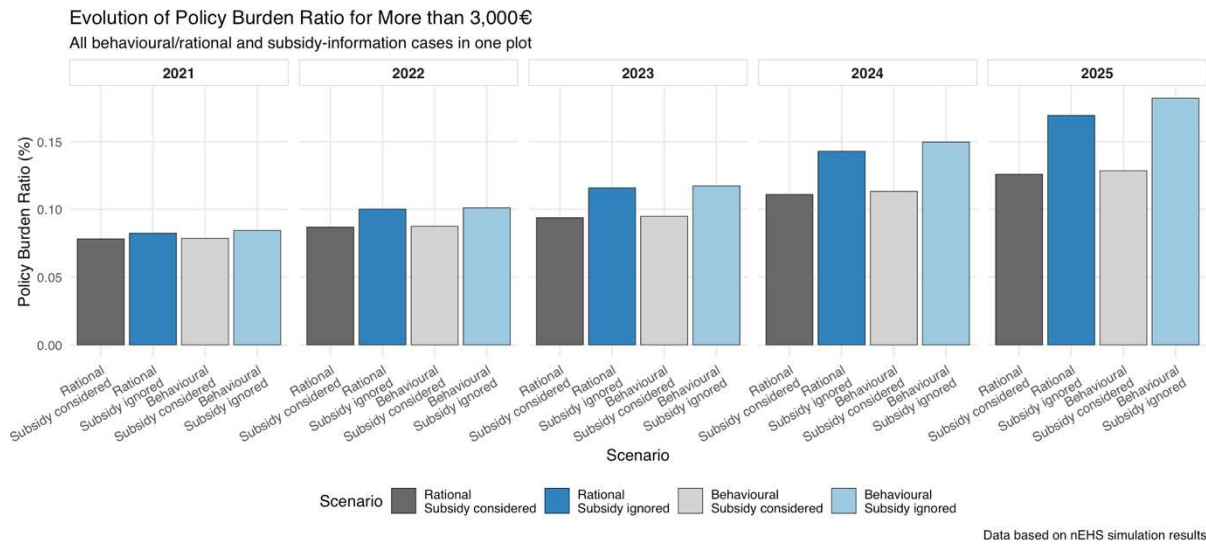


Figure 2: Evolution of policy burden ratio for income-class "More than 3.000€"

7.2.2 Adoption Gap and Unequal Adaptive Capacity

The steering effect of carbon pricing depends heavily on a household's ability to transition to low-carbon technologies, yet the simulation reveals a stark adoption gap across income levels. Under rational assumptions, cost-optimising incentives drive adoption rates to converge across income groups by 2025. In this rational benchmark, the lowest income group reaches a heat pump stock share of 28.77%, closely matching the 27.62% achieved by the highest income group. From a purely cost-optimising perspective, low-income households possess strong incentives to switch technologies to reduce long-term heating expenditures.

Once behavioural frictions are introduced, a substantial implementation gap emerges. By 2025, adoption among households below 1.000€ monthly income reaches only 22.05% in the behavioural scenario, compared to 29.17% among the highest income group. This indicates that financial incentives alone are insufficient to ensure equal adoption outcomes once behavioural barriers such as capital constraints, risk aversion, and limited adaptive capacity are incorporated into the model. Financially constrained households adjust more slowly to price signals, which causes them to remain dependent on fossil heating systems for longer periods. Consequently, behavioural frictions reinforce unequal exposure to transition costs, as low-income households continue to face rising carbon costs without being able to realise the long-term operating savings achieved by wealthier groups.

Table 6: Heat Pump Stock Evolution by Income Class (2025)¹²

Income Class	Rational	Behavioural
Less than 1.000€	28.77%	22.05%
More than 3.000€	27.62%%	29.17%

7.3 Revenue Recycling and Support Measures

This section examines whether support measures can reduce the unequal burdens associated with carbon pricing. Specifically, the effects of investment subsidies and credit support on adoption behaviour and distributional outcomes are analysed.

7.3.1 Subsidy Effects

Subsidies are a vital mechanism for reducing adoption gaps, though they do not eliminate them entirely. In the behavioural scenario where subsidies are ignored, heat pump adoption among households earning less than 1.000€ per month remains extremely low at approximately 1.5%. When subsidies are included, adoption in this lowest income tier increases substantially to 22.05%. Despite this improvement, low-income households continue to lag behind wealthier groups, who reach 29.17% adoption, indicating that upfront investment costs remain a major barrier for capital-constrained households.

7.3.2 Credit Extension

Evaluating supplementary financial instruments shows that while representative household income classes can theoretically service a KfW supplementary credit through annual energy cost savings, effective program accessibility is highly unequal. The primary impediment to widespread policy participation is the owner-occupier constraint embedded in the financing mechanism. Removing the ownership restriction significantly increases program accessibility across all income brackets, but its application disproportionately harms lower-income groups.

In the “credit with frictions” scenario, accessibility for the lowest income group falls from 60.00% without the ownership constraint to just 10.79% when the ownership constraint is applied, representing a reduction of 49.21 percentage points. The 1.000-1.999€ cohort experiences a nearly identical 49.76 percentage-point drop. In the “credit high access” scenario, the same pattern persists: accessibility in the lowest income groups decreases from 84.00% without the ownership restriction to 15.10% with the restriction applied, representing a steep

¹² In the microsimulation, it was assumed that the heat-pump stock before the application of the policy was 0. Detailed results for more years and income classes can be found in Annex A.

decline of 68.90%. While higher income groups also see reductions under the owner-occupier constraint, the magnitude of the effect becomes gradually smaller as income rises, confirming that the owner-occupier structure remains the primary barrier preventing low-income households from accessing support frameworks.

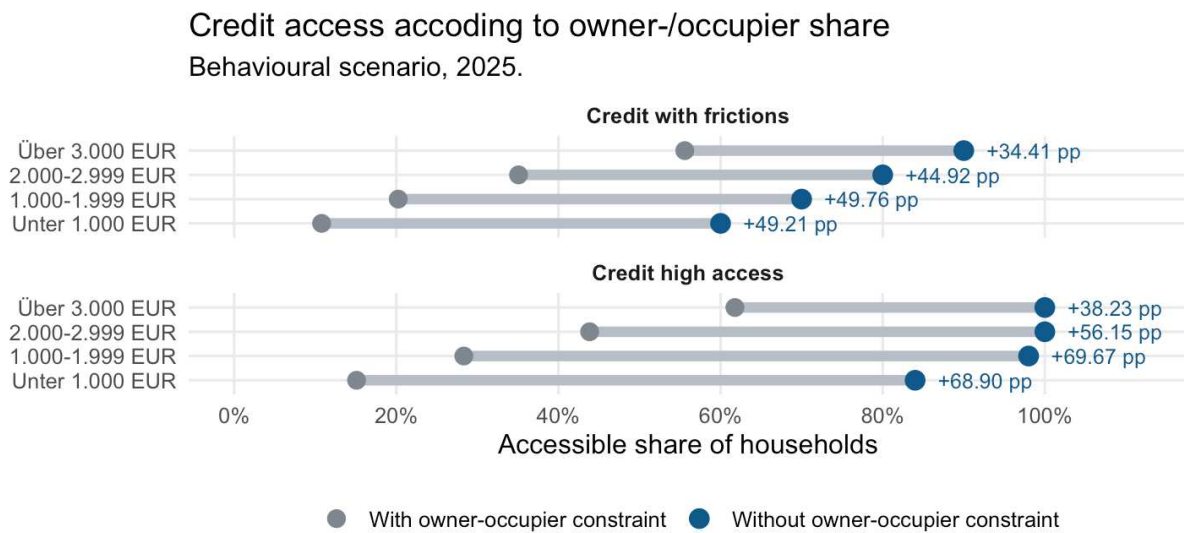


Figure 3: Credit access according to owner-occupier share

7.4 Sensitivity Analysis

The variation of the underlying behavioural parameter specifications serves to assess the robustness of the model, thereby highlighting how individual frictions alter technology diffusion, household expenditures, and the distributional impacts of the nEHS across income groups.

7.4.1 Hurdle Rates

Hurdle rates influence the adoption of low-carbon technologies by shaping households' investment decisions. Higher hurdle rates, reflecting stronger behavioural frictions resulting in greater perceived investment barriers, are associated with lower adoption probabilities and slower heat pump diffusion, whereas lower hurdle rates facilitate adoption. Higher hurdle rates amplify perceived upfront costs, leaving more households dependent on fossil heating systems and resulting in slightly higher policy burden ratios over time. Conversely, lower hurdle rates accelerate technology diffusion and contribute to modest reductions in energy burdens. The resulting shifts in policy burden ratios demonstrate that lower-income households continue to face substantially higher relative burdens across all scenarios, reflecting persistent affordability challenges.

Table 7: Policy burden ratio by income class and hurdle rate scenario in 2025

Income Class	original scenario	higher r_i I	higher r_i II	lower r_i I	lower r_i II
Less than 1.000€	0.42	0.43	0.44	0.41	0.40
1.000-1.999€	0.25	0.25	0.26	0.24	0.24
2.000 - 2.999€	0.15	0.15	0.16	0.14	0.14
More than 3.000€	0.08	0.09	0.09	0.08	0.08

7.4.2 Market Heterogeneity

Broader behavioural diversity across the market alters policy effectiveness by expanding the pool of households that respond positively to subsidies and projected operational savings. Higher heterogeneity scenarios generally increase heat pump adoption probabilities and cumulative technology diffusion, which moderately lowers average heating costs and expenditure burdens. However, these benefits are unevenly distributed across income groups, as high-income households exhibit the strongest responsiveness to behavioural incentives and leverage their financial position to adopt heat pumps early. For low-income groups, adoption changes remain comparatively limited, implying that behavioural diversity alone is insufficient to fully override persistent liquidity, affordability, and capital constraints.

Table 8: Policy burden ratio by income class; market heterogeneity and behavioural scenarios applied in 2025

Income Class	original scenario	higher v I	Higher v II	lower v I	lower v II
Less than 1.000€	0.339	0.326	0.319	0.360	0.388
1.000-1.999€	0.273	0.274	0.275	0.272	0.271
2.000 - 2.999€	0.170	0.170	0.170	0.171	0.173
More than 3.000€	0.128	0.129	0.129	0.128	0.128

7.4.3 Imperfect Information

Incorporating informational and cognitive barriers, by varying price elasticity, inattention rates, and adjustment delays, substantially reduced heat pump adoption among lower-income households while higher income households remain comparatively unaffected. Vulnerable households adjust more slowly to policy signals due to these informational frictions, which

limit their responsiveness to carbon pricing and subsidy incentives. This slower technology diffusion prolongs their dependence on fossil-based heating technologies and significantly increases their exposure to rising carbon costs, resulting in more regressive policy outcomes.

Table 9: Policy Burden Ratio in 2025 (% of income)

Income class	Behavioural Scenario	Imperfect Information Scenario
Less than 1.000€	0.34	0.90
1.000-1.999€	0.27	0.43
2.000 - 2.999€	0.17	0.22
More than 3.000€	0.13	0.11

While isolated informational frictions, such as inattention only or adjustment delays only, raise the burden ratio for the lowest income class moderately to approximately 0.40%-0.43%, compounding their barriers in the full imperfect-information scenario spikes the policy burden ratio to 0.90%.

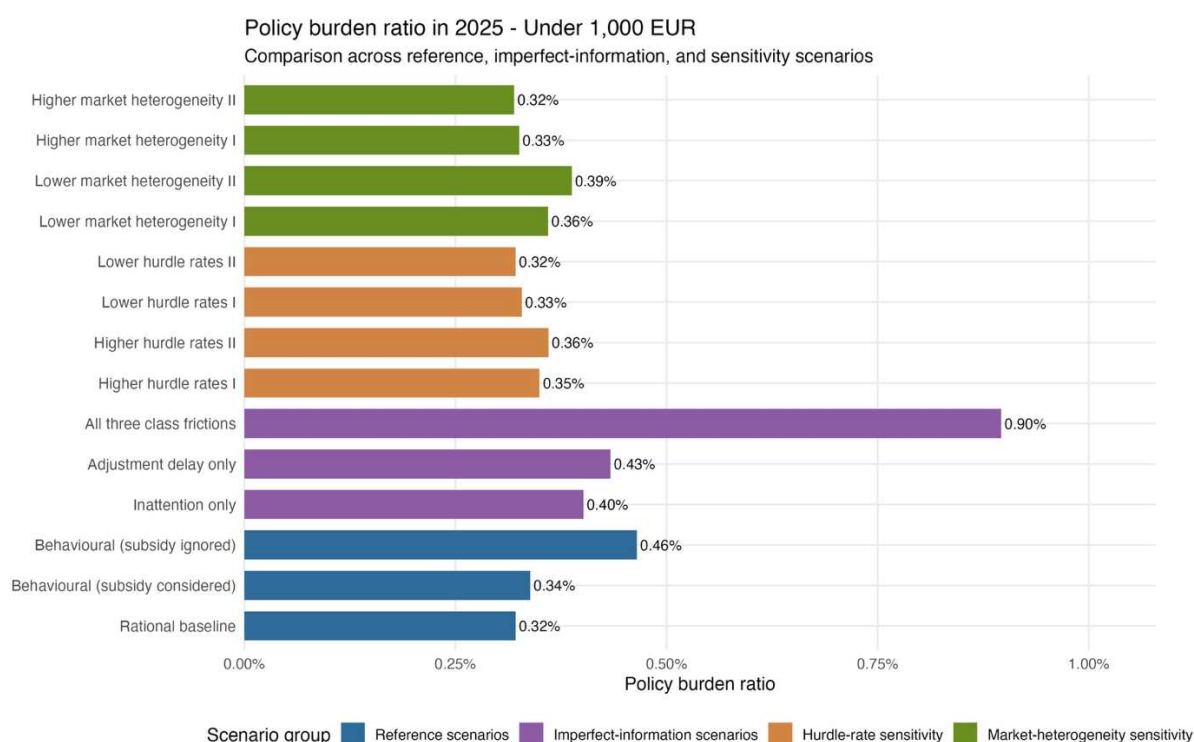


Figure 4: Policy burden ratio in 2025 for income class "Less than 1.000€"

Relative to the standard behavioural reference scenario with subsidies considered (0.34%), lower hurdle rates and higher market heterogeneity slightly reduce the policy burden ratio to approximately 0.32%-0.33% due to faster adoption. In contrast, higher hurdle rates increase

the burden ratio to around 0.35%, indicating that stronger investment barriers delay technology adoption and prolong exposure to carbon pricing. For the middle- and high-income cohorts, the overall sensitivity to these parameters declines systematically¹³, highlighting their greater baseline adaptive capacity.

7.5 Synthesis of Policy Interaction and Distributional Outcomes

The simulation results collectively demonstrate that the long-term distributional equity of the nEHS is determined by a complex interplay of price signals, behavioural barriers, and institutional structures. While carbon pricing inherently exerts a regressive pressure that disproportionately affects low-income households, the introduction of behavioural frictions amplifies these inequalities by creating a distinct technology adoption gap. Financially constrained households are frequently prevented from transitioning to low-carbon technologies due to capital limitations, risk aversion, and high informational barriers, leaving them in fossil-fuel dependence while wealthier households quickly capitalise on long-term operational savings.

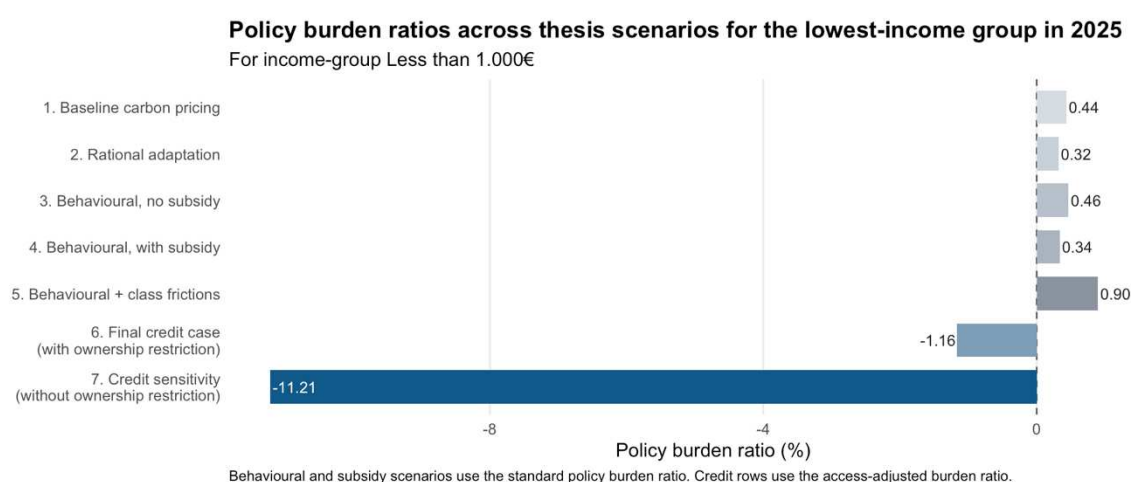


Figure 5: Comparison of all policy burden ratios in 2025

A comparison of the simulated scenarios highlights both the potential and the structural limitations of current revenue recycling mechanisms. Direct technology subsidies prove highly effective at stimulating heat pump adoption among vulnerable groups, significantly lowering policy burden ratios relative to an unassisted behavioural scenario. Moreover, the introduction of credit programs expands financial feasibility, generating substantial net economic benefits through long-term energy cost savings.

¹³ The exact results can be found in Annex B.

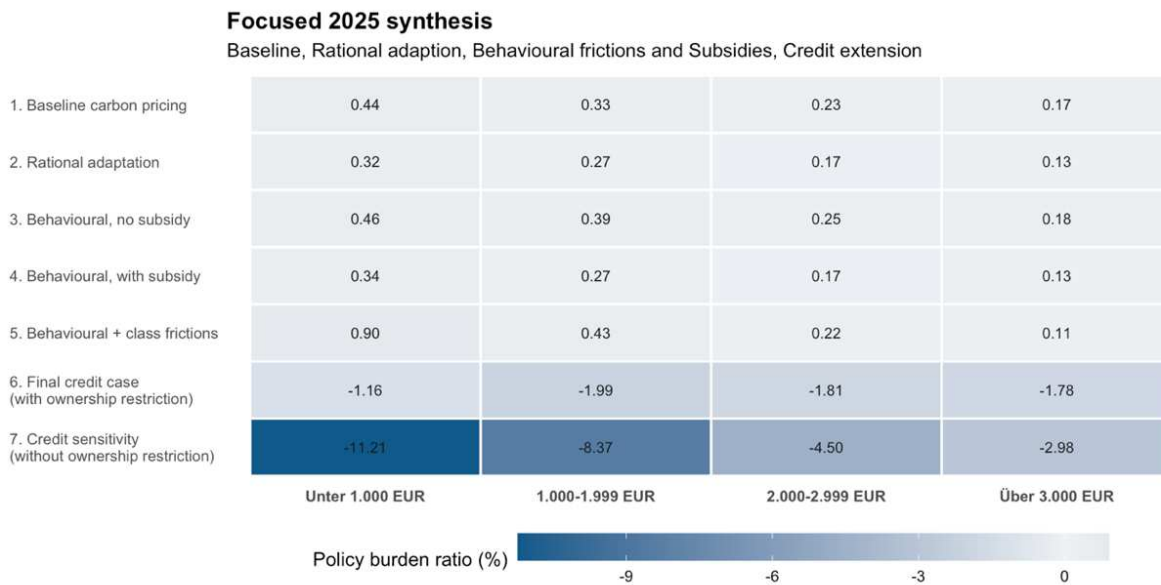


Figure 6: Policy burden ratio across all analysed scenarios

However, financial incentives alone are structurally insufficient to fully eliminate the regressive outcomes of the energy transition. The simulation reveals that institutional constraints override purely economic incentives.

Specifically, the owner-occupier restrictions embedded in credit financing mechanisms severely limit actual programme accessibility for low-income cohorts. When this tenure constraint is enforced, lower-income groups are largely excluded from credit utilisation, causing their net financial relief to lag far behind wealthier households. Conversely, isolating and removing this ownership friction yields the most substantial reduction in net policy burdens for the lowest income bracket by unlocking unhindered technology deployment. Ultimately, while subsidies and credit extensions are vital instruments for mitigating transition costs, the tenant-landlord dilemma and the prevailing property-ownership structure remain the primary structural barriers to achieving an equitable and behaviourally resilient decarbonisation pathway.

8. Limitations

While the microsimulation provides valuable insights into the distributional effects of carbon pricing and behavioural frictions within the German nEHS, several limitations should be acknowledged. As with all simulation-based analyses, the results depend on assumptions regarding household behaviour, technology adoption, and future policy developments.

Consequently, the findings should be interpreted as indicative estimates of distributional tendencies rather than precise forecasts of future outcomes.

A first limitation concerns the aggregation of households into representative income groups. Although this approach enables a transparent comparison of distributional effects across income distribution, it cannot fully capture heterogeneity within income categories. In particular, households experiencing energy poverty or constrained financial circumstances may face substantially greater adaptation barriers than reflected by group averages.

A second limitation relates to the representation of financial resources. The analysis primarily relies on household income as an indicator of economic capacity, while household wealth, savings, and other forms of private capital are not explicitly modelled. However, investment decisions regarding heating-system replacement depend not only on current income but also on accumulated assets and access to liquidity. Since wealth inequality in Germany exceeds income inequality (Bartels & Schroeder, 2020), the model may overestimate the ability of some lower-income households to finance residual investment costs, even with available subsidies or credit schemes.

Additionally, the microsimulation abstracts from detailed building characteristics and renovation requirements. The economic viability of heat pumps depends strongly on factors such as building age, insulation quality, and existing heating infrastructure. In practice, many households may require complementary renovation measures before adopting low-carbon heating technologies. These additional costs are not explicitly represented in the model and may therefore lead to an overestimation of adoption probabilities.

Another limitation concerns the parameterisation of behavioural frictions. Behavioural responses are represented through hurdle rates and associated adoption assumptions derived from the existing literature. While this approach allows behavioural factors to be incorporated systematically into the microsimulation framework, actual household decision-making processes remain highly heterogeneous and difficult to observe directly. Alternative behavioural assumptions could therefore lead to different adoption trajectories and policy burden outcomes.

Finally, the analysis is subject to uncertainty regarding future policy developments, technology costs, and energy prices. The simulations are based on current policy frameworks and available projections, which may change considerably over the coming decades. Consequently, the results should be interpreted as illustrating the mechanisms through which behavioural frictions

and financial constraints affect distributional outcomes rather than predicting future adoption rates or policy burdens with certainty.

Despite these limitations, the microsimulation offers a useful framework for analysing how behavioural frictions influence the distributional consequences of carbon pricing. Future research could build on this work by incorporating household-level microdata, explicit modelling of housing tenure and landlord-tenant interactions, more detailed building characteristics, and empirical validation of behavioural parameters using observed adoption behaviour.

9. Discussion

The following discussion interprets the empirical results of this thesis in light of the two core research questions: whether accounting for behavioural frictions reveals stronger regressive effects of the German nEHS on low-income households, and the extent to which these frictions alter the estimated distributional outcomes within a microsimulation framework.

9.1 Behavioural Frictions Amplify Regressive Carbon Pricing Effects

To answer the first research question directly: accounting for behavioural frictions reveals substantially stronger regressive effects of carbon pricing on German households than conventional rational-choice frameworks suggest. Under standard neoclassical rational assumptions, households are modelled as frictionless optimisers who respond relatively quickly and elastically to the carbon price signals imposed by the nEHS by cutting fossil fuel consumption and investing in low-carbon technologies like air-to-water heat pumps. However, once realistic behavioural frictions are integrated into the microsimulation framework, this adoption process slows down considerably.

This friction-induced inertia does not affect the population uniformly. Rather, it introduces a substantial distributional skew. Lower-income households are disproportionately affected because they face multiple reinforcing barriers. Liquidity constraints prevent them from absorbing high upfront capital costs, and they also face higher perceived investment risks associated with unfamiliar renewable technologies. This situation is further complicated by bounded rationality and information overload resulting from overly complex policy and subsidy designs. There is also a persistent status quo and a tendency to avoid change, even when long-term economic indicators are favourable.

The convergence of these barriers' places vulnerable demographics under a "double burden": they are hit immediately with rising fossil-based heating costs via the upstream carbon price, yet they lack the financial and cognitive capacity to invest in the very technologies required to mitigate those costs. This empirical finding is highly consistent with behavioural economics literature on the energy efficiency gap. It validates the premise that households frequently fail to execute economically beneficial investments despite significantly positive net present values, demonstrating that a price signal alone cannot overcome existing cognitive and structural scarcity.

9.2 Unequal Adaptive Capacity as the Central Distributional Mechanism

The core contribution of this thesis lies in shifting analytical focus away from the price shock itself toward the underlying disparities in households' responsiveness. The simulation results suggest that the regressive outcomes of the nEHS are driven less by the carbon price in isolation and more by unequal adaptive capacity across the income distribution.

While carbon pricing creates a uniform fiscal incentive to decarbonise, a household's actual ability to respond is entirely contingent upon its endowment of financial, structural, and behavioural resources. The structural divergence between income groups clearly highlights this mechanism. Higher income households maintain a consistently high probability of adoption and experience rapid technology diffusion, allowing their long-term policy burden ratio to decline over time as they successfully decouple from fossil fuels. Conversely, lower-income households experience a disproportionately low probability of adoption and stagnant technology diffusion, leaving them with an escalating long-term policy burden ratio as they remain dependent into fossil-based systems.

These findings indicate that carbon pricing and technological adaptation cannot be evaluated as separate policy silos. Rather, the distributional consequences of carbon pricing emerge endogenously, with the capacity to adapt. Affluent households leverage their liquidity to escape the carbon tax by rapidly adopting heat pumps, while lower-income households remain structurally reliant into carbon liabilities.

9.3 The Role of Subsidies

When evaluating the simulated subsidy scenarios modelled after the "Bundesförderung für effiziente Gebäude (BEG)" framework, the limits of purely financial interventions become evident. On the positive side, targeted subsidies substantially improve heat-pump adoption rates among lower-income groups. Adoption probabilities increase severalfold relative to the

friction-heavy behavioural baseline, which subsequently drives as a significant improvement in policy burden ratios for participating households.

However, despite these generous capital injections, substantial distributional gaps remain. Lower-income households continue to lag significantly behind higher income groups in aggregate technology deployment. Behavioural barriers, bounded rationality, and deep financing constraints persist even when substantial subsidies are available on paper.

This friction underpins a critical interpretation: investment support addresses affordability, but it does not fully solve accessibility. Coping with complex, stackable grant applications and finding the means to pre-finance remaining costs means that financial aid alone is insufficient if the accompanying behavioural and institutional barriers are left unaddressed.

9.4 Credit Support and the Importance of Housing Tenure

The integration of the KfW credit-extension module provides a nuanced policy insight: credit expansion is not a universal solution for the energy transition. Instead, the owner-occupier requirement emerges as the dominant structural barrier to programme accessibility.

The simulation highlights a stark divergence based on legal eligibility criteria. Without ownership restrictions, credit accessibility appears high across all income groups, including low-income households. However, once realistic owner-occupier conditions are imposed, access to credit heavily decreases for the lowest income groups.

This indicates that many vulnerable households are excluded from the transition, not because they lack the financial capacity to service a low-interest loan, but because they fail to satisfy the baseline institutional requirements of the program. This finding broadens the academic discussion from narrow income inequality toward deeper structural housing inequalities. Financial and debt-based instruments may successfully improve participation among low- and middle-income homeowners, but they are less effective in addressing distributional concerns or alter adaptation probabilities among tenants.

9.5 Policy Implications

Translating these microsimulation findings into actionable policy recommendations yields three distinct imperatives for designing a socially just transition. First, policymakers should pair carbon pricing with adaptive capacity measures rather than implementing it in isolation. Carbon pricing needs to be paired with structural measures that actively enhance households' adaptive capacity, which means that states must deploy non-monetary interventions, such as

localised advisory programmes, simplify application procedures, and targeted informational campaigns, to lower cognitive frictions alongside direct financial investment support.

Second, policymakers should implement progressively targeted support that focuses intensely on low-income cohorts. As confirmed by the baseline simulations, universal carbon pricing without progressive compensation structures risks triggering regressive impacts and deepening energy poverty.

Third, design frameworks need to prioritise access design over nominal subsidy levels. The credit-extension module demonstrates that institutional access barriers matter just as much as nominal subsidy rates, with features like ownership requirements heavily dictating overall participation. Consequently, effective climate policy requires not only sufficient financial backing but also equitable access to support mechanisms, ensuring that tenants and vulnerable groups are not institutionally barred from adapting.

9.6 Future Research

While this thesis refines our understanding of friction-aware policy design, several limitations must be acknowledged. The microsimulation relies on representative household archetypes rather than individual, highly granular household trajectories. Furthermore, behavioural parameters, such as implicit discount rates and status quo biases, are calibrated from existing literature and assumptions rather than primary empirical observations. Complex housing market dynamics, split incentives, and landlord-tenant interactions are also structurally simplified in the current model framework, while long-term technology costs and energy price paths remain highly uncertain.

In order to address these limitations, future research should prioritise several pathways. Scholars should focus on integrating richer, household-level behavioural modelling using empirical microdata, alongside explicitly modelling rental markets and the landlord-tenant dilemma. Additionally, future models would benefit from accounting for dynamic feedback loops between technology adoption rates and manufacturing cost reductions. Finally, conducting empirical validation of these behavioural parameters using observed heating transition data as the nEHS matures will be vital to refining these predictive frameworks.

10. Conclusion

This thesis contributes to the growing literature on the distributional effects of carbon pricing by incorporating behavioural frictions into a household-level microsimulation. By integrating behavioural economics with empirical micro-level data tailored to different income classes and the German National Emissions Trading System (nEHS), this study quantified how behavioural, institutional, and financial barriers alter the distribution of climate policy burdens across heterogeneous German households.

This thesis finds that accounting for behavioural frictions reveals stronger regressive effects of carbon pricing on low-income households. Behavioural barriers such as liquidity constraints, imperfect information, and status quo bias limit households' ability to adapt to rising carbon prices, thereby increasing their relative policy burden. Incorporating behavioural frictions into the microsimulation framework substantially changes the estimated distributional effects of carbon pricing. Compared to rational-choice assumptions, behavioural scenarios result in lower adoption rates of low-carbon technologies, higher policy burden ratios, and greater disparities between income groups. This demonstrates that model assumptions regarding household behaviour are not merely technical choices but can substantially influence estimated policy outcomes.

The findings suggest that a socially just transition requires more than just carbon pricing. Although carbon pricing is an important mechanism for reducing emissions, its effectiveness and fairness depend on households' ability to respond to price signals. Therefore, policymakers should complement carbon pricing with measures that strengthen adaptive capacity, reduce informational and financial barriers, and improve access to low-carbon technologies. The findings further suggest that the effectiveness of support policies depends not only on the amount of financial assistance provided, but also on households' ability to access and utilise these measures. Particular attention should therefore be given to low-income households and renters, who often face structural constraints that limit their ability to participate in the transition. More broadly, the findings suggest that the distributional consequences of climate policy depend not only on the design of carbon pricing itself, but also on households' ability to respond to it. Accounting for behavioural frictions is therefore essential for evaluating both the effectiveness and fairness of climate policy.

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References

- Ackermann, I., & Radulescu, D. (2024). Unveiling the Energy Price Tag – Assessing the Degree of Regressivity of Household Energy Expenditures Among European Countries. *Cesifo Working Papers*(11390).
- Andersen, P. M. S. (2010). Europe's experience with carbon-energy taxation. *S.A.P.I.EN.S. Surveys and Perspectives Integrating Environment and Society*, (3.2). <https://journals.openedition.org/sapiens/1072>
- Andersson, J., & Atkinson, G. (2020). The distributional effects of a carbon tax: The role of income inequality. https://doi.org/10.1163/9789004322714_cclc_2020-0148-0748
- Antosiewicz, M., Fuentes, J. R., Lewandowski, P., & Witajewski-Baltvilks, J. (2022). Distributional effects of emission pricing in a carbon-intensive economy: The case of Poland. *Energy Policy*, 160, 112678. <https://doi.org/10.1016/j.enpol.2021.112678>
- Apeti, A. E., Bambe, B. W. W., Edoh, E. D., & Ly, A. (2025). Wealth inequality and carbon inequality. *Ecological Economics*, 227, 108406. <https://doi.org/10.1016/j.ecolecon.2024.108406>
- Ascari, G., Colciago, A., Haber, T., & Wöhrmüller, S. (2025). Inequality Along the European Green Transition. *The Economic Journal*, ueaf130. <https://doi.org/10.1093/ej/ueaf130>
- Asuene. (2025, June 25). Comparing Carbon Tax and Emissions Trading Systems (ETS): Regulatory Divergence and Convergence | Blog | ASUENE | The enterprise climate cloud platform | Carbon Calculation Decarbonization SaaS. ASUENE. <https://asuene.com/us/blog/comparing-carbon-tax-and-emissions-trading-systems-ets-regulatory-divergence-and-convergence>
- Austin, D. (2012). Addressing Market Barriers to Energy Efficiency in Buildings.
- Avelino, F., Wijsman, K., Van Steenberghe, F., Jhagroe, S., Wittmayer, J., Akerboom, S., Bogner, K., Jansen, E. F., Frantzeskaki, N., & Kalfagianni, A. (2024). Just

Sustainability Transitions: Politics, Power, and Prefiguration in Transformative Change
Toward Justice and Sustainability. *Annual Review of Environment and Resources*,
49(1), 519–547. <https://doi.org/10.1146/annurev-environ-112321-081722>

Bach, S., Hamburg, M., & Deutsches Institut für Wirtschaftsforschung, DIW Berlin. (2025).
Verteilungswirkungen des nationalen Emissionshandels auf private Haushalte (Climate
Change No. 72). Umweltbundesamt.
<https://doi.org/https://doi.org/10.60810/openumwelt-8105>

Bach, S., Hermann, B., Michelle, H., & Niklas, I. (2019). DIW Berlin: Ecological Tax Revenue
Still Yields Lower Pension Contributions and Higher Pensions Today [Text]. DIW
Berlin.
[https://www.diw.de/en/diw_01.c.617907.en/nachrichten/ecological_tax_revenue_stil...
d_higher_pensions_today.html](https://www.diw.de/en/diw_01.c.617907.en/nachrichten/ecological_tax_revenue_stil...d_higher_pensions_today.html)

BAFA, B. für W. und A. (2024). Allgemeines Merkblatt zum Zusatzantrag für den
Einkommensbonus.
[https://www.bafa.de/SharedDocs/Downloads/DE/Energie/beg_merkblatt_allgemein_z
usatzantrag.html](https://www.bafa.de/SharedDocs/Downloads/DE/Energie/beg_merkblatt_allgemein_zusatzantrag.html)

BAFA, B. für W. und A. (2025, May 20). Informationsblatt CO₂-Faktoren. Bundesamt für
Wirtschaft und Ausfuhrkontrolle.
[https://www.bafa.de/SharedDocs/Downloads/DE/Energie/eev_infoblatt_co2_faktoren
_2025.html](https://www.bafa.de/SharedDocs/Downloads/DE/Energie/eev_infoblatt_co2_faktoren_2025.html)

Baranzini, A., van den Bergh, J. C. J. M., Carattini, S., Howarth, R. B., Padilla, E., & Roca, J.
(2017). Carbon pricing in climate policy: Seven reasons, complementary instruments,
and political economy considerations. *WIREs Climate Change*, 8(4), e462.
<https://doi.org/10.1002/wcc.462>

- Barrez, J. (2024). Public acceptability of carbon pricing: Unravelling the impact of revenue recycling. *Climate Policy*, 24(10), 1323–1345.
<https://doi.org/10.1080/14693062.2024.2376747>
- Barrez, J., & Bachus, K. (2023). Public Acceptability of Carbon Pricing. E4BEL Working Paper. <http://hiva.kuleuven.be>
- Bartels, C., & Schroeder, C. (2020). Income, consumption and wealth inequality in Germany: Three concepts, three stories? *Forum for a New Economy: Basic Papers*, 02/2020.
- Bartholdsen, H.-K., Eidens, A., Löffler, K., Seehaus, F., Wejda, F., Burandt, T., Oei, P.-Y., Kemfert, C., & Hirschhausen, C. von. (2019). Pathways for Germany's Low-Carbon Energy Transformation Towards 2050. *Energies*, 12(15), 2988.
<https://doi.org/10.3390/en12152988>
- Batini, N., Parry, I., & Wingender, P. (2020). Climate Mitigation Policy in Denmark: A Prototype for Other Countries (SSRN Scholarly Paper No. 3758068). Social Science Research Network.
<https://www.imf.org/en/publications/wp/issues/2020/11/12/climate-mitigation-policy-in-denmark-a-prototype-for-other-countries-49882>
- Battistini, N., Bobasu, A., & Gareis, J. (2023). Who foots the bill? The uneven impact of the recent energy price shock. https://www.ecb.europa.eu/press/economic-bulletin/focus/2023/html/ecb.ebbox202302_05~d811cd64f4.en.html
- Bauermann, K. (2016). German Energiewende and the heating market – Impact and limits of policy. *Energy Policy*, 94, 235–246. <https://doi.org/10.1016/j.enpol.2016.03.041>
- BDEW. (2026, December 1). BDEW - Strompreisanalyse Januar 2026. https://www.bdew.de/media/documents/BDEW_Strompreisanalyse_012026_1.pdf

- Beiser-McGrath, L. F., & Bernauer, T. (2019). Could revenue recycling make effective carbon taxation politically feasible? *Science Advances*, 5(9), eaax3323. <https://doi.org/10.1126/sciadv.aax3323>
- Bennett, N. J., Blythe, J., Cisneros-Montemayor, A. M., Singh, G. G., & Sumaila, U. R. (2019). Just Transformations to Sustainability. *Sustainability*, 11(14), 3881. <https://doi.org/10.3390/su11143881>
- Berry, A. (2019). The distributional effects of a carbon tax and its impact on fuel poverty: A microsimulation study in the French context. *Energy Policy*, 124, 81–94. <https://doi.org/10.1016/j.enpol.2018.09.021>
- Biggs, R., Schlüter, M., & Schoon, M. L. (2015). *Principles for Building Resilience*. Cambridge University Press. <https://www.cambridge.org/universitypress/subjects/life-sciences/natural-resource-management-agriculture-horticulture-and/principles-building-resilience-sustaining-ecosystem-services-social-ecological-systems>
- Blascha, J., & Daminatob, C. (2020). Behavioral Anomalies and Energy-related Individual Choices: The Role of Status-quo Bias. <https://journals.sagepub.com/doi/epdf/10.5547/01956574.41.6.jbla>
- Bloess, A. (2019). Impacts of heat sector transformation on Germany's power system through increased use of power-to-heat. *Applied Energy*, 239, 560–580. <https://doi.org/10.1016/j.apenergy.2019.01.101>
- BMVJ. (2026). BEHG - Gesetz über einen nationalen Zertifikatehandel für Brennstoffemissionen. Bundesministerium für Justiz und für Verbraucherschutz. Gesetze Im Internet. <https://www.gesetze-im-internet.de/behg/BJNR272800019.html>
- Boyce, J. K. (2018). Carbon Pricing: Effectiveness and Equity. *Ecological Economics*, 150, 52–61. <https://doi.org/10.1016/j.ecolecon.2018.03.030>

- Briganti, P., Metallo, C., Pagliuca, M. M., & Varriale, L. (2023). Exploring Citizens' Behavior to Promote Environmental Sustainability: The Role of Information Overload and Urban Sustainable Policies. *Sustainability*, 15(5), 4272. <https://doi.org/10.3390/su15054272>
- Brzezinski, M., & Kaczan, M. (2025). Carbon taxes in Europe do not hurt the poor: Evidence from existing taxation schemes. *Ecological Economics*, 233, 108585. <https://doi.org/10.1016/j.ecolecon.2025.108585>
- Burger, A., Lünenbürger, B., Tews, K., Weiß, J., & Zschüttig, H. (2022). CO2-Bepreisung im Verkehrs- und Gebäudebereich sozialverträglich gestalten.
- Burret, D. H. (2024). Vergleich der europäischen und nationalen Energie- und Klimaziele und methodische Erläuterungen.
- Calel, R., & Dechezleprêtre, A. (2016). Environmental policy and directed technological change: Evidence from the european carbon market. *Review of Economics and Statistics*, 98(1), 173–191. https://doi.org/10.1162/REST_a_00470
- Callan, T., Lyons, S., Scott, S., Tol, R. S. J., & Verde, S. (2009). The distributional implications of a carbon tax in Ireland. *Energy Policy*, 37(2), 407–412. <https://doi.org/10.1016/j.enpol.2008.08.034>
- Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., ... Ha, M. (with Lee, H.). (2023). IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. (P. Arias, M. Bustamante, I. Elgizouli, G. Flato, M. Howden, C. Méndez-Vallejo, J. J. Pereira, R. Pichs-Madruga, S. K. Rose, Y. Saheb, R. Sánchez Rodríguez, D. Ürge-Vorsatz, C. Xiao, N. Yassaa, J. Romero, J. Kim,

- E. F. Haites, Y. Jung, R. Stavins, ... C. Péan, Eds.; First). Intergovernmental Panel on Climate Change (IPCC). <https://doi.org/10.59327/IPCC/AR6-9789291691647>
- Canzler, W., & Wittowsky, D. (2016). The impact of Germany's Energiewende on the transport sector – Unsolved problems and conflicts. *Utilities Policy*, 41, 246–251. <https://doi.org/10.1016/j.jup.2016.02.011>
- Caron, J., Cole, J., Goettle, R., Onda, C., Mcfarland, J., & Woollacott, J. (2018). Distributional implications of a national co2 tax in the u.s. across income classes and regions: A multi-model overview. *Climate Change Economics*, 09(01), 1840004. <https://doi.org/10.1142/S2010007818400043>
- Cigna, L., Fischer, T., Abuannab, E. H., Heins, E., & Rathgeb, P. (2023). Varieties of Just Transition? Eco-Social Policy Approaches at the International Level. *Social Policy and Society*, 22(4), 730–746. <https://doi.org/10.1017/S1474746423000192>
- Claudia, S., Dawkins, E., & Suljada, T. (2022). The impact of the EU Emissions Trading System on households: How can the Social Climate Fund support a just transition? Stockholm Environment Institute. <https://doi.org/10.51414/sei2022.024>
- Climate Justice Alliance. (2026). Just Transition—Climate Justice Alliance. <https://climatejusticealliance.org/just-transition-2/>
- co2online. (2026). Wärmepumpe: Kosten, Funktion & Förderung. <https://www.co2online.de/modernisieren-und-bauen/waermepumpe/>
- Corrado, L., & Silgado-Gómez, E. (2023). Assessing the effects of fiscal policy news under imperfect information. *Oxford Economic Papers*, 75(2), 574–587. <https://doi.org/10.1093/oep/gpac028>
- Csereklyei, Z. (2020). Price and income elasticities of residential and industrial electricity demand in the European Union. *Energy Policy*, 137, 111079. <https://doi.org/10.1016/j.enpol.2019.111079>

- Cui, Y., Wu, W., & Taghizadeh-Hesary, F. (2025). Assessing the economic impact of carbon pricing on single and childless households: A case of 28 European countries. *Sustainable Futures*, 10, 100927. <https://doi.org/10.1016/j.sftr.2025.100927>
- DEHSt. (2025). Nationales Emissionshandelssystem (nEHS) – Verkauf nationaler Emissionszertifikate – Bericht zum vierten Quartal und Gesamtjahr 2025.
- Destatis. (2021). Type of use of the housing unit by households (Version 2018) [Pdf]. <https://www.destatis.de/EN/Themes/Society-Environment/Housing/Tables/households-in-owner-occupied-property-germany.html>
- Devine, A., & Lawlis, T. (2019). Nutrition and Vulnerable Groups. *Nutrients*, 11(5), 1066. <https://doi.org/10.3390/nu11051066>
- Díaz, A. O., & Medlock, K. B. (2021). Price elasticity of demand for fuels by income level in Mexican households. *Energy Policy*, 151, 112132. <https://doi.org/10.1016/j.enpol.2021.112132>
- Dietsch, P. (2024). A fairer and more effective carbon tax. *Nature Sustainability*, 7(12), 1584–1591. <https://doi.org/10.1038/s41893-024-01429-0>
- Dietz, S., Rising, J., Stoerk, T., & Wagner, G. (2021). Economic impacts of tipping points in the climate system. *Proceedings of the National Academy of Sciences of the United States of America*, 118(34), e2103081118. <https://doi.org/10.1073/pnas.2103081118>
- Döbbeling-Hildebrandt, N., Miersch, K., Khanna, T. M., Bachelet, M., Bruns, S. B., Callaghan, M., Edenhofer, O., Flachslund, C., Forster, P. M., Kalkuhl, M., Koch, N., Lamb, W. F., Ohlendorf, N., Steckel, J. C., & Minx, J. C. (2024). Systematic review and meta-analysis of ex-post evaluations on the effectiveness of carbon pricing. *Nature Communications*, 15, 4147. <https://doi.org/10.1038/s41467-024-48512-w>
- Dominioni, G., & Heine, D. (2019). Behavioural Economics and Public Support for Carbon Pricing: A Revenue Recycling Scheme to Address the Political Economy of Carbon

- Taxation. *European Journal of Risk Regulation*, 10(3), 554–570.
<https://doi.org/10.1017/err.2019.44>
- Domurat, R., Menashe, I., & Yin, W. (2021). The Role of Behavioral Frictions in Health Insurance Marketplace Enrollment and Risk: Evidence from a Field Experiment. *American Economic Review*, 111(5), 1549–1574. <https://doi.org/10.1257/aer.20190823>
- Douenne, T., & Fabre, A. (2022). Yellow Vests, Pessimistic Beliefs, and Carbon Tax Aversion. *American Economic Journal: Economic Policy*, 14(1), 81–110.
<https://doi.org/10.1257/pol.20200092>
- Dr. Kjell, B., Von Manteuffel, B., Offermann, M., Köhler, B., Dr. Bürger, V., Sr. Braungardt, S., & Klinski, S. (2023). Wärmepumpensysteme in Bestandsgebäuden.
- Drews, S., & van den Bergh, J. C. J. M. (2016). What explains public support for climate policies? A review of empirical and experimental studies. *Climate Policy*, 16(7), 855–876. <https://doi.org/10.1080/14693062.2015.1058240>
- Driscoll, D. (2023). Populism and Carbon Tax Justice: The Yellow Vest Movement in France. *Social Problems*, 70(1), 143–163. <https://doi.org/10.1093/socpro/spab036>
- Dubois, G., Sovacool, B., Aall, C., Nilsson, M., Barbier, C., Herrmann, A., Bruyère, S., Andersson, C., Skold, B., Nadaud, F., Dorner, F., Moberg, K. R., Ceron, J. P., Fischer, H., Amelung, D., Baltruszewicz, M., Fischer, J., Benevise, F., Louis, V. R., & Sauerborn, R. (2019). It starts at home? Climate policies targeting household consumption and behavioral decisions are key to low-carbon futures. *Energy Research & Social Science*, 52, 144–158. <https://doi.org/10.1016/j.erss.2019.02.001>
- Dütschke, E., Preuß, S., Brunzema, I., & Piria, R. (2023). Using the revenues from carbon pricing—Insights into the acceptance and perceptions of particularly burdened groups. *Energy Policy*, 175, 113468. <https://doi.org/10.1016/j.enpol.2023.113468>

- EEA. (2025, October 3). Share of environmental taxes in total tax revenues in Europe.
<https://www.eea.europa.eu/en/analysis/indicators/share-of-environmental-taxes-in>
- Emmerling, J., Andreoni, P., Charalampidis, I., Dasgupta, S., Dennig, F., Feindt, S., Fragkiadakis, D., Fragkos, P., Fujimori, S., Gilli, M., Grottera, C., Guivarch, C., Kornek, U., Kriegler, E., Malerba, D., Marangoni, G., Méjean, A., Nijssse, F., Piontek, F., ... Tavoni, M. (2024). A multi-model assessment of inequality and climate change. *Nature Climate Change*, 14(12), 1254–1260. <https://doi.org/10.1038/s41558-024-02151-7>
- Eriksson, F. A., Karlsson, A., Zetterberg, L., Bragadóttir, H., Von Bahr, J., Rootzén, J., Möllersten, K., & Kloo, H. (2023). Use of Economic Instruments in Nordic Environmental Policy 2018–2021. <https://pub.norden.org/temanord2023-520/about-this-publication.html#id07712>
- ESRI, O'Malley, S., Roantree, B., ESRI, Curtis, J., & ESRI. (2020). Carbon taxes, poverty and compensation options. ESRI. <https://doi.org/10.26504/sustat98>
- Eßer, J. (2025). The Behavioral Effects of Carbon Pricing: Experimental Evidence on Fuel Consumption. *Beiträge zur Jahrestagung des Vereins für Socialpolitik 2025: Revival of Industrial Policy*.
- European Commission. (2016). The EU Emissions Trading System (EU ETS). https://climate.ec.europa.eu/eu-action/carbon-markets/about-eu-ets_en
- European Environmental Agency. (2024). Just sustainability transitions—From concept to practice (No. 12/2024). <https://www.eea.europa.eu/en/analysis/publications/just-sustainability-transitions>
- Eurostat, the statistical office of the E. U. (2024). Heat pumps—Technical characteristics by technologies (nrg_inf_hptc). European Commission. https://ec.europa.eu/eurostat/cache/metadata/en/nrg_inf_hptc_esms.htm

- Federation of European Waste-to-Energy Companies. (2024). The ongoing assessment of the potential inclusion of municipal waste incineration and other waste management processes, notably landfilling, in the EU ETS. FEAD - European Waste Management Association. <https://fead.be/position/fead-position-paper-on-the-ongoing-assessment-of-the-potential-inclusion-of-municipal-waste-incineration-and-other-waste-management-processes-notably-landfilling-in-the-eu-ets/>
- Feindt, S., Kornek, U., Labeaga, J. M., Sterner, T., & Ward, H. (2021). Understanding regressivity: Challenges and opportunities of European carbon pricing. *Energy Economics*, 103, 105550. <https://doi.org/10.1016/j.eneco.2021.105550>
- Fragkos, P., Fragkiadakis, K., Sovacool, B., Paroussos, L., Vrontisi, Z., & Charalampidis, I. (2021). Equity implications of climate policy: Assessing the social and distributional impacts of emission reduction targets in the European Union. *Energy*, 237, 121591. <https://doi.org/10.1016/j.energy.2021.121591>
- Fried, S., Novan, K., & Peterman, W. B. (2021). Recycling Carbon Tax Revenue to Maximize Welfare. *Finance and Economics Discussion Series*, 2021.0(23), 1–30. <https://doi.org/10.17016/feds.2021.023>
- Frondel, M., & Schubert, S. A. (2021). Carbon pricing in Germany's road transport and housing sector: Options for reimbursing carbon revenues. *Energy Policy*, 157, 112471. <https://doi.org/10.1016/j.enpol.2021.112471>
- George, J. F., Werner, S., Preuß, S., Winkler, J., Held, A., & Ragwitz, M. (2023). The landlord-tenant dilemma: Distributional effects of carbon prices, redistribution and building modernisation policies in the German heating transition. *Applied Energy*, 339, 120783. <https://doi.org/10.1016/j.apenergy.2023.120783>

- Gibb, D., & Chu, V. H. Y. (2026). Socio-economic inequalities in climate policies: Unpacking energy efficiency barriers in low-income households. *Journal of Asian Public Policy*, 19(2), 319–341. <https://doi.org/10.1080/17516234.2024.2376364>
- Gillingham, K., & Palmer, K. (2014). Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence | *Review of Environmental Economics and Policy*: Vol 8, No 1. *Review of Environmental Economics and Policy*. <https://www.journals.uchicago.edu/doi/10.1093/reep/ret021>
- Godefroid, M.-E., Plattfaut, R., & Niehaves, B. (2022). How to measure the status quo bias? A review of current literature. *Management Review Quarterly*, 73(4), 1667–1711. <https://doi.org/10.1007/s11301-022-00283-8>
- Gordon, H., Burtraw, D., & Williams, R. C. (2015). A Microsimulation Model of the Distributional Impacts of Climate Policies (SSRN Scholarly Paper No. 2622667). Social Science Research Network. <https://doi.org/10.2139/ssrn.2622667>
- Goulder, L. H., & Schein, A. (2013). Carbon Taxes vs. Cap and Trade: A critical review. NBER WORKING PAPER SERIES.
- Gsottbauer, E., & van den Bergh, J. C. J. M. (2025). Pricing instruments in environmental and climate policy when polluters are boundedly rational. *Npj Climate Action*, 4(1), 96. <https://doi.org/10.1038/s44168-025-00284-9>
- Gugler, K., Haxhimusa, A., & Liebensteiner, M. (2023). Carbon pricing and emissions: Causal effects of Britain's carbon tax. *Energy Economics*, 121, 106655. <https://doi.org/10.1016/j.eneco.2023.106655>
- Gugushvill, D., & Otto, A. (2021). Determinants of Public Support for Eco-Social Policies: A Comparative Theoretical Framework | *Social Policy and Society* | Cambridge Core. <https://www.cambridge.org/core/journals/social-policy-and->

society/article/determinants-of-public-support-for-ecosocial-policies-a-comparative-theoretical-framework/BA49DC0C7597CB724100EBD7560396EE

- Gul, F., & Pesendorfer, W. (2004). Self-control, revealed preference and consumption choice. *Review of Economic Dynamics*, 7(2), 243–264. <https://doi.org/10.1016/j.red.2003.11.002>
- Günther, C., Pahle, M., Govorukha, K., Osorio, S., & Fotiou, T. (2025). Carbon prices on the rise? Shedding light on the emerging second EU Emissions Trading System (EU ETS 2). *Climate Policy*, 26(1), 92–103. <https://doi.org/10.1080/14693062.2025.2485196>
- Günther, C., Pahle, M., Govorukha, K., Osorio, S., & Fotiou, T. (2026). Carbon prices on the rise? Shedding light on the emerging second EU Emissions Trading System (EU ETS 2). *Climate Policy*, 26(1), 92–103. <https://doi.org/10.1080/14693062.2025.2485196>
- Gupta, J., Liverman, D., Prodani, K., Aldunce, P., Bai, X., Broadgate, W., Ciobanu, D., Gifford, L., Gordon, C., Hurlbert, M., Inoue, C. Y. A., Jacobson, L., Kanie, N., Lade, S. J., Lenton, T. M., Obura, D., Okereke, C., Otto, I. M., Pereira, L., ... Verburg, P. H. (2023). Earth system justice needed to identify and live within Earth system boundaries. *Nature Sustainability*, 6(6), 630–638. <https://doi.org/10.1038/s41893-023-01064-1>
- Hainsch, K. (2023). Identifying policy areas for the transition of the transportation sector. *Energy Policy*, 178, 113591. <https://doi.org/10.1016/j.enpol.2023.113591>
- Hartmann, P., Marcos, A., & Barrutia, J. M. (2023). Carbon tax salience counteracts price effects through moral licensing. *Global Environmental Change*, 78, 102635. <https://doi.org/10.1016/j.gloenvcha.2023.102635>
- Hedegaard, T. F., & Kongshøj, K. (2024). Carbon tax revenues and how to spend them: Danes' attitudes toward revenue recycling. *Politics & Policy*, 52(5), 992–1012. <https://doi.org/10.1111/polp.12619>
- Hernández, J. F. L. (2026). Revision of the EU emissions trading system.

- Homar, A. R. (2023). An examination of the effects of loss aversion on pro-environmental decisions.
- Hübler, M., Wiese, M., Braun, M., & Damster, J. (2024). The distributional effects of CO₂ pricing at home and at the border on German income groups. *Resource and Energy Economics*, 77, 101435. <https://doi.org/10.1016/j.reseneeco.2024.101435>
- Huttarsch, J.-H., & Matthies, E. (2024). Perceived carbon pricing effectiveness impacts its perceived fairness – Applying and extending a theoretical framework. *Journal of Environmental Psychology*, 97, 102356. <https://doi.org/10.1016/j.jenvp.2024.102356>
- ICAP, I. C. A. P. (2024). German National Emissions Trading System. International Carbon Action Partnership.
- ICAP, I. C. A. P. (2025, February 6). German National Emissions Trading System | International Carbon Action Partnership. <https://icapcarbonaction.com/en/ets/german-national-emissions-trading-system>
- International Labour Organization. (2015). Guidelines for a just transition towards environmentally sustainable economies and societies for all. International Labour Organization. <https://www.ilo.org/publications/guidelines-just-transition-towards-environmentally-sustainable-economies>
- ISE, F. (2025). Wärmepumpen heizen auch im Altbau klimafreundlich.
- Jacobs, L., Quack, L., & Mechtel, M. (2022a). Distributional effects of carbon pricing by transport fuel taxation. *Energy Economics*, 114, 106290. <https://doi.org/10.1016/j.eneco.2022.106290>
- Jasanoff, S. (2018). Just transitions: A humble approach to global energy futures. *Energy Research & Social Science*, 35, 11–14. <https://doi.org/10.1016/j.erss.2017.11.025>
- Jia, Z., Skagseth, S., Thoresen, T. O., & Vattø, T. E. (2026). A practical framework for behavioral microsimulation using external evidence.

- Kalkuhl, M., Flachsland, C., Knopf, B., Amberg, M., Bergmann, T., Kellner, M., Stüber, S., Haywood, L., Roolfs, C., & Edenhofer, O. (2022). Effects of the energy price crisis on households in Germany.
- Kanashiro Uehara, T. (2024). Planetary Welcare principles for just and sustainable futures: A compass for system change, trade reforms, and transformations. *Sustainability: Science, Practice and Policy*, 20(1), 2300885. <https://doi.org/10.1080/15487733.2023.2300885>
- Keliauskaitė, U., McWilliams, B., Sgaravatti, G., & Tagliapietra, S. (2026). How to finance the European Union's building decarbonisation plan. <https://www.bruegel.org/policy-brief/how-finance-european-unions-building-decarbonisation-plan>
- Kettner, C., Leoni, T., Köberl, J., Kortschak, D., Sommer, M., & Kulmer, V. (2026). Investigating equity and efficiency in carbon pricing with revenue recycling: A combined macro- and micro-modelling approach. *Energy Policy*, 209, 114994. <https://doi.org/10.1016/j.enpol.2025.114994>
- KfW. (2024). Heating subsidy: Application process opens today for owner-occupied single-family homes | KfW. KfW. https://www.kfw.de/About-KfW/Newsroom/Latest-News/News-Details_798016.html
- KfW. (2025). Einzelmaßnahmen Ergänzungskredit – Wohngebäude (358, 359) | KfW. KfW. [https://www.kfw.de/inlandsfoerderung/Privatpersonen/Bestehende-Immobilie/Förderprodukte/Einzelmaßnahmen-Ergänzungskredit-Wohngebäude-\(358-359\)/](https://www.kfw.de/inlandsfoerderung/Privatpersonen/Bestehende-Immobilie/Foerderprodukte/Einzelmaßnahmen-Ergänzungskredit-Wohngebäude-(358-359)/)
- KfW. (2026). Heizungsförderung für Privatpersonen – Wohngebäude (458) | KfW. [https://www.kfw.de/inlandsfoerderung/Privatpersonen/Bestehende-Immobilie/Förderprodukte/Heizungsförderung-für-Privatpersonen-Wohngebäude-\(458\)/](https://www.kfw.de/inlandsfoerderung/Privatpersonen/Bestehende-Immobilie/Foerderprodukte/Heizungsfoerderung-für-Privatpersonen-Wohngebäude-(458)/)

- Kleinhüchelkotten, S., & Moser, S. (2016). Repräsentative Erhebung von Pro-Kopf-Verbräuchen natürlicher Ressourcen in Deutschland (nach Bevölkerungsgruppen).
- Knight, C. (2013). What is grandfathering? *Environmental Politics*, 22(3), 410–427. <https://doi.org/10.1080/09644016.2012.740937>
- Knobloch, F., Huijbregts, M. A. J., & Mercure, J.-F. (2019). Modelling the effectiveness of climate policies: How important is loss aversion by consumers? *Renewable and Sustainable Energy Reviews*, 116, 109419. <https://doi.org/10.1016/j.rser.2019.109419>
- Köppl, A., & Schratzenstaller, M. (2023). Carbon taxation: A review of the empirical literature. *Journal of Economic Surveys*, 37(4), 1353–1388. <https://doi.org/10.1111/joes.12531>
- Kröger, D., Peper, J., & Rehtanz, C. (2023). Electricity market modeling considering a high penetration of flexible heating systems and electric vehicles. *Applied Energy*, 331, 120406. <https://doi.org/10.1016/j.apenergy.2022.120406>
- Lackner, T., & Nabernegg, S. (2026). Who pays for decarbonizing homes? (SSRN Scholarly Paper No. 6618598). Social Science Research Network. <https://doi.org/10.2139/ssrn.6618598>
- Lambert, P., Kakwani, & N. (1995). Vertical equity and horizontal inequity: A new approach to measurement. <https://doi.org/10.1920/wp.ifs.1995.9502>
- Lay, J. (2009). Sequential Macro-Micro Modelling with Behavioural Microsimulations. *International Journal of Microsimulation*, 3(1), 24–34. <https://doi.org/10.34196/ijm.00022>
- Li, F. G. N. (2017a). Actors behaving badly: Exploring the modelling of non-optimal behaviour in energy transitions. *Energy Strategy Reviews*, 15, 57–71. <https://doi.org/10.1016/j.esr.2017.01.002>

- Li, F. G. N. (2017b). Actors behaving badly: Exploring the modelling of non-optimal behaviour in energy transitions: online supplementary information. *Energy Strategy Reviews*, 15, 57–71. <https://doi.org/10.1016/j.esr.2017.01.002>
- Linden, J., O'Donoghue, C., & Sologon, D. M. (2024). The many faces of carbon tax regressivity—Why carbon taxes are not always regressive for the same reason. *Energy Policy*, 192, 114210. <https://doi.org/10.1016/j.enpol.2024.114210>
- Lunn, P. (2024). Perceived Fairness and the Green Transition. JRC Publications Repository. <https://publications.jrc.ec.europa.eu/repository/handle/JRC139534>
- Maestre-Andrés, S., Van den Berg, J., & Drews, S. (2019). Perceived fairness and public acceptability of carbon pricing: A review of the literature. 19(9). <https://doi.org/https://doi.org/10.1080/14693062.2019.1639490>
- Maier, S., Poli, S. D., & Amores, A. F. (2025). Carbon Taxes on Consumption: Distributional Implications for a Just Transition in the EU.
- Malerba, D., Chen, X., Feng, K., Hubacek, K., & Oswald, Y. (2022). The impact of carbon taxation and revenue redistribution on poverty and inequality. In IDOS Policy Brief 11/2022 (Version 1.0). German Institute of Development and Sustainability. <https://doi.org/10.23661/IPB11.2022>
- Marcos, A., Hartmann, P., Barrutia, J. M., & Apaolaza, V. (2022). Carbon Taxes Beyond Emissions' Reduction: Co-benefits and Behavioural Failures in Emerging Markets. In N. Nguyen, H. V. Nguyen, C. D'Souza, & C. Strong (Eds.), *Environmental Sustainability in Emerging Markets: Consumer, Organisation and Policy Perspectives* (pp. 243–262). Springer Nature. https://doi.org/10.1007/978-981-19-2408-8_11
- Marcu, A., Coker, E., Bourcier, F., Caneill, J.-Y., Schleicher, S., Hernández, F. L., Caruana, N., Chawah, P., & Finlayson, R. (2025). 2025 State of the EU ETS Report.

- Marek, M. (2026, February 10). Heat Pump Installation Costs: Germany vs. Europe Study. HEAT PUMPS WATCH. <https://heatpumpswatch.org/heat-pump-installation-costs-germany-vs-europe/>
- Matei, L. (2025). Guiding Principles for Just Transition.
- Mathur, A., & Morris, A. C. (2014). Distributional effects of a carbon tax in broader U.S. fiscal reform. *Energy Policy*, 66, 326–334. <https://doi.org/10.1016/j.enpol.2013.11.047>
- Mayer, J., Dugan, A., Bachner, G., & Steininger, K. W. (2021). Is carbon pricing regressive? Insights from a recursive-dynamic CGE analysis with heterogeneous households for Austria. *Energy Economics*, 104, 105661. <https://doi.org/10.1016/j.eneco.2021.105661>
- Mehleb, R. I., Kallis, G., & Zografos, C. (2021). A discourse analysis of yellow-vest resistance against carbon taxes. *Environmental Innovation and Societal Transitions*, 40, 382–394. <https://doi.org/10.1016/j.eist.2021.08.005>
- Mengesha, I., & Roy, D. (2025). Carbon pricing drives critical transition to green growth. *Nature Communications*, 16(1), 1321. <https://doi.org/10.1038/s41467-025-56540-3>
- Merkel, E., McKenna, R., Fehrenbach, D., & Fichtner, W. (2017). A model-based assessment of climate and energy targets for the German residential heat system. *Journal of Cleaner Production*, 142, 3151–3173. <https://doi.org/10.1016/j.jclepro.2016.10.153>
- Mintz-Woo, K. (2024). Carbon Pricing is not Unjust. *Global Challenges*, 8(1), 2300089. <https://doi.org/10.1002/gch2.202300089>
- Möhren, S., Meyer, J., & Seeliger, A. (2021). Einfluss der CO₂-Bepreisung nach BEHG auf die Kosten von Wärmeversorgung und Nutzung von Abwärme in deutschen Industriebetrieben. *Zeitschrift für Energiewirtschaft*, 45(1), 25–33. <https://doi.org/10.1007/s12398-020-00291-9>
- Monar, C. (2024). Maximising benefits of carbon pricing through carbon revenue use:

- Murphy, R., & Murphy, M. (2012). The Tragedy of the Atmospheric Commons: Discounting Future Costs and Risks in Pursuit of Immediate Fossil-Fuel Benefits. *Canadian Review of Sociology/Revue canadienne de sociologie*, 49(3), 247–270. <https://doi.org/10.1111/j.1755-618X.2012.01294.x>
- Naegler, T., Sutardhio, C., Weidlich, A., & Pregger, T. (2021). Exploring long-term strategies for the german energy transition—A review of multi-Sector energy scenarios. *Renewable and Sustainable Energy Transition*, 1, 100010. <https://doi.org/10.1016/j.rset.2021.100010>
- Nguyen, T. T. H., & Song, W. (2021). CARBON PRICING AND INCOME INEQUALITY: AN EMPIRICAL INVESTIGATION.
- Nurhayati, Y., Ifrani, Said, M. Y., & Yanova, M. H. (2024). Carbon Pricing Policy to Support Net Zero Emission: A Comparative Study of Indonesia, Finland and Sweden. *Environmental Policy and Law*, 54(1), 53–63. <https://doi.org/10.3233/EPL-230047>
- OECD. (2019). The use of revenues from carbon pricing (OECD Taxation Working Papers No. 43; OECD Taxation Working Papers, Vol. 43). <https://doi.org/10.1787/3cb265e4-en>
- OECD. (2022, November 6). Germany’s annual sectoral emissions targets. OECD Publishing. OECD. https://www.oecd.org/en/publications/ipac-policies-in-practice_22632907-en/germany-s-annual-sectoral-emissions-targets_2148cd0e-en.html
- OECD. (2026, April 23). Carbon pricing in Denmark: How does it work? ECOSCOPE. <https://oecd ecoscope.blog/2026/04/23/carbon-pricing-in-denmark-how-does-it-work/>
- Patton, M. Q. (2019). Transformation to Global Sustainability: Implications for Evaluation and Evaluators. *New Directions for Evaluation*, 2019(162), 103–117. <https://doi.org/10.1002/ev.20362>

- Pedersen, E. R. G., Lüdeke-Freund, F., Henriques, I., & Seitanidi, M. M. (2021). Toward Collaborative Cross-Sector Business Models for Sustainability. *Business & Society*, 60(5), 1039–1058. <https://doi.org/10.1177/0007650320959027>
- Peterson, S., & Maamoun, N. (2025). Klimapolitik und sozialer Ausgleich in Deutschland und Schleswig-Holstein.
- Pitkänen, A., von Wright, T., Kaseva, J., & Kahiluoto, H. (2022). Distributional fairness of personal carbon trading. *Ecological Economics*, 201, 107587. <https://doi.org/10.1016/j.ecolecon.2022.107587>
- Pomerleau, K., & Asen, E. (2019). carbon tax and revenue recycling: Revenue, economic, and distributional implications. Tax Foundation.
- Povitkina, M., Carlsson Jagers, S., Matti, S., & Martinsson, J. (2021). Why are carbon taxes unfair? Disentangling public perceptions of fairness. *Global Environmental Change*, 70, 102356. <https://doi.org/10.1016/j.gloenvcha.2021.102356>
- Priesmann, J., & Praktijnjo, A. (2025). Estimating Short- and Long-Run Price and Income Elasticities of Final Energy Demand as a Function of Household Income. SSRN. <https://doi.org/10.2139/ssrn.4924764>
- Puentes, R., & Roberto, E. (2008). Commuting to Opportunity: The Working Poor and Commuting in the United States. Brookings. <https://www.brookings.edu/articles/commuting-to-opportunity-the-working-poor-and-commuting-in-the-united-states/>
- Rausch, S., Metcalf, G. E., & Reilly, J. M. (2011). Distributional impacts of carbon pricing: A general equilibrium approach with micro-data for households. *Energy Economics*, Supplemental Issue: Fourth Atlantic Workshop in Energy and Environmental Economics, 33, S20–S33. <https://doi.org/10.1016/j.eneco.2011.07.023>

- Reaños, T., & Angel, M. (2019). Distributional impacts of carbon taxation and revenue recycling: A behavioural microsimulation.
- Rickels, W., Rischer, C., Schenuit, F., & Peterson, S. (2024). Mögliche Effizienzgewinne durch die Einführung eines länderübergreifenden Emissionshandels für den Gebäude- und Straßenverkehrssektor in der Europäischen Union. *Perspektiven der Wirtschaftspolitik*, 25(1), 70–80. <https://doi.org/10.1515/pwp-2023-0022>
- Römer, D. (2022). KfW Energy Transition Barometer 2022.
- Römer, D., & Salzgeber, J. (2023). KfW Energy Transition Barometer 2023.
- Roofs, C., Kalkuhl, M., Amberg, M., Bergmann, T., & Kellner, M. (2021). Documentation of the CO₂-price incidence webtool «MCC CO₂-Preis-Rechner». <https://doi.org/10.5281/ZENODO.5094561>
- Rüb, D. (2024). Inequality beyond income quantiles: Distributional effects of climate mitigation policies. *Ecological Economics*, 216, 108019. <https://doi.org/10.1016/j.ecolecon.2023.108019>
- Ruhnau, O., Bannik, S., Otten, S., Praktiknjo, A., & Robinius, M. (2019). Direct or indirect electrification? A review of heat generation and road transport decarbonisation scenarios for Germany 2050. *Energy*, 166, 989–999. <https://doi.org/10.1016/j.energy.2018.10.114>
- Schaffrin, A. (2013). Who pays for climate mitigation? An empirical investigation on the distributional effects of climate policy in the housing sector. *Energy and Buildings*, 59, 265–272. <https://doi.org/10.1016/j.enbuild.2012.12.033>
- Schlemminger, M., Peterssen, F., Lohr, C., Niepelt, R., Bensmann, A., Brendel, R., Hanke-Rauschenbach, R., & Breitner, M. H. (2025). Flexibility is the key to decarbonizing heat supply: A case study based on the German energy system. *Energy Conversion and Management*, 324, 119300. <https://doi.org/10.1016/j.enconman.2024.119300>

- Schmitz, H., & Madlener, R. (2016). Heterogeneity in Price Responsiveness for Residential Space Heating in Germany.
- Schrems, I., Auf der Maur, A., Kemmler, A., Trachsel, T., Saad, N., Bach, S., Knautz, J., & Umweltbundesamt (UBA), D.-R. (Germany). (2022). The effect of national fuel emissions trading. Evaluations and analyses. Basis for the first progress report of the Federal Government pursuant to Section 23 BEHG in 2022 (UBA-FB--001024; Vol. 45/2022). Umweltbundesamt (UBA), Dessau-Roßlau (Germany).
<https://inis.iaea.org/records/czsgd-4jk18>
- Shangguan, C., Shangguan, Z., & Sun, W. (2024). Impact assessment framework of just energy transition: Based on the justice principles. *Frontiers in Environmental Science*, 12.
<https://doi.org/10.3389/fenvs.2024.1491946>
- Siciliano, G., Wallbott, L., Urban, F., Dang, A. N., & Lederer, M. (2021). Low-carbon energy, sustainable development, and justice: Towards a just energy transition for the society and the environment. *Sustainable Development*, 29(6), 1049–1061.
<https://doi.org/10.1002/sd.2193>
- Singh, P., Amekudzi-Kennedy, A., Ashuri, B., Chester, M., Labi, S., & Wall, T. A. (2023). Developing adaptive resilience in infrastructure systems: An approach to quantify long-term benefits. *Sustainable and Resilient Infrastructure*, 8(sup1), 26–47.
<https://doi.org/10.1080/23789689.2022.2126631>
- Smith, G. S., Anjum, E., Francis, C., Deanes, L., & Acey, C. (2022). Climate Change, Environmental Disasters, and Health Inequities: The Underlying Role of Structural Inequalities. *Current Environmental Health Reports*, 9(1), 80–89.
<https://doi.org/10.1007/s40572-022-00336-w>

- Soares, C. D. (2012). Earmarking revenues from environmentally related taxes. In J. E. Milne & M. S. Andersen (Eds.), *Handbook of research on unvironmental taxation* (pp. 102–121). Edward Elgar Publishing Ltd. <https://doi.org/10.4337/9781781952146.00014>
- Stankuniene, G., Streimikiene, D., & Kyriakopoulos, G. L. (2020). Systematic Literature Review on Behavioral Barriers of Climate Change Mitigation in Households. *Sustainability*, 12(18), 7369. <https://doi.org/10.3390/su12187369>
- Stark, A., Gale, F., & Murphy-Gregory, H. (2023). Just Transitions’ Meanings: A Systematic Review. *Society & Natural Resources*, 36(10), 1277–1297. <https://doi.org/10.1080/08941920.2023.2207166>
- Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, 347(6223), 1259855. <https://doi.org/10.1126/science.1259855>
- Stoll, C., & Mehling, M. A. (2021). Climate change and carbon pricing: Overcoming three dimensions of failure. *Energy Research & Social Science*, 77, 102062. <https://doi.org/10.1016/j.erss.2021.102062>
- Swatuk, L. A., Wirkus, L., Krampe, F., Thomas, B. K., & Silva, L. P. B. da. (2018). The boomerang effect: Overview and implications for climate governance. In *Water, Climate Change and the Boomerang Effect*. Routledge.
- Tessum, C. W., Paoletta, D. A., Chambliss, S. E., Apte, J. S., Hill, J. D., & Marshall, J. D. (2021). PM2.5 polluters disproportionately and systemically affect people of color in the United States. *Science Advances*, 7(18), eabf4491. <https://doi.org/10.1126/sciadv.abf4491>

- Thema, J. (2024). Modelling policy scenarios: Refocussing the model-policy logic for the case of German passenger transport. *Energy, Sustainability and Society*, 14(1), 38. <https://doi.org/10.1186/s13705-024-00467-y>
- Thomas, A. (2021). Framing the just transition: How international trade unions engage with UN climate negotiations. *Global Environmental Change*, 70, 102347. <https://doi.org/10.1016/j.gloenvcha.2021.102347>
- Thornton, P., Wollenberg, E., Cramer, L., & Flintan, F. (2025). Options for a just transition for livestock under climate change. *Outlook on Agriculture*, 54(3), 222–233. <https://doi.org/10.1177/00307270251365668>
- Torkayesh, A. E., & Venghaus, S. (2024). Decoding the transport policy maze towards climate neutrality: Cross-sectoral policy landscapes. *Renewable and Sustainable Energy Reviews*, 206, 114865. <https://doi.org/10.1016/j.rser.2024.114865>
- Tovar, M., & van der Ploeg, A. (2021, November 2). Carbon tax recycling and popular support in Germany. CEPR. <https://cepr.org/voxeu/columns/carbon-tax-recycling-and-popular-support-germany>
- Tower Renewal Partnership. (2017). German retrofit financing: KfW - Housing, Home Modernization and energy conservation. http://towerrenewal.com/wp-content/uploads/2017/04/20170331_Case-Study_KFW.pdf
- Tribaldos, T., & Kortetmäki, T. (2022). Just transition principles and criteria for food systems and beyond. *Environmental Innovation and Societal Transitions*, 43, 244–256. <https://doi.org/10.1016/j.eist.2022.04.005>
- Tversky, A., & Kahneman, D. (1992). Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and Uncertainty*, 5(4), 297–323. <https://doi.org/10.1007/BF00122574>

- Tvinnereim, E., & Mehling, M. (2018). Carbon pricing and deep decarbonisation. *Energy Policy*, 121, 185–189. <https://doi.org/10.1016/j.enpol.2018.06.020>
- UBA. (2026, March 30). Der Nationale Emissionshandel. Umweltbundesamt. <https://www.umweltbundesamt.de/der-nationale-emissionshandel>
- UBA, U. (2025, May 26). Indicator: Greenhouse gas emissions. Umweltbundesamt. <https://www.umweltbundesamt.de/en/data/environmental-indicators/indicator-greenhouse-gas-emissions>
- Umweltbundesamt (UBA). (2026). Nationales Emissionshandelssystem (nEHS) – Verkauf nationaler Emissionszertifikate – Bericht zum vierten Quartal und Gesamtjahr 2025.
- UNRISD, & ULIP, E. M. of the U. of L. I. in P. (2018). Social and solidarity economy for the Sustainable Development Goals: Spotlight on the social economy in Seoul: full report. UNRISD.
- van der Ploeg, F. (2023). Fiscal Costs of Climate Policies: Role of Tax, Political, and Behavioural Distortions. *The Economist*, 171(2), 119–137. <https://doi.org/10.1007/s10645-023-09419-x>
- van der Ploeg, F. (2025). Why green subsidies are preferred to carbon taxes: Climate policy with heightened carbon tax salience. *Journal of Environmental Economics and Management*, 130, 103129. <https://doi.org/10.1016/j.jeem.2025.103129>
- Vandyck, T., Della Valle, N., Temursho, U., & Weitzel, M. (2023). EU climate action through an energy poverty lens. *Scientific Reports*, 13(1), 6040. <https://doi.org/10.1038/s41598-023-32705-2>
- Vella, A., Mayeres, I., Platsakis, O., Acipinar, R. K., Dauwe, T., Sarantaridis, D., Gores, S., & Skribbe, R. (2026). EU ETS2 and social climate fund: Enabling decarbonisation in transport and buildings that works for all. Zenodo. <https://doi.org/10.5281/ZENODO.18242768>

- Verbruggen, A., Laes, E., & Woerdman, E. (2019). Anatomy of Emissions Trading Systems: What is the EU ETS? *Environmental Science & Policy*, 98, 11–19. <https://doi.org/10.1016/j.envsci.2019.05.001>
- Wang, X., & Lo, K. (2021). Just transition: A conceptual review. *Energy Research & Social Science*, 82, 102291. <https://doi.org/10.1016/j.erss.2021.102291>
- Wendl-Damerius, A. (2021, November 24). Germany's Emissions Trading Scheme on Fuels. 12th EU ETS Compliance Conference. https://climate.ec.europa.eu/system/files/2021-12/20211124_p2_en.pdf
- Wiese, F., Thema, J., & Cordroch, L. (2022). Strategies for climate neutrality. Lessons from a meta-analysis of German energy scenarios. *Renewable and Sustainable Energy Transition*, 2, 100015. <https://doi.org/10.1016/j.rset.2021.100015>
- Wilgosh, B., Sorman, A. H., & Barcena, I. (2022). When two movements collide: Learning from labour and environmental struggles for future Just Transitions. *Futures*, 137, 102903. <https://doi.org/10.1016/j.futures.2022.102903>
- Winkler, H. (2020). Towards a theory of just transition: A neo-Gramscian understanding of how to shift development pathways to zero poverty and zero carbon. *Energy Research & Social Science*, 70, 101789. <https://doi.org/10.1016/j.erss.2020.101789>
- World Bank Group. (2017, May 9). What is Carbon Pricing? World Bank Group. Carbon Pricing Dashboard. <https://carbonpricingdashboard.worldbank.org/what-carbon-pricing>
- Wright, C., & Nyberg, D. (2024). Corporations and climate change: An overview. *WIREs Climate Change*, 15(6), e919. <https://doi.org/10.1002/wcc.919>
- Wulff, N., Esmaili Aliabadi, D., Hasselwander, S., Pregger, T., Gils, H. C., Kronshage, S., Grimme, W., Horst, J., Hoyer-Klick, C., & Jochem, P. (2025). Energy system

implications of demand scenarios and supply strategies for renewable transportation fuels. *Energy Strategy Reviews*, 58, 101606. <https://doi.org/10.1016/j.esr.2024.101606>

Annex

Annex A

Table 10: Overview of Microsimulation Scenarios including main purpose

Scenario	Behavioural frictions	Subsidies	Credit support	Ownership restriction	Main purpose
Baseline carbon pricing	No	No	No	n.a.	Introduces the direct distributional impact of the nEHS
Rational adoption	No	Yes	No	n.a.	Provides the benchmark for economically optimal adoption.
Behavioural, no subsidy	Yes	No	No	n.a.	Examines how behavioural barriers affect adaption and policy burden.
Behavioural, with subsidy	Yes	Yes	No	n.a.	Evaluates whether subsidies remain effective under realistic behavioural conditions.
Behavioural, income-specific frictions	Yes, income-specific	Yes	No	n.a.	Assesses whether low-income households face disproportionate barriers to adaption.
Credit case with ownership restriction	Yes, income-specific	Yes	Yes, credit with frictions	Yes	Evaluates the accessibility of credit-supported heating investments under current programme conditions.
Credit sensitivity without ownership restriction	Yes, income-specific	Yes	Yes, credit with frictions	No	Tests the potential improvement in accessibility if ownership barriers are removed.

Table 11: Baseline Calibration Table

Income Class	Subsidy	Energy (kWh)	CO2 (kg)	Income (€) ¹⁴	Invest (€)	Price elasticities				Behavioural frictions ¹⁵	
						electricity		Heating		Hurdle rates	Market heterog. ¹⁶
						LR	SR	LR	SR		
Less than 1.000€	Subsidy considered	11.401,5	3.361,3	10.000€	4.500€	-0.29	-0.31	-0.50	-0.51	17%	L = 0 to H = 4
Under 1.000€	Subsidy ignored	11.401,5	3.361,3	10.000€	22.500€	-0.29	-0.31	-0.50	-0.51	17%	L = 0 to H = 4
1.000-1.999€	Subsidy considered	10.915,7	2.773,4	18.000€	4.500€	-0.37	-0.35	-0.40	-0.37	15%	L = 5 to H = 7
1.000-1.999€	Subsidy ignored	10.915,7	2.773,4	18.000€	22.500€	-0.37	-0.35	-0.40	-0.37	15%	L = 5 to H = 7
2.000-2.999€	Subsidy considered	10.134,1	2.619,3	30.000€	11.250€	-0.43	-0.38	-0.34	-0.30	13%	L = 7 to H = 9
2.000-2.999€	Subsidy ignored	10.134,1	2.619,3	30.000€	22.500€	-0.43	-0.38	-0.34	-0.30	13%	L = 7 to H = 9
Over 3.000€	Subsidy considered	9.759,0	2.279,5	> 36.000€	11.250€	-0.57	-0.42	-0.21	-0.17	9%	L = 10 to H = 19
More than 3.000€	Subsidy ignored	9.759,0	2.279,5	> 36.000€	22.500€	-0.57	-0.42	-0.21	-0.17	9%	L = 10 to H = 19

¹⁴ Mean average point of annual income

¹⁵ Explanations for the determination of the parameters can be found in the annex.

¹⁶ The model uses the mean average of the market heterogeneity values

Sensitivity Analysis

Table 12: Overview of Robustness and Sensitivity Analyses-scenarios

Scenario Block	Variations	Purpose
Imperfect-Information sensitivity	Inattention only Delay only Combined class frictions	Isolates the contribution of individual behavioural mechanisms.
Hurdle-rate sensitivity	Higher investment hurdle rates Lower investment hurdle rates	Tests sensitivity to alternative assumptions regarding investment behaviour.
Market-heterogeneity sensitivity	Higher levels of household heterogeneity Lower levels of household heterogeneity	Assesses the robustness of results to different adoption patterns

Table 13: hurdle rates specified to household income classes

Household income classes	Hurdle rates (r_i)	Explanation
Less than 1.000€	17 %	Limited access to capital creates very high barriers to investment (Keliauskaitė et al., 2026; Römer & Salzgeber, 2023).
1.000 -1999€	15 %	Households weigh up the costs and benefits on a case-by-case basis, but have limited resources (Keliauskaitė et al., 2026; Römer & Salzgeber, 2023).
2.000 – 2.999€	13%	Households weigh up the costs and benefits on a case-by-case basis, but have limited resources (Keliauskaitė et al., 2026; Römer & Salzgeber, 2023).
More than 3000€	9%	Greater financial flexibility lowers the required rate of return for efficiency measures (Keliauskaitė et al., 2026; Römer & Salzgeber, 2023).

Table 14: Market heterogeneity specified to household income classes

Household income classes	Market heterogeneity (v)	Explanation
Less than 1.000€	L = 0 to H = 4	Market players hardly react to prices (Schmitz & Madlener, 2016).
1.000 -1999€	L = 5 to H = 7	Price-conscious, but a complete switch would require very significant cost savings (Schmitz & Madlener, 2016)
2.000 – 2.999€	L = 7 to H = 9	Price-conscious, but a complete switch would require very significant cost savings .
More than 3000€	L = 10 to H = 19	Strong reaction to prices, but prices do not dictate all decisions (Schmitz & Madlener, 2016).

Table 15: Heat Pump Stock Evolution by Income Class (2021-2025)¹⁷

Income Class	2021	2022	2023	2024	2025
Less than 1.000€	6.62%	12.69%	18.36%	23.74%	28.77%
1.000-1.999€	6.65%	12.79%	18.54%	23.94%	28.99%
2.000 - 2.999€	6.50%	12.22%	17.61%	22.89%	27.87%
More than 3.000€	6.45%	12.09%	17.40%	22.65%	27.62%

Scenario: Rational, Subsidies considered

Income Class	2021	2022	2023	2024	2025
Less than 1.000€	5.17%	9.52%	13.66%	17.93%	22.05%
1.000-1.999€	6.64%	12.74%	18.44%	23.83%	28.88%
2.000 - 2.999€	6.55%	11.93%	17.01%	22.34%	27.38%
More than 3.000€	6.67%	12.89%	18.69%	24.11%	29.17%

Scenario: Behavioural, Subsidies considered

Table 16: definition of hurdle rates for different scenarios

scenario	original	lower hurdle rates		Higher hurdle rates	
HH income classes	Hurdle rates (r_i)	Hurdle rates (r_i) I	Hurdle rates (r_i) II	Hurdle rates (r_i) I	Hurdle rates (r_i) II
Less than 1.000€	17 %	14 %	11 %	20 %	23 %
1.000 -1999€	15 %	12 %	9 %	17 %	20 %
2.000 – 2.999€	13%	10 %	8 %	15%	17%
More than 3000€	9%	8 %	7,5 %	12%	15%

¹⁷ In the microsimulation, it was assumed that the heat-pump stock before the application of the policy was 0.

Table 17: Adoption probability by income class and hurdle rate scenario in 2025

Income Class	original scenario	higher r_i I	higher r_i II	lower r_i I	lower r_i II
Less than 1.000€	5.10	4.61	4.26	5.44	5.85
1.000-1.999€	6.63	6.58	6.42	6.66	6.67
2.000 - 2.999€	6.48	6.11	5.32	6.65	6.66
More than 3.000€	6.67	6.66	6.53	6.67	6.67

Note: Adoption probability values are expressed as percentages

Table 18: Definition of market heterogeneity for different scenarios

scenario	original	lower hurdle rates		Higher hurdle rates	
HH income classes	ν	ν I	ν II	ν I	ν II
Less than 1.000€	2	1	0	3	4
1.000 -1999€	6	5	3	7	9
2.000 – 2.999€	8	6	5	9	10
More than 3000€	14,5	10	12	16	19

Table 19: Adoption probability in different heterogeneity parameter scenarios

Income Class	higher ν I	higher ν II	lower ν I	lower ν II
Less than 1.000€	+0.176	+0.304	-0.223	-0.477
1.000-1.999€	+0.012	+0.021	-0.024	-0.169
2.000 - 2.999€	+0.033	+0.058	-0.098	-0.171
More than 3.000€	+0.000	+0.000	-0.005	-0.001

Table 20: Imperfect-information parameters by Income groups¹⁸

Income class	Price elasticity	Inattention Rate (%)	Adjustment Delay
Less than 1.000€	-0.05	40	12 Months
1.000-1.999€	-0.10	30	9 Months
2.000 - 2.999€	-0.20	20	6 Months
More than 3.000€	-0.30	10	3 Months

Table 21: Heat Pump stock share in 2025 in %

Income class	Behavioural Scenario	Imperfect Information Scenario	Difference (pp)
Less than 1.000€	22.0	13.9	8.1
1.000-1.999€	28.9	25.3	3.6
2.000 - 2.999€	27.4	22.0	5.4
More than 3.000€	29.2	29.1	0.1

Credit extension

Table 22: Assumptions of the KfW credit extension

Parameter	Value
Heat-pump investment cost	2.500€
Interest rate	2%
Loan maturity	20 years
Maximum KfW credit	120.000€
Programme start	2024
Income threshold	90.000€
Owner occupier share	Less than 1.000€ 17.98%
	1.000-1.999€ 28.91%
	2.000-2.999€ 43.85%
	More than 3.000€ 61.77%

¹⁸ The imperfect information parameters presented in Table 12 were selected by the author based on a synthesis of scientific literature on behavioural frictions in energy economics, ensuring alignment with empirical evidence while tailored to the nEHS context. (Battistini et al., 2023; Jacobs et al., 2022; Jia et al., 2026; Lay, 2009)

Table 23: Impact of the owner-occupier constraint on effective credit accessibility across income groups in 2025

Income Class	Credit scenario	Access with owner constraint (%)	Access without owner constraint (%)	Change (percentage points)
Less than 1.000€	Credit with frictions	10.79	60	+49.21
1.000-1.999€	Credit with frictions	20.24	70	+49.76
2.000 - 2.999€	Credit with frictions	35.08	80	+44.92
More than 3.000€	Credit with frictions	55.59	90	+34.41
Less than 1.000€	Credit high access	15.10	84	+68.90
1.000-1.999€	Credit high access	28.33	98	+69.67
2.000 - 2.999€	Credit high access	43.85	100	+56.15
More than 3.000€	Credit high access	61.77	100	+38.23

Annex B

Results Baseline Scenarios – Middle income households

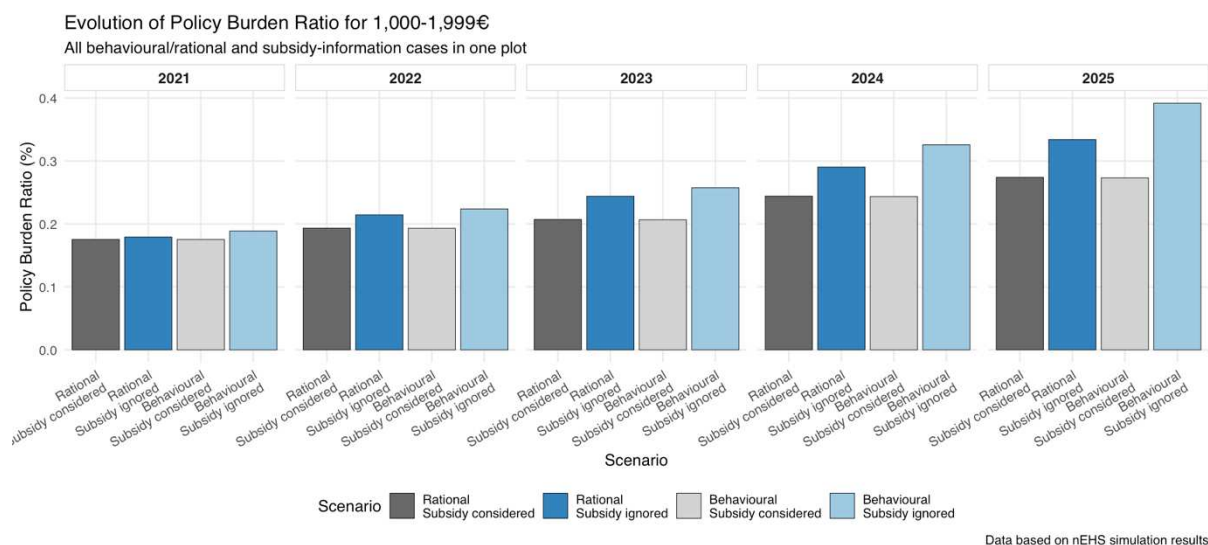


Figure 7: Evolution of Policy Burden Ratio for Income classes "1.000€-1.999€"

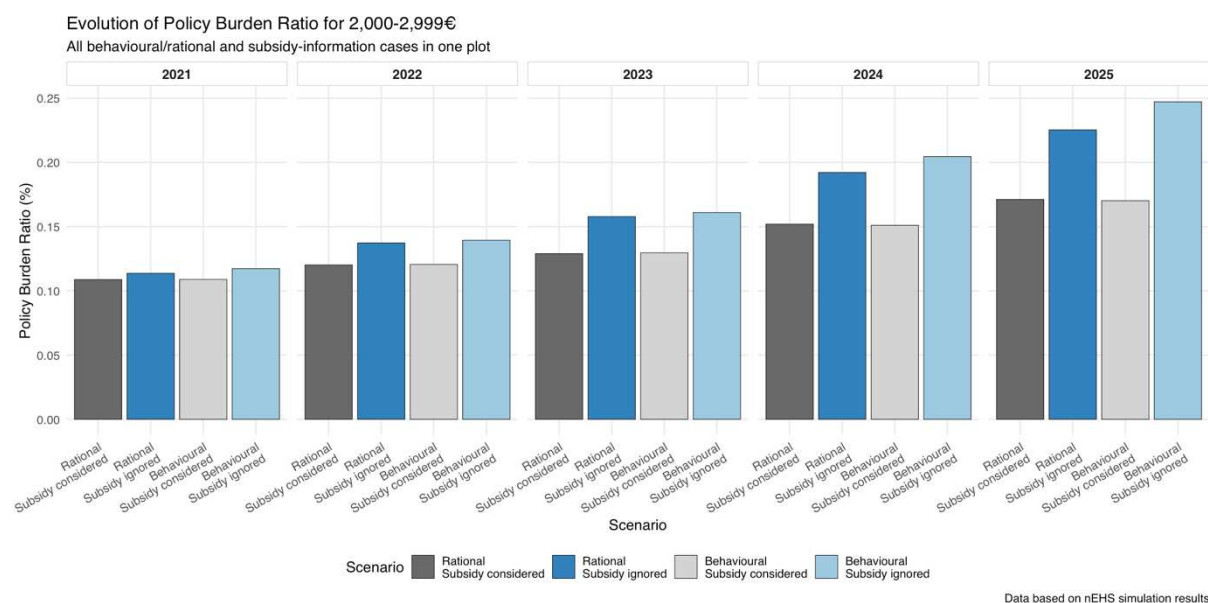


Figure 8: Evolution of Policy Burden Ratio for income class "2.000-2.999€"

Results of the Sensitivity Analysis

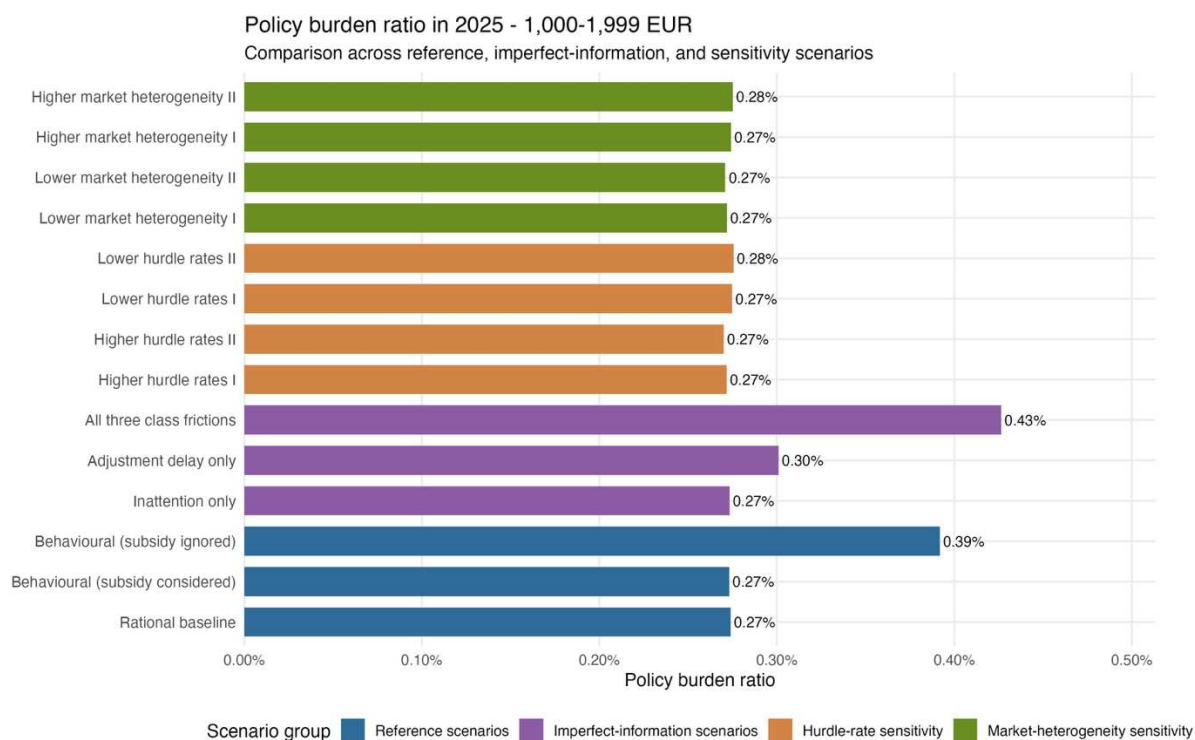


Figure 9: Policy burden ratio in 2025 for income class "1.000-1.999€"

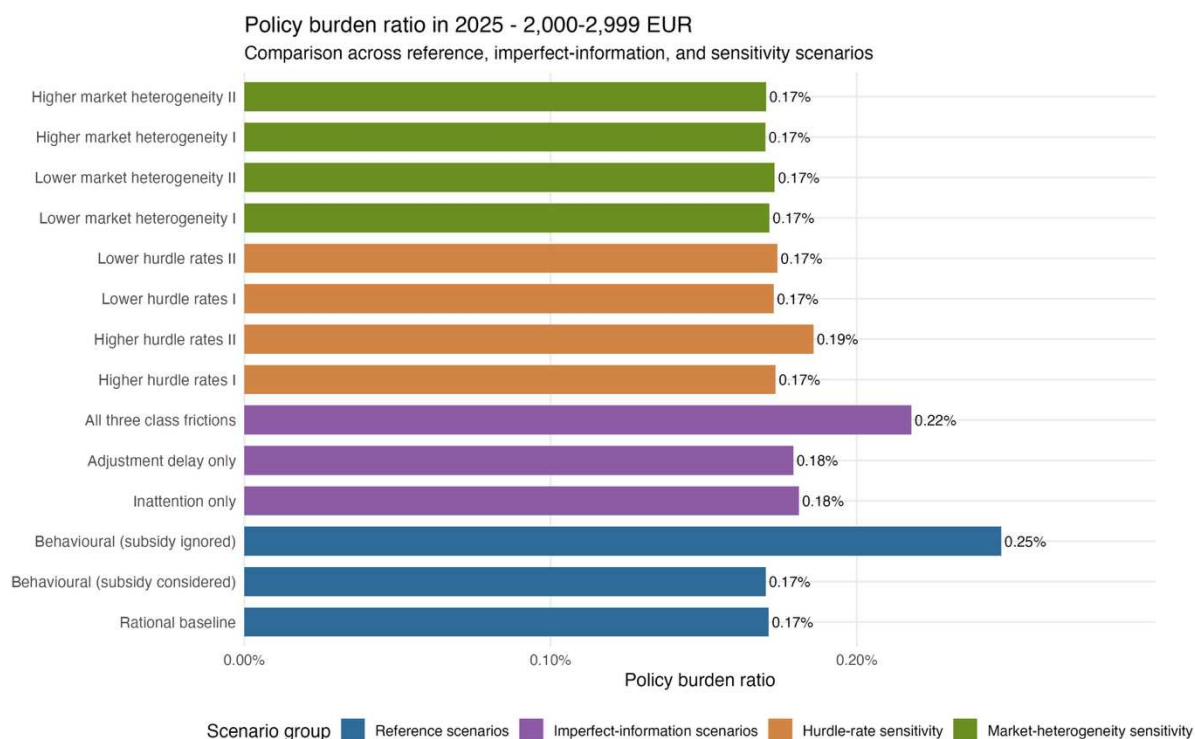


Figure 10: Policy burden ratio in 2025 for income class "2.000-2.999€"

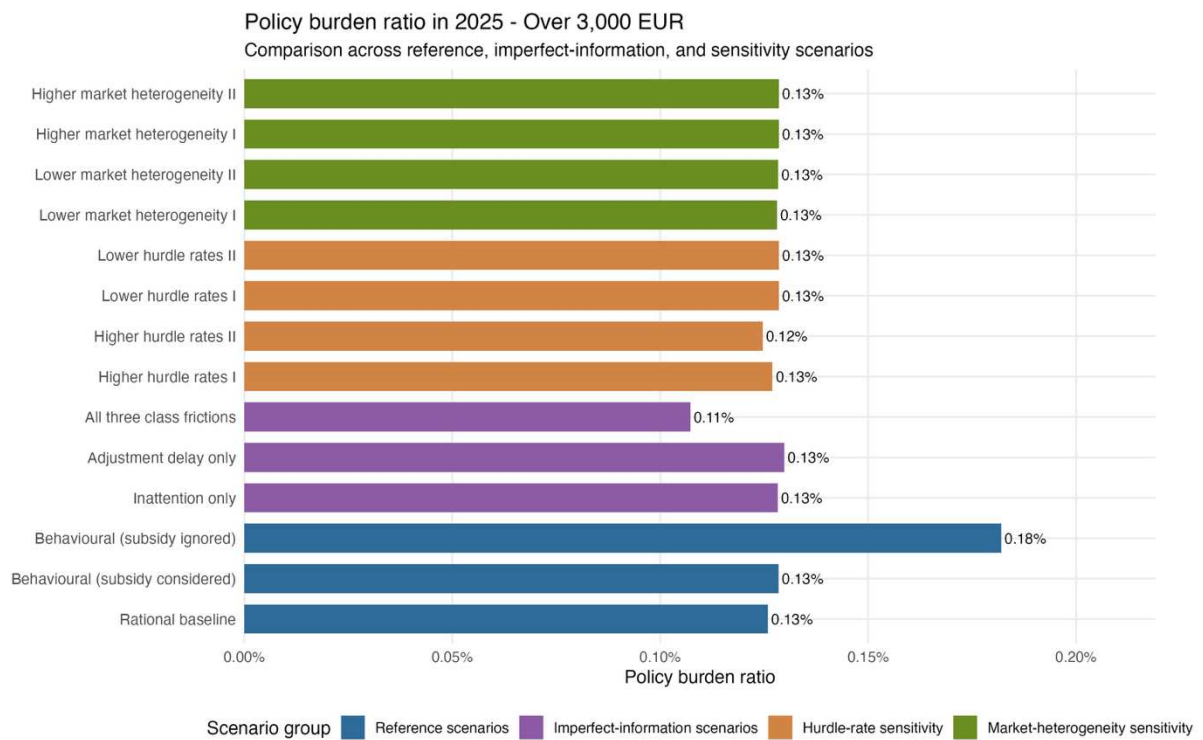


Figure 11: Policy burden ratio in 2025 for income class “More than 3.000€”

Declaration on the Use of Artificial Intelligence (AI) Tools

The undersigned Carla Wagner student ID number 904894 enrolled at Ca' Foscari in the Master's Degree Programme in Joint Degree in Sustainable Development, author of the final degree thesis "Distributional effects of Climate Policies on German Low-Income Household: Incorporating Behavioural Frictions into a Microsimulation, thesis supervisor Prof. Carlo Carraro aware of the penalties provided for in Article 76 of the Consolidated Act set out in Presidential Decree no. 445 of 28 December 2000, and of the loss of benefits provided for in Article 75 of the same Consolidated Act in the event of false or misleading statements, under his/her own responsibility pursuant to Articles 46 and 47 of Presidential Decree no. 445 of 28 December 2000,

DECLARES

that she **HAS** used generative artificial intelligence technologies to support various aspects of the research and writing of his/her final paper/degree thesis, in particular

- ☐ revision and optimisation of texts to improve clarity and coherence; DeepL, GrammarLy, ChatGPT-5.5, version released April 2026, Gemini 3.5, version released May 2026, Perplexity (no specific version available)
- ☐ generation of charts and diagrams for data presentation;
- ☐ support for the automatic drafting of sentences;
- ☐ production of illustrative images to complement the methodological section;
- ☐ other

All chapters have been optimised by at least one of the indicated AI-Tools. All of the suggestions made by AI were critically reviewed and adapted before including them in the thesis. The accuracy, quality, and reliability of AI-generated content were verified against the original academic literature or primary sources cited.

DECLARES FURTHER

that all material generated by AI has been carefully checked, reviewed and reworked by the author, who assumes full responsibility for the quality, accuracy and scientific integrity of the work.